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DISASTER RESILIENT GALVESTON

A multidisciplinary project on the design of sustainable measures to counteract coastal and pluvial flooding issues in Galveston

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A multidisciplinary project on the design of sustainable measures to counteract coastal and pluvial flooding issues in Galveston

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TEXAS A&M INSTITUTE FOR A DISASTER RESILIENT TEXAS

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Preface

Howdy, before you lies a report on the flooding issues in Galveston and a set of solutions addressing them. This report is written as part of a Multi-Disciplinary Project, which is an elective course that can be chosen within the faculty of civil engineering and geosciences. In this project students from different disciplines come together to work on a project. The disciplines represented are: Hydraulic and Offshore Structures, Hydraulic Engineering, Construction Management Engineering and Urbanism.

We would like to thank our assessors Davide Wüthrich and Luca Luorio for the opportunity to do this project, their contagious enthusiasm and guidance. We would also like to thank Bas Jonkman for providing site-specific knowledge during the early stages of the project. Thank you, Johan Ninan for your insightful tips on stakeholder engagement. In addition to this, we would like to thank Yoonjeong Lee and dr. Merelll from Texas A&M University and Bee Kothuis from the Dutch consulate for hosting us and supporting us in our project whilst in Galveston.

Abstract

The report tackles Galveston's flooding challenges, which are currently in development with the US Army Corps of Engineers (USACE) ring barrier. However, the current design, predominantly addressing coastal flooding, falls short in dealing with pluvial flooding, relying heavily on pumps. This top-down approach neglects environmental and stakeholder considerations, resulting in a decoupled response to compound flooding, lacking adaptability, and overlooking the impact of chronic flooding on local businesses. The central research question revolves around reshaping the Galveston ring barrier in The Strand area for enhanced functionality against both coastal and pluvial flooding, sustainable management of catastrophic and chronic flooding, and improved public space value.

The methodology consist of a literature review, fieldwork in 'The Strand,' stakeholder engagement in Texas, the design of multiple alternatives that deal with the issue at hand and evaluation through a Multi-Criteria Analysis. Two alternative designs, sensitive to identified issues, are presented for the Strand area. The outcome emphasizes an interdisciplinary approach incorporating the knowledge of the different academic backgrounds of the team, with designs adaptable for broader implementation in Galveston.

The design alternatives centres on measures to counteract flooding, specifically cloudburst roads, retention areas, and a promenade. Caution is advised in interpreting results, emphasizing the need for further investigation into hydraulic conditions. Climate change effects are underscored, considering sea level rise, precipitation rates, and increased hurricanes. The project area, focusing on a 1 km stretch, offers local adaptation measures, with potential extension to larger areas to explore system behaviour on a larger scale.

The study notes the uncommon implementation of sustainable drainage systems in the United States, highlighting the importance of addressing common failure causes such as incomplete knowledge and poor communication. While two measures for pluvial flooding are examined, the report suggests a more detailed design should consider additional factors like green roofs and their impact on runoff speed and drainage capacity.

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1. Introduction

1.1 General context

During the 19th century, Galveston rose to power and became one of the most prosperous cities in the Southern United States, also known as the 'Queen City of the Gulf'. Galveston owed this title to its convenient location along the Gulf of Mexico resulting in extensive port facilities and bathing resorts. However, the water which brought prosperity to the city, was also a major threat. Due to the catastrophic 1900 Galveston Hurricane, the deadliest natural disaster in US history (Galveston & Texas History Center, 2023), decimated the city and its bustling economy.

The Galvestonians however bounced back and took on a massive challenge constructing the Galveston seawall shielding the city's Gulf shoreline from storm surges. The seawall was very effective in reducing storm surge induced flooding but gave rise to other concerns. To raise the land behind the seawall, material was excavated from sandbanks located offshore, which normally dissipate wave energy. This led to increased wave impact on Galveston's beaches. Together with wave reflection due to the seawall's vertical profile this resulted in significant narrowing of recreational beaches. The seawall also created an elevation gradient across the island, draining excess rainfall to the bay-area which contributes significantly to high frequency of occurrence flooding with low inundation levels which is also known as chronic flooding.

Low frequency of occurrence flooding with high inundation levels which is also known as catastrophic flooding, was encountered during hurricane Ike (2008) and Harvey (2017) and caused respectively 24 billion dollars (Miu & Vipulanandan, 2009) and 125 billion (Amadeo, 2019) dollars' worth of damages. These damages find its origin in several sources, including wind pressure, uplift, wind- and water-borne debris impact, storm surge, waves, and rain. Notably, water-related storm damage, consisting of hydrostatic and hydrodynamic forces on structures, has been more impactful than wind-related damages in recent Gulf of Mexico hurricanes (Mosqueda, 2007). Debris impact is frequently underestimated and requires better containment (Ayscue, 1996). Regrettably, there is currently no building code for flood protection. Only empirical formulas for calculating hydrostatic and wave loads on buildings are available, often resulting in buildings not adequately designed to withstand substantial flooding (Null, 2006).

In recent years, numerous plans have been proposed to address flooding issues mentioned above, one of these plans is the Texas Coastal Resiliency Masterplan which was a direct response to the havoc wreaked by hurricane Ike. The plan is outlined a report called the 'Coastal Texas protection and restoration feasibility study' and was published in august 2021. In this plan, a system of measures is proposed to protect not only Galveston, but the complete Galveston Bay including its port and petrochemical facilities from hurricane damage. This system of measures will be referred to as the 'Ike Dike' in this report. The 'Ike Dike' consists of a system of levees, storm surge barriers, gates and fortified dunes to prevent flooding as can be seen in Appendix K figure 1 (USACE, 2021). This project will focus mainly on the problems surrounding the implementation of one of the sub-components, the so called 'Ring Barrier', which is a levee and gate system surrounding the City of Galveston designed with a crest elevation of 4.2 meters. The current 'Ring Barrier' proposal designed by US Army Corps of Engineers can be seen in figure 1.1. Texas A&M in collaboration with Dutch engineers and architects like Defacto responded to this design and published reports challenging the Ring Barrier's lack of integration in public space (Defacto, 2023) (Merell et al., 20).

Figure 1.1: ‘Ring Barrier’ system as proposed by USACE (2021).

As project area, the downtown area of Galveston bordering the bay, commonly referred to as ‘The Strand’ is chosen. The Strand is filled with bustling economic activity consisting of numerous businesses like restaurants, bars and stores but also institutions like banks, insurance companies, libraries and a medical centre. Therefore, chronic flooding has a large impact on this area as local businesses have to be closed frequently and revenues subsequently dwindle. At the waterfront, The Strand borders a cruise terminal to its West and a port terminal to its East. Between this, waterfront restaurants and several marinas hosting fishing and leisure boats are present. Throughout The Strand a multitude of well-preserved historical buildings can be found, which are usually limitedly adaptable to flooding issues due to architectural heritage legislations. In American fashion, the area contains ample parking lots and wide roads.

To the project’s interest, ‘The Strand’ has an unique interaction with the Ring Barrier’s flood wall. Currently, the land-water interaction is limited and the current ring barrier design only reduces this feature further. The waterfront has the potential to become a major economic and recreational hub if the land-water interaction is enhanced. Furthermore, the flooding issues faced in The Strand are diverse as the area is struck by storm surge and waves from the bay and excess rainfall area from the interior of the island. Therefore, the area is in need of a integrative solution that can handle variable boundary conditions, this fits in very well with the intended interdisciplinary approach.

Figure 1.2: An overview of the project area

1.2 Problem statement

The city of Galveston deals with various flooding issues, consisting of both catastrophic and chronic events, originating from coastal and pluvial sources (also known as compound flooding). To counter the extreme storm surge threat from the bay, the US Army Corps of Engineers (USACE) made a preliminary plan to construct a ring barrier around the city. However, the current design is not able to respond effectively to pluvial flooding, as it obstructs precipitation runoff and therefore relies heavily on pumps to get rid of excess rainwater which demand extensive investment, maintenance and operation efforts. Without a redesign, this barrier could disrupt the spatial land-water interaction and fail to realize its potential for enhancing the public space.

These issues associated with the current ring barrier design follow predominantly from the top-down approach many engineers use, imposing a designed upon the environment without considering the environment and its stakeholders from the very start of the design process.

Moreover, the current design's response to compound flooding is decoupled. To be more specific, distinct measures are implemented for each flooding issue. Floodwalls are for example implemented to counter coastal flooding and pumps are implemented to counter pluvial flooding which leads to low adaptability. An adaptive system is paramount to be able to cope with diverse and intensifying boundary conditions, which is relevant more than ever in today's changing climate.

Furthermore, the ring barrier plan fails to address chronic flooding without disrupting local business. Chronic flooding is usually neglected in designs and its impact on American society is underestimated as most damages are retrieved from insurance records. Once again, the combined design of floodwalls and pumps responds in the same way to catastrophic flooding as to chronic flooding. A less radical intervention would make a better fit to counter chronic flooding to ensure that business inside the barrier can proceed as usual during flooding. During redesigning focus should lie on resolving all impacts of chronic flooding and reduce the impacts of catastrophic flooding as much as possible. Designing complete protection against an extreme event would inevitably make a city unliveable.

In short, a system is needed that realizes the potential for enhancing the public space while protecting against compound flooding and is able to adapt itself to changing boundary conditions. To move the design towards this idealistic system the following core research question is addressed:

How can the Galveston ring barrier be reshaped in The Strand area to increase functionality regarding both coastal and pluvial flooding and sustainably deal with both catastrophic and chronic flooding while being integrated and valuable for the public space?

This core research question is further subdivided into three sub questions, each corresponding to a specific discipline. The research questions explored are as follows:

Hydraulic & Offshore Structures:
How can the Galveston ring barrier flood wall be reshaped by making it multifunctional and thus improve spatial value in The Strand?

Hydraulic Engineering:
How can the height of the flood wall be reduced in certain sections to allow overtopping and how can the overtopped water and excess rainfall be drained and retained in a sustainable way to prevent flooding of The Strand?

Construction Management & Engineering

What are the main stakeholder concerns regarding the Ring Barrier design in the Strand area and how can these be incorporated into the design?

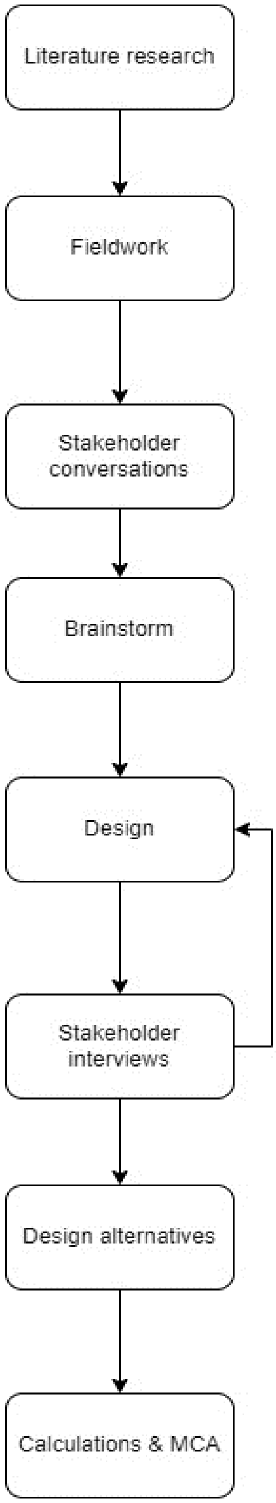
The above-described problem statement can be dismantled into a list of easy-to-assess bullet points, shown in table 1.1 The aim is to use these bullet points as guidelines throughout the report to assess the performance of individual elements and the system as a whole and reiterate accordingly.

Table 1.1:The requirements for the system design in The Strand project area

Location	Requirement
Whole project area	Functionality of the city should not be disrupted: - Disruption of accessibility of harbours for shipping should be minimized - Closure of roads should be minimized - Closing of local businesses should be avoided where possible - Barrier should not disturb loading and unloading of cruise & fishing ships Proposed interventions should be multi-purpose and resistant to changing boundary conditions.
Land-water interface	Added spatial value: - Accessibility of water should be increased - Continuous walkway along the coast - Inclusion of multifunctionality such as terraces, retention, green spaces, shops
Coastline	Protection against coastal flooding: - Protection against storm surge - Wave dissipation in front of structures
Land-inwards	Protection against pluvial flooding: - Maximized retention area - Optimize drainage capacity

1.3 Methodology

1.3.1 Procedure



The procedure that was followed began with an extensive literature review conducted before departing for Texas, aimed at gathering information on existing infrastructure, boundary conditions, elevations and historical information about Galveston. In this stadium it was opted to select the historical downtown area also known as 'The Strand' as project area. This area was chosen because diverse hydraulic boundary conditions result in compound flooding and a clear potential for development of public space is present. Once on Texan soil, a fieldwork was conducted within The Strand with emphasis on existing flood control measures. From this fieldwork it became clear what opportunities and threats lie within Galveston's urban layout.

Following the fieldwork, engagement with Texas A&M staff involved in the USACE ring barrier design took place. Their assessment led to helpful insights but above all one crucial realization – the design must safeguard against chronic flooding, an overlooked issue till this point. With these concerns in mind, the problem statement was reiterated. Next to boundary conditions for catastrophic flooding, boundary conditions for chronic flooding have been set up to assess the design's performance to frequently occurring rainfall, storm surge and waves. The idea behind separation of catastrophic and chronic boundary conditions is to design the system to resist catastrophic boundary conditions and assess performance and serviceability of the system when exposed to chronic boundary conditions.

Next, in a brainstorming phase, the knowledge gained in previous stages was put to use to generate preliminary design ideas. The approach was to be as creative as possible, based on the ideology that it's easier to make creative, innovative concepts more feasible than to make feasible, safe concepts more creative. These preliminary concepts led to the development of a series of elements that can be strategically implemented in multiple locations within The Strand, based on case studies within The Strand's 14th, 20th, and 22nd street.

In the subsequent design phase, the elements following from the brainstorming phase were combined into a coherent system which can handle variable boundary conditions. Stakeholder engagement has been an important aspect in this stage as the elements are presented to various stakeholder groups consisting of local architects, business owners and the city council. Their input and concerns have been taken into account while further developing the system and its corresponding elements. To visualize the influence of each stakeholder and organize their specific concerns, a stakeholder map has been developed.

To conclude the design phase, multiple designs have been proposed for The Strand. To make a well-informed evaluation of these alternatives, a Multi-Criteria Analysis (MCA) has been carried out. Rather than selecting a single 'best' design after evaluating, the focus shifts towards critically reflecting upon the strengths and weaknesses of each alternative. Ultimately, the choice of a final design is heavily influenced by political considerations and is inherently subjective. Therefore it is chosen to leave this decision outside of the scope of this project, the reader can judge him/herself which measures fit in the environment most adequately.

1.3.2 Elaboration stakeholder engagement

Additionally, stakeholder concerns were taken into account when talking to involved parties. During the period in Texas, multiple interviews and natural conversations were conducted, gaining insights in the concerns of locally based parties and other parties involved. The conversations are labelled in table 1.2 A distinction is made in interview/conversation rounds. The first round is done before any design ideas were made, purely focussing on gaining information about the issue at hand. The second round was done after making design ideas and focussed on gathering insights on how local stakeholders would respond to these ideas. First round conversations were mainly natural, following no predesigned structure. For stakeholders only interviewed in the second round, he structure of these interviews was as follows. First, after a brief introduction of the project, stakeholders were asked about the current situation and how they were affected by it. Next, they were asked about the way the situation was dealt with and how they would like to see the solution. After getting them to think about the situation and possible solutions, they were faced with the design ideas the team came up with and asked about their thoughts on this.

Table 1.2: Interviews/conversation rounds

Serial number	Stakeholder organization	Date	Duration	Round	Additional info
1	Texas A&M professor	27/9/23 to 18/10/23	5 hr	1 & 2	Multiple conversations bundled
2	City council	10/10/2023	2 hr	2	
3	Local inhabitants	1/10/23 to 5/10/23	72 min	1 & 2	Multiple conversations bundled
4	Local restaurant owner 1	4/10/23	20 min	2	
5	Local restaurant owner 2	4/10/23	15 min	2	
6	Local business owner 1	5/10/23	90 min	2	
7	Local business owner 2	27/10/23 & 18/10/23	3 hr	1 & 2	Multiple conversations bundled
8	Local bar owner 1	4/10/23	20 min	2	
9	Local bar owner 2	4/10/23	30 min	2	
10	Texas A&M Students	27/9/23 to 18/10/23	2 hr	1 & 2	Multiple conversations bundled

After the first round conversations, the gathered information was taken into account when creating the first design ideas and iterating the problem statement. The problem statement needed to be iterated, since there were some issues that came forward in these conversations that were unknown/unthought of before going to Texas. After the second round of interviews, the gathered feedback on the design ideas were incorporated in the design, based on the legitimacy of these stakeholder concerns as well. This process is visualized in Figure 1.3.

1.3.3 Contextualisation

Next to answering the research questions, the broader aim of this project is to propose a series of elements that serve as a paradigmatic symbol to demonstrate that integrated spatial design is a viable alternative to a top-down approach. As the chance that these proposed elements will be genuinely implemented in Galveston is marginal, this project should serve as a design exercise in which a toolbox is developed which is applicable for a multitude of coastal cities worldwide facing similar problems as Galveston. Think of Tokyo, New York, Mumbai, Jakarta, Shanghai, Cairo and Miami which are all (and in increasing matter) in need of solutions like these (Hanson et al., 2010). It has become clear that the rising cost of flooding is not a problem that can be solved with technical solutions alone, but in combination with a change of thinking from engineers, urban planners, economists, policy makers and all others involved. This paradigm shift is not obvious but requires extensive collaboration between the aforementioned disciplines.

The interdisciplinarity of this project is used a strength instead of a weakness by being receptive to new insights from other disciplines and actively using these ideas in the design process. Generally, engineers want to jump right into the design without considering the urban environment, resulting in a top-down approach. From the urbanism perspective, an analysis is conducted to make sure the design will fit into the environment both spatially and culturally. From the CME (Construction Management Engineering) perspective, the top-down approach is avoided by incorporating stakeholder concerns to guarantee the design is not imposed on the involved parties. From the HE (Hydraulic Engineering) & HOS (Hydraulic & Offshore Structures) perspective, knowledge about flooding and technical feasibility is provided. It was encouraged to work outside of the usual student's discipline and therefore learn from other disciplines.

As this project is part of a broader exchange of knowledge between the Netherlands and Texas there should be an awareness in which ways our project contributes. The aim is to bridge different academic backgrounds within our group but also bridge the different academic and cultural backgrounds within the whole project. This goal is pursued by regularly presenting ideas to Texas A&M students and staff and process their perspectives into the design but also discuss informally to get a grasp of the general paradigm. One large contributing factor is the difference in reducing the damages caused by disasters, which can be represented as the product of the consequences when a flood happens and the probability that a flood occurs: **"risk = consequences x probability"**. Typically, the Dutch approach focuses on reducing the likelihood of flooding whereas the American approach emphasizes the mitigation of consequences. In this report a combined Dutch-American approach is applied and risk is reduced by considering both consequences and probability.

2. Analysis

In this chapter, relevant existing research literature on the topic of Galveston flooding is discussed as well as data gathered while in Texas. The data and information consist of elevation and soil details, storm surge and precipitation data, tidal conditions, an evaluation of existing flooding measures in Galveston during fieldwork, and a comprehensive stakeholder analysis. These aspects will be discussed sequentially in the following sections.

2.1 Elevation and soil conditions

For the elevation data, 2 datasets have been used. First a digital elevation model (DEM) from NOAA, this dataset looks at the ground elevation without taking structures and roads into account. Secondly a lidar model from NOAA was used. This dataset looks at the elevation from datapoints that considers structures and road surfaces. The first dataset was used to gain an insight into the general elevation for the entire island, the latter dataset was used in the design and when detail was important.

The elevation along the waterfront at the Strand is determined from 2 datasets provided by NOAA. The first dataset contains the height of the ground level with regards to the mean high water, which will be referend to as the Digital Elevation Model (DEM). A plot of this dataset can be seen in figure 2.1.

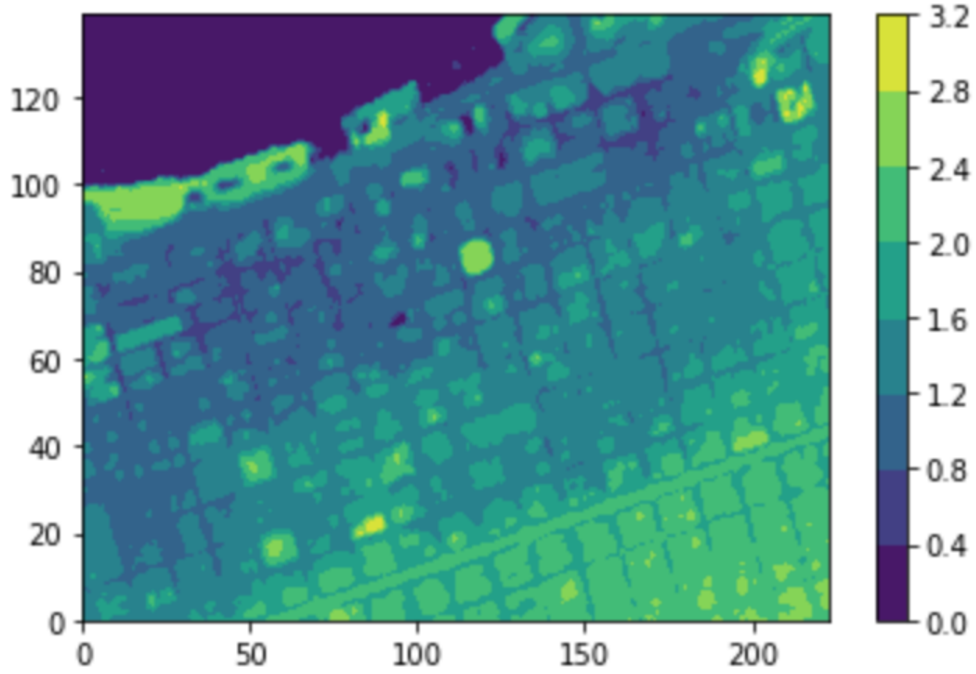


Figure 2.1: Elevation map for the Strand, height in meters in regard to MHW. The MHW is 0.309 m above the NAVD88 for a datapoint in front of pier 21 (NOAA, 2023b).

The second dataset used is the 2018 TWDB Lidar DEM and takes into account structures built. This dataset is used for cross-sections of market street, mechanic street, the Strand and boulevard drive. This can be seen in figure 2.2.

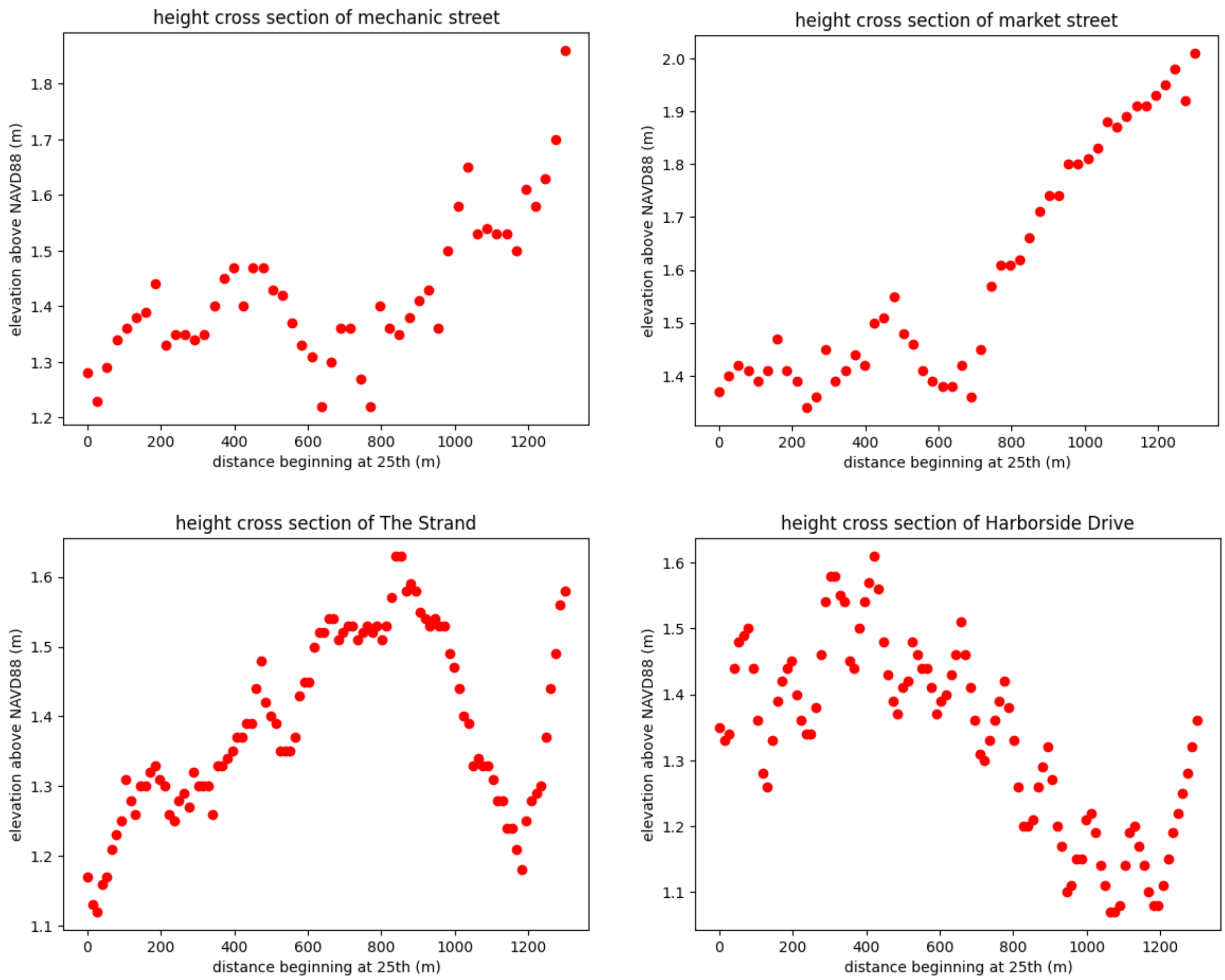


Figure 2.2: Height cross sections of Harborside drive, The Strand, Mechanic Street and Market Street. At x = 0, the location of 25th street and at x=1400 the location of 14th street.

Galveston is situated on a barrier island. In natural conditions these barrier islands are regularly flooded by sea water during storms. The Galveston series consists of mostly fine sand from the surface to about 3 to 5 meters below the surface. These fine sands are drained and have a high permeability. The groundwater table under normal conditions is usually situated about 76 to 122 centimetres below the surface. During severe storms or high tides, the groundwater table approaches the surface for a period of a few days in some areas (USDA, 2020).

After the first layer of sand there are a series of clay and sand layers. For the construction of the second cruise terminal, which is near the strand, a geotechnical investigation found the following geotechnical profile in table 2.1.

Table 2.1: Geotechnical profile under cruise terminal 2 (HVJ ASSOCIATES INC, 2014)

Soil	From	to
Sand with silt/silty sand (SP-SM) (SM)	surface	2.4 to 4.9 meters
Soft to stiff clay (CH)	2.4 to 4.9 meters	17.7 to 20.7 meters
First to Stiff lean clay (CL)	17.7 to 20.7 meters	24.4 meters

2.2 Hydraulic boundary conditions

2.2.1 Tidal conditions

The water level in the bay has great influence on how much water can be discharged in the bay. The bay water level varies daily due to tidal effects, hence the energy head gradient for which passive drainage without pumps is required depends predominantly on this tidal effect. Moreover, chronic flooding is predominantly determined by tidal conditions. Coastal flooding in Galveston is relatively severe during the highest spring tide of the year, popularly named 'King Tide'. Of course there are other factors like wind and wave set-up in play but the tidal component is the biggest contributor to frequently occurring high water levels.

Figure 2.3 visualizes datum levels that can be used as a reference point for either water levels or ground elevations. All heights and elevations in this report will use NAVD88 as a datum. This is the conventional reference level in American literature, comparable with NAP in the Netherlands. In this figure the absolute datum is MLLW (Mean Low Low Water).

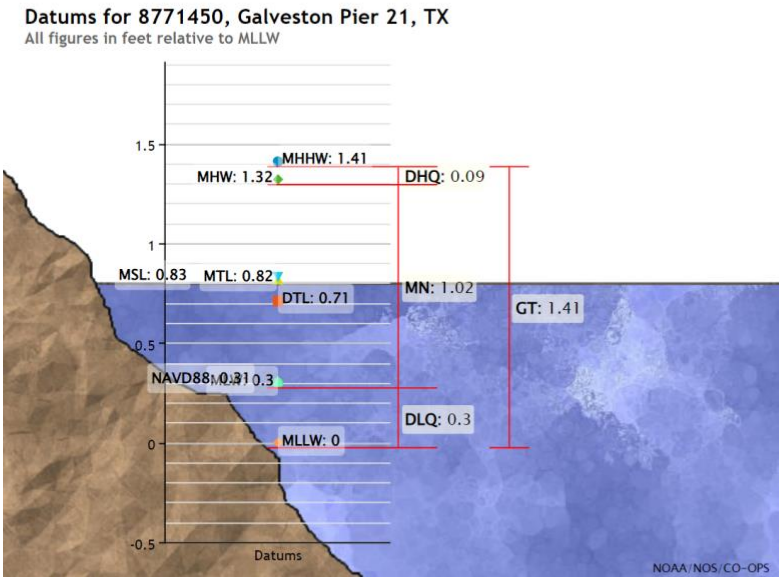


Figure 2.3: Water level datums for tidal station Galveston Pier 21 (NOAA 2019).

In figure 2.4, the tidal signal measured at a buoy within the project area (Pier 21) is depicted. It can be seen that the tide is predominantly diurnal (one high tide and low tide a day) around spring tide but becomes semidiurnal (two hight tides and low tides a day) during neap tide. From the same NOAA dataset it was retrieved that the highest tidal water level in 2023 was +0.71 m NAVD88.

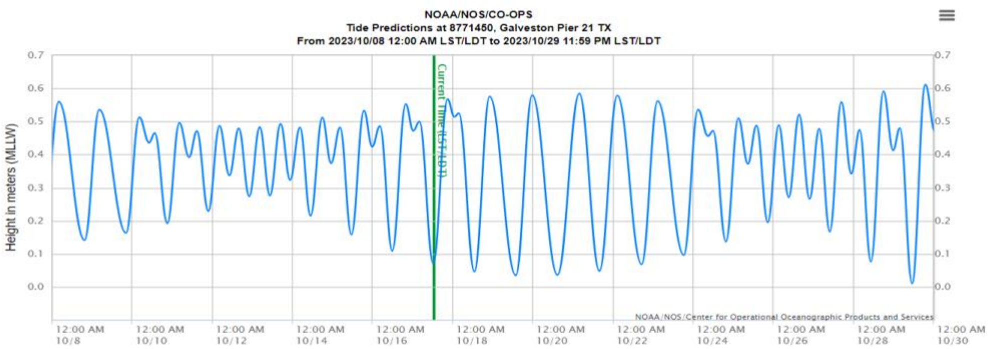


Figure 2.4: Tidal predictions for tidal station Galveston Pier 21 (NOAA 2023).

2.2.2 Precipitation

To design a system that can handle excess precipitation adequately, there should first be a comprehensive understanding about how this excess precipitation moves through the system. This can be separated in the following fluxes and storage: input (flux), infiltration (flux), conveyance (flux) and retention (storage). The precipitation rate is the input, all water that does not get infiltrated in the soil has to either be conveyed on the street or in a drainage channel. Next, the conveyed water has to move either to the bay or has to be retained within the system when water levels in the bay are too high. This process is schematized and visualised in figure 2.5.

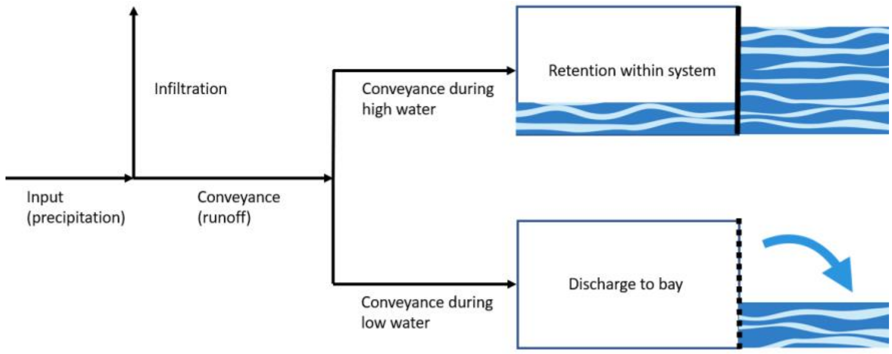


Figure 2.5: Visualisation of excess precipitation fluxes and storage.

This system has three bottlenecks, either the infiltration capacity, conveyance capacity or the retention capacity is too low. The infiltration and conveyance capacity will be designed on a short peak of extreme precipitation (1-hour event, 100-year return period). The retention capacity will be designed on a longer sustained period of extreme precipitation (6-hour event, 10-year return period) . To retrieve these design precipitation rates a weather station located in The Strand is used. NOAA (2023e) has defined 6-hour and 1-hour rainfall intensities per return period. From figure 2.6 a precipitation rate of 1.8 inch/hr or 46 mm/hr (6-hour duration and 10-year return period) and 5 inch/hr or 127 mm/hr (1-hour duration and 100-year return period) are retrieved. For chronic flooding a frequently occurring 1-hour duration precipitation rate of 1.8 inch/hr or 46 mm/hr with 1 year return period is retrieved from figure 2.6.

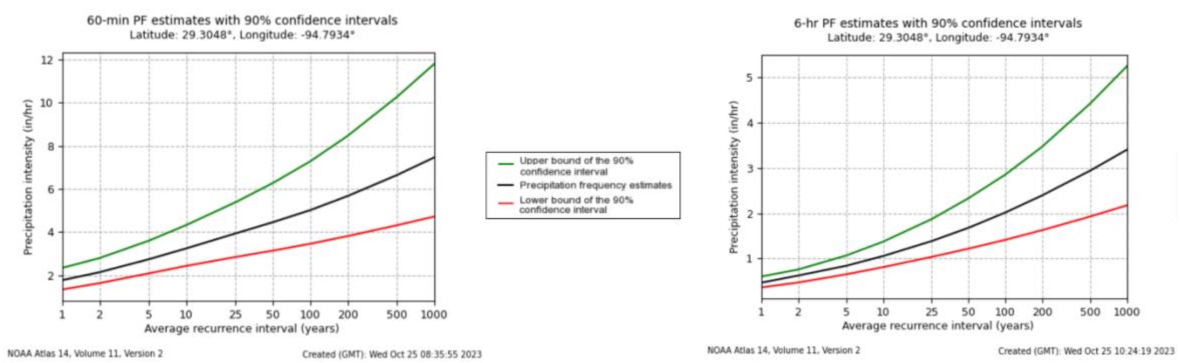


Figure 2.6: Extreme values precipitation for a 1-hour 6-hour rain event

To conclude, 46 mm/hr will be used as an extreme 6-hour precipitation rate and 127 mm/hr will be used as an extreme 1-hour precipitation rate. These conditions correspond with catastrophic flooding. Furthermore, 26 mm/hr will be used as an frequently occurring 1-hour precipitation rate. This condition corresponds with chronic flooding.

2.2.3 Extreme water levels and wave heights

The biggest contributor to extreme water levels is storm surge, high winds over a long fetch result in water being pushed to shore. On top of other components like high tide, wave set-up, barometric set-up and Coriolis set-up (Stoeten, 2013) this result in extreme water levels. Catastrophic coastal flooding is mainly tied to the hurricane storm surge resulting in these extreme water levels. Chronic coastal flooding, on the other hand, is predominantly a result of high tide with moderate wind and/or wave set-up.

For catastrophic flooding, two locations are of importance: The Strand and the seawall. For The Strand, which coincides with location 17276, Merell et al. (2021) used an extreme water level of 3.14 meters above NAVD88 combined with a significant wave height of 1.17 meters which are based on a hurricane with a 100 year return period. The values with a 90% Confidence Interval has been chosen because some conservatism is desired. These numbers including confidence intervals can be found in table 2.2 . When comparing with the extreme value analysis conducted by USACE (2021) in figure 2.7, the values from Merell et al. (2021) underestimate extreme water level with 1.43 meter. This can be explained by the fact that The Strand lies in the relative sheltered Galveston Channel. Therefore, it receives less storm surge than the location directly on Galveston Bay used in USACE (2021).

To conclude, +3.14 meter NAVD88 will be used as an extreme water level and 1.17 meter will be used as an extreme significant wave height at The Strand. These conditions correspond with catastrophic flooding.

Table 2.2: Storm surge and wave data from the Texas A&M response to the USACE Ring Barrier design (Merell, 2021)

Point	**WSE (m NAVD88) – 50 % CI**	**WSE (m NAVD88) – 90% CI**	**Hs (m) – 50% CI**	**Hs (m) – 90% CI**
17276 (The Strand)	2.53	3.14	1.00	1.17

Figure 2.7 Location of extreme water level data measurement points (Merell et al., 2021)

On the seawall, higher extreme water levels and wave heights are expected due to larger fetch distances. From figure xxx an 100-year return period extreme water level of +5.18 meter NAVD88 can be read. Ebersole et al. (2015) analyzed wave conditions just offshore of the seawall for different proxy storms. Root mean squared wave heights corresponding with this analysis can be found in figure 2.8. A root mean squared wave height of 5 meters follows. Converting to significant wave height requires multiplication by 1.4 (Holthuijsen, 2007), this results in $H_s = H_{rms} \times 1.4 = 7$ m.

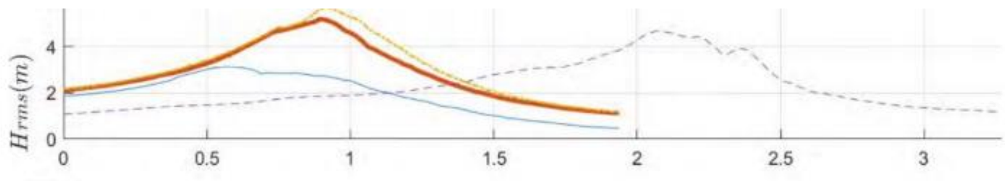


Figure 2.8: Wave conditions offshore of Galveston seawall, orange line depicts the 100 year proxy storm (Ebersole et al. (2015).

To conclude, +5.18 meter NAVD88 will be used as an extreme water level and 7 meter will be used as an extreme significant wave height at the Seawall. These conditions correspond with catastrophic flooding.

For chronic flooding, only data from The Strand is relevant because it is assumed there will be no overtopping at the seawall during chronic flooding that can reach The Strand due to the downward slope. As discussed in section 2.3.1, the highest forecasted tide within the year 2023 is +0.71 m NAVD88. To check if this is a realistic design water level, figure 2.9can be consulted and the extreme water level for a 1 year return period is +0.76 m NAVD88. This is within reasonable limits.

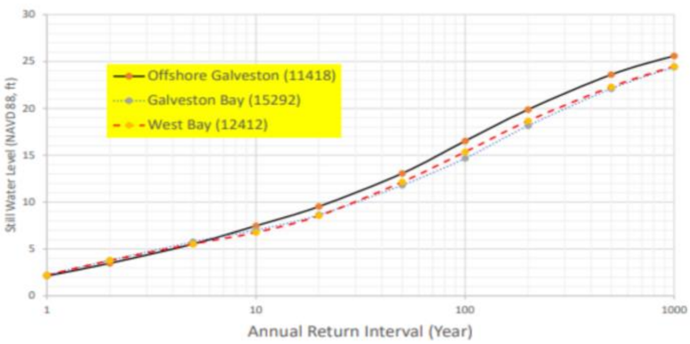


Figure 2.9: Extreme water levels for different locations per return period (USACE, 2021)

Wave data retrieved from location near The Strand are very sparse. Corson et al. (2002) retrieved spectral wave data for one month (February 1997). H_{m0} reached Significant wave height H_{m0} reached 0.5 m a couple of times in this month, thus this will be used as a frequently occurring design wave height. obtained by integration of the variance spectrum can be assumed to be equal to the significant wave height H_s obtained directly from the surface elevation time series (Holthuijsen, 2007).

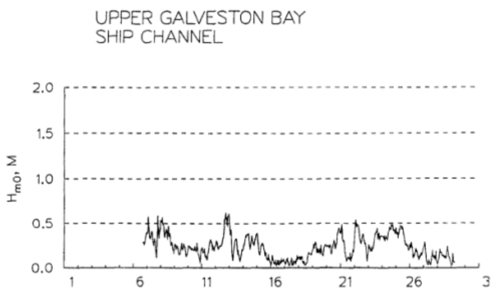


Figure 2.10: Spectral significant wave height H_{m0} during February 1997 (Corson et al., 2002).

To conclude, +0.71 meter NAVD88 will be used as a frequently occurring high water level and 0.5 meter will be used as a frequently occurring significant wave height at The Strand. These conditions correspond with chronic flooding.

2.3 Boundary conditions: scenarios and system response

To effectively arrive at a design that is able to fulfil the problem statement it should be very clear which boundary conditions the set of measures is designed to withstand and which boundary conditions can occur together and which cannot. As previously stated, the design should resolve all issues surrounding chronic flooding while functions within the city are maintained. For catastrophic flooding, the goal is to relieve issues but completely resolving these issues is not expected. In essence, the chronic flooding conditions will be viewed as the Serviceability Limit State (SLS) at which point the system can't maintain basic serviceability anymore. The catastrophic flooding will be viewed as the Ultimate Limit State (ULS) at which point the system fails as a whole. As a result, from now on there will be referred to respectively SLS or ULS conditions when discussing chronic or catastrophic flooding.

The first step in the process of retrieving ULS conditions is to understand which type of hurricanes could make landfall close to Galveston and what magnitude of storm surge, wave heights and rainfall rates coincide with these hurricane scenarios. Hurricanes can either make landfall West, East or directly on the Galveston coast. Due to the counter clockwise spinning on the Northern hemisphere caused by Coriolis (Stansfield, 2009) the storm surge and wave height at Galveston's waterfronts depends on the location of landfall.

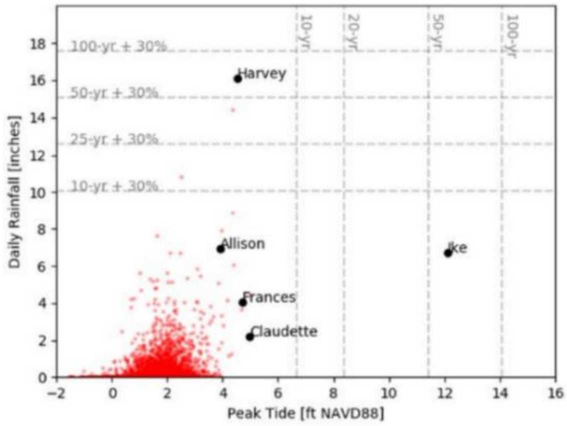


Figure 2.11*1*: Correlation extreme daily rainfall and extreme water level (USACE, 2021)

The three hurricane scenarios that are considered are:

1. **West landfall,** resulting in strong winds combined with large fetch coming from the Gulf and therefore 100-year extreme water levels and wave heights at the seawall side. On top of this, 6-hour duration 10-year precipitation rate that challenge retention capacity can occur.
2. **East landfall**, resulting in strong winds coming from Galveston Bay resulting in 100-year extreme water levels and wave heights at The Strand. These will be less due to the shorter fetch and relative sheltering of The Strand within the Galveston Bay and Channel. On top of this, 6-hour duration 10-year precipitation rates can occur which challenge retention capacity.
3. **Galveston landfall.** If the eye of the hurricane moves over Galveston and in a worst-scenario stalls above Galveston. This scenario would result in an extreme 1-hour duration 100-year precipitation rate and lays a heavy burden on the drainage system and challenges conveyance capacity. In addition to this moderate storm surge heights will occur. The likeliness of extreme storm surge and extreme precipitation occurring simultaneously is very low as discussed by USACE (2021). This is visualized in figure 2.11, where it can be seen that for lower values, storm surge and precipitation are positively correlated whereas for higher values these variables are not correlated anymore.

The ULS/catastrophic boundary conditions retrieved in sections 2.3.2 and 2.3.3 can be instantly translated to these hurricane scenarios. The mentioned extreme water levels and wave heights at the seawall coincide with a **West landfall** hurricane. The mentioned extreme water levels and wave heights at The Strand coincide with an **East landfall** hurricane. The mentioned extreme 6-hour and 1-hour precipitation rates coincide with a **Galveston landfall** hurricane.

A visual overview of how these hydraulic boundary conditions depend on hurricane scenarios can be seen in figure K.2. This figure was frequently used in early project stages to understand and present scenarios.

In contrast to the ULS conditions, the SLS conditions can all happen simultaneously as they frequently occur and are not bound to a single event like a hurricane. Thus, the SLS/chronic flooding conditions regarding precipitation rates, water levels and wave heights retrieved in sections 2.3.1 up to 2.3.2 are expected to all happen simultaneously.

The idealistic response mechanisms that are needed from the flexible system design can be seen in figure 2.12, where ξ depicts water level, H_s depicts significant wave height and p depicts precipitation rate. The system response mechanisms are shown both for ULS and SLS conditions. There are three different response mechanisms that can be integrated in one system.

- Top left shows the desired response mechanism when only pluvial flooding threatens Galveston, the system should stay open to maintain functions inside Galveston.
- Bottom right shows the desired response mechanism when only coastal flooding threatens Galveston, the system should close to keep water outside.
- Top right shows the desired response mechanism when compound flooding threatens Galveston. In this situation, gates should close but excess precipitation can therefore not drain to the bay. Sufficient retention capacity should be implemented within the barriers to store water locally.

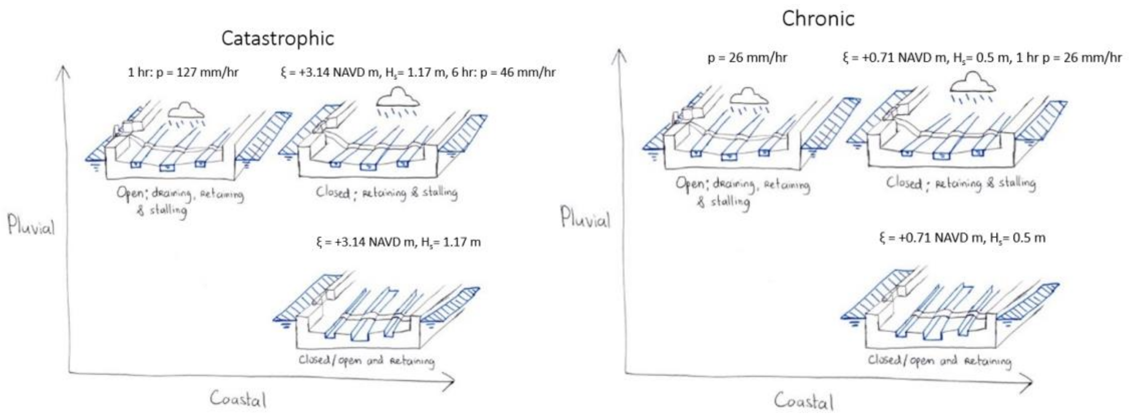


Figure 2.12 Idealistic system response mechanism to various hydraulic boundary conditions

It should be realized that this data analysis is not state of the art. However, the relevancy of this project lies not in how boundary conditions are retrieved but how these are used within the design process. In essence, significantly different numbers could be used and the design process and accompanied paradigm shift would not change significantly.

To conclude, the relevant assumptions are documented in table 2,3 to clearly display which structural and hydraulic boundary conditions are used in the design process.

2.4 Overview boundary conditions

Table 2.3: Assumed structural and hydraulic boundary conditions used in design process

What?	Where?	When?
Barrier modifications		
3.2 km long storm surge barrier 6.55 m above NAVD88	Galveston – Bolivar Gap	Built within 50 years
51.5 km of dune and berm segments, 4.26 m above NAVD88	West Galveston and Bolivar Peninsula	Built within 50 years
Ring barrier system of 4.27 m around City of Galveston	Around City of Galveston	Built within 50 years
Modification of Galveston Seawall to accommodate 6.4 m of storm surge	Entire current Galveston Seawall	Built within 50 years
ULS conditions		
1 hour precipitation rate of 127 mm/hr during Galveston landfall hurricane	Within the whole Ring Barrier	Return period of 100 years
6 hour precipitation rate of 46 mm/hr during East or West landfall hurricane	Within the whole Ring Barrier	Return period of 10 years
Storm surge of 3.14 m above NAVD88 during East landfall hurricane	At point 17276 (The Strand), see figure 2.7 for exact location	Return period of 100 years
Significant wave height of 1.17 m during East landfall hurricane	At point 17276 (The Strand), see figure 2.7 for exact location	Return period of 100 years
Storm surge of 5.18 m during West landfall hurricane	At Seawall, exact location: Pleasure Pier	Return period of 100 years
Significant wave height of 5 m during West landfall hurricane	At Seawall, exact location: Pleasure Pier	Return period of 100 years
SLS conditions		
1 hour precipitation rate of 26 mm/hr	Within the whole Ring Barrier	Return period of 1 year
King tide, highest tidal water level of the year of +0.71 m NAVD88	At point 17276 (The Strand), see figure 2.7 for exact location	Return period of 1 year
Wave height corresponding with chronic flooding of Hs = 0.5 m	At point 17276 (The Strand), see figure 2.7 for exact location	Return period of 1 year

2.5 Fieldwork

2.5.1 Description Fieldwork

During the workshop a fieldwork-trip was done to familiarize with the environment that is investigated. The area that was focused on during the workshop is the Historic district The Strand. A section from the strand was taken that stretches from 14th to 25th street, which is approximately 1 kilometre in length. The area was taken 3 blocks land-inward from the sea-side. An overview of the area can be seen in Figure 1.2

During the fieldwork sketches were made of the cross-sections of the streets, so that later these can be used to evaluate if certain measures can be implemented in the area. It was also investigated which measures are already taken in the area to protect The Strand from floodings in the past. An overview of these measures can be found in section 2.8.2.

2.5.2 Existing Measures

The measures that are already taken in the project area are listed in table C.1, appendix C and are categorized by function, material, typology and scale.

The fieldwork showed that there are a lot of measures to prevent- or adapt to mostly chronic flooding. However, these measures have all been implemented very locally and work on a small scale to limit chronic flooding, they do not really work as a system. Moreover, the measures are mainly focussed on adapting to chronic flooding rather than preventing it. This essentially means the people have accepted that the area will flood on a frequent basis.

It was also concluded that there are a lot of opportunities to further extent and improve these measures. Furthermore, multiple threats were identified that could limit the capacity of the system, such as drainage points that are clogged with debris. This was not only the case in the project area, but in the whole of Galveston. Also, not all electrical facilities were heightened to prevent them from flooding during chronic and catastrophic events. This could have severe consequences as it could lead to power outages or gas leaks. A few examples of this can be found in figure 2.13.

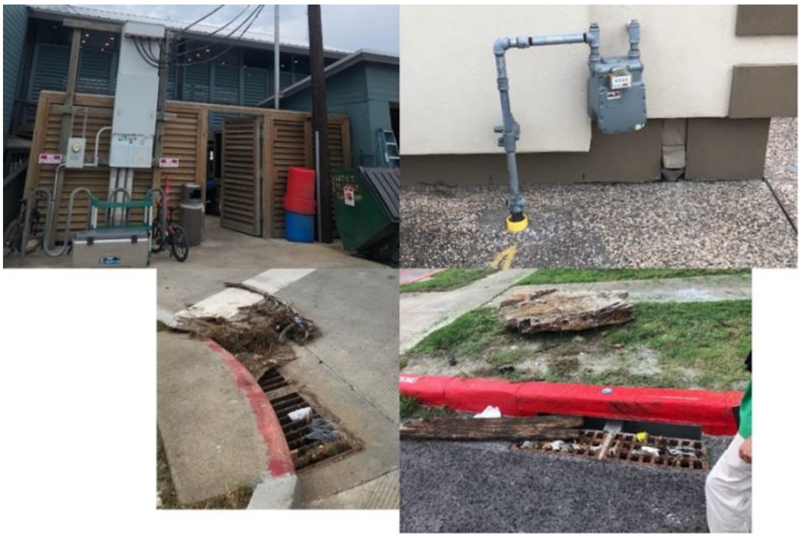


Figure 2.13: Some threats encountered during the fieldwork. Clockwise from top left to bottom left: exposed electric facilities, exposed natural gas pipeline, larger debris and plastics clogging drainage, palm leaves and plastics clogging drainage.

2.5.3 Connection land and water (with pictures)

Another opportunity that arose from the SWOT-analysis was the fact that there is quite some room at the water-land interface to implement measures here. An overview of a few places that are interesting can be seen in figure 2.14.

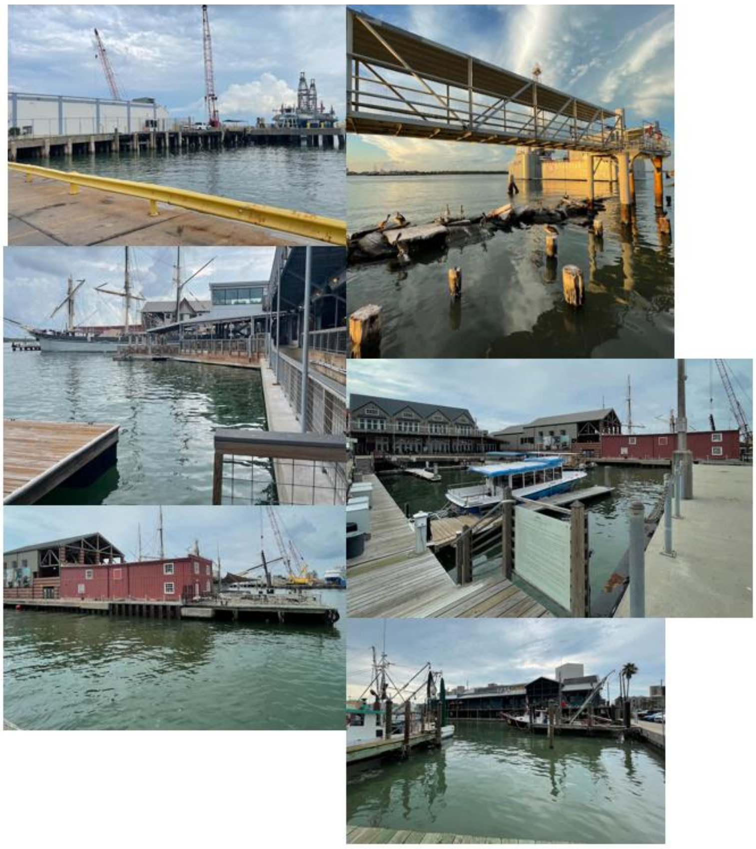


Figure 2.14: The connection between land and water in The Strand

It can be seen that the water is not really used as a resource but is rather seen as an obstacle. It would be very interesting to take this into account into the design stage. This could be done by implementing multifunctional measures that add spatial value to the coast, for example by providing possibilities for recreation. This could be done by making the water more accessible for pedestrians.

2.5.4 Evaluation fieldwork

The fieldwork was very useful to get an impression of the project area. It is very easy to get an idea of the dimensions of buildings and the size of the area. This can be used to get a feeling if the dimensions allow certain new measures to be implemented. There were also a lot of adaptive and preventive measures that had already been taken to reduce flood risk. When looking at the engineering behind the landscape, one of these measures is further zoomed into. This is the drainage system that currently drains the pluvial water in Galveston. A sketch can be found in Appendix C Figure C.1.

The most important outcome of the fieldwork are the strengths, weaknesses, threats and opportunities that are identified in the area. These are tabulated in a SWOT format and visualized in table 2.6

Table 2.6: The SWOT-Analysis is first performed on the project area in The Strand

Strength - Large sewage holes provide drainage capacity - A lot of pavements in The Strand area are elevated by approximately 0.30 m, protecting against floods from overtopping - Streets have high curvature, which helps with drainage - A lot of buildings, industry, roads and railroads are elevated to prevent them from chronic flooding	**Weakness** - A lot of concrete is used for the surface of for example parking lots, therefore high discharge peaks occur frequently - Elevation gradient from South to North along the island, therefore the project area is the most low-lying area and runoff water flows towards here - Almost no coastal protection measures have been taken - Buildings near the coastal area have not been elevated and/or not flood proof and water tight
Opportunity - Possibility to expand economical area of historical district - Plenty of unused land that can be developed - A lot of parking lots that can be used for water retention - Cruise terminal, possibility for economic development - There is a lot of room at the water-land interface to implement measures - At the bay side of 20th street there is already a small levee that can be extended - At some locations there are small green areas that could be extended to make floodable parks - Old historical buildings are usually overdesigned, allowing for greens roofs. Moreover, the facades cannot be changed but the roofs can.	**Threat** - Sewage holes are not cleaned sufficient and permanently blocked by debris - Economic activities will reduce due to increased flooding in future - Water damage to power cables

An example of an important opportunity which occurs frequently are parking lots which can be used for water retention. Some parking lots also contain walls around them to limit access to vehicles. These walls could be an opportunity by either extending the walls and thus creating a flood barrier or substituting the walls with temporary flood barriers which can be moved to places where needed in case of flooding. Next to this, at 20th street there is a small levee that now mainly functions as a decorative piece. This levee could be extended to create a flood barrier. Moreover, there are extensive stretches of undeveloped land at the borders of The Strand which can be used to combine water retention and spatial value. A striking example is the mystique-surrounded Maison Rouge located right on Harborside Drive, this place was once the home of famous pirate Jean Lafitte but is now left deteriorated with only one landmark sign. This place has potential to be transformed in an attractive green area with historic, recreational and flood-protective value. Lastly, there are several locations where green areas are present that have the possibility to be extended. A visualization of the opportunities mentioned above can be seen in figure 2.15.

Figure 2.15: Some opportunities encountered during the fieldwork. Clockwise from top left to bottom left: discontinuous parking lot walls at The Strand, discontinuous parking lot walls at port area, abandoned foundation at undeveloped terrain, historical landmark surrounded by undeveloped terrain.

Based on the SWOT analysis outcome, two areas can be identified where weaknesses and opportunities occur simultaneously a lot and can be combined. The first area that comes to mind is 20th street. At the bay side of this street there are almost no coastal protection measures. There is however a small decorative levee. This levee provides an opportunity for green coastal protection, as it could be adapted to protect against storm surges. Further land inwards at 20th street, there are multiple parking lots which provide opportunities for water retention. Also, there are already some small green spaces in this street which could be further developed to make them into floodable parks.

22nd street is a good candidate for the implementation of a drainage facility. The elevation of 22nd street is relatively low in comparison to other roads in the Strand. In addition to this, at the end of 22nd street there is parking lot at the waterfront which can be converted into an outflow of the drainage. The consequences of removing the road for car traffic at 22nd street are relatively minor because there are not too many businesses along this road. Furthermore, there is also enough parking along 22nd street available to cope with the removal of street parking.

2.6 Stakeholder review

This chapter focuses on the stakeholders active in this phase of the ring barrier project. That means that stakeholders are discussed whom have a direct interest in the design of the project. First, a Salience model is created to visualize the different kinds of stakeholders active and to indicate the power, urgency and legitimacy they wield in the project. Next, the concerns of these stakeholders is discussed and ways to take these concerns into account are elaborated.

Stakeholder diagram

In the project, multiple stakeholder(-groups) are involved. The stakeholders identified are presented in table 2.7, together with their main concerns and position on the Salience model diagram.

In this power/interest grid, multiple stakeholders are placed based on regulatory power (for governmental bodies) and influence one can exercise, as well as presumed interest in the issue stated in the problem statement. These stakeholders are elaborated in the table 2.7.

Table 2.7: Stakeholders

Pictogram in diagram	Stakeholder name	Main concern	Position Salience model	Additional info
	City of Galveston	Protecting the city of Galveston the most feasible way, keeping inhabitants involved with the design process	7	
	State of Texas	Making sure Galveston and inland areas are protected while economic activities can continue the most possible	4	
	United States Army Corps of Engineers	Creating a feasible solution for the flooding issue at hand	1	
	Federal Government United States	Making sure the design is done according to the regulations and feasible in a larger coastal resilience plan for the state of Texas	4	
	Galveston Port	Maintaining access to water, keeping economical activities continuous	5	Company responsible for the port grounds
	Galveston Wharves	Maintaining operation at the waterline, keeping economical activities continuous	5	Representing all businesses active in the port of Galveston
	Institute for a Disaster Resilient Texas	Provide essential disaster risk reduction research, aid state agencies with data analytics and decision tools, and offer evidence-based solutions to enhance Texas community resilience	4	

	Galveston Inhabitants	Staying safe from flooding, keeping property and belongings intact while also maintaining current way of life	6	
	Restaurants at the Strand Area	Making sure the restaurants are accessible, maintaining current economic activities	2	
	Texas A&M University at Galveston	Facilitating research for flooding issues, protecting campus/students from flooding	6	
	America's Small Business Development Center – Galveston County	Maintaining business operation as much as possible, keeping revenue generation up	2	Representing all small businesses in the Strand
	Construction companies	Generating revenue when constructing the project, while delivering to best capacity what is asked.	4	Representing all construction companies involved
	Texas Flood Insurance	Maintaining revenue and keeping operations going	3	Representing all insurance companies involved with flooding issues

To identify the power a stakeholder wields, the urgency the issue has for a stakeholder and the legitimacy of its arguments, the Salience model can be used (Mitchell et al., 1997). This 3D diagram identifies 8 different stakeholder roles which have different positions in the diagram. Besides, the Salience model is able to verify whether a stakeholder concern is legitimate and should be taken into account. Figure 2.16 provides an empty Salience model diagram, pointing out the 8 different positions stakeholders can have on the diagram.

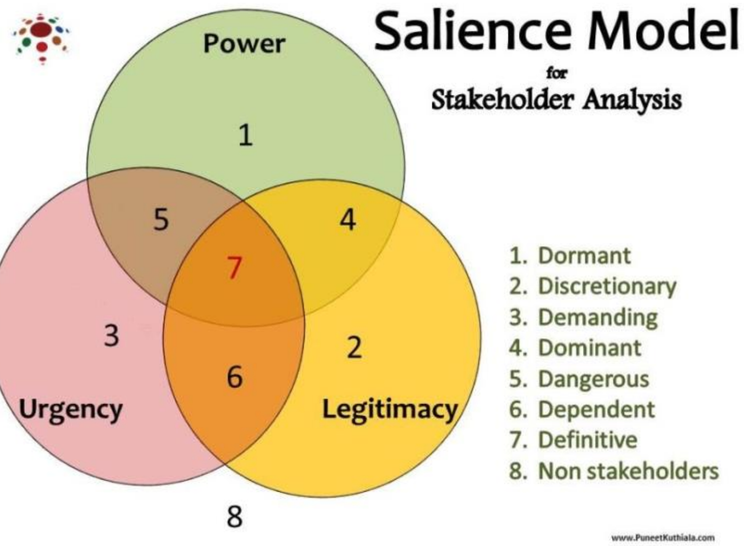


Figure 2.16 *2*: Salience Model template (Kuthiala, 2018)

When looking at the identified stakeholders from the table above, the stakeholder(-groups) are visualized in the diagram as follows:

Figure 2.17

When taking a look at the Salience diagram, it is noted that not all stakeholders have legitimate concerns. The concerns from the insurance industry for example, is solely focussed on their own interests and since they wield no power, it is not necessary to take these concerns fully into account when designing a solution. It is, however, important to keep track of these non-legitimate stakeholders to avoid blocking of the project or other kind of nuisance.

Concerns and stakeholder groups

Following from table 2.7 and the Salience model, six legitimate concern categories are identified that can have significant influence on the project. These categories, called subunits, are presented in table 2.8, together with the instances where these subunits are shown to bystanders and other stakeholders. In an additional column, the first order observation as noted by the team is added.

As mentioned before, in terms of feasibility only technical feasibility is taken into account for this project. It is noted that stakeholders like construction companies and governmental bodies are very concerned with the monetary aspect of the project, but this will not be further elaborated upon.

Table 2.8: Instances, subunits and first order observations

Serial number	Instances	Subunit	1st order observation
1	Show people the view over the water that can be lost in the current design (interview #7)	Keep waterfront accessible	Social resources
2	Presenting research in order to maintain political support	Creating public support	Scientific resources
4	City council posts updates of the project on social media (interview #2)	Creating public support	Social resources
5	Restaurants rebuilt on poles	Maintaining economic activities	Scientific resources
6	USACE looking looking for the most0 feasible way to construct (interview #2	Technical feasibility	Scientific resources
7	City council meanders with the voters demands (interview #2)	Creating public support	Human resources
8	Restaurant owners showing how high the water was during hurricane Ike (interviews #4 & 5)	Maintaining economic activities	Human resources
9	Emphasize the importance of keeping current events going (interviews #1 & 10)	Existing events needs to continue	Human resources
10	Seeing the events in the city	Existing events needs to continue	Human resources
11	City council emphasizing the importance of the waterfront accessibility in interview (interview #2)	Keep waterfront accessible	Social resources
12	Galveston port creating new cruise terminal	Keep ports accessible	Economic resources
13	Parking lots are being built next to the waterfront	Maintaining economic activities	Economic resources

Maintaining economic activity

The Strand area is filled with stores and restaurants. Since Americans rely on cars as their primary mode of transportation (Moody et al., 2021), accessibility of those stores by car is a crucial aspect of the stability of economic activity in the area. Therefore, the loss of accessibility of the stores and restaurants in the area is mentioned often when discussing concerns with different groups of stakeholders. Inhabitants wish to visit the restaurants and stores in the area, business and restaurant owners need to maintain their customers and guests. The same goes for the accessibility of the water front. Since there are multiple businesses located at the water front that make use of the water, accessibility from the water is essential when looking to continue economic activities in this part of Galveston.

Moreover, there is potential for economic growth when developing the area, as stated in the SWOT analysis and initial problem statement. If this could be exploited, stakeholder groups such as business owners, the city of Galveston and inhabitants could profit from the increase of revenue and increase of recreational activities.

Public support and community feeling

At the moment of writing, the public support for the Ring Barrier project is extremely low. This is not only due to the lack of spatial value created by the project as mentioned in the problem statement, but also due to the lack of information about the project amongst the people. Even though informing the community and connecting people is outside of the scope of the project, providing opportunities for the public in the design could get more Galvestonians involved and up to date with the project.

Furthermore, when talking to business owners about the ring barrier, it is noted that everyone is solely occupied by their own interests. Business owners that are located further away from the harbour couldn't care less about the aesthetic value of the ring barrier or the potential of added spatial value. They try to take care of themselves and ask for support from the city if needed, but what happens to their neighbour is of no concern to them. This resonates with the information given by the district representative in the city council. With only 12% of the people actually voting from those who can legally vote for the city council (D. Collins, Strand District Representative for Galveston City Council, October 9th 2023), it is clear that there is not much feeling for a community.

Technical feasibility

Technical feasibility is a crucial aspect for construction companies and government stakeholders. During the design phase of the project, it's essential to consider technical feasibility as it involves calculating whether the proposed design aligns with established standards and is a viable solution for the problem outlined in Chapter 1.

Continuing events

Galveston has multiple annual events where lots of public is drawn to (Visit Galveston, n.d.). These include the large Mardi Grass events where people enjoy a parade across town and a weeklong celebrations throughout the city, as well as the October fest where lots of pub crawls are enjoyed (M. Heckler, Student at TAMUG, October 10th 2023). Continuance of these events is important for the businesses, but even more so for the people who enjoy it. Some of these events, like the Mardi Grass celebrations, are locked-in traditions that cannot be altered easily. It is important to preserve and guarantee the continuance of these traditions and as much as possible.

2.7 Experience

In the time spent in Galveston and surrounding areas, it is noted that there are substantial cultural differences between the Dutch and Texans. This sub-chapter focusses on the experience the team had with the Texan culture and way of mind in Galveston.

Staying in Galveston revealed a range of experiences and observations. The prevailing individualistic state of mind stood out, with a notable absence of a strong community feeling. Galvestonians rely heavily on the use of cars, primarily due to limited alternative infrastructure. Because of this, parking is almost deemed sacred with residents fearing not to find an ideal parking spot when being confronted with a possible small reduction in parking space. Moreover, the idea of asphalt removal encountered quite some resistance, confirming the dependency of inhabitants on their car.

Conversations with locals often revolved around recollections of Hurricane Ike's high water levels, reflecting their concerns about coastal flooding, although, discussions emphasized the higher priority given to addressing chronic flooding. If inhabitants were faced with the currently proposed design, a general absence of community spirit coupled with a somewhat insurance-centric mindset and short-term vision came forward. Inhabitants looked at the problem from an individualistic perspective. Furthermore, we observed that many residents appeared uninformed about significant plans, such as the US Army Corps of Engineers' ring barrier, underscoring the need for improved community awareness and engagement as mentioned before. This aligns with the notation of a lack of community feeling and a individualistic mindset.

Staying for a longer period in Galveston provided the opportunity to experience Texan culture and way of mind. This provided additional insights and understanding about the current situation and how it is handled.

3 Design

After conducting a brainstorm session based of the evaluation of the fieldwork, it was decided to design four main components in the Strand. A mind map that was made during this brainstorm session can be seen in Appendix L. In this chapter, the process of developing these components is discussed. For each element a function plot is added to display which type of flooding this specific element can prevent or mitigate. Next, additional stakeholder concerns that came up when being presented with these components are elaborated. Finally, multiple design alternatives are presented to show how these components can work together and how the additional stakeholder concerns are taken into account.

3.1 Elements

In this section the different elements that will be implemented in the Strand are described. The goal of introducing these elements is to make clear for what kind of flooding (coastal, pluvial, catastrophic & chronic) the measure is effective for, how it functions and what are strategic locations to implement these elements. The elements are:

- A promenade located along the coast that focuses on dealing with coastal flooding from the bay.
- A water drainage system that is called Cloudburst road, focussing on pluvial issues.
- A system of water retention interventions that is implemented.
- A tidal basin is constructed to allow drainage of water during high precipitation combined with high tide.

Promenade

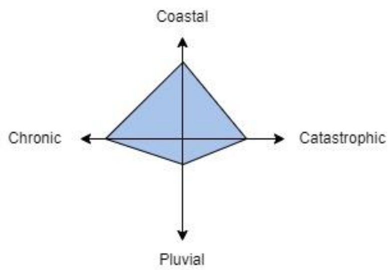


Figure 3.1 : Function plot promenade

At the bay side of the strand that runs from 14th to 25th street, there is currently very little protection against storm surge. Storm surge during an East landfall hurricane event could lead up to an elevation of the water level of 3.1 meters, which would result in catastrophic flooding and severe damage to infrastructure. During high tides, the rising water level can lead to chronic flooding. This causes less damage, but a lot of nuisance for inhabitants and stakeholders such as business owners. The coastal protection in this area should counteract both events, while also contributing to the spatial quality of the bay. A great way in which both could be included is by constructing a multifunctional promenade. This allows people to walk along the water and creates space for other functions to be included, such as parks, terraces and seating areas.. An overview of a few reference projects can be seen in figure G.1.

At the coastal side of 20th street there is already a small earthen levee. This levee can be extended in both height and width, creating a dike that can withstand a hurricane storm surge. This dike provides a great opportunity to increase spatial value when incorporating multifunctionality in the design. Recreational space could be incorporated on top of the dike or inside the dike, as well as additional economical activities such as restaurants, small museums or shops.

An option would be to extend this dike along the coast and thus create a promenade, for example in front of Katie's restaurant. The dike sections can be connected by constructing movable gates. In this way, the waterfront is still accessible for traffic.

It is also possible to lower the dike along the entire section, if one allows overtopping to some extent. The overtopped water could either be captured inside a retention basin, which has to be created additionally, or in the fishing boat marina located along 20th street. An overview of these possible areas can be seen in figure 3.2.

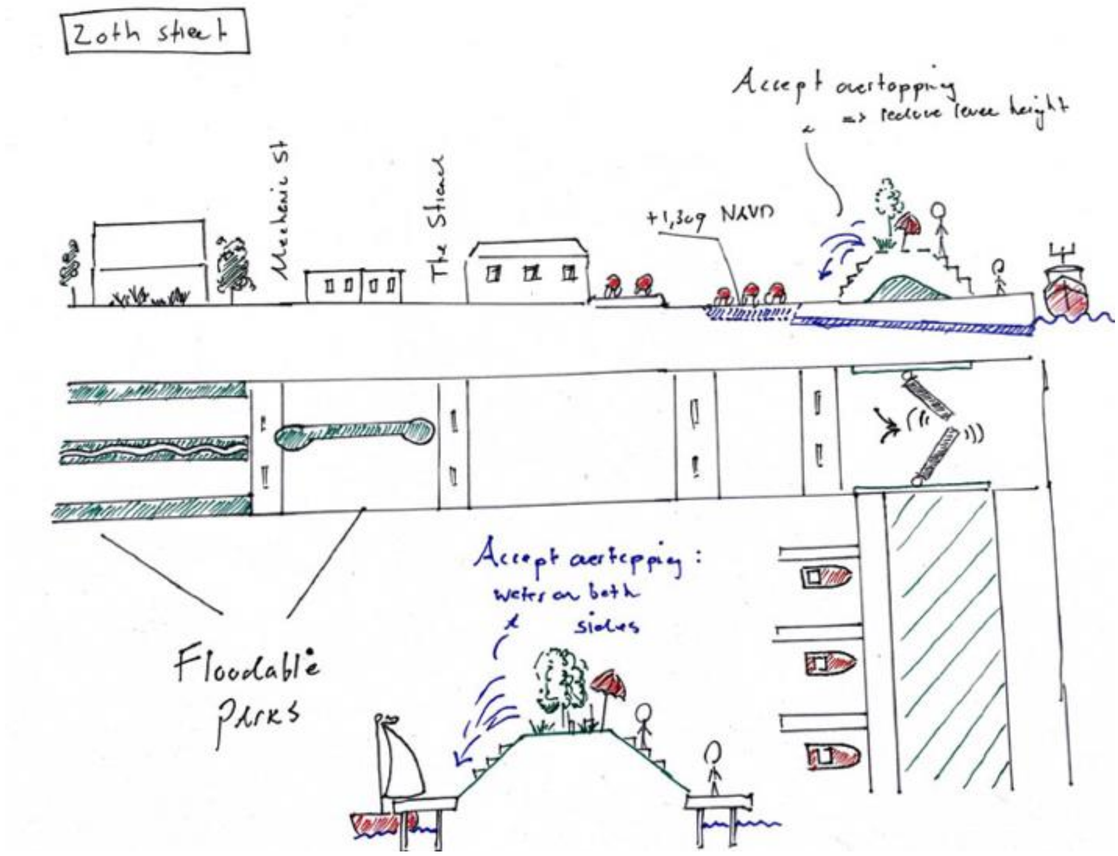


Figure 3.2: Preliminary sketches to display concept of promenade

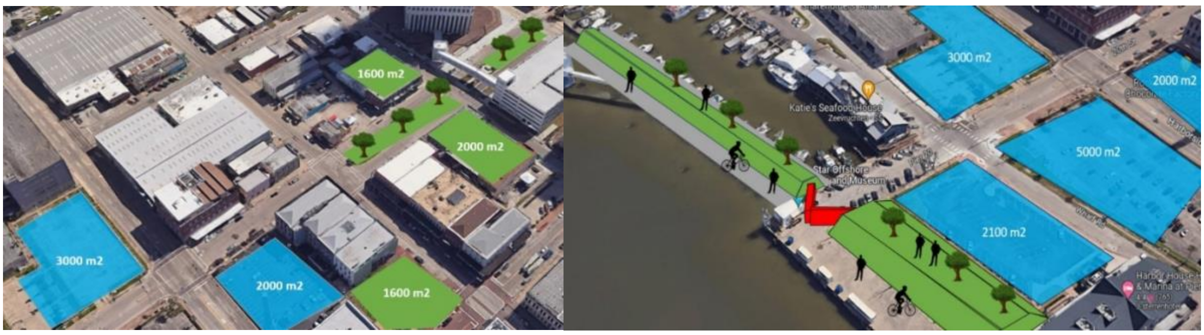


Figure 3.3. Visualisation of possibilities for development and retention

Cloudburst road

The idea of the cloudburst road is to transform a normal road into a storm water channel while maintaining other functions in dry conditions. A cloudburst road can facilitate the discharge of stormwater through its geometry. In addition to this, if the surface of the cloudburst road is permeable, it can also discharge water towards the subsurface trough infiltration The cloudburst road would be constructed lower than the surrounding area with adjacent roads sloped towards it. When there is a high intensity rainfall event, the cloudburst road will turn into a stormwater drain and discharge the rainwater to a body of water or infiltrate rainwater into the subsurface. The inspiration for this idea was taken from the cloudburst masterplan that was implemented in Copenhagen, Denmark. Appendix G, figure G.2.

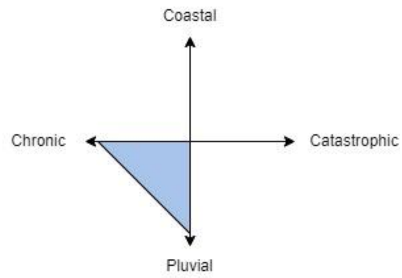


Figure 3.3: Function plot

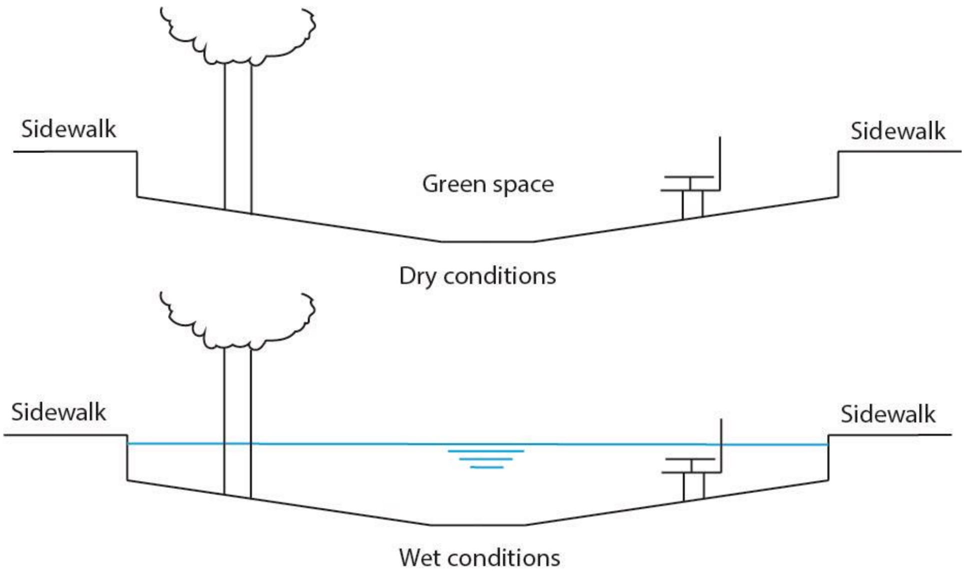


Figure 3.4: Conceptual sketch of cloudburst road

For a cloudburst road, the function of a road can be maintained, however when increasing the depth of the channel it is more practical to transform the road into a park. A case study is done for 22nd street since the fieldwork highlighted this street to have potential for implementation of extensive green areas used in a design like this cloudburst road. This doesn't mean that 22nd street is the only place where a cloudburst road can be implemented but that the designs for these streets have been elaborated further because they have high potential for development. 22nd street does not function as a main road for the area and could be fully turned into a linear park with a deeper channel. The roads adjacent to 22nd street could be given a small gradient towards 22nd street, so that storm water will flow into the main discharge channel on 22nd street. The sidewalk along 22nd street could still be maintained and placed above the waterline so that businesses along 22nd street would still be accessible. Culverts or bridges could be placed under streets crossing 22nd street like The strand, so that the disruption for car traffic will be kept to a minimum. In addition to the function of water discharge and recreation, the cloudburst road would also combat the urban heat island effect and provide more biodiversity inside the city.

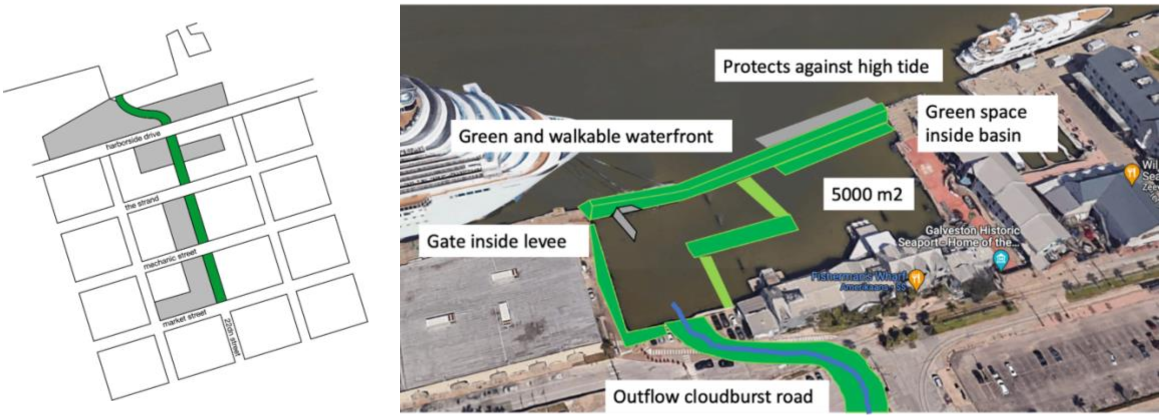


Figure 3.5: Map of the cloudburst road in green, parking spaces in grey and outflow into basin

The outflow of the cloudburst road can be placed next to the Fisherman's Warf. Currently there is a parking lot at the waterline, this can be seen in figure 3.5. A basin with a multifunction levee like at 20th street can be created. Not only will the levee defend against high tides and storm surges and have multiple functions. But the addition of a levee and gate will allow for control of the water level inside the basin. In case of a scenario where there will be a high tide and rainfall, the gate can be closed at low tide, creating a basin. The cloudburst road can then still discharge rainwater into the basin without needing pumps, this will allow for a more robust system.

Retention areas

During the fieldwork is was found that there are plenty of spaces where retention areas can be implemented. These areas do not have to replace existing infrastructure, but can be integrated in the current lay-out. Retention areas can be created underneath existing parking spaces, empty lots or in between current buildings.

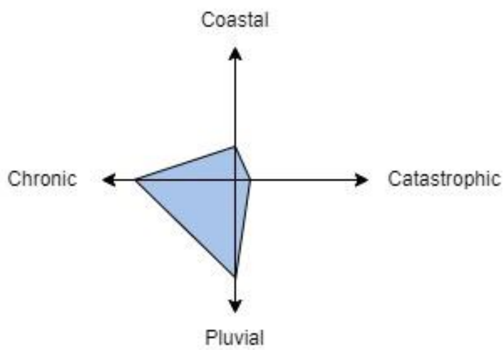


Figure 3.6: Function plot retention areas

At the moment, there are a lot of parking lots in the Strand, predominantly used by people going on cruises. Underneath the parking lots, space can be created to retain water. By digging out the soil beneath the parking lots and place concrete slabs and metal rosters on top, water is allowed to drain, turning the parking lot into a retention area easily. Increasing the permeability of the parking lots would also be an option, since the soil underneath the Strand consists of a sand layer of 3 – 5 meters that drains very quickly (USDA, 2020).
Moreover, there are multiple areas where small parks are present. Lowering and extending these existing parks, increases the capacity to store water when needed. Additionally, these parks can provide shade and cooling via evaporation, therefore enhancing current spatial value.
When encountering a larger area such as a vacant lot, one could think of implementing a water plaza. A water plaza is an empty space where for example a lowered basketball court or a dog park can be constructed. During flooding events, this area can then be used as retention. Furthermore, there is potential for the implementation of green roofs in the Strand area, especially in historical buildings originally constructed with excess bearing capacity (C. Gorman, Assistant Director & Historic

Preservation Office, October 18th,2023). These green roofs, despite imposing substantial loads, are suitable for such buildings. Roof alterations are permitted as long as the building facades remain unaltered for pedestrians. Finally, overtopping basins can be strategically created behind the promenade to retain bay water overflow, thereby allowing for the construction of lower flood protection measures.

By combining all the separate retention areas, a system is created which can have significant capacity. The retention areas should be connected to drainage facilities, such as the previously mentioned cloudburst road or the existing drainage system.

Tidal basin

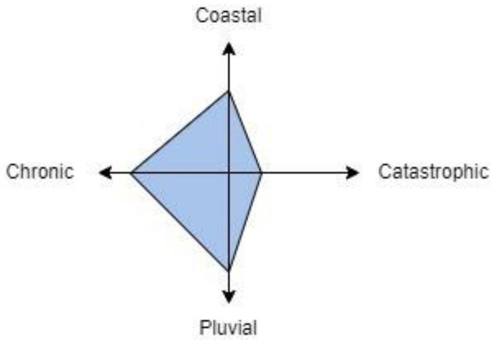


Figure 3.7: Function plot tidal basin

As mentioned before in the fieldwork evaluation, using the small basins along the bay area for increasing the water retention capacity of the city during high tide has lots of potential. The quay walls surrounding these basins are high enough to let the water rise around 0.5 meter before encountering flooding issues. The concept of the tidal basin capitalizes on this feature. When closing off the basin at low tide when a heavy rainfall event is predicted, a tidal basin can store a volume of water equal to the product of the basin area and the possible water level rise. Storing the water inside the basin enables the existing drainage system to function for a longer period of time compared to the current situation.


Figure 3.8 tidal basins

Together, these elements can effectively handle all potential hurricane scenarios in Galveston. When combined, these four components create a comprehensive system that addresses both pluvial and coastal flooding. While these components are designed to fully deal with chronic flooding, their capacity to mitigate the impact of catastrophic flooding is somewhat limited.

3.2 Additional stakeholder concerns

In this chapter, additional stakeholder concerns are presented that came up when the stakeholders were faced with the aforementioned design elements. These additional concerns are taken into account when implementing the design elements in the proposed design alternatives for The Strand area. Presenting the elements to different stakeholder groups provided valuable information and insights into the way people think about the issue and how they deal with the problem at hand. The additional concerns mentioned by stakeholders is shown in table 3.1

Table 3.1: Additional stakeholder concerns and how this is taken into account in the final design

Preliminary solution	Concern	Stakeholder	Solution
Water retention areas	Stagnant water leads to nuisance from vermin	All people in Galveston	Ensure a continuous flow of water by having increasing surface permeability, use fountains in retention areas
Flood parks	Homeless people gathering and setting up tents	Galveston residents, business owners	Prevent large plains of grass for tents, ensure sufficient illumination
Not yet considered	Car wakes	Business owners	Extent existing wake-breakers
Use buildings as barriers	Some buildings will be demolished and cruise terminal will be built on the same place	Cruise terminal owners, harbour authorities, Galveston City Council	New cruise terminal should be constructed floodproof or barrier should be built more towards coast
Green roofs, retention areas etc.	Private property not developable	Private property owners, Galveston City Council	Choose property that's easily obtained or owned by the Galveston City Council
Green roofs	Prohibited monumental buildings	Galveston city council, home owners between Mechanic str. & Strand	Place green roofs outside these streets on newer buildings
Cloudburst roads	Reduced accessibility	Business owners	Ensure sufficient parking spots around cloudburst road and think through construction sequence

Vermin due to stagnant water

When faced with the design from the cloudburst road and water retaining areas, both inhabitants and local businesses owners mentioned the nuisance they experience from vermin like rats and mosquitoes. In order to deal with this, knowledge about the origin of the mosquitoes and rats is needed. It turns out that mosquitoes need approximately 28 hours to breed in standing water (terminix.com, 2023) and rat-like vermin is attracted to stagnant water in general (EvoGov.com, n.d.). A solution would be to make sure the water keeps flowing as much as possible by for example making the surface permeable or implementing sufficient drainage. This could be applied in the area of cloudburst road where water is discharging. However, the purpose of retention areas is to retain water. In these areas, fountains would be a solution to keep the water flowing. This would also reduce the risks of other bacteria, such as legionella.

Homeless people

Various stakeholders, including shop owners and city council members, have expressed concerns about issues related to homelessness in Galveston. They have noted that some individuals experiencing homelessness engage in behaviours such as sleeping on the streets and using drugs in public areas. These actions have been identified as impacting the overall quality and perception of public spaces and the stakeholders pointed out that the preliminary designs would facilitate these actions. The origin of this problem is outside of the scope of this project, but nuisance caused by it can be reduced to a minimum. This can be done by avoiding dark corners in the design as well as areas where tents could be placed. Another option would be changing the surface texture, for example using gravel instead of grass in specific places.

Car wakes

Multiple stakeholders such as shop owners indicated that during chronic flooding a lot of damage originates from people who drive with their pickups at high speed through the streets of Galveston. The moving vehicles create waves that flow into the businesses, causing a lot of damage. Currently, this problem is being tackled by construction small wake breakers. These are blocks of concrete that are approximately 30 cm in height, which can also be used to sit on. Since people in Galveston have been dealing with these issues for a long time and this solution seems to work, the plan is to extent these wake breakers. A possibility would be to include plants in the wake breakers, making them attractive for public space.

Construction of new cruise terminals

At the Eastern edge of the project area there are two large buildings that are now part of the harbour infrastructure. According to stakeholders, these buildings will be demolished in the near future to construct new terminals for the cruise ships. Since Galveston is the most important departure location for cruises in the west of the US, the stakeholders were certain that these terminals would be constructed on the short term. This could be included into the design by making the new terminals flood proof, or by constructing the barrier closer to the coast. In this way, not every new building that is being built in this location needs to be made flood-proof.

Private property

Property laws in Texas are quite strong so getting property owners on board is essential for any changes related to a privately owned building or piece of land. Many property owners could be hesitant to changes made to their property because of the strong sense of individualism and lack of cohesion in this part of the US. So in order to be most effective on the short term, it would make sense to start with plans to public property. In addition to this, to get private property owners on board a subsidy or other financial incitive could be given. This financial incentive would be more effective than a call on the sense of community.

Monumental buildings

Between the strand and mechanic street there are many historical buildings. The laws for monumental buildings are quite strong in the city of Galveston. In addition to this, it is not always clear which organisation is responsible for what regulation. As a result, it is very complex to make any changes to monumental buildings. It would be best to start with changes to non-monumental buildings.

Reduced accessibility

Interventions into the spatial design could reduce the accessibility of car traffic and car parking. In the United States car traffic, even in downtown areas, is still the mode of transportation for most people. A business could be severely affected by a lack of parking nearby. For areas without sufficient parking, interventions that would limit the amount of parking space available would not be possible. For these areas, easy pedestrian accessibility is also necessary. In addition to this, interventions that would limit the car traffic would only be possible in areas where there are alternative routes nearby.

3.3 Design alternatives and calculations

Two alternatives to deal with the problem are designed, implementing the previously mentioned elements and stakeholder feedback. The **first alternative** focusses on protecting the area at the coastline by shortening the coastline, thus leading to a more protective strategy. The **second alternative** makes use of the existing buildings and is more land-inwards, leading to a more acceptive strategy. Both alternatives should be feasible and possible to implement in the area. For designing the alternatives, the list of requirements of Table 1.1, which is introduced in the problem statement, is taken into account. Both design alternatives consist of five sections, with the configuration of these sections varying between the alternatives. The sections are as follows:

- Section 1 consists of the quay wall of the most Western cruise terminal. Important aspects to consider are the functioning of the cruise terminal, the loading and unloading of ships and the access of cruise passengers to the promenade to increase foot traffic and thus economic activity along the waterfront.
- Section 2 encompasses the mooring part of cruise terminal's quay wall and the adjacent basin which is in front of the restaurant 'Fisherman's wharf'. Important aspects to consider are accessibility for leisure boats, restaurant business and functioning as a foot traffic portal to the Eastern part of the waterfront. There is also potential to use this basin for retention purposes.
- Section 3 consists of the small basin encircled by the 'Pier 21' collection of shops, hotels, museums and restaurants. Important aspects to consider are that the floodwall doesn't disturb business activities or blocks bay views. An ideal situation would be enhanced economic activity due to increased foot traffic.
- Section 4 comprises the wide basin which hosts the fisherman's fleet of the adjacent seafood markets and restaurants. Important aspects to consider are the access of the basin for fishing ships and the potential retention capacity.
- Section 5 consists of the quay wall of the most Eastern port container terminal which is planned to be transformed into a third Galveston cruise terminal. Important aspects to consider are the functioning of the container terminal in the short term, how the floodwall can blend into the future cruise terminal and the transition phase between these two states.

For the construction of the different section of the promenade, both serviceable limit state (SLS), which corresponds to chronic flooding and ultimate limit state (ULS), which corresponds to catastrophic flooding need to be taken into account. These assumptions are already mentioned in table 3.2 but are, for convenience, once again listed in table 3.2 Only SLS and ULS conditions for the storm surge are used for the design of the promenade, as its main purpose is to protect against storm surge from the sea, not to drain or retain pluvial water.

Table 3.2: The SLS and ULS conditions that are used for the design of the levee height

SLS	**King tide +0.71 m NAVD88**	**1 year return period Hs: 0.50 m**
ULS	**Storm surge + 3.14 m NAVD88**	**100 year return period Hs: 1.17 m**

- During SLS conditions, king tide is the governing condition. This is the highest spring tide that occurs within a year. The maximum king tide that is predicted for the coming year at measurement location Pier 21 at the Strand is +0.71 m NAVD88 (NOAA, 2023). It can be assumed that other effects that contribute to the water level such as setup are included in this number. The significant wave height for a 1 year return period is approximately 0.50 m (Corson et al., 2002). Based on the tidal data, it can be seen that this king tide persists for approximately 6 hours.

- During ULS conditions a storm surge of +3.14 m NAVD88 is assumed together with a significant wave height of 1.17 m. The maximum storm surge lasts for approximately 12 hours. It can be assumed that other effects, such as setup and tides are included in the water level of +3.14 m.

In the following section, these conditions will be applied to both design alternatives that are made for the promenade.

3.3.1 Protective strategy

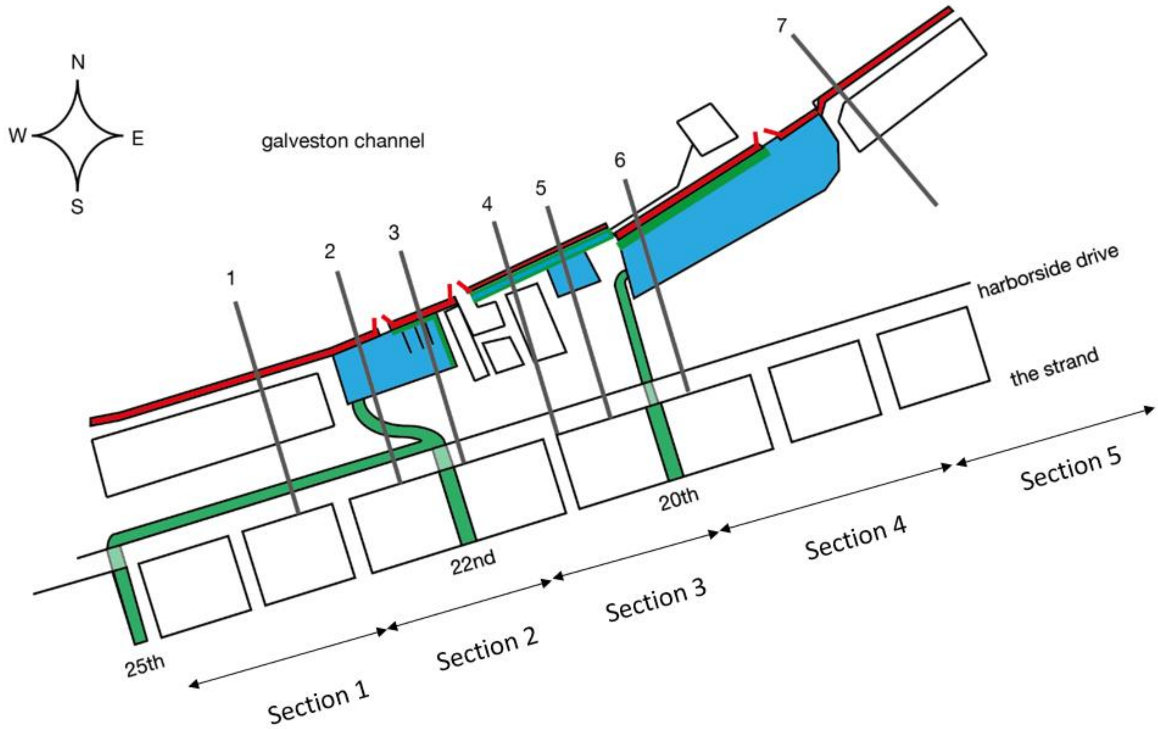


Figure 3.9: Alternative 1 is designed as a protective strategy by shortening the coastline

Section 1

Cruise ships are so big that loading and unloading usually happens with large machinery which can reach quite far. Using the LIDAR data, it is found that the cruise terminal is at an elevation of NAVD88 +2.76 m. A cross section of section 1 can be found in figure H.1 number 1. Since the storm surge is at maximum at NAVD88 +3.14 m during ULS, a wall of at least 0.38 m need to be implemented. It is chosen to apply a wall that is higher to limit overtopping. This is done to protect the cruise terminal building against overtopping damage.

Since the water depth right in front of the coast is very deep, it can be assumed that there is no influencing foreshore and non-impulsive wave conditions occur. The following formula is now used to calculate the required crest freeboard of the coastal protection measures:

$$R_C = \frac{H_{m0}}{2.12}\left(-\ln\left(\frac{q}{0.054\sqrt{g \cdot H_{m0}^3}}\right)\right)^{\frac{1}{1.3}}$$

Formula 1, source: Eurotop, 2018

ULS wave height is combined with an overtopping discharge of 20 L/s/m here. It can be assumed that terminal buildings can withstand this overtopping since they are built to withstand significant loads. This leads to a crest freeboard of 1.07 m and a total height of 1.45 m. By constructing the wall, the buildings behind it do not have to be strengthened and made flood proof.

Section 2
In section 2 it is chosen to use the existing mooring wall as a storm surge wall and extend this into a storm surge wall to the East to close the harbour. The land area behind the wall, at the location of Fisherman's Wharf, is at NAVD88 + 1.40 m. A cross section can be found in figure H.1 number 2.

To protect this area of a storm surge of NAVD88 + 3.14 m in ULS, the wall needs to be raised at minimum to this level. On top of this, a crest freeboard is needed to protect against overtopping. During ULS, the overtopping should not be too large, as this could lead to flooding of the tidal basin. Therefore 5 L/s/m is chosen, resulting in a crest freeboard of 1.53 m and a total crest height of NAVD88 + 4.67 m. During SLS, the overtopping discharge should be very low to leave sufficient space for pluvial water to be stored in the tidal basin, as this is the main purpose of the basin. Since the wall is already raised well above the required height for SLS, it is assumed that the overtopping during SLS can be at maximum 0.1 L/s/m.

During 6 hour SLS conditions, an overtopping rate of 0.1 L/s/m will lead to an increase in water level in tidal basin 1 (width 70 m land inwards) and 2 (width 50 m land inwards) of respectively 0.03 m and 0.04 m (see figure 3.18). Since there is quite some uncertainty in the overtopping discharge of 0.1 L/s/m, it will later be investigated what the influence of varying this overtopping discharge is on the tidal basins and thus the required water retention in the Strand. This will be treated in the section on the connection of the promenade and cloudburst road. In the wall in section 2, a movable gate will be put so that the harbour is still accessible for boats. Three different types of gates will be considered, which are a roller gate, hinge gate and vertical gate that lifts from the seabed. To prevent difficulties during maintenance, a roller gate or hinge gate would be the best option. An overview of the different types of gates can be seen in Appendix A In the harbour, a small boardwalk will be created to allow pedestrians to walk along the water and facilities will be created in the water, such as small piers to make the water accessible and allow boats to dock. Also, a bridge will be made that crosses the outlet of cloudburst road. A sketch can be seen in the section on the connection of the promenade and cloudburst road. The green areas here should be sufficiently enlightened to prevent homeless people from gathering here.

The pier at the East part of section 2 is at NAVD88 + 1.65 m. Here a levee is created that provides seating areas and a viewing point to the water. Using the same overtopping discharge again, the height of the levee here also needs to be at NAVD88 + 4.67 m. A cross section of this part is in figure H.1 number 3.

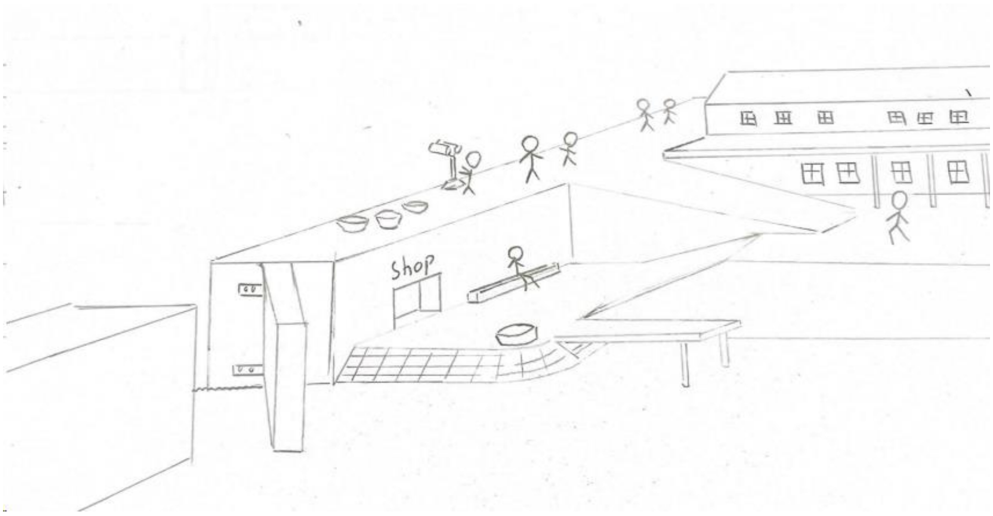


Figure 3.10, An overview of the levee on the East side of section 2

Section 3

At section 3 it is chosen to extent the storm barrier along the shoreline, so that the shops and restaurants behind it will be protected. This is done using a levee. The height of the pier here is at NAVD88 + 2.14 meter. A cross section can be seen in figure H.1. number 4 and 5. The levee will consist of 2 separate levees, to create a promenade in the form of a green park, in which people can walk and relax. In between the levees, additional water can be retained. This can lower the height of the levees, since more overtopping is allowed. A cross section of this levee can be seen in figure 3.11. For the promenade, an overtopping discharge of 5 L/s/m is accepted. This is done because the promenade mainly consist of concrete with grass cover, making it resistant to higher overtopping amounts. During 6 hour SLS conditions this leads to a required retention volume of 108 m^2. Assuming ULS conditions persist for 12 hours, a retention volume of 216 m^2 would be required.

The approach is to counteract the effects of chronic flooding, but only reducing the impact of catastrophic flooding. Therefore the retention capacity is sufficient if it is at least 108 m^2. During ULS conditions, the levee needs to be raised to NAVD88 + 3.14 m and a crest freeboard of 1.53 m is needed, leading to a total height of NAVD88 + 4.67 m. During SLS conditions the levee should be raised to NAVD88 + 0.71 m and a crest freeboard of 0.47 m is needed, resulting in an elevation of NAVD88 + 1.18 m. It can thus be seen that based on SLS conditions, no storm wall is needed here, since the pier is at NAVD88 + 2.14 m. The levee is thus only needed during ULS, therefore it is chosen to partly make it flexible. Because of practical limitations to flexible walls, the flexible height is set to 2 m. The levee should thus be permanently raised to NAVD88 + 2.67 m. For the flexible barrier, 3 different alternatives are considered, which can be seen in Appendix B. The first alternative is the mobile dike, which consists of hoses which are filled with water. A net around the hoses will absorb any loads on the barrier. The second alternative is a self-closing barrier that closes automatically by using buoyancy from water flowing underneath the barrier. The third alternative is a wall that mechanically rotates out of the ground. An overview of these alternatives can be found in Appendix B Table B.1. Out of these alternatives it is chosen to implement the rotary wall. This is most easy to integrate in the levee. It also saves a lot of space compared to the mobile dike, it is less expensive and technically complex than the self-closing barrier and it fulfils the height requirement of 2 m.

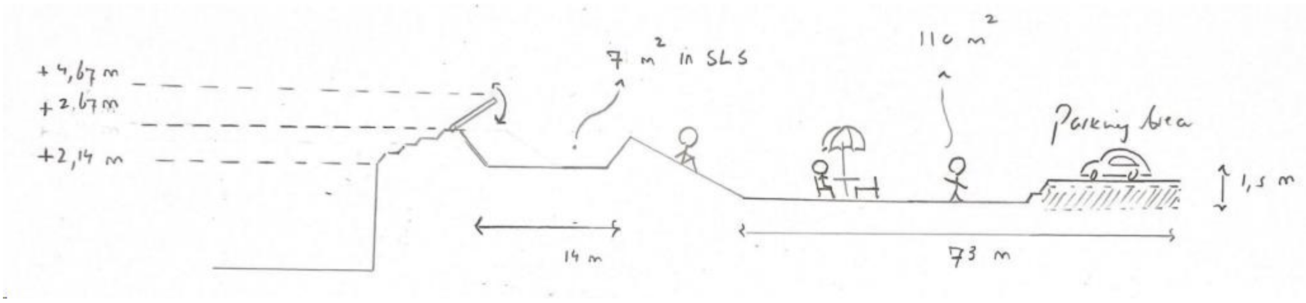


Figure 3.11, The multifunctional levee that is created for alternative 1 with the third flexible barrier alternative

Using this geometry, it is calculated that the permanent retention capacity (without the flexible barrier lifting up) is more than 108 m^2, so SLS conditions are fulfilled. Moreover, the overtopping of 5 L/s/m will most likely not occur during SLS conditions, as the levee is already elevated higher than required based on SLS.

Behind this levee terraces can be created in an area that is lowered by 1.5 m to retain more water, also contributing to the requirement of 108 m^2. The terrace areas are also made as a compensation measure for the restaurants at the pier, which are next to the levee and could disagree with some plans. This area should have sufficient lightning to prevent homeless people from accessing this space. At the location of the parking lot behind the levee, a water retention area will be created by retaining water underneath it, using concrete slabs and metal rosters.

The retention area on top of the levee and behind the levee should discharge the water when the storm surge has passed. This is done to prevent nuisance from vermin. The water can be discharged towards the bay since the retention areas are at higher elevation than the water in the bay. This is even the case when the area is lowered by 1.50 m. Valves may be needed to prevent inflow of water via the discharge channels during storm surges.

Section 4

The levee created in section 3 will be extended into section 4, creating a long promenade along the water, which can be used by pedestrians to walk at the water-edge. In this location the dike can have three main purposes. Firstly, it acts as a breakwater for the harbour. Secondly it provides additional recreation space. Lastly, it acts as a barrier for storm surge. Incorporating this in the design meets the goal of increasing spatial value. A cross section can be seen in figure H.1 number 6. At the water-edge, a system of steps will be created on which people can recreate and giving them access to the water. This can also enhance the wave dissipation. The levee in the harbour will contain seating areas, a rubble mound to access the water and facilitate piers to allow fishing ships to dock. An overview can be seen in figure 3.12 It could also be chosen to heighten this levee more than necessary and to create other functions such a shops inside the levee. Currently, the pier at the harbour is at NAVD88 +1.58 m. Using the same overtopping discharge as in section 2, the height of the levee needs to be at NAVD88 + 4.67 meter. As calculated, during an SLS event that persists for 6 hours, the overtopping discharge of 0.1 L/s/m will lead to an increase in water level of 0.04 meter in tidal basin 2.

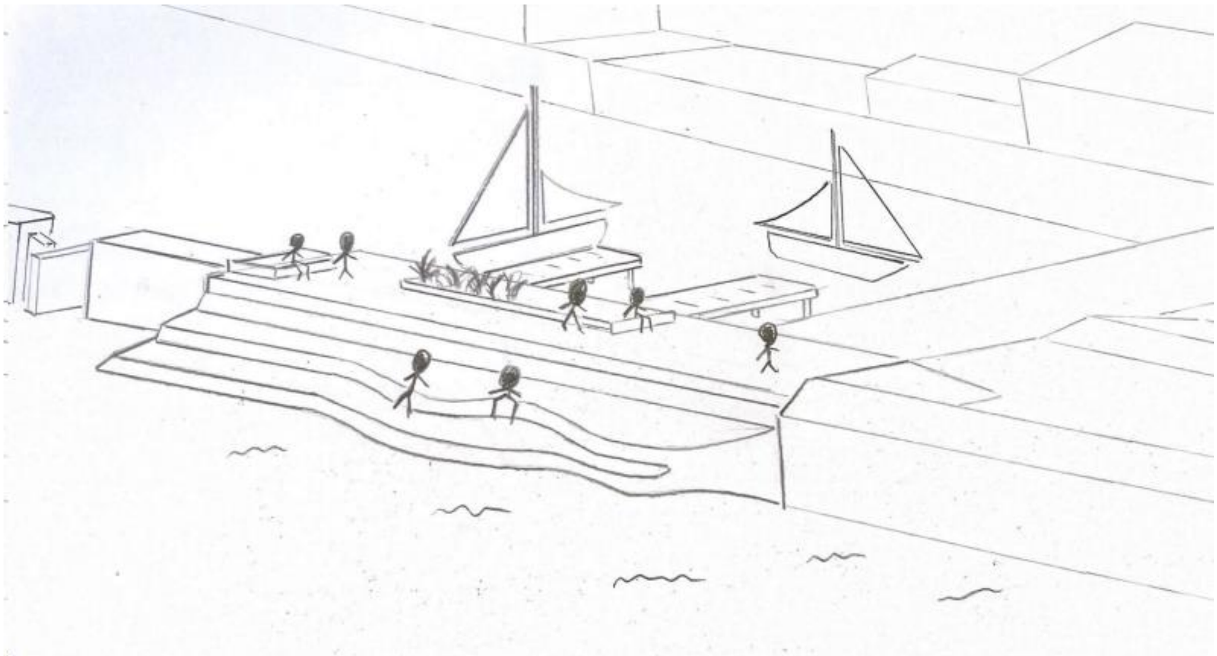


Figure 3.12 An overview of the levee in front of tidal basin 2

Section 5

At the connection between section 4 and section 5, a movable gate will be constructed in the form of a hinge- or roller gate. A vertical gate that lifts from the seabed would lead to maintenance issues. This is the end of the promenade. At the East side of the gate, a wall will be created having the same elevation as the levee in section 4. At the North side of this wall, a new harbour can be created which can be used if the movable gate needs to shut.

Section 5 currently consists of buildings owned by the port which are very large. In section 5, a small wall will be constructed in front of these buildings. This can be seen in figure H.1 number 7. This wall will be low enough so that the waterfront is still accessible for ship loading- and unloading. In the future, these buildings will be demolished and a new cruise terminal will be constructed in this place. Then loading- and unloading is still possible, just like as in section 1. The quay wall is at an elevation of NAVD88 + 2.68 m. The wall will be raised to NAVD +3.14 m, corresponding to a height of 0.46 m. ULS wave height is combined with an overtopping discharge of 20 L/s/m, leading to a crest freeboard of 1.07 m. The total height is thus 1.53 m. As an alternative, the wall could also be reshaped into a levee or temporary structure in the places where this benefits the access to the waterfront.

3.3.2 Acceptive strategy

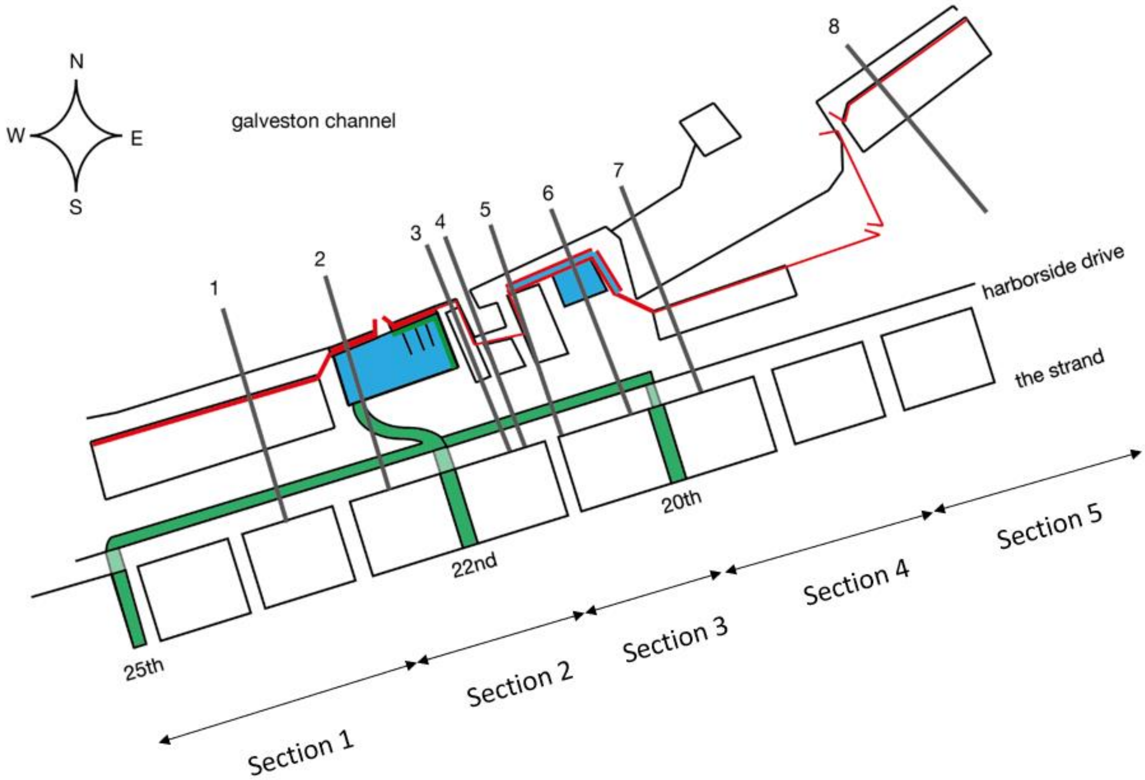


Figure 3.13, Alternative 2 that is designed for an acceptive strategy

Section 1

Since this alternative is based on an acceptive approach, it is chosen to move the barrier back and incorporate it into the existing cruise terminal, which is the main difference with alternative 1. This is feasible since it can be assumed that the building is designed to resist significant loads. A cross section can be found in figure H.2 number 1. The elevation of the cruise terminal's quay wall is at NAVD88 + 2.76 meter. A conservative assumption is made that on top of the storm surge water level, the building has to be made flood proof for one time the significant wave height as it's assumed that waves will break in the shallow water in front of the cruise terminal. During a maximum storm, the water depth on the quay wall is 3.14 – 2.76 = 0.38 m and waves will break if they exceed approximately 60% of the water depth. Since the waves are 1.17 m, they will break and a bore will form. This can be damaging for a structure, therefore a conservative height is used. Taking into account a maximum storm surge of NAVD88 + 3.14 m and a significant wave height of 1.17 m, the building would have to be made flood proof to a level of NAVD88 + 4.31 meter. This will result in a total flood proof height of 1.55 m. Usually, buildings can be made flood proof up to 3 m (De Graaf et al., 2012). Therefore, this is feasible. The façade should be made fully floodproof whereas the openings should contain closeable warehouse doors which can be closed when king tide or storm surge water levels occur.

Section 2

Section 2 does not differ from alternative 1, since this section is constrained by the implementation of Cloudburst road. Therefore the height of the storm surge wall and levee is also the same as in alternative 1.

Section 3

At section 3, alternative 2 uses the buildings that are already present along the harbour to protect against storm surge. The assumptions regarding loads made in section 1 are continued to be used, which means that all buildings that are not protected by a flood wall should be made flood proof up to NAVD88 + 4.31 m. Firstly, the building most land inward is built on a ground level of NAVD88 + 2.78 m and has to protected till NAVD88 + 4.31 m, which results in a feasible floodproof height of 1.53 m. The facades facing East and West, closer to the water, are built on a ground level of NAVD88 + 2.14 m. With protection till NAVD88 + 4.31 m this means a floodproof height of 2.17 m, which seems just on the edge of what's feasible. To ensure properly floodproofing these buildings, extra caution is needed as the buildings are initially not designed to withstand large loads, many transitions are needed and buildings are close to one another. Since the buildings are used as flood barrier, the lifetime of these buildings, which is short compared to the coastal protection structures, will determine the lifetime of the flood wall. When new buildings are constructed it should therefore be taken into account that they are also made flood proof to the required height.

In between the buildings, both a permanent- and a closable flood wall need to be constructed. The location of the permanent wall is at NAVD88 + 1.83 m and can be seen in figure H.2 number 4. Based on an overtopping amount of 5 L/s/m during ULS (See Table 3.2), a significant wave height of 1.17 m and using Formula 1, the elevation of the wall would be NAVD88 + 4.67 m.

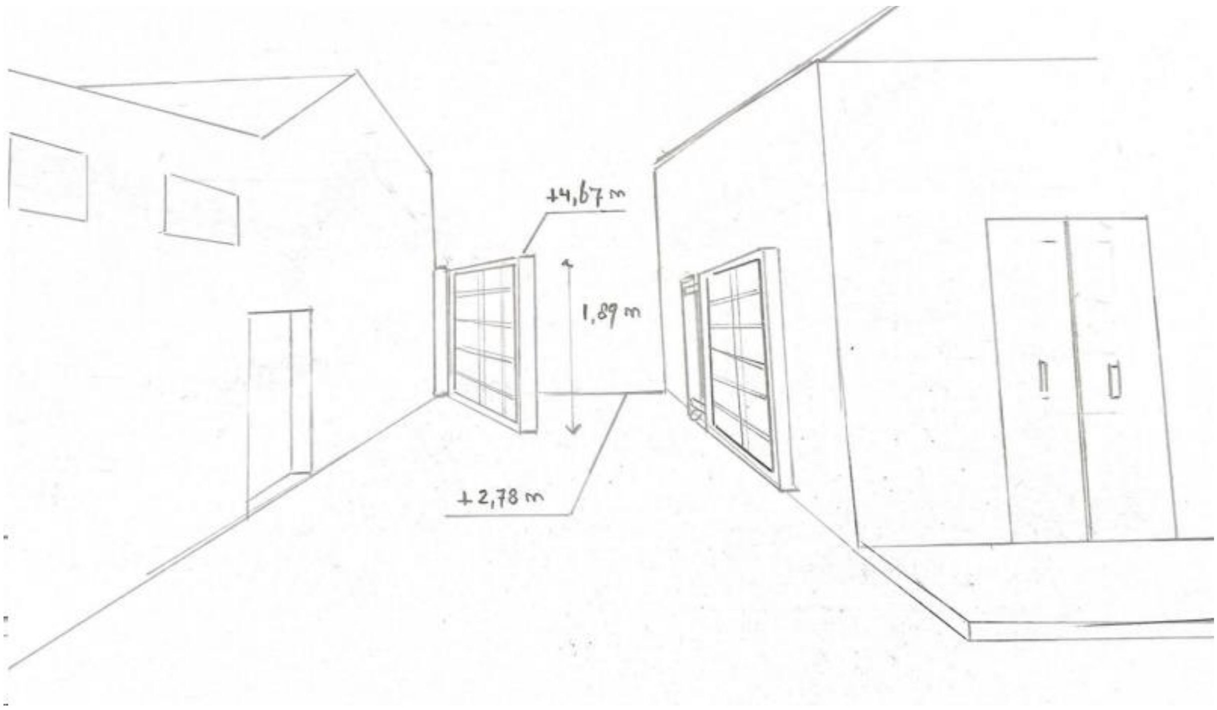


Figure 3.14, The movable gate that is incorporated in the buildings

The closable gate allows access for pedestrians and vehicles and the elevation here is NAVD88 + 2.78. A cross section can be seen in figure H.2 number 5. The relatively high elevation can be explained by a gradient that has already been made in the street to make chronic flooding less likely. This can be seen in Appendix C Table C.1 measurement 10. Using the same overtopping amount as for the permanent wall, the elevation would again have to be NAVD88 + 4.67 meter. This gate will be a hinge gate, as in open position it can be placed parallel to the buildings to save space. A sketch of how this gate will be integrated into the public space is shown in figure 3.14

At the East side of section 3, an L-shaped levee is created which is multifunctional. The height of the pier is NAVD88 + 2.14 m which can be seen in figure H.2 The levee here will not have any flexible parts, therefore the height is fully based on ULS conditions. A cross section of the levee can be seen in figure 3.15

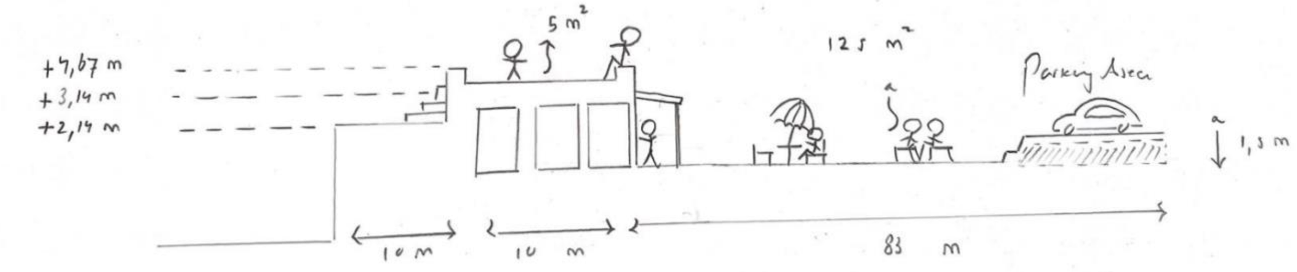
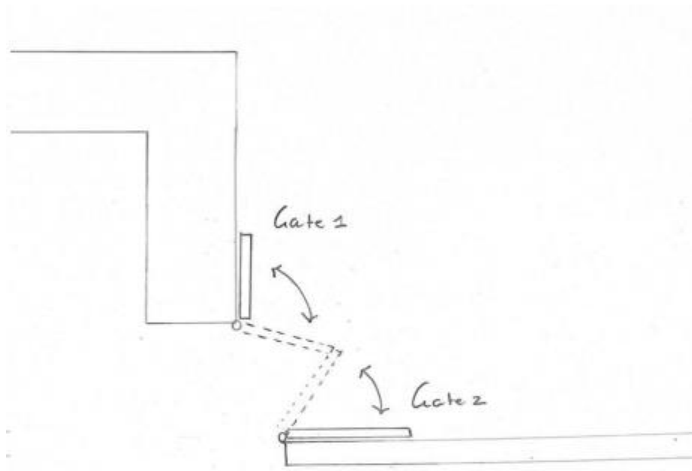


Figure 3.15, The multifunctional levee that is created for alternative 2

Combining this with an overtopping discharge of 5 L/s/m and using Formula 1, the levee would have to be elevated to NAVD88 + 4.67 m. Additional spatial value is given to the levee by making an elevated walkway on top of it. In this way it can be used for multiple functions, such as public seating area, terraces and green space. Inside the levee, there is space for other functions, such as shops or a restaurant. To prevent nuisance from homeless people the area should be sufficiently enlightened. In the area behind the levee, currently a small green space is present. This space will be used for extra recreation area and combined with water retention by lowering it by 1.5 m. A detail of the levee can be seen in figure 3.15. It can be seen that there is sufficient retention capacity to fulfil the requirement of 108 m^2. Since the height of the levee is fully based on ULS conditions, overtopping of 5 L/s/m will most likely not occur during SLS conditions. Therefore the retention capacity will certainly be sufficient during SLS. When the storm surge has passed, the retained water on top of the levee and behind the levee should be discharged towards the bay. This is possible since the retention area is at higher elevation than the bay, even when lowered by 1.50 m. Valves may be needed to prevent inflow during storm conditions. A cross section can be found in figure H.2 number 6.

Section 4

At the connection of section 3 to section 4, a movable gate will cross the road. The construction and integration of this gate would require much attention, as it crosses the road diagonally. A sketch of this gate can be seen in figure 3.16. The elevation of the land at the gate is NAVD88 + 1.72 meter. Using the same design conditions as for the gates in section 3, the height of the movable gate would be NAVD88 + 4.67 meter. A detail of the gate can be seen in figure 3.16. Here it is chosen to implement a hinge gate. In open position this gate can be places parallel to the coastal protection structures, preventing any obstruction to pedestrians and traffic. At section 4, alternative 2 uses the existing building land-inward as water retaining structure, rather than creating a levee in the harbour as in alternative 1. The benefit of using this building is that the harbour does not have to be closed during high tides. Furthermore, the view of for example Katie's restaurant will not be obstructed. One downside is that the buildings need to be made flood-proof and the port in front of Katie's restaurant can't be used as retention basin for cloudburst road. The building is at NAVD88 + 1.48 meter. Taking into account ULS conditions and using the same approach as in section 1, the flood proof height needs to be at NAVD88 + 4.31 m. A cross section can be found in figure H.2 number 7.



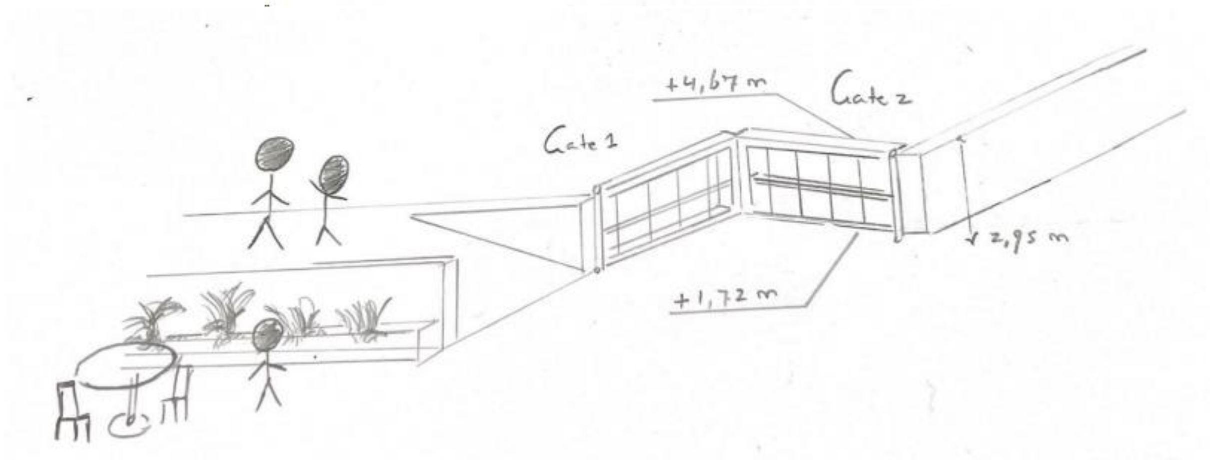


Figure 3.16, A top view and 3D view of the gate that crosses the road diagonally

Section 5

At the connection of section 4 and section 5 the flood wall will be built along the waterfront and movable hinge gates are implemented to allow for traffic to pass the wall. The land area at the interface of section 4 and 5 is at NAVD88 + 1.48 meter. Using the same overtopping discharge as the gates in section 3, the height of the hinge gate and wall here should be NAVD88 + 4.67 meter.

At section 5 it is chosen to incorporate the flood wall in the existing buildings at the pier, which will benefit access to the waterfront for loading and unloading of ships. The current building will be demolished and a new cruise terminal will be built in the near future, which will provide opportunities to incorporate flood proof walls into the new design. The elevation of the quay wall is NAVD88 +2.68 meter and ULS conditions are taken into account. Using the same approach as in section 1, the buildings here should be made flood proof to a height of NAVD88 +4.31 m. This can be seen in figure H.2. number 8. At the sides of the buildings, hinge gates are built to allow traffic to access the quay wall. These hinge gates can be placed parallel to the buildings in open position. They will be raised to the same level as the flood proof walls.

Cloudburst roads

The cloudburst road can be complimentary or even replace the current sewage system. Cloudburst roads can be designed in several ways with different functionalities and discharge capacities. In this rapport a simplified design is proposed. These designs also bring differences in the amount of disruption to the current situation and the amount of green space that the design includes. In general, the more discharge capacity and green space the design has, the more disruption it will bring to the current situation. Since the cloudburst roads are above ground instead of underground like the sewage system and do not require pumps, maintenance, operation and constructing cost should be lower. In figure 3.17 the different designs are sketched and in table 3.3 the different designs as well as a sewage system are descripted. There are 2 different alternatives for the cloudburst roads. For alternative 2, all cloudburst roads will drain into tidal basin 1 and for alternative 1, there is a tidal basin 2 where there will be an extra outflow. For the calculation of the drainage capacity, alternative 1 and 2 are the same.

To account for stakeholder concerns, several features are incorporated into the design in figure 3.17. First, large open areas where homeless people could set up tents are avoided. Furthermore, a half green cloudburst road can be introduced instead of a full green cloudburst road can be constructed in areas where there is little parking or would still need to be used by cars. Barriers along the cloudburst roads where cars drive trough can be installed to prevent wakes. And finally, the permeable surface will prevent water staying stagnant where mosquitos can nest.

Table 3.3: Different cloudburst road designs

Designs	Functions	Discharge capacity	Costs	Green space	Disruption
Traditional sewage system	- Discharge large amounts of storm water	Large	Large	None	None
Cloudburst road (car road)	- Discharge limited amounts of storm water - Facilitate car traffic	Small	Small	None	Small
Cloudburst road (one way car road, other way green space)	- Discharge medium amounts of storm water - Facilitate car traffic - Recreation	Medium	Small	Medium	Medium
Cloudburst road (complete road green space)	- Discharge large amounts of storm water - Recreation	Large	Medium	Large	Large

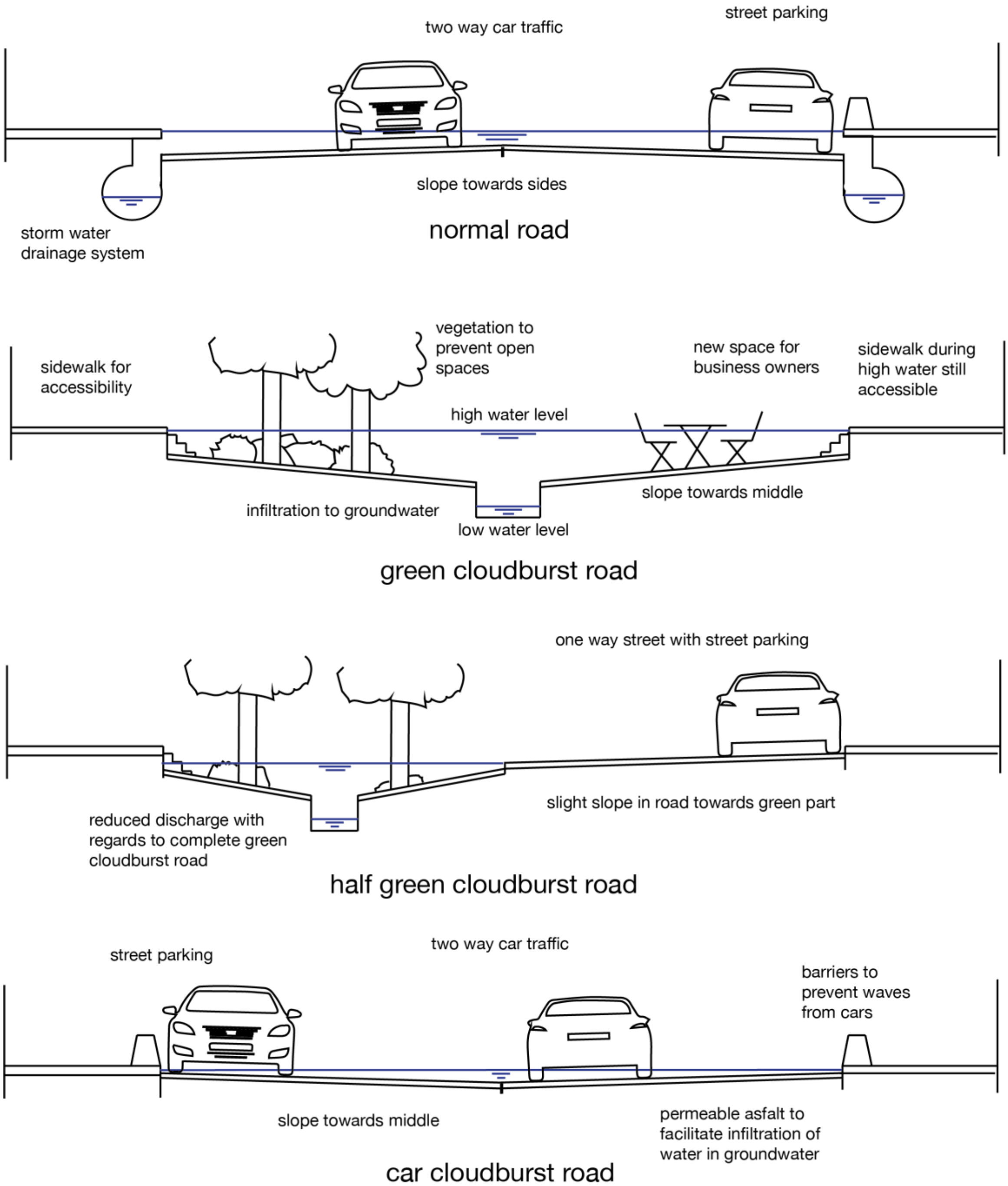


Figure 3.17 different designs for cloudburst roads

Three different roads are selected for the design of large cloudburst roads based on their elevation and current function, these are 25th, 22nd and 20th street. Since 25th street is a major road, this will be a one-way cloudburst road to minimize the disruption. 20th and 22nd will be complete cloudburst roads. The adjacent roads will be cloudburst roads with a gradient towards these large roads. An extra block next to 25th street is added to the drainage area and 17th street to 14th street will be excluded from the drainage area since there are no good candidate for cloudburst roads. Roads where the cloudburst road intersects with harborside drive, the strand, market street and mechanic street will go over the cloudburst road via a bridge.

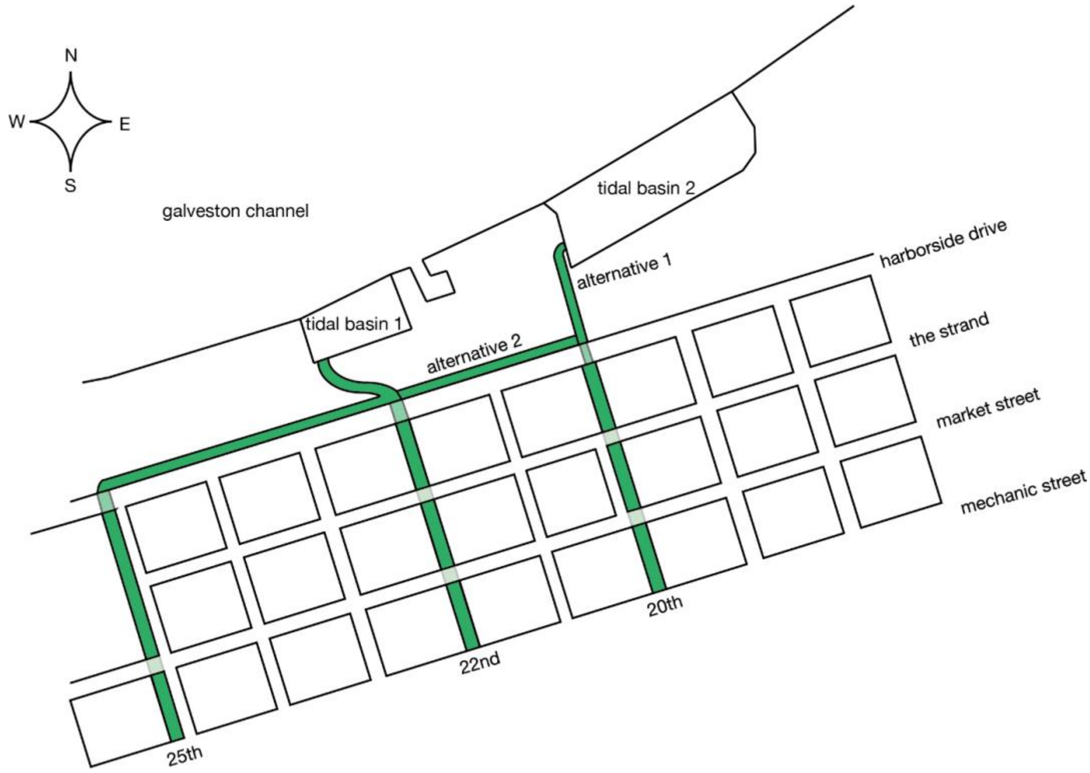


Figure 3.18, map of cloudburst roads in green. Shaded areas represent cloudburst road going under a bridge.

Every block is about 100 by 100 meters. Sidewalks are 5 meters wide each and roads are 15 meters wide except for the roads on 25th street and parts of 20th street where the roads are 25 meters wide. The total area in figure 3.18 is about 0.5 km^2, this is the total drainage area.

The cloudburst roads work in 2 different ways when dealing with catastrophic and chronic flooding. For chronic flooding or SLS, most of the discharge capacity comes from infiltration with a low discharge towards the basin. Other functions, like recreation or outdoor seating, inside the cloudburst roads would not be possible but objects will not be damaged. For catastrophic or ULS, the discharge capacity comes from the maximum the channel can discharge in combination with the infiltration capacity. During such an event the cloudburst road is not usable for other functions and objects like tables or vegetation will be damaged, but there will be no flooding of buildings or other roads.

For simplicity it is assumed that all 3 cloudburst roads drain away the same amount of water. The needed drainage capacity (Qmax) is calculated by multiplying the maximum precipitation rate (p) by the total drainage area.

$$Qmax = A_{strand} * p$$

The geometry of the cloudburst roads is first designed for ULS. This is an hourly rain event with a 100-year return period. This is the catastrophic pluvial flooding event. If the system is able withstand this event, it should be able to withstand less severe chronic pluvial flooding event. The precipitation rate associated is 5 inch/hr, this amounts to 127 mm an hour. The total discharge capacity needed is:

$$Qmax = 17.64 \ {m^3}/{s}$$

Per cloudburst road this amounts to:

$$Qroad = 5.88 \ {m^3}/{s}$$

For the cloudburst roads the design discharge capacity is the relevant design variable. In the event of maximum precipitation, the system needs to be able to drain this precipitation away without uncontrolled flooding.

The maximum discharge through cloudburst roads is calculated using open channel flow. In open channel flow it is assumed that the flow is uniform and stationary.

$$Q = A \cdot \frac{1}{n} \cdot R^{\frac{2}{3}} \cdot S^{\frac{1}{2}}$$

Where:

Q = discharge

A = surface of the cross section of the cloudburst road

n = Gauckler-Manning coefficient, dependent on the cloudburst road surface material

R = hydraulic radius of the cross-section

S = the slope of the cloudburst road

The hydraulic radius and the surface of the cross section are geometric values. The cross-section of a cloudburst road is simplified to:

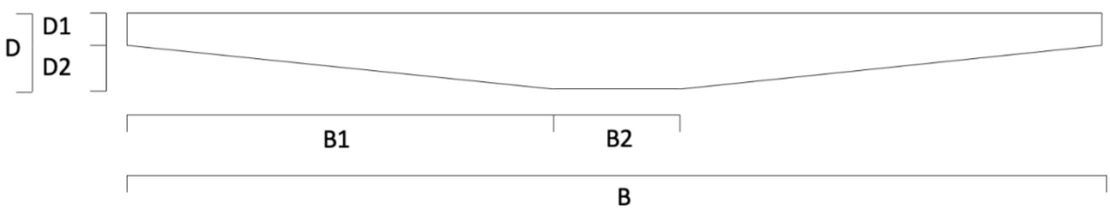


Figure 3.19: Geometry of a cloudburst road

$$A = D1 * B + D2 * B1 + D2 * B2$$

$$R = \frac{A}{\left(2 * D1 + B2 + 2 * \left(\sqrt{B1^2 + D2^2}\right)\right)}$$

The green surfaces of the cloudburst road facilitate infiltration into the subsurface. It is assumed for this calculation that the groundwater table, in case of maximum precipitation will remain below the surface. This means that the infiltration into the subsurface is only limited by the hydraulic conductivity of the subsurface. The discharge infiltrating into the subsurface is determined by:

$$Qinfiltation = k * L * B$$

k = hydraulic conductivity

L = length of the cloudburst road

B = width of the green space of the cloudburst road

So, the total discharge capacity of a cloudburst road is determined by:

$$Qcatastropic = A \cdot \frac{k}{n} \cdot R^{\frac{2}{3}} \cdot S^{\frac{1}{2}} + Qinfiltration$$

For 22nd and 20th the length of the road is about 400 meters in both alternative 1 and 2. For 25th street is about 600 meters. The width of 25th street is only 12.5 meters and the width of 22nd and 20th street are 15 meters. This causes the slope and the hydraulic radius also to change. The hydraulic conductivity of sand is equal to 2*10^-4 (Structx, 2023). For the strickler-manning coefficient, the cloudburst roads are modelled as a weedy earth channel. The strickler-manning coefficient then comes to 0.03 (Engineering toolbox, 2023).

Table 3.4 cloudburst roads design for the catastrophic scenario

streets	k (m/s)	n (s/m^(1/3))	B1 (m)	B2 (m)	D1 (m)	D2 (m)	L (m)	B (m)	A (m^2)	Q (m^3/s)
25th	$2 * 10^{-4}$	0.03	1	10.5	0.5	0.1	600	12.5	6.9	6.03
22nd /20th	$2 * 10^{-4}$	0.03	3.5	8	0.5	0.1	400	15	6.6	6.00

SLS is where most of the discharge is infiltrated into the subsurface with some run off to the tidal basin. This is an hourly rain event with a 1-year return period. This is a chronic pluvial event. The precipitation with this is 1.8 inch/hr or 46 mm/hr. The required discharge capacity will be equal to 6.39 m^3/s.

The total infiltration capacity of the 3 cloudburst roads is equal to:

$$Qchronic = k * ((2 * L_{22th} * B_{22th}) + (L_{25th} * B_{25th}))$$

$$Qchronic = 3.9 \ m\hat{}3/s$$

The remaining discharge per cloudburst road is 0.83 m^3/s. This discharge would hinder other functions in the cloudburst road but would not damage any structures or objects inside it.

At Market Street the elevation for all 3 streets is about 1.4 meters above NAVD88. The outflow into the basins is at 0.8 meters above NAVD88. As the basin nears it capacity of 1 meter above NAVD88 there will be some backflow into the cloudburst road. The lowest elevation point in the Strand is 1 meter above NAVD88, so if the water level in the basin is kept to its maximum the water backflowing into the cloudburst road will not cause any flooding in the strand.

Water retainment areas and tidal basins

For both alternative 1 and 2 the design of the inland water retainment areas is the same. For alternative 2, there is no tidal basin 2. The design variable for the water retainment area's is dependent on the event of maximum precipitation combined with a high water that would force the gates to close in the tidal basins. It is assumed that since a tidal cycle takes about 6 hours, the gates in the tidal basins can open again after 6 hours. This means that the total volume of water the water retainment areas need to store is 6 hours of a large precipitation event. For this compound event, a maximum precipitation of 6 hours with a 10-year return period is chosen, this value is equal to 1.1 inch/hr or 28 mm/hr. This would be the ULS, for the SLS the water retainment areas would be partly filled. The total volume of water needed to be retained is equal to:

$$V_{max} = p * 6 * A_{strand} = 84000\ m^3$$

There are 2 ways of water storage considered in the design. First there are the two tidal basins and there are the water retention areas.

For the design of the tidal basins, it is assumed that the water level prior to closing is at the mean sea level. The mean sea level is at 0.25 meter above NAVD88. The lowest elevation in the Strand is about 1 meter above NAVD88. Since the system is dependent on the This leaves 0.75 meters of water height for retainment in both basins. In the overtopping calculations for the levee the water level will rise with 3 cm in tidal basin 1 and 4 cm in tidal basin 2 during a 6 hour tidal cycle. Tidal basin 1 has a surface area of about 5000 m^2 and a potential storage height of 0.72 meters and tidal basin 2 has a surface area of about 19000 m^2 and a potential storage height of 0.71 meters. For alternative 1 there is a storage of 17000 m^3 and for alternative 2 there is a storage of 3600 m^3. The rest of the needed storage needs to be facilitated by the water retainment areas.

Water retainment areas can be designed in 2 ways. Either the area has a permeable layer to the side and bottom so that the water will be able to drain into the soil, or the side and bottom of the area are made impermeable, and the water drains via a dedicated drainage. Since the water table is relatively close to the surface in Galveston, the water retainment area might fill up with groundwater if the storage area is constructed too deep. To combat this, the side and bottom of the water retainment area can be made impermeable by a layer of concrete. In this case the water retainment area can be constructed deeper. The water retainment area will not however be able to drain trough the soil. This principle can be applied to the parking lot areas that are transformed into retention areas. This can be seen in figure 3.19.

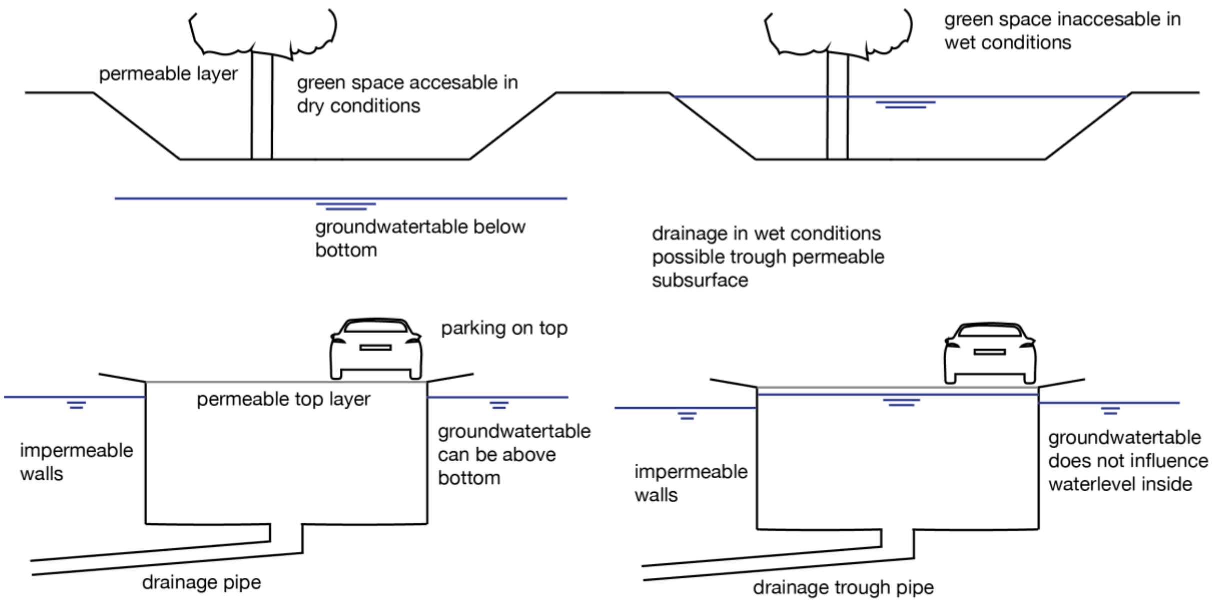


Figure 3.19: 2 designs for water retainment areas

One of the stakeholder concerns was for mosquitos to lay their eggs in still standing water. To prevent this from happening, there cannot be still water inside the water retainment areas for more than 24 hours. For the shallow water retainment basin, where water drains away to the subsurface, this will be used as the first design constraint. It is assumed that water will always be able to drain to the subsurface. By using the hydraulic conductivity of the subsurface and a maximum drainage time of 24 hours, the maximum height of water in the basin (h) can be determined.

$$h = k * t$$

k = hydraulic conductivity of the subsurface

t = time of drainage

This means that the shallow water retainment basins cannot have a larger water height inside them of about 0.4 meters. The second design constraint is the groundwater table. On average the groundwater table is 1 meter below the subsurface, so 0.4 meters will not cause groundwater to flow back into the water retainment area.

Since the walls of the second design are impermeable, the depth of the water retainment parking lots can be a design valuable for the required capacity. The limitations for the depth of the water retainment parking lots are failure due to buoyancy from the groundwater or an economical cost.

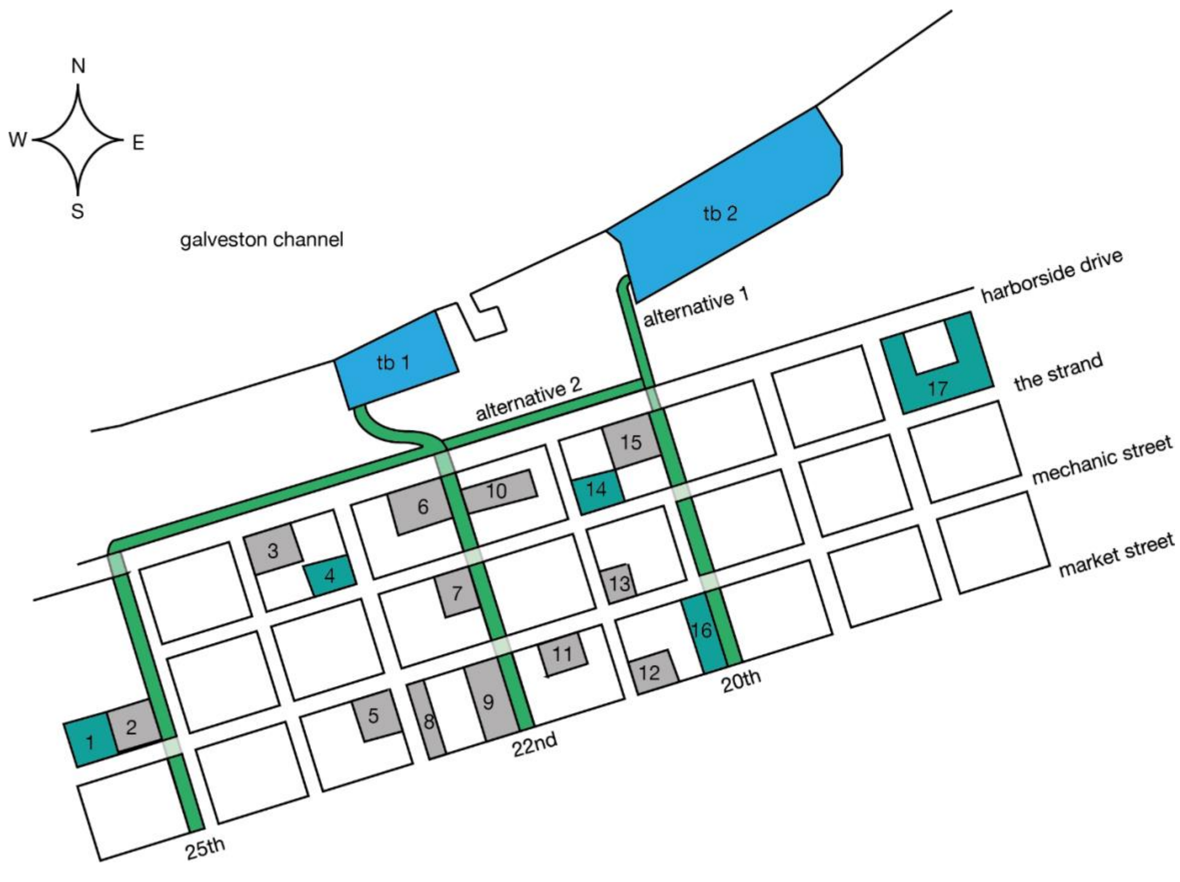


Figure 3.20: Water retainment areas

The total required volume for water storage can be determined using:

$$V_{max} = V_{tidal\ basin} + V_{parks} + V_{parking\ lots}$$

The depth for the water retainment parks is equal to 0.4 meters. The depth of the water retainment parking lots is found by dividing the residual needed volume by the total area of the water retainment parking lots. The total area of the parks is equal to 12800 m^2 and the total area for the parking lots is equal to 19000 m^2.

Table 3.5: Area per retention area

Retainment area	type	Area (m^2)
1	Park	2400
2	Parking lot	1600
3	Parking lot	1200
4	Park	1200
5	Parking lot	1000
6	Parking lot	2600
7	Parking lot	750
8	Parking lot	1600
9	Parking lot	2400
10	Parking lot	1600
11	Parking lot	1800
12	Parking lot	1000
13	Parking lot	1000
14	Park	1200
15	Parking lot	2400
16	Park	2000
17	Park	6000

$$V_{parks} = \sum A_{parks} * 0.4 = 5120\ m^3$$

$$V_{parking\ lots} = V_{max} - V_{tidal\ basins} - V_{parks}$$

$$d_{parking\ lots} = \frac{V_{parking\ lots}}{\sum A_{parking\ lots}}$$

The total surface area for parking lots is 19000 m^2. For alternative 1 the depth of the water retainment parking lots needs to be 3.26 meters and for alternative 2 the depth of the water retainment parking lots needs to be 3.96 meters.

Connection promenade and cloudburst road

Up until now cloudburst road and the promenade were treated quite separately. However, there are a few places at which both designs intersect. Extra attention should be paid to these connections, as the designs should work together as a system. The first location that needs to be further investigated is the interface of the tidal basins with the promenade. Here, an overtopping of 0.1 L/s/m was assumed during 6 hour SLS conditions. As this is only an assumption, it is evaluated what the influence is of varying this discharge on the required retention capacity in the Strand. This can be seen in Table 3.6 Here alternative 1 is considered for the promenade, in which case both tidal basins are available.

Table 3.6: The influence of varying overtopping discharge on the required retention capacity

Overtopping discharge [L/s/m]	Increase tidal basin 1 [m]	Increase tidal basin 2 [m]	Required retention depth parking lots [m]
0.05	0.02	0.02	3.23
0.1	0.03	0.04	3.26
0.5	0.15	0.22	3.46
1	0.31	0.43	3.72

It can be seen that for higher overtopping discharges the retention capacity of the tidal basins decreases rapidly. It is thus beneficial to construct the levees in front of tidal basin 1 and 2 higher than necessary. In this way, the basins can be used in an optimal way for the retention of pluvial water.

Another interesting point for the connection is the outflow of cloudburst road in tidal basin 1. An overview of this can be seen in figure 3.21 Here a bridge is created to allow pedestrians to cross the cloudburst road and walk on a continuous promenade along the waterfront.

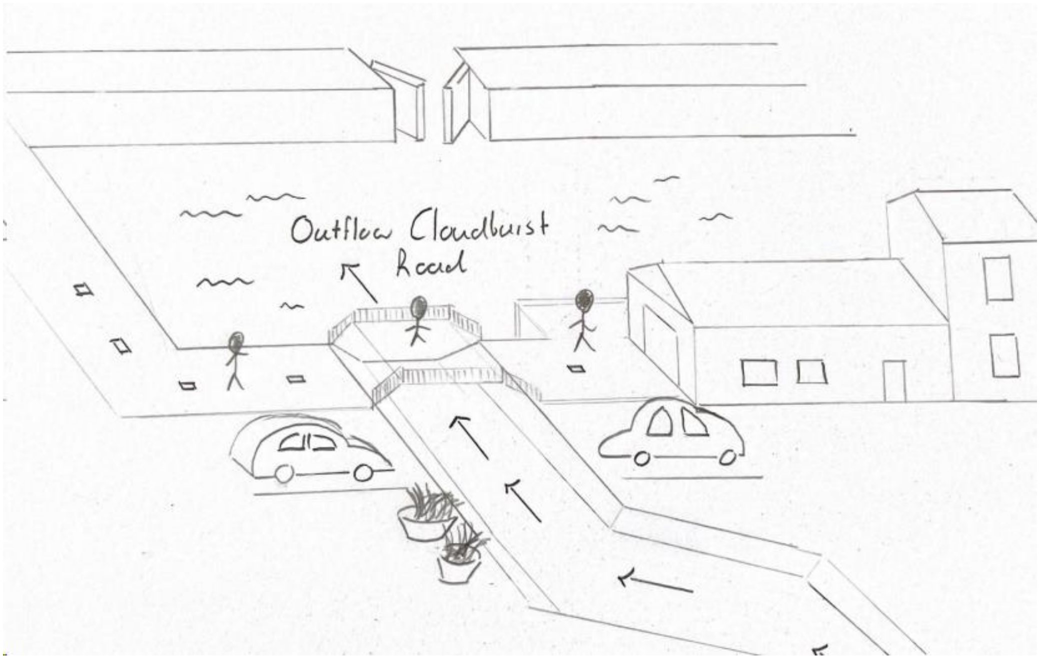


Figure 3.21 The intersection of cloudburst road and the promenade at the outflow in tidal basin 1

4 Evaluation and conclusion

In this chapter, the beforementioned design alternatives are evaluated to see what their strengths and weaknesses are. In order to do so, the chapter will start with an MCA. This MCA will be based on the evaluation of the different designs and taking all information from stakeholders into account. After this MCA is conducted, the outcome is discussed concluding the research done in Galveston.

4.1 Multi-criteria analysis

To ensure a well-informed assessment of the strengths and weaknesses of each design alternative, the team conducts a Multi-Criteria Analysis (MCA). This method consists of assigning a set of design criteria, which is separated in: a modified version of the design requirements (table 1.1), stakeholder concerns (table 2.7) and additional stakeholder concerns(table 3.1).
First of all, a weight (W) is assigned to each criteria (i) corresponding to its importance. Secondly, each system component gets a score (S) based on its performance regarding each criteria. As end result, after summing up all products of the weighing and score, every system component receives a total score:

$$S_{comp,total} = \sum W_i * S_{comp,i}$$

Two separate MCA's are performed, one for the waterfront design (i.e. the promenade system) and one for the inland design (i.e. the cloudburst road system):

1. The waterfront design is divided in sections and alternatives. Section 1.1 corresponds with section 1, alternative 1. In the same matter, section 4.2 corresponds to section 4, alternative 2. These combinations are elaborated in section
2. The inland design is divided in the following alternatives based on degree of intervention: green cloudburst road, half green cloudburst road, car cloudburst road and normal car road. These alternatives are elaborated in figure 3.17.

Ultimately, the outcome of the MCA analysis will provide valuable insights into the comparative performance of these alternatives. It is explicitly chosen to not select one alternative for both designs that performs best. Rather, this question is left open to the reader, since it is very dependent on the project area and other context. In this way, a toolbox of alternatives is created that can each be implemented in different scenarios and environments. This also allows for easier implementation and extension of the design in other urban areas in Galveston, or even outside of Galveston. An overview of the MCA that is performed can be found in Appendix I. In the next section, the conclusion from the MCA will be evaluated.

The MCA has to be interpreted to be able to arrive at a grounded conclusion. From the MCA it is shown that sections 2 to 4 from alternative 1 perform well when multifunctionality and retention are top priority. These sections are easy to interconnect, resulting in few gates and few awkward transitions. Furthermore, visitors can walk along the promenade continuously and interact with the water and therefore spatial value is enhanced. Local businesses can profit from this. Debris impact risk is significantly reduced due to the fact that equipment that can go adrift is secured within the barrier. Flexibility to changing boundary conditions is assured by the closable barrier. Alternative 1 contains two tidal basins thus more retention area is provided. By contrast, sections 2 to 4 from alternative 2 performs best when short term feasibility and port accessibility are top priority as buildings are integrated in the barrier. Adapting this to future conditions is challenging due to the limited lifetime of these incorporated buildings. Furthermore, both leisure boats and fishing boats can access the marinas at all time due to absence of gates.

Sections 1 and 5 are subject to different priorities than sections 2 to 4. When short term feasibility and easy implementation are top priorities, section 1 and 5 from alternative 1 would be a promising option. The barrier on top of the quay wall is easy to extend and interconnection with other segments is easy resulting in less gates. Less importantly, alternative 1 performs well in preventing stagnant water and debris impact. However, port operations play a big role in these sections and this barrier disrupts these operations significantly. Sections 1 and 5 from alternative 2 perform regarding port operations. When incorporating the barrier in the port buildings, not only port operations can continue undisturbed but also costs are cut because the building should only be made waterproof. The cost argument weighs less heavily in section 5 as the integrated barrier most likely has to be destroyed due to plans for a new cruise terminal.

For the cloudburst road a MCA is done to compare 4 different alternatives. A complete green cloudburst road, a half green cloudburst road a car cloudburst road and a normal car road with a traditional storm water drain. From the MCA it is found that the complete green cloudburst road scores the best and a normal car road score the worst. This is to be expected, since drainage capacity and flexibility are weighted rather high. For all three streets a complete green cloudburst road should then be chosen. Since there is more room on 25th street, here a half green cloudburst road is chosen since it would have almost the same drainage capacity as a complete green cloudburst road and would minimize the disruption. The MCA can be seen in figure I.2.

4.2 Conclusions

In this chapter, first a conclusion is provided about the multidisciplinary approach that was used during the project, after which the research questions stated in the beginning of this document are provided.

4.2.1 Multidisciplinary approach

In the project, the fusion of Construction Management and Engineering, Hydraulic Engineering, and Hydraulic & Offshore Structures illustrates a multidisciplinary approach that transcends traditional urban flood management. The project integrates stakeholder insights and environmental considerations into its design, demonstrating an awareness of the social, economic, and ecological dimensions. This approach is reflected in the incorporation of commercial spaces within flood defences, showcasing a balance between economic vitality and structural safety. Meanwhile, innovative hydraulic solutions, like adaptive flood walls and retention basins, blend technical precision with urban design, addressing both coastal and pluvial flooding while enhancing the area's aesthetic appeal. This was all achieved due to the interaction and valuable insights between the different disciplines.

The project’s strength lies in its ability to integrate structural integrity with public usability in the reshaping of the Galveston ring barrier. Here, multifunctional levees and promenades represent a integration of adequate flood protection with attractive public spaces, a result of the collaborative mindset of the different engineering disciplines while coming to a design. The result at the end of the project is, due to the multidisciplinary approach, an integrated solution that would not have been reached when approaching the issue from a single discipline perspective.

4.2.2 Original research questions

During this project the following research question was answered: **How can the Galveston ring barrier be reshaped in The Strand area to increase functionality regarding both coastal and pluvial flooding and sustainably deal with both catastrophic and chronic flooding while being integrated**

and valuable for the public space? This question was split up into three sub-questions related to each discipline. These are:

Hydraulic & Offshore Structures:
How can the Galveston ring barrier flood wall be reshaped by making it multifunctional and thus improve spatial value in The Strand?

The answer to this question is clear. The way in which the barrier can be reshaped is mainly dependent on the interests of the local- stakeholders and the boundary conditions at hand. At the sections in the port, which are sections 1 and 5, multifunctionality is not highly valued. Rather, access to the waterfront is most important to continue with port operations. Therefore multiple alternatives can be implemented, such as flood walls and flood proof buildings. Since the ports are at high elevation, these can be low and easily implemented on the short term. In the touristic part of the project area, which is section 2 to 4, multifunctionality is valued much more. In this area the density of buildings and restaurants is very high, therefore it is best to implement new measures along the waterfront. Since the elevation right at the waterfront is high, construction of a promenade here allows for moderate height. Therefore levees can be built, which can be combined easily with other functions, such as recreation and restaurants. These levees can be built in multiple setups, each creating its own unique interaction with the waterfront.

Hydraulic Engineering:
How can the height of the flood wall be reduced in certain sections to allow overtopping and how can the overtopped water and excess rainfall be drained and retained in a sustainable way to prevent flooding of The Strand?

There is a great difference between the hydraulic boundary conditions during SLS and ULS storm surge conditions. ULS conditions happen at very low frequency, but in order to be safe the coastal protection needs to be raised to this levee. Therefore, most of the time there is redundant height that disadvantageous for access to the waterfront. The height can be reduced by installing flexible barriers that only need to move up during ULS conditions. Behind these barriers, overtopping retention basins can be integrated in the promenade, which are designed for SLS storm surge conditions. At other locations, the height can be reduced by allowing overtopping in the tidal basins. Specifically during ULS storm surge conditions this can lower the height significantly. In SLS storm surge conditions, the height is designed to leave sufficient space in the tidal basins to store pluvial water. When SLS storm surge conditions happen simultaneously with extreme precipitation, the tidal basins can be used to drain water from the Strand. Any additional water can be stored in pluvial retention facilities that are created in the Strand.

Construction Management & Engineering
What are the main stakeholder concerns regarding the Ring Barrier design in the Strand area and how can these be incorporated into the design?

The main concerns with stakeholder groups that came forward during the project are maintaining the accessibility of the waterfront the port, the ongoing economic activities and the livability of the area that should not be compromised by an increase of mosquitoes for example. The final design alternatives take these concerns into account, after verification of their legitimacy through the Salience model. By focusing on water accessibility in the design through the promenade. By keeping the water flowing through the cloudburst road, mosquito eggs will not be able to hatch, keeping nuisance at a minimum. Moreover, by incorporating space for small shops in the promenade, economic activities can continue and it even provides opportunity to support upcoming shops or new stores. Additionally, the homeless issue addressed is deliberately not taken into account, since this concerns lacks legitimacy in this project.

This project shows that there is great potential for a multifunctional approach to flooding in the Strand area. It demonstrates that a multifunctional approach allows to integrate flooding measures in the existing space, and by doing so it does not compromise American concerns such as car accessibility and parking space. While this is typically considered to be a European approach, it shows that this can also be implemented in cities in the United States. Moreover, a multifunctional approach more sustainably deals with both coastal- and pluvial flooding during chronic- and catastrophic events than the original ring barrier plan. This is because the required pump capacity can be lowered, since the tidal basins allow to discharge water during high water level events. Lastly, this alternative brings the number of required gates down, making it more robust.

5 Recommendations

The current study focuses on the process of design of the measures to counteract flooding. The goal of this study is to investigate the feasibility and effectiveness of the cloudburst road, retention areas and promenade for the scenarios that can occur. It gives an indication of the order of magnitude of retention volume, discharge capacity and others in comparison to the most extreme conditions that can occur. However, the results of this study should be treated with caution. Some hydraulic boundary conditions, such as precipitation data and storm surge data should be investigated more thoroughly by for example conducting a joint probability analysis. Further research could look into this.

Since the project aims at coming up with a better alternative to the Ring Barrier Plan, the same context is used with regards to climate change. The Ring Barrier Plan does not take into account sea level rise and future precipitation rates for the design. This is a very important aspect, as it is known that in the future the sea level will rise significantly in Galveston and rain showers will be more intense. Furthermore, it is very probable that hurricanes will occur more frequently in the future. The proposed designs in this project should therefore be tested for these conditions. This is an interesting subject for further research. This research could investigate how the design can be made in a way such that it is easily adaptable to climate change. This should be done by taking climate change effects into account during the design process. The storm surge walls and levees could for example be made in such a way that they are easy to raise according to sea level rise projections. Cloudburst road and the retention areas could also be adapted so that there is sufficient space to store additional water in the future.

To come up with a detailed design, the project area was chosen to be a stretch of only 1 km in length which contains the Strand. In this way, adaptation measures could be made on a very local scale. However, the proposed designs are very suitable to be implemented in other parts in Galveston. In a further study it would therefore be valuable to extend this design to a bigger area and see what other challenges these areas would bring. By doing so, it could also be investigated how the system of cloudburst road, retention areas and tidal basins would behave on a larger scale.

Sustainable drainage systems like cloudburst roads or water retention areas are not often implemented in the United States. A research article in the Blue-green systems journal looked at the root causes of failure of sustainable drainage systems in The Netherlands. Researchers found that most of the common causes are incomplete knowledge about the technical performance of the systems or interaction with other systems, poor communication with stakeholders and a lack of experience in construction of these systems (Vollaers et al., 2021). When implementing a design with sustainable drainage systems it is vital to pay special attention to these issues.

Lastly, for the pluvial flooding only two measures have been studied for the design. Other examples of sustainable drainage measures such as green roofs that slow down the flow of water have not been considered. For the simplified design it was not possible to incorporate this factor, so this was not considered. If the runoff from the precipitation is slowed down, then the drainage capacity of the cloudburst roads can be reduced. For a more detailed design, the incorporation of this reduction in runoff speed should lead to a smaller required drainage capacity.

6 Reflection

Reflection on process

Vince:

In my opinion the setup of the MDP was very good. I think the main challenge was the scoping of our research questions and project areas. During the first 2 weeks in the Netherlands we had a lot of ideas and some project areas like the industrial areas and wetlands that seemed very interesting, but once we visited them in person they were not at all. That is also why physically going to Galveston was extremely valuable, also to hear a lot of opinions and experiences of the local community. The thing that was particularly challenging during the scoping was the fact that we were stuck on this idea of hard protection and completely solving the problem in a very engineering way. Luca really pushed us towards the architecture approach, which is more focused on the integration of the flood barrier into the environment and reducing the consequences instead of complete protection. I also think that the idea of multifunctionality is very interesting. For me it was the first time doing a project about that, but it is definitely something that I want to do more in the future. I also feel like my master track Hydraulic & Offshore Structures was very relevant for this project, since a lot of the calculations and theory were brought to practice during the trip.

Kjell:

Firstly, I think that the gap in expertise due to the absence of architecture students was filled in very well. Not only the design but also the student group proved to be resilient and all showed creative skills supplementing their engineering skills. Furthermore, I acquired interesting new insights by talking to a multitude of people during the project. These insights altered my vision on how to deal with flooding issues. There is not one individual perfect solution that can be applied to all environments but rather a set of preventive and adaptive solutions that work together well. I think we can learn a lot from this approach as climate change is no longer a problem for the future but is encountered right now and this becomes visible in the Netherlands sooner than we would like to admit. At first, this more adaptive way of thinking was uncomfortable but I think it grew on us.

On a critical note, the interdisciplinarity of the project was sometimes quite challenging. In hindsight, I think in the final stages of the design we worked out the promenade, cloudburst road and stakeholder part of the project separately where we should have done it parallel to each other. This caused problems in the structure and flow of the report. Another challenge within the interdisciplinary aspect was the sometimes heated discussion we could have within the group. Due to different backgrounds and personalities we could sometimes not get on the same level. In the end, we could put these discussions into perspective due to our awareness of the interdisciplinary nature of the project. The personality tests performed beforehand also helped with this.

Siebe:

The setup of the MDP worked quite well in my option. It was nice to have time before and after the trip to Texas to prepare for and process the information collected there. I found the multi-disciplinary aspect of the project sometimes quite challenging. As an engineer, it was sometimes difficult to look at problems and solutions form an architectural point of view. None the less, I think that in this process I learned a lot.

Max:

The project process was thoughtfully structured, starting with informative lectures in Delft, followed by a workshop in Texas, complemented by additional time spent there. This approach allowed for a gradual buildup of knowledge, gaining insights before, during, and after our Texas visit. The access to Texas A&M facilities and on-site supervisor expertise proved very valuable. Organizing the interviews posed a challenge for me. The ones that did happen were mainly with parties expressing interest in the project or during impromptu face-to-face conversations without prior scheduling. Many others, contacted via email or approached in person, showed no interest in participating, either by ignoring emails or questions. Additionally, some individuals who initially appeared keen to assist during face-to-face interactions remained unresponsive when contacted online through email, WhatsApp, or Instagram direct messages. If these individuals had responded to the messages, the interviews could have been more comprehensive. Nonetheless, I am pleased with the conducted interviews as they proved valuable, offering insightful perspectives not only on people's concerns but also on their overall mindset.

In terms of the group process, the dynamic was interesting, considering my different masters background from the majority who specialized in hydraulic engineering. Initially I found it difficult to make my mark on the project, since the project predominantly focused on the hydraulic engineering aspect of the design. I managed to contribute by highlighting previously unaddressed stakeholder concerns and considering these when brainstorming potential solutions. The group dynamics also evolved significantly over time, transitioning from an initial influx of solution ideas to a more focused approach as the project neared completion.

Reflection on outcome

Vince:

I think the outcome is very different to what I expected it to be when we started doing the project. At first I thought it was doable to analyse a much bigger project area, but it turned out that coming up with a design that takes everything into account is way more difficult than I expected. I think what is very nice about our design that it really is a system that works together and can deal with all kinds of different scenarios. Furthermore, I am really happy that we built a barrier that integrates into the environment and is very multifunctional. I think that including multifunctionality is definitely something I will take more into account when doing future projects.

Kjell:

In my opinion the end result of this project shows that integration of the flood barrier is possible without comprising typical American values and priorities where I first thought these were conflicting values. For example, car accessibility could still be assured with the modified ring barrier design. To explain myself a bit more: even though the US is a developed country and the culture shock was not that big, I felt a bit alienated about the way the Americans tackle their problems and wanted to shove off all our design issues on this typical American approach. However, eventually we came up with creative designs and made it work. From the start we had to narrow down our scope significantly but I think this enabled us to develop a design of high quality.

Siebe:

I feel satisfied with the outcome of this MDP. In the beginning we had quite a large scope and once in Galveston, we had to narrow it down quite a bit. None the less, I feel that we identified the problems quite well and feel that we proposed good matching solutions.

Max:

In the end, I'm quite satisfied with the results. The idea of not presenting 1 solution but more and reflect on the strengths and weaknesses of both solutions is really nice I think. There is no best solution, the decision is not made by us and is subjective. That insight was really nice to make. I'm also happy with how the time in Texas was spent. I think we really made the most out of it, taking the opportunity to gather knowledge from a different perspective and culture.

The decision to focus on the smaller Strand area instead of taking the industrial area and wetlands into account as well, was an unexpected but nice twist for me. I didn't expect this at front, but I'm glad that we did. The decision made sure that we were able to look deeper in the activities that surround the Strand area and dive deeper into the design of a suitable solution(s) for this specific area.

Reflection on experience

Vince:

I think doing a project abroad was a great experience. It was great to get to know engineers and architects from a different culture and see how things are done at a university abroad. It was also really interesting to see how the local culture and community and their view towards a project is very different than in the Netherlands. We were really surprised about hearing that a lot of people are not aware of the plans for the ring barrier or that they just do not care about it. I also found it very absurd that natural hazards such as floods and hurricanes are so normal for these people. In their view everything is expendable, as long as they can get it back via insurance. They have just accepted that every few years all their belongings get destroyed. But this is something that corresponds to the policy in the US, as they are much more focused on reducing the consequences than protecting against floods.

Kjell:

I liked the change of approach that was paired to this project. Instead of doing calculations and writing reports behind my desk I could experience the real world and directly get in contact with people involved in the project. I miss these kind of things in the education Delft offers. This resulted in completely different solutions and visions than a normal Civil Engineering project would come up with. Outside of the project we were able to undertake some adventures into heartland Texas. I am very grateful for this opportunity which would probably not have been possible when opting for an internship or additional thesis. Moreover, I would like to thank all project members but also supervisors for their passionate attitude towards the project. This attitude made sure we could learn things from the project and from each other.

Siebe:

This MDP was a great experience. It was the first time for me in the US, so some things were somewhat of a culture shock. Being able to work on the MDP at the campus of Texas A&M was a great addition because we were able to casually talk to students and professors. From these casual conversations we were able to get a better idea of the way of life in Galveston and how flooding issues affect people personally.

Max:

I learned a lot from multi-disciplinary aspect, lots of information about hydraulic structures and how other people look at a problem with different kinds of interest and eye for details. Also nice to incorporate the urbanism aspect of the project, providing a different look upon the problem rather than solely from a civil engineering perspective. Moreover, it was very nice to experience Texan culture. The difference in way-of-mind when tackling a problem like discussed in this report was really interesting to see. Also, the individualistic mindset was noticeable when talking to stakeholders and people in the area. This opened my eyes, the way people in Texas think of a solution for a problem is really different from what I'm used to.

Additionally, we've done a personality test at the start of the project. The results from that test, which showed what peoples characteristic traits are, were very clear when staying in Texas. For me, it was nice to have the knowledge from these tests when we were having heated discussions in the team. It was nice to see. Having these results allowed me to put my project colleagues' attitudes into perspective during heated discussions, leading to increased understanding and smoother discussions. Additionally, I also used the results (partially) when assigning tasks in the project to empower individuals in their areas of strength. For a closer look at the results from these tests, see Appendix F.

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Appendices

Appendix A: Gate types

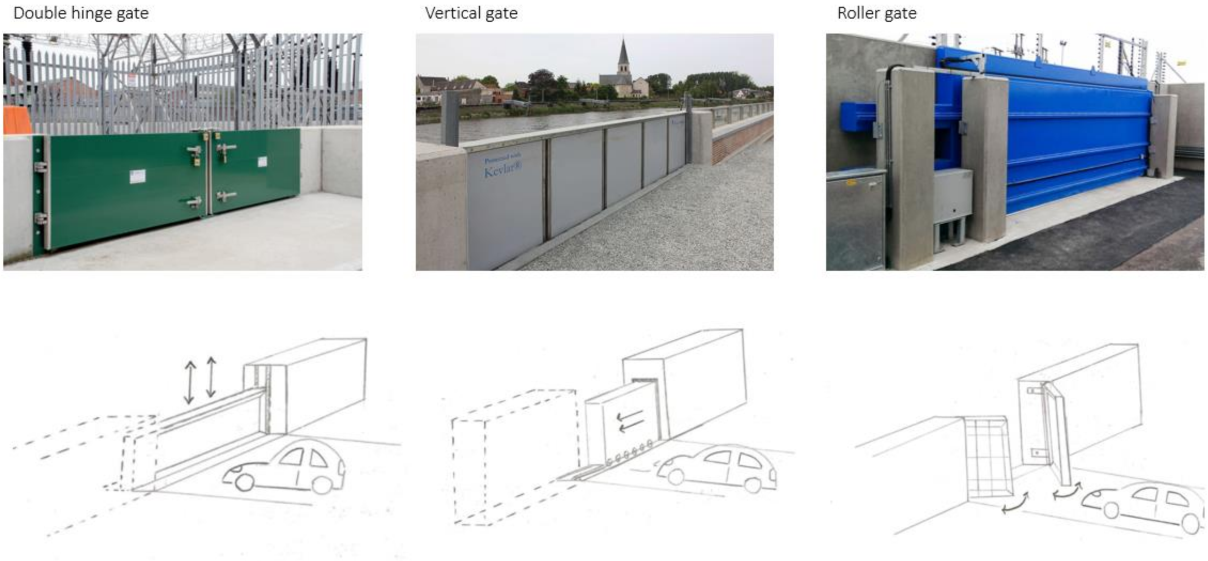


Figure xxx: Double hinge, vertical and roller gates opening mechanisms and integration into landscape (Flood Control International, 2023a)

Table A.1 : The different alternatives that are considered for the gates

Alternative	Advantage	Disadvantage
Roller gate	• It can be integrated into the flood wall, saving space • It does not need a lifting mechanism	• When the roller gate is integrated into the flood wall, no other functions can be integrated inside the wall
Vertical gate	• In open condition the gate is below ground level, saving a lot of space	• The gate lifts out of the ground, leading to difficulties for maintenance • Electrical or hydraulic systems required that allow the gate to be lifted
Hinge gate	• In open position it can be placed parallel to buildings to save space • It does not need a lifting mechanism	• In some spaces it could lead to obstruction of the view

Appendix B: Flexible barrier types

Figure xxx: Mobile inflatable barrier, self-closing vertical barrier and flip-up barrier technical drawings and integration into landscape (Flood Control International, 2023b, Mobiele Dijken, 2023 & Chan, 2023)

Table B.1 : The different alternatives that can be used for the flexible barrier

DAlternative	Advantage	Disadvantage	Retaining height
Mobile dike	• Can handle hydrodynamic loads such as overtopping • Easy to implement over long distance • 90 times faster installation than sand bags	• Relative complex installation • Horizontal stability can be compromised at high water levels	Up to 2.70 m
Self-closing barrier	• Operation is automated • No electrical systems involved	• Expensive • Closing depends only on water level and not on wave height • Built in segments of 10 m • Permanent intermediate posts required	Up to 1.50 m
Rotary wall	• Easy to integrate in levee • Does not take a lot of space	• Applied in sections of 12 m • Permanent intermediate posts required	Up to 2 m

Appendix C: Existing measures

In the strand, found during the fieldwork:

Table C.1 An overview of the measures that are already taken to reduce flood-damage in The Strand

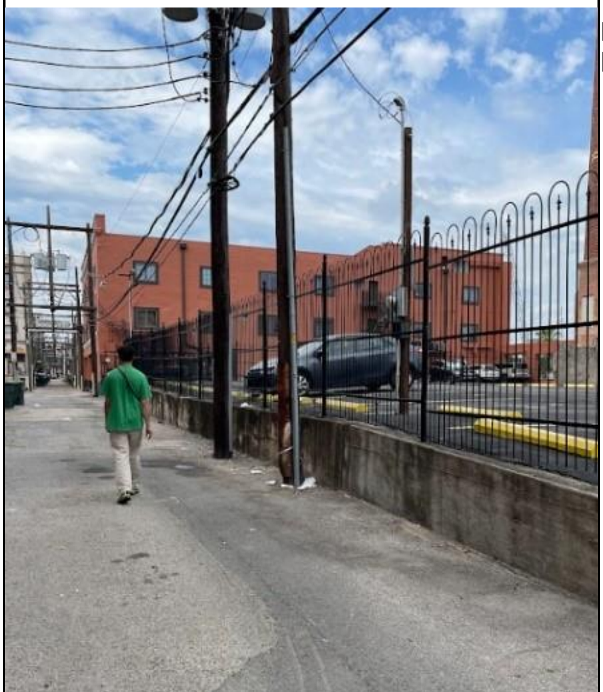
Photo + number	**Description**	**Typology**	**Material**	**Prevent/adapt**
1. 	Curvature street	Street	Concrete/asphalt	Prevent
 2.	Heightened pavements	Public space	Concrete	Adapt
3. 	Port drainage	Infrastructure	Concrete & steel	Prevent

4. 	City drainage	Infrastructure	Concrete	Prevent
5. 	Earthen dike	Public space	Soil & vegetation	Prevent
6. 	Elevated shops	Public building	Concrete	Adapt

7. 	Stone houses near shore	Private building	Stone	Prevent
8. 	Elevated houses	Private building	Wood	Adapt
9. 	Skyscraper on levee of approx. 1.75 m	Private building	Concrete	Adapt
10. 	Elevation pier on sea-side by approx 1 m to prevent water entering the streets	Street	Concrete	Prevent

11. 	Elevated railroad	Infrastructure (mobility)	Concrete & steel	Adapt
12. 	Building on mound	Public building	Soil & vegetation	Adapt

13. 	Industry on mound	Infrastructure	Concrete	Adapt
14. 	Elevation road	Infrastructure (mobility)	Concrete	Adapt

15. 	Crawl space foundation	Prive building	Concrete	Adapt
16. 	Watertight electrical equipment	Infrastructure (energy supply)	Steel	Prevent
17. 	Elevated parking lots	Public space	Concrete	Adapt

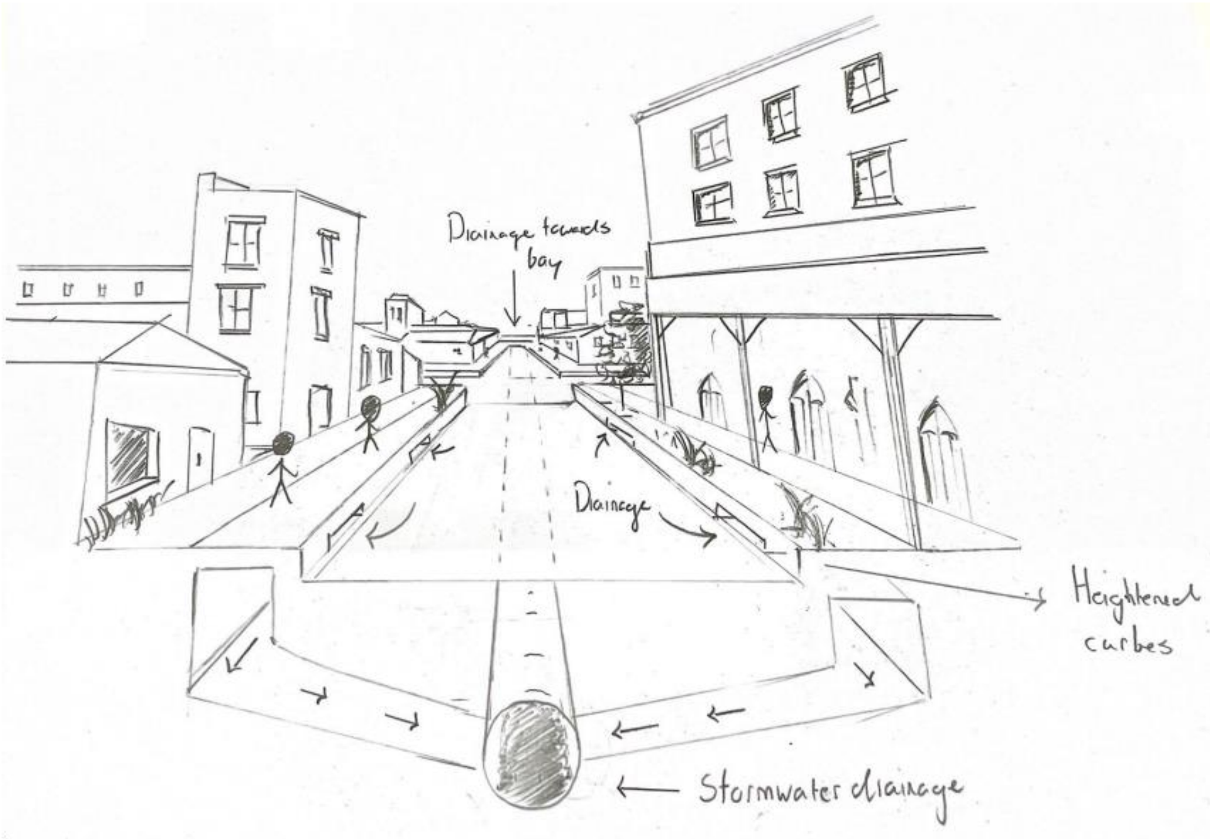


Figure C.1: Engineering behind the landscape: the current drainage system in Galveston

Appendix D: Stakeholder engagements

District representative in Galveston City Council

Moment of conversation: 10/10/2023

Concern(s):

- City needs protection from flooding, both chronical and coastal
- Proposed barrier goes straight through district representing
- Certain inhabitants of the district must not lose their view/connection to the water
- Homeless people in the city cause a problem, however flooding is a bigger problem
- Monetary feasibility
- Lack of knowledge amongst Galvestonians, difficult to reach

General attitude towards problem:

- Not concerned with the possible increase of spatial value
- Working towards a quick solution for the flooding rather than waiting for the big masterplan to take shape (proactive)

Restaurant owner 1

Moment of conversation: 4/10/23

Concern(s):

- Continuous business in the restaurant
- Customers must be able to access the restaurant
- Thinks chronical flooding is a bigger problem than coastal flooding

General attitude towards problem:

- If the solution works against the flooding, all is fine
- Mostly concerned with own business

Restaurant owner 2

Moment of conversation: 4/10/23

Concern:

- Customers should be able to reach the restaurant easily
- Current ring barrier plan would affect amount of customers

General attitude towards problem:

- Restaurant is elevated so coastal flooding is covered, focus on chronical flooding
- Not necessarily focussed on spatial value, purely own interest of possibility of losing customers

Bar owner 1

Moment of conversation: 4/10/23

Concern(s):

- Admitted the chronical flooding was an issue seen the drop of customers

General attitude towards problem:

- Had no clue about the ring barrier problem
- Very much a "whatever dude" attitude, couldn't care less about the design. Very acceptant of the flooding, both chronical and coastal
- Was positively surprised about the plans, happy that some action is going to be taken but feared the government would take a long time to realize the plans.

Business owner 1

Moment of conversation: 5/10/23

Concern:

- Main focus on chronical flooding, business is flooding every time
- Wakes originating from cars cause a lot of damage
- Increase in spatial value causes homeless people to come to his area

General attitude towards problem:

- Is active within the community about the flooding
- Cares about his own business but also about others
- Really focused on chronical flooding, coastal flooding not so much

Local inhabitants

Moment of conversation: 1/10/23 to 5/10/23

Concern(s)

- Chronical flooding is annoying
- Coastal flooding is really bad, but insurance covers a lot so it's "fine"

General attitude towards problem:

- Very acceptant of coastal flooding
- Very little knowledge about the current designs
- Admitting chronical flooding is a big issue but work their way around it
- Very much concerned about their personal activities and concerns and couldn't care less about that of others. If everyone thinks of himself, everyone is thought of
- Does not care about the final form of the design. It's nice if there is an increase in spatial value, but if a steel wall can do the same and is cheaper than that's good also.

Bar owner 2

Moment of conversation: 4/10/23

Concern(s):

- Customers must be able to sit comfortably outside on the terrace
- Mosquitos cause lots of inconvenience when sitting in the area of still standing water

General attitude towards problem:

- Doesn't really care about the possibility of increased spatial value, does care about solutions for chronical and coastal flooding
- View over the water from restaurant is not really nice, looking at industrial buildings anyway so a steel wall or nice promenade has no effect on his bar. Is content as long as it works for his bar

Professor Texas A&M at Galveston

Moment of conversation: multiple conversations from 27/9 to 18/10

Concern:

- Coastal flooding is a major problem
- Sees the possibility of increase in spatial value, underscores the importance of monetary issues

General attitude towards problem:

- Actively involved with politics surrounding the design

Business owner 2

Moment of conversation: 27/10/23 & 18/10/23

Concern:

- Lack of spatial value in current design
- Chronical flooding is a major issue
- Current design blocks of own view from house
- Preserve nature/other locations with value where possible

General attitude towards problem:

- Actively involved, concerned with the community

Students TAMUG

Moment of conversation: multiple conversations from 27/9 to 18/10

Concern(s):

- Concerned about both chronical and coastal flooding, but chronical has priority

- Lots of fun activities happen in the area all year round, when looking at solutions we need to take into account these activities and make sure they are continuing.

General attitude towards problem:

- Interested, willing to think along when discussing ideas
- Willing to be actively involved with the designs

Appendix E: Elevation data python script

In [2]:
```
import netCDF4
import numpy as np
import matplotlib.pyplot as plt
%matplotlib inline
```

In [3]:
```
#https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa
#https://www.earthinversion.com/utilities/reading-NetCDF4-data-in-python/

#MHW Mean High Water, The average of all the high water heights observed o

#the dif between elevation and NAVD88 is 0.309 m https://tidesandcurrents.
```

In [4]:
```
data = netCDF4.Dataset('galveston_13_mhw_2007.nc')
```

In [5]:
```
print(data.variables.keys())
```

```
dict_keys(['crs', 'lat', 'lon', 'Band1'])
```

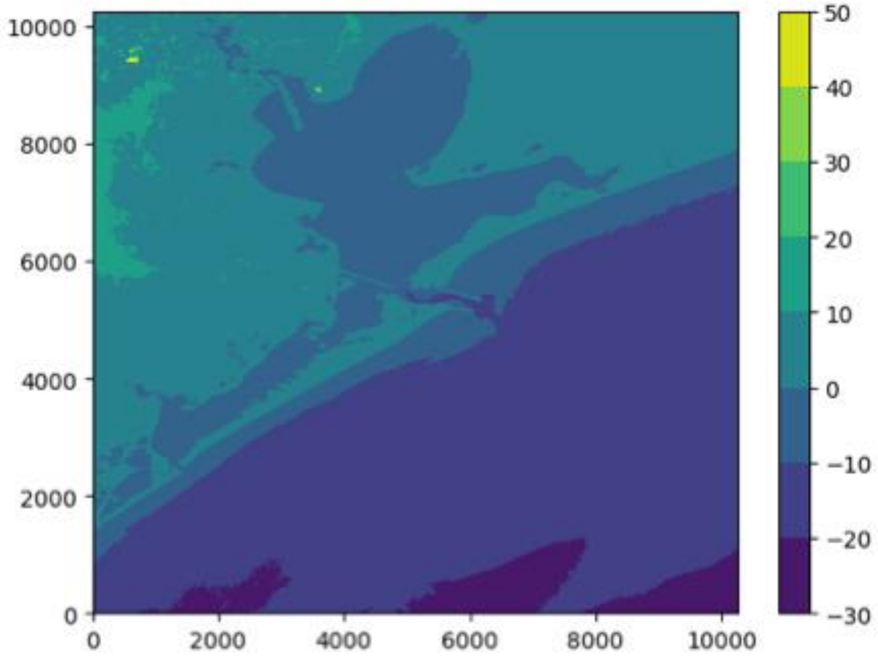
In [6]:
```
lat = data.variables['lat']
lon = data.variables['lon']
h = data.variables['Band1']
print(h)
print(lat[0])
print(lat[-1])
print(lon[0])
print(lon[-1])
```

```
<class 'netCDF4._netCDF4.Variable'>
float32 Band1(lat, lon)
    long_name: GDAL Band Number 1
    _FillValue: -9999.0
    grid_mapping: crs
    units: meters
    positive: up
unlimited dimensions:
current shape = (10261, 10261)
filling on
28.8500000126
29.799999985999999
-95.25
-94.3000000266
```

In [7]:
```
#lat and lon degrees in arrays
lats = lat[:]
lons = lon[:]
#function to determine the closest lat and lon in array
def getclosest_i(lats_lons, c):
    #find squared distance
    dist_sq = (lats_lons - c)**2
    #find index for closest arg
    min_index = dist_sq.argmin()
    return(min_index)
```

In [8]:
```
zoom_out = plt.contourf(h[:])
plt.colorbar(zoom_out)
```

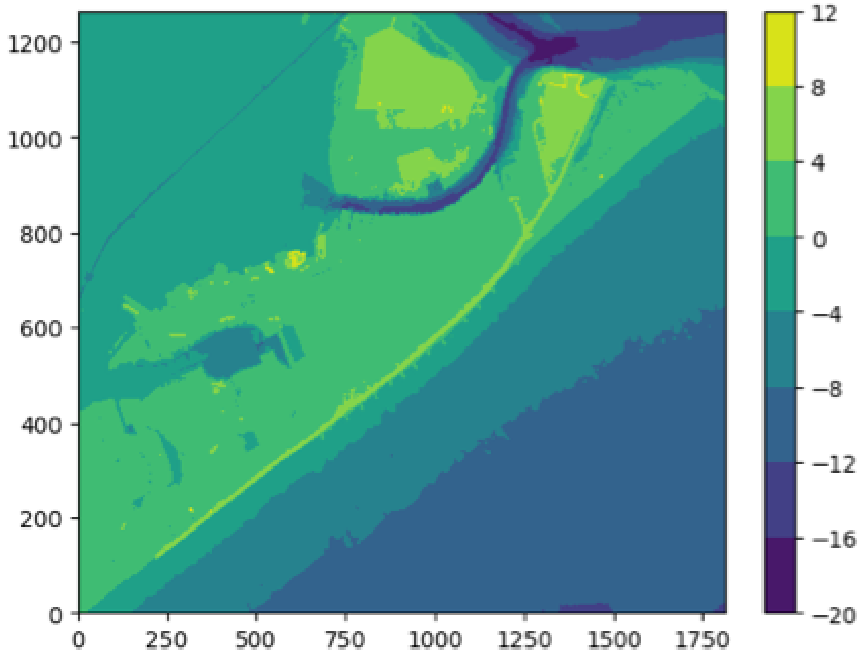
Out[8]: <matplotlib.colorbar.Colorbar at 0x108fddd00>



In [9]:
```
#(29.348644, -94.888977), (29.231275, -94.721243)
```

In [10]:
```
h_galv = h[getclosest_i(lats, 29.231275):getclosest_i(lats, 29.348644), ge
galv = plt.contourf(h_galv)
plt.colorbar(galv)
```

Out[10]: <matplotlib.colorbar.Colorbar at 0x1091b8040>



In [11]:

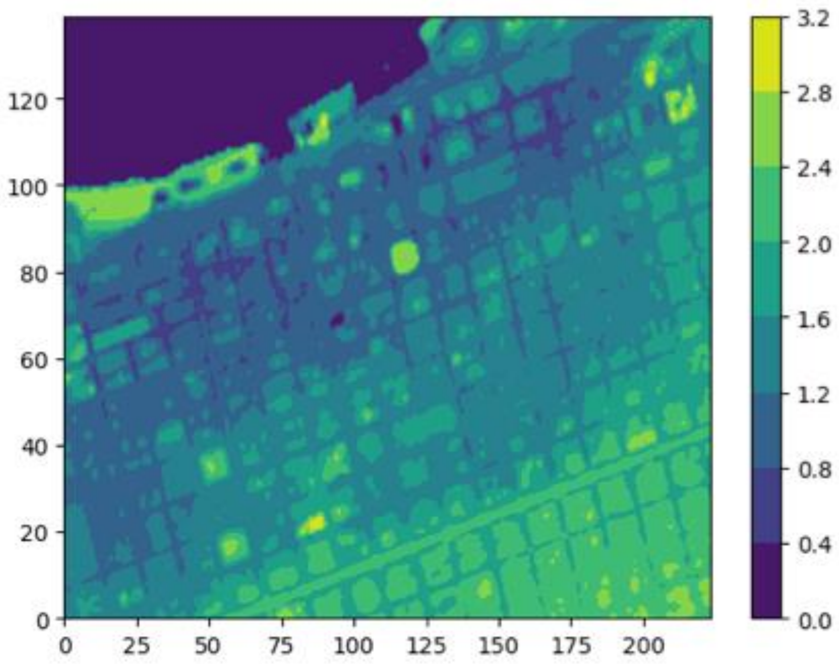
```
#(29.312115, -94.800807), (29.299178, -94.780119)
```

In [27]:

```
h_galv = h[getclosest_i(lats, 29.299178):getclosest_i(lats, 29.312115), get
for i in range(len(h_galv)):
    for j in range(len(h_galv[i])):
        if h_galv[i][j] <= 0:
            h_galv[i][j] = 0
galv = plt.contourf(h_galv)
plt.colorbar(galv)
```

```
-7.166504
```

Out[27]: <matplotlib.colorbar.Colorbar at 0x109616fa0>



In [13]:
```
#for datapoint 1 to 7
datapoints = [[29.309206483442324, -94.79485232030797], [29.30882317865718!
```

In [14]:
```
h_det = h[:, :]
```

In [15]:
```
for i in range(len(datapoints)):
    print(f'the height for point {i+1} is {h_det[getclosest_i(lats, datapo:
```

```
the height for point 1 is 2.782423957824707 meters
the height for point 2 is 1.3655500259399413 meters
the height for point 3 is 1.5666090097427368 meters
the height for point 4 is 2.05566702747345 meters
the height for point 5 is 2.0803249921798708 meters
the height for point 6 is 1.5596289482116699 meters
the height for point 7 is 1.3399150218963622 meters
```

In [16]:
```
#(29.306859636045473, -94.79552787735477)
```

In [17]:
```
print(f'the height for the point is {h_det[getclosest_i(lats, 29.306859636(
```

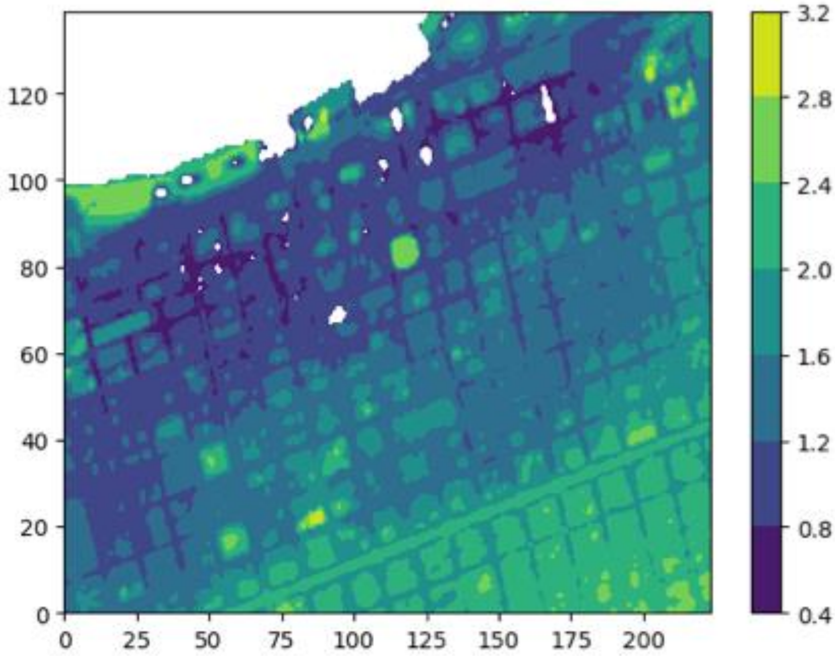
```
the height for the point is 1.1116139736175537 meters
```

In [18]:
```
#29.305922286065467, -94.79399840072017
print(f'the height for the point is {h_det[getclosest_i(lats, 29.30592228€
```

```
the height for the point is 0.8111469745635986meters
```

In [19]:
```
h_galv = h[getclosest_i(lats, 29.299178):getclosest_i(lats, 29.312115), ge
for i in range(len(h_galv)):
    for j in range(len(h_galv[i])):
        if h_galv[i][j] <= 0.5:
            h_galv[i][j] = np.nan

galv = plt.contourf(h_galv)
plt.colorbar(galv)
```

Out[19]: <matplotlib.colorbar.Colorbar at 0x109366e50>



In [20]:

In [21]:
```
#set of datapoints allong waterfront
datapoints = [(29.30572178923906, -94.79262668380672), (29.30658533737812,
for i in range(len(datapoints)):
    print(f'the height for point {i+1} is {h_det[getclosest_i(lats, datapo
```

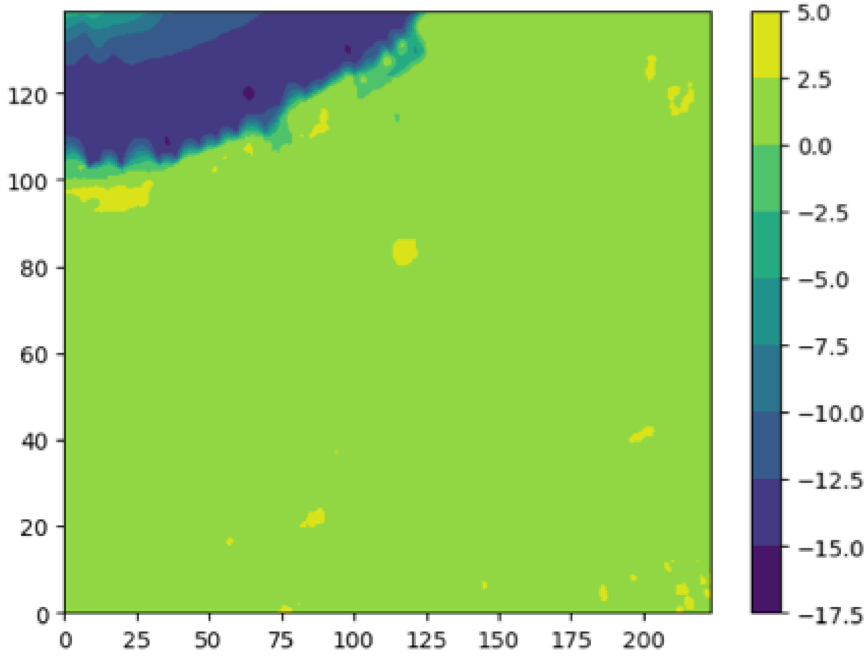
```
the height for point 1 is 1.167856976032257 meters
the height for point 2 is 1.1981050219535827 meters
the height for point 3 is 1.0967349853515624 meters
the height for point 4 is 1.3630649890899658 meters
the height for point 5 is 0.6830740120410919 meters
```

In [22]:
```
#29.30911804876539, -94.79191766389744
print(f'the height for the point is {h_det[getclosest_i(lats, 29.30911804876
```

```
the height for the point is 1.3091150369644164 meters
```

In [23]:
```
h_galv = h[getclosest_i(lats, 29.299178):getclosest_i(lats, 29.312115), ge
galv = plt.contourf(h_galv)
plt.colorbar(galv)
```

Out[23]: <matplotlib.colorbar.Colorbar at 0x10944e2e0>



In [24]:
```
#height of random point
lat = 29.308858929023035
lon = -94.79439887206114
print(f'the height for the point is {h_det[getclosest_i(lats, lat), getclo
```

```
the height for the point is 0.6830740120410919 meters
```

In [1]:
```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import folium
```

```
/Users/siebevanderburg/Desktop/MDP /venv/lib/python3.9/site-packages/urllib
3/__init__.py:34: NotOpenSSLWarning: urllib3 v2.0 only supports OpenSSL 1.
1.1+, currently the 'ssl' module is compiled with 'LibreSSL 2.8.3'. See: ht
tps://github.com/urllib3/urllib3/issues/3020
  warnings.warn(
```

In [2]:
```
data = pd.read_csv('data.txt')
```

In [3]:
```
#array of all longitudes and latitudes
lons = data['Longitude(decimal degrees)'].to_numpy()
lats = data['Latitude(decimal degrees)'].to_numpy()
h = data['Elevation (meters)'].to_numpy()
```

In [4]:
```
#function to determine the closest lat and lon in array
def getclosest_i(lats, lons, lat, lon):
    #find squared distance
    dist_sq = (lats - lat)**2 + (lons - lon)**2
    #find index for closest arg
    min_index = dist_sq.argmin()
    return(min_index)
```

In [5]:
```
#change to wanted point (29.30992929671021, -94.79305315105582):
lat = 29.30992929671021
lon = -94.79305315105582

print(f'the elevation is {data.iloc[getclosest_i(lats, lons, lat, lon)]}')
```

```
the elevation is Longitude(decimal degrees)   -94.793054
Latitude(decimal degrees)     29.309930
Elevation (meters)             2.180000
Name: 9796670, dtype: float64
```

In [6]:
```
harb= [[29.307380528295454, -94.79707088599751], [29.307758220342084, -94.
```

In [7]:
```
harb_elev = np.zeros(len(harb))
for i in range(len(harb)):
    lat = harb[i][0]
    lon = harb[i][1]
    harb_elev[i] = data.iloc[getclosest_i(lats, lons, lat, lon)].values[2]
```

In [8]:
```
print(harb_elev)
```

```
[1.35 1.4  1.32 1.51 1.4  1.37 1.35 1.22 1.09 1.07 1.04 1.36]
```

In [9]:
```
strand = [[29.30657825893024, -94.79666275841642], [29.306861348425397, -9
```

In [10]:
```
strand_elev = np.zeros(len(harb))
for i in range(len(harb)):
    lat = strand[i][0]
    lon = strand[i][1]
    strand_elev[i] = data.iloc[getclosest_i(lats, lons, lat, lon)].values[
print(strand_elev)
```

```
[1.17 1.3  1.22 1.34 1.44 1.43 1.53 1.57 1.49 1.36 1.13 1.58]
```

In [11]:
```
mechan = [[29.30566450945919, -94.79636702123295], [29.30597973782367, -94
```

In [12]:
```
mechan_elev = np.zeros(len(harb))
for i in range(len(harb)):
    lat = mechan[i][0]
    lon = mechan[i][1]
    mechan_elev[i] = data.iloc[getclosest_i(lats, lons, lat, lon)].values[
print(mechan_elev)
```

```
[1.28 1.36 1.27 1.42 1.4  1.43 1.37 1.28 1.34 1.55 1.61 1.86]
```

In [13]:
```
market = [[29.30480001835814, -94.79610411993818], [29.305091360623205, -9
```

In [14]:
```
market_elev = np.zeros(len(harb))
for i in range(len(harb)):
    lat = market[i][0]
    lon = market[i][1]
    market_elev[i] = data.iloc[getclosest_i(lats, lons, lat, lon)].values[
print(market_elev)
```

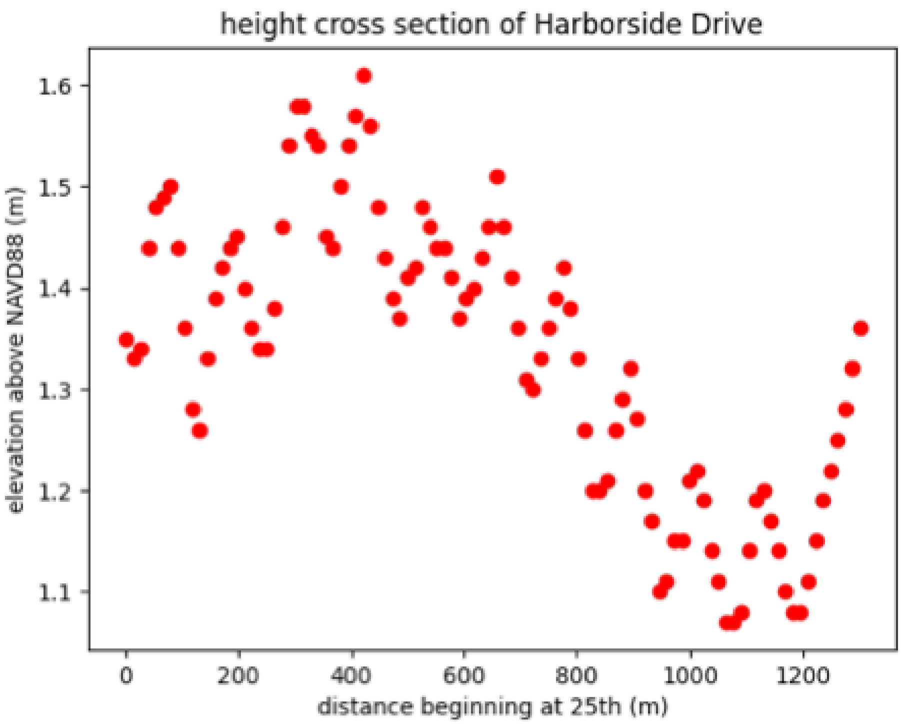
```
[1.37 1.33 1.33 1.35 1.52 1.35 1.41 1.6  1.78 1.84 1.89 2.01]
```

In [15]:
```
#market, cross-section
cross_sec_begin = [29.307380528295454, -94.79707088599751]
cross_sec_end = [29.310735533234077, -94.78441917804568]

lat_dist_cross = cross_sec_end[0] - cross_sec_begin[0]
lon_dist_cross = cross_sec_end[1] - cross_sec_begin[1]

lat_points = np.linspace(cross_sec_begin[0], cross_sec_end[0], 100)
lon_points = np.linspace(cross_sec_begin[1], cross_sec_end[1], 100)

elevation = np.zeros(len(lat_points))
lat_points_find = np.zeros(len(lat_points))
lon_points_find = np.zeros(len(lat_points))
```

In [16]:
```
for i in range(len(lat_points)):
    lat = lat_points[i]
    lon = lon_points[i]
    point = data.iloc[getclosest_i(lats, lons, lat, lon)]
    elevation[i] = point.values[2]
    lat_points_find[i] = point.values[1]
    lon_points_find[i] = point.values[0]
```

In [17]:
```
import matplotlib.pyplot as plt
plt.plot(np.linspace(0, 1300, 100), elevation, 'or')
plt.title('height cross section of Harborside Drive')
plt.xlabel('distance beginning at 25th (m)')
plt.ylabel('elevation above NAVD88 (m)')
```

Out[17]:
```
Text(0, 0.5, 'elevation above NAVD88 (m)')
```



In [18]:
```
map = folium.Map(location=[29.30, -94.79])
for i in range(len(lat_points_find)):
    folium.Marker([lat_points_find[i], lon_points_find[i]], popup='Point')
```

In [19]:
```
map
```

Out[19]: Make this Notebook Trusted to load map: File -> Trust Notebook

In [20]:
```
coord = [[29.309889692136377, -94.79213094270763], [29.309584856216055, -9
```

In [21]:
```
coord_elev = np.zeros(len(coord))
for i in range(len(coord)):
    lat = coord[i][0]
    lon = coord[i][1]
    coord_elev[i] = data.iloc[getclosest_i(lats, lons, lat, lon)].values[2
print(coord_elev)
```

```
[1.85 1.68 1.72 1.48]
```

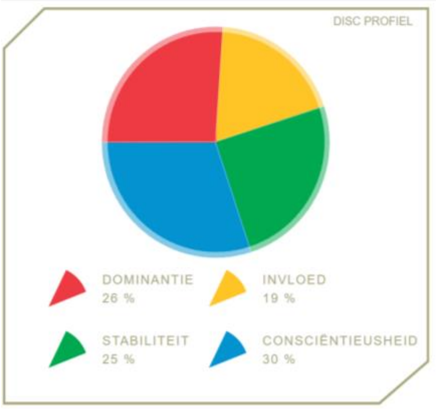
In [21]:

Appendix F: Personality tests

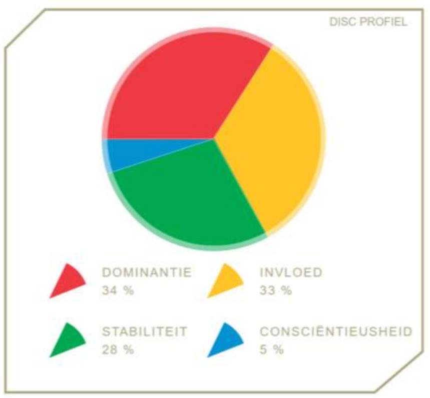
At the start of the project, the team conducted a DiSC test amongst themselves. A DiSC test is a personality test to see whether someone is extra- or introvert, goal- or person oriented and to see what someone’s strengths and challenges are. The result consists of a distribution of 4 colours, having the following characteristics:

- Red: Dominance. People with a Dominance personality are ambitious, independent self-starters who prioritize achieving their goals. They may exhibit leadership qualities, but their competitive nature and impatience with differing perspectives can lead to workplace conflicts.
- Yellow: Influence. People with the Influence personality are known for their enthusiasm, people-oriented nature, and sociable qualities. They excel at team collaboration, motivating others with their positive attitude and strong people skills, although they might occasionally overlook details due to their spontaneous and idealistic tendencies. These individuals thrive in collaborative, creative projects and are assets to any team
- Blue: Compliance. People with the Compliance personality exhibit a penchant for meticulous research, accuracy, and a strive for perfection. They prefer hands-on, independent work and follow rules diligently, although their inclination towards detail-oriented decision-making may sometimes lead to perfectionism.
- Green: Steadiness. People with a Steadiness profile excel in harmonious team environments, known for their dependability and even-tempered nature. They value routine, are cautious about change, and tend to avoid risks, often maintaining the status quo unless encouraged otherwise.

In the team, the results are as follows:

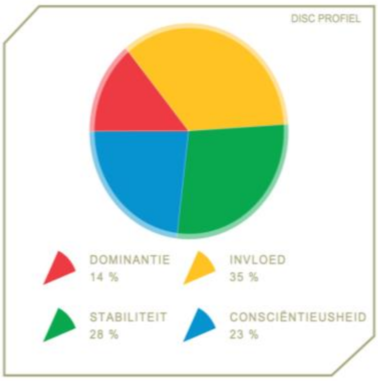


Results DiSC test Vince

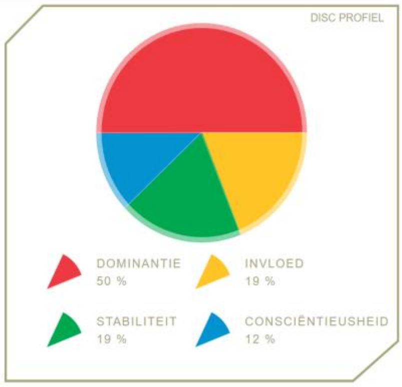


Resı

Results DiSC test Kjell



Results DiSC test Siebe



Results DiSC test Max

One can see that there are multiple personalities in the team. This causes dynamic within the team to be diverse and provides opportunities for everyone to excel in their own strengths.

Appendix G: Reference projects

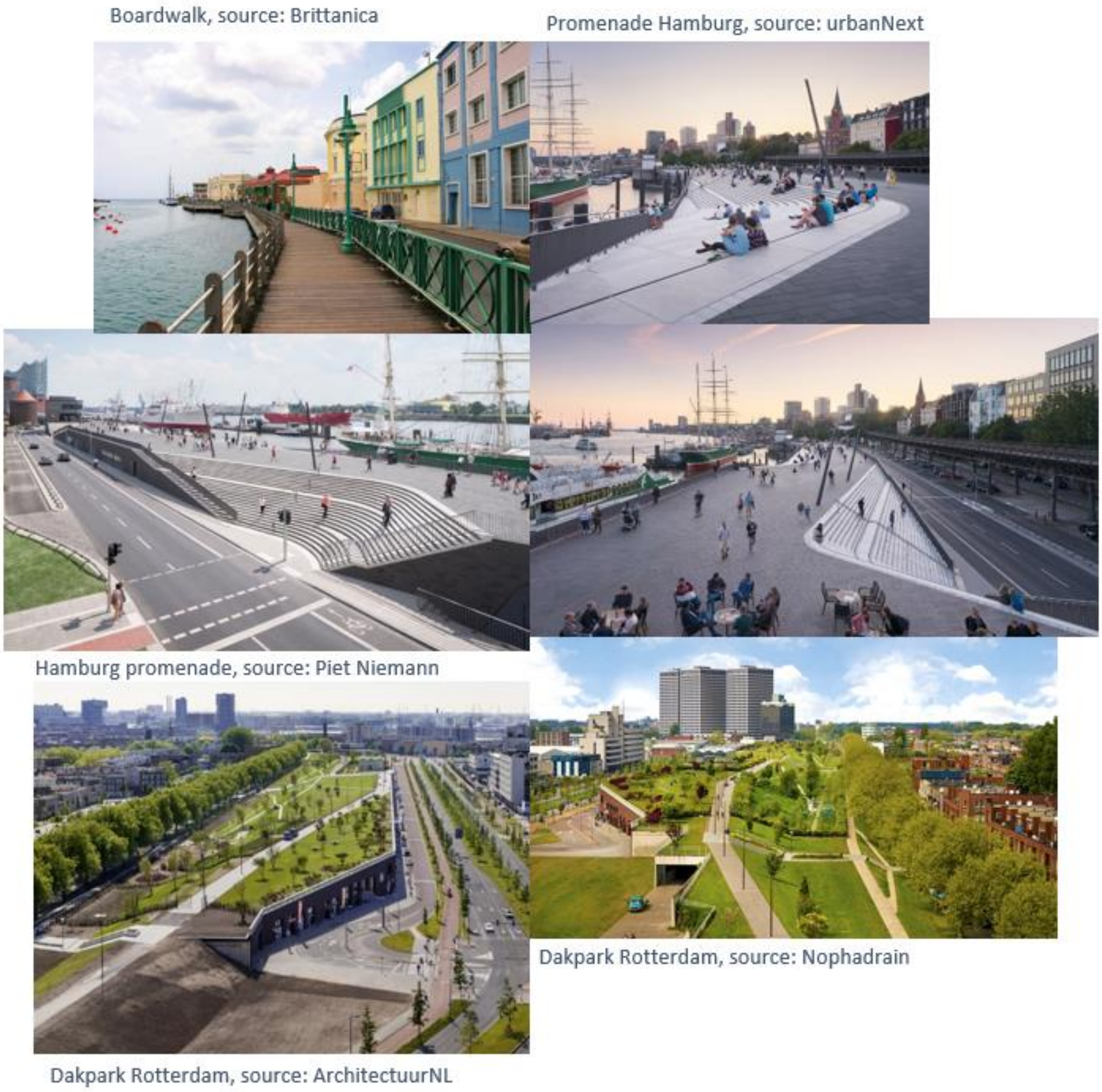


Figure G.1 Reference projects for the promenade

Figure G.2 Reference project cloudburst roads (ASLA, 2023)

Appendix H: Sketches alternatives promenade

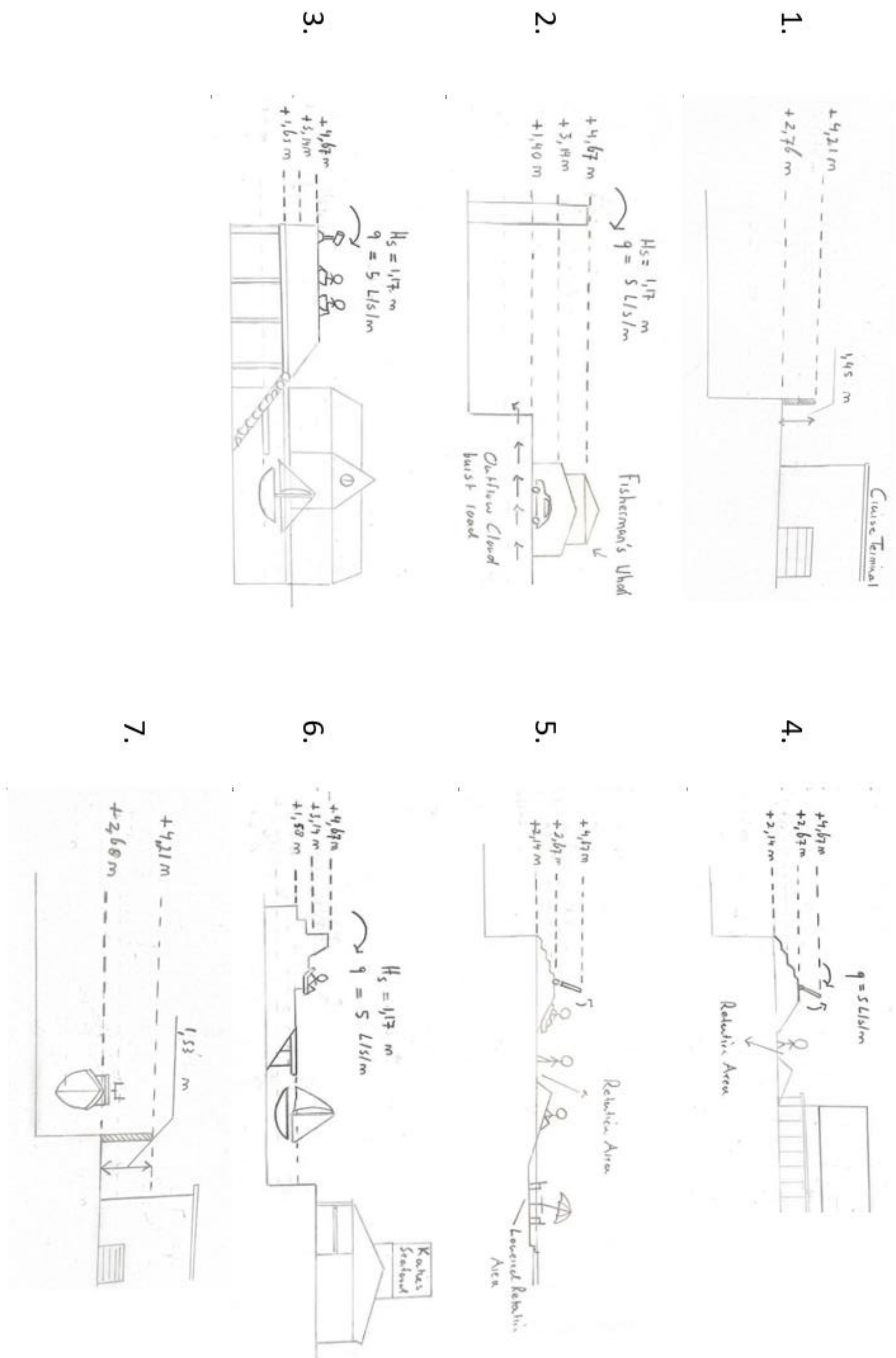


Figure H.1 Cross sections alternative 1 promenade

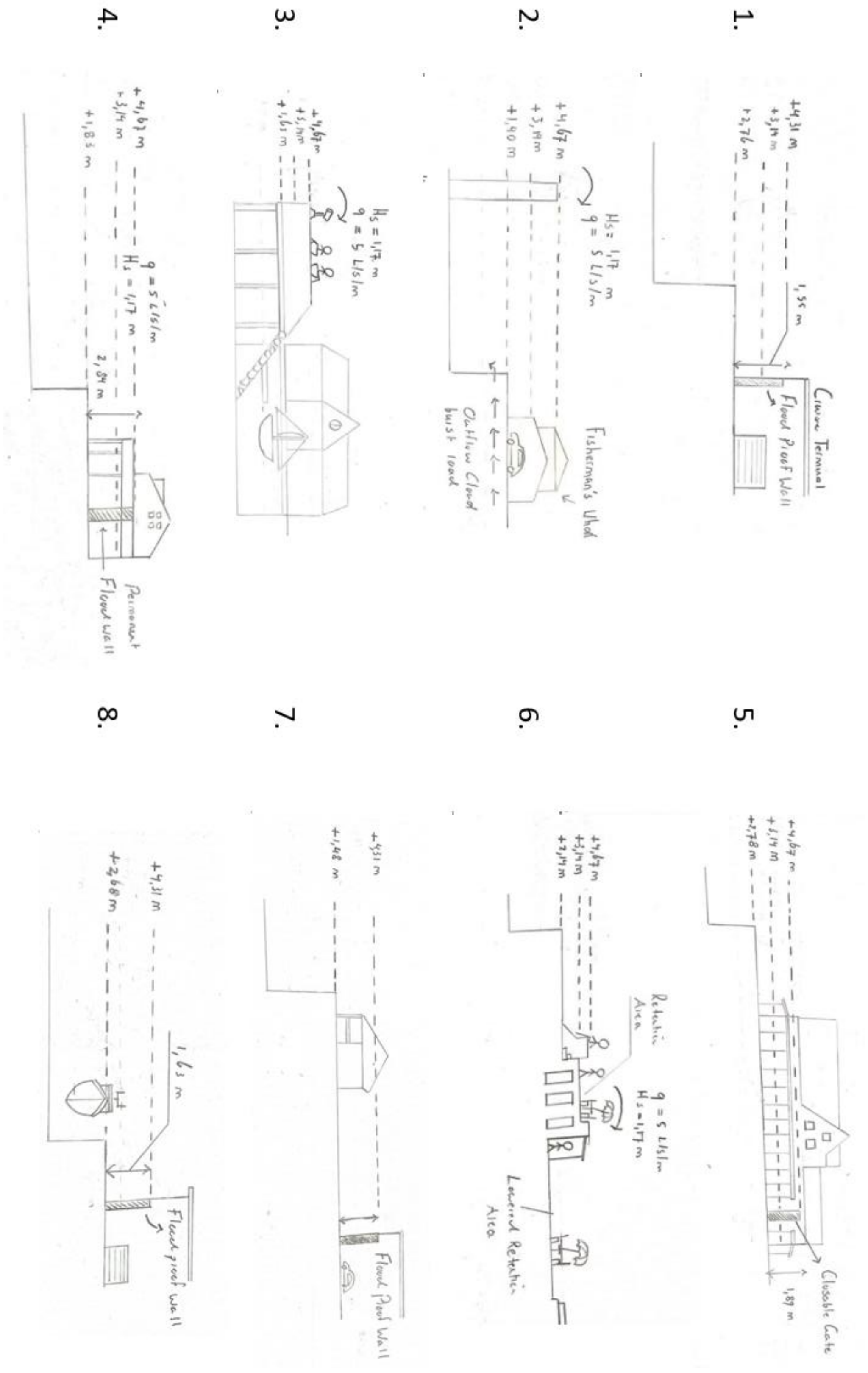


Figure H.2 Cross sections alternative 2 promenade

Appendix I: Multicriteria-Analysis design alternatives

Table I.1: Eleboration on MCA criteria for waterfront design alternatives

Requirements	
Drainage capacity pluvial	The amount of conveyance and infiltration within the component
Retention area	The amount of retention area for both coastal and pluvial water within the component
Wave dissipation	The level of wave dissipation that occurs at the waterfront in the component
Storm surge protection	The amount of storm surge and wave height the design can withstand
Continuous boulevard	How easy it is for pedestrians to walk continuously along the boulevard
Port operations	Level of disruption the cruise- and cargo ships-terminals experience
Flexibility/resiliciency	The ease at which the alternative can adapt to changing boundary conditions, such as climate change and changing pluvial- and coastal conditions
Interconnection sections	How easy the alternative can be connected to the adjacent sections
Interconnection waterfront-inland	How well the inland and waterfront designs connect and amplify each other's strengths
Added spatial value • Ecological value • Recreational value • Cultural value	• Ecological: development of high quality green space and conserving marine biology • Recreational: attractiveness and amount of recreation space • Cultural: conservation of cultural identity of bay area
Initial stakeholder concerns	
Accessibility & economics local business	Level of disruption for local economics and businesses
Accessibility fishing/leisure boats	Level of disruption the fishing/leisure boats experience
Accessiblity waterfront	How easy it is to get to the waterfront for pedestrians
Debris • Large debris impact prevention • Small debris clogging prevention	• Impact from floating boats / containers and other large objects • Clogging of drainage due to tree leaves and other small objects
Additional stakeholder concerns	
Stagnant water	The amount of water that will be stagnant in retention basins after overtopping has occurred
Homeless people	The likeliness of nuisance due to homeless people
Incorperatjon buildings/plots	How well existing buildings can be incorporated and the ease at which projects can be developed at the location

Criterium / Section	Weight	Section 1.1	Section 1.2	Section 2	Section 3.1	Section 3.2	Section 4.1	Section 4.2	Section 5.1	Section 5.2
Drainage capacity pluvial	0,8	0	0	1	1	-1	1	1	0	0
Retention area	0,8	0	0	2	2	1	2	-2	0	0
Wave dissipation	0,6	-1	1	0	-1	0	2	-1	-1	1
Storm surge protection	1	1	1	1	1	2	2	1	1	1
Continuous boulevard	0,7	0	0	1	2	-1	2	-1	0	0
Port operations	0,8	-1	2	0	0	0	0	0	0	2
Flexibility/resiliency	0,7	1	-1	0	2	0	1	0	1	-1
Interconnection sections	0,6	1	-1	1	2	-1	1	-2	2	-2
Interconnection waterfront-inland	0,6	0	0	1	2	-1	1	-1	0	0
Added spatial value										
• Ecological value	0,4	0	0	1	1	0	1	0	0	0
• Recreational value	0,4	0	0	2	1	2	1	-1	0	0
• Cultural value	0,2	0	0	1	2	2	1	0	0	0
Accessibility & economics local business	0,7	0	0	1	2	1	1	0	0	0
Accessibility fishing/leisure boats	0,7	0	0	1	-1	1	-1	1	0	0
Accessiblity waterfront	0,7	-1	1	2	2	0	2	1	-1	1
Debris										
• Large debris impact prevention	0,3	1	-1	1	1	-1	2	-2	1	-2
• Small debris clogging prevention	0,2	0	0	1	-1	-1	0	0	0	0
Stagnant water	0,5	-1	1	1	1	1	1	1	-1	1
Homeless people	0,3	0	0	-1	-1	-1	1	1	0	0
Incorperation buildings/plots	0,7	-1	1	1	1	2	0	1	-1	1
		-0,7	**3,5**	**10,9**	**12,3**	**3,8**	**12,7**	**-1**	**0,7**	**2,6**

Figure I.1: MCA matrix for assessing inland design alternatives. Blue: requirements, green: initial stakeholder concerns, red: additional stakeholder concerns

Table I.2 Elaboration on MCA criteria for inland design alternatives

Requirements	
Drainage capacity pluvial	The amount of conveyance and infiltration within the component
Retention area	The amount of retention area for both coastal and pluvial water within the component
Flexibility/robustness	The ease at which the alternative can adapt to changing boundary conditions, such as climate change and changing pluvial- and coastal conditions
Added spatial value • Ecological value • Recreational value • Cultural value	• Ecological: development of high quality green space • Recreational: attractiveness and amount of recreation space • Cultural: conservation of cultural identity of bay area
Initial stakeholder concerns	
Accessibility & economics local business	Level of disruption for local economics and businesses
Debris • Small debris clogging prevention	• Impact from floating boats / containers and other large objects
Additional stakeholder concerns	
Stagnant water	The amount of water that will be stagnant in retention basins
Homeless people	The likeliness of nuisance due to homeless people
Car wakes	Protection against waves caused by cars driving through inundated streets
Incorperation plots	How well projects can be developed at the location, community owned plots are better developable than private plots
Feasibility green roofs	How well buildings are dimensioned for increased loads and if legislations allow for green roof development

Criterium \ Section/connection	Weight	green cloudburst road	half green cloudburst road	car cloudburst road	normal car road
Drainage capacity	1,2	2	1	0	1
Flexibility/robustness	0,7	2	2	2	0
Added spatial value					
• Ecological value	0,4	2	1	-1	-1
• Recreational value	0,4	2	1	0	0
• Cultural value	0,2	2	1	0	0
Accessibility & economics local business	1,7	-2	-1	1	1
Debris					
• Small debris clogging prevention	0,2	2	1	0	-1
Stagnant water	0,5	0	0	0	-1
Homeless people	0,3	2	1	0	0
Car wakes	0,7	0	0	-2	-1
		3,4	2,4	1,3	1,1

Figure I.2 MCA cloudburst road

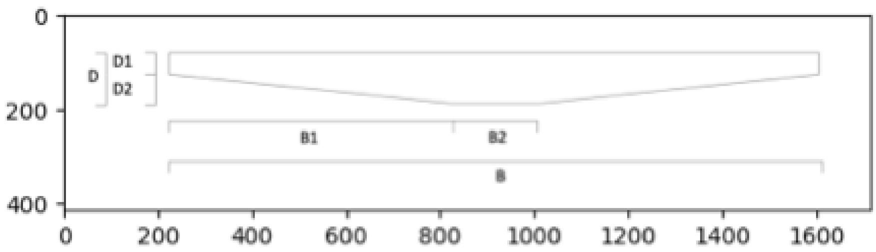
Appendix J: Cloudburst road python sheet

In [31]:
```
from PIL import Image
import matplotlib.pyplot as plt
import numpy as np
```

In [32]:
```
#the discharge in the Cloudburst roads is calculated using the Manning Forı
# v = (1 / n) * R^(2/3) * S^(1/2), Q = v * A
# k = 1 (metric units)
# n = Gauckler-Manning coefficient
# R = Hydraulic radius of the cross-section
# S = Slope
# A = Area of the cross-section
```

In [33]:
```
#the Hydraulic radius is dependent on the wetted parameter which is depend
#R =  A / P , P = 2 * D1 + B2 + 2 * (sqrt(B1^2+D2^2)), A = D1 * B + D2 * B
img = Image.open('cross-section_cloudburst.png')
plt.imshow(img)
```

Out[33]:
```
<matplotlib.image.AxesImage at 0x10e3f57f0>
```



In [34]:
```
#geometric design variables
D1 = 0.5
D2 = 0.1
B1 = 3.5
B2 = 8
L = 400
```

In [35]:
```
#geometric calculations
D = D1 + D2
B = B1 + B2
P = 2 * D1 + B2 + 2 * np.sqrt(B1**2 + D2**2)
A = (D1 * B) + (D2 * B1) + (D2 * B2)
R = A / P
S = D / L
```

In [36]:
```
#Gauckler-Manning coefficient, dependent on surface, asphalt = 0.016, flooı
n = 0.03
```

In [37]:
```
Qflow = A * (1 / n) * (R**(2/3)) * (S**(1/2))
```

In [38]:
```
#in addition to open channel flow, it is assumed that there is infiltratio
k = 2 * 10 ** -4
Qinfil = L * B * k
```

In [39]:
```
print('the maximum discharge is equal to:', Qflow+Qinfil, 'm^3/s')
```

```
the maximum discharge is equal to: 6.0040270318256805 m^3/s
```

In [40]:
```
print(R, S, A)
```

```
0.4311730205246556 0.0015 6.8999999999999995
```

Appendix K: Ike Dike

Figure K.1: 'Ike Dike' system as proposed by USACE (Grist, 2023).

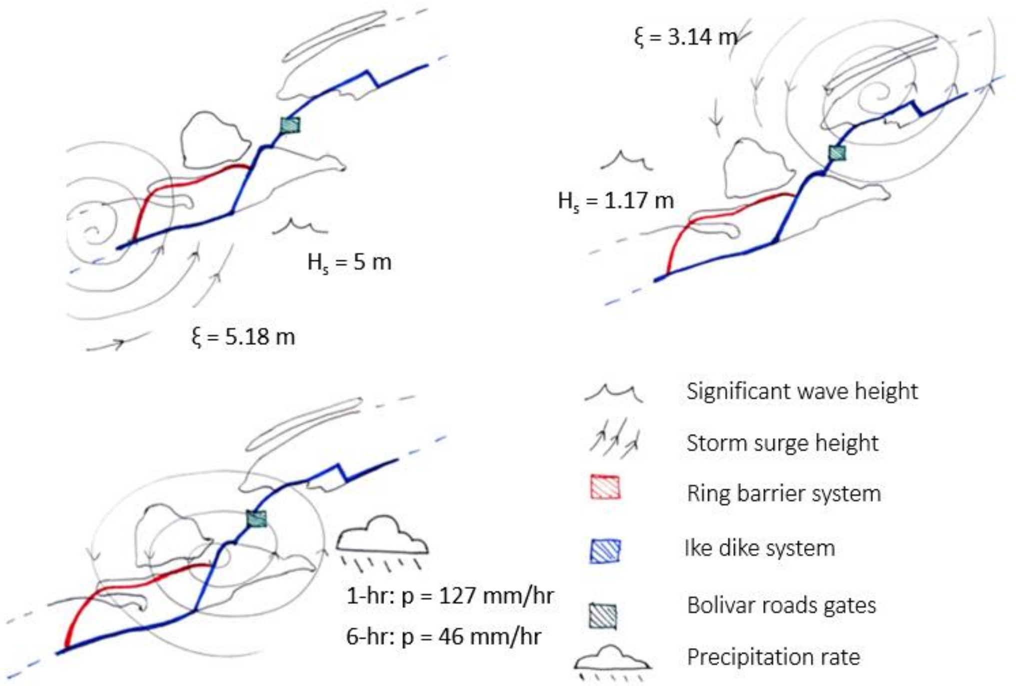


Figure K.2: 'Ike Dike' system including hydraulic boundary conditions per hurricane scenario

Appendix L: Mind map brainstorm session

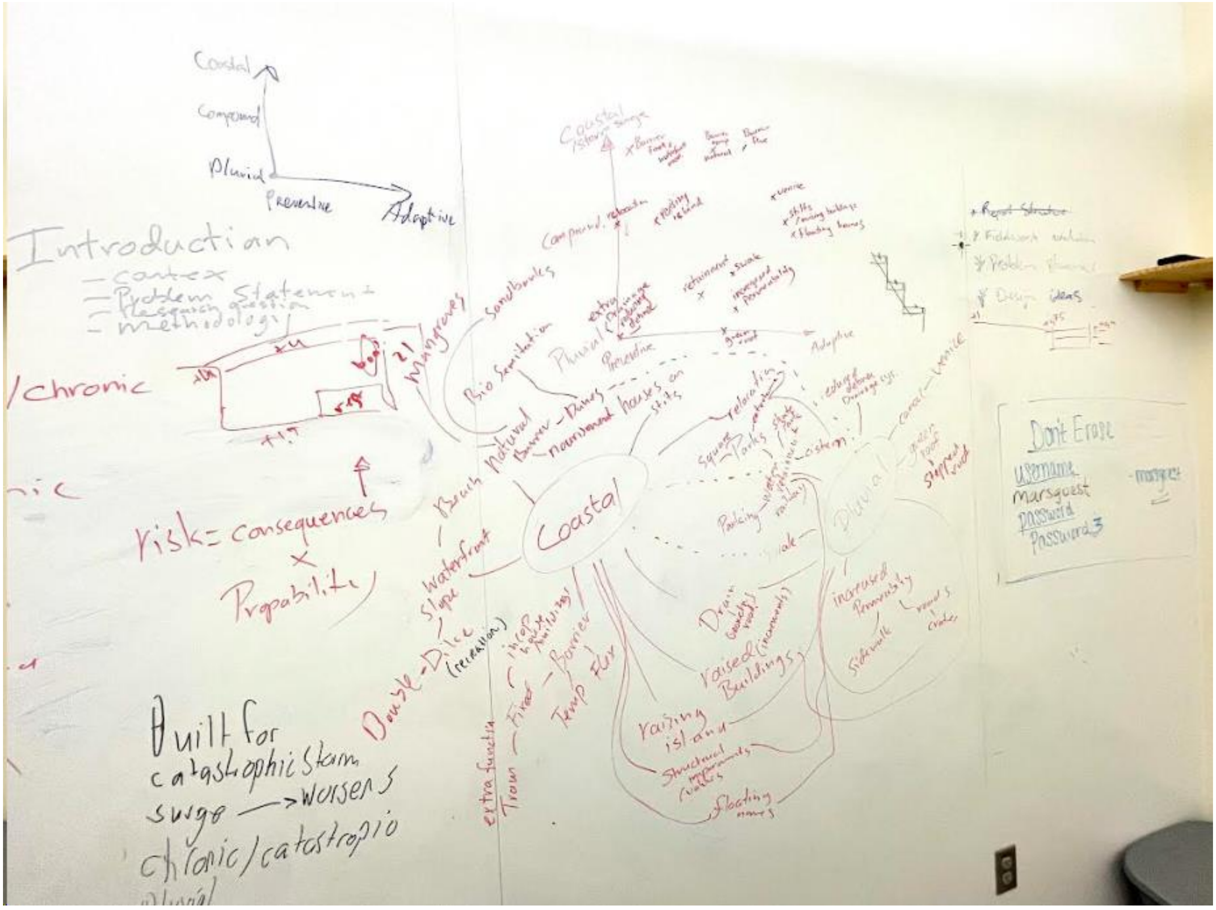


Figure L.1: Brainstorm ideas that were used for the design of the measures