Delft University of Technology

CIE4061-09 Multidisciplinary Project

Flood Management Campeche

Project San Francisco de Campeche

Authors:

Tessa de Kruijf	4132017
Kevin Frederik	4137302
Ivar Janmaat	4085221
Sebastiaan Woerlee	4234030

Group MP226

Supervisors:

Dr. G. Posada Vanegas	UACAM
Dr. E. Rivera Arriaga	UACAM
Dr. E. Mendoza Baldwin	UNAM
Ir. H.J. Verhagen	TU Delft
Dr. ir. C.R. Braam	TU Delft
Dr. J.A. Annema	TU Delft

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Preface

This report concludes our multidisciplinary project regarding the inundation risks in San Francisco de Campeche, Mexico, generated by hurricanes. The project took place in July and August of 2017 with a group of four students of the Delft University of Technology (TU Delft), all of us having different disciplines. The research took place under supervision of the TU Delft, the Instituto de Ecología, Pesquerías y Oceanografía del Golfo de México (later referred to as EPOMEX) and the Universidad Nacional Autónoma de México (later referred to as UNAM).

During the project, we have learned to work in another country with another culture. It was very informative to experience the process of such a project in Mexico, simply because the working procedure, communication and available information sources were that different from what we are used to. Besides, the multidisciplinarity in the project challenged us to think outside our own box and to learn from each other.

We like to give a special thanks to our supervisor and host, dr. Gregorio Posada Vanegas, for his hospitality and availability. Besides, we like to thank him for bringing us in contact with other researchers and taking us to field trips throughout the city. We thank dr. Edgar Mendoza Baldwin for providing us with this project and his great effort in the preparation of the project. Furthermore, we greatly thank dr. Evelia Rivera Arriaga, for investing time in us and bringing us in contact with local authorities. We give our thanks to ir. Henk Jan Verhagen, for initiating the contact with the UNAM and, together with dr. Jan Anne Annema and dr.ir. René Braam, for their overall supervision of the project.

Campeche, August 2017.

Tessa de Kruijf
Kevin Frederik
Ivar Janmaat
Sebastiaan Woerlee

Abstract

The focus of this research is to provide solutions to the city of Campeche to decrease the inundation risks generated by a hurricane with an occurrence of once in fifty years. Campeche is a city located at the Gulf of Mexico on the Yucatan Peninsula. The rapid growth of the city is one of the reasons it is having troubles with the water and flood management of several areas throughout the city. Although the municipality has already executed some improvements to the drainage system during the last years, it is still lacking to cope with heavy rainfall and storm surges due to hurricanes at several areas in the city.

In order to gain a better understanding of the location and the way it works in Campeche a location, stakeholder and political analysis have been performed. Boundary conditions, program requirements and preferences have been formulated based on this analysis. By examining hurricanes over the last decades, a hurricane has been simulated with an occurrence of once in the fifty years. In the situation characterisation the city has been divided into several catchment areas to determine their vulnerability (expressed in total amount of water accumulation), taking into account the capacity of the current drainage system in the event of such a hurricane.

Four solutions have been chosen to elaborate. In this elaboration, calculations have been performed on the design and construction. For the implementation of the options suitable locations have been determined and the possibilities and risks have been defined.

In order to test the elaborated solutions on socioeconomic factors in combination with ecology, safety and politics, a multi-criteria analysis has been performed. It can be concluded that all options differ a lot from each other. Every option tackles another side of the problem and therefore they score on totally different aspects. In the discussion, it is further elaborated what the supplementary advantages and disadvantages of the proposed solutions are. Using this, the integral system of water management measures is considered.

A few fields can be found on which could be made an improvement in the future. Firstly, the political system requires short term measures to count on enough support. Besides, citizens should be kept informed and have to be made aware of the flooding problem. Drainage expansion needs to take place in order to relief the most crucial parts in the city from their excess of water during extreme weather conditions. Lastly, when expanding the city, the amount of green space and inundation risks of the concerning area should be always kept in mind.

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1 Introduction

1.1 Problem description

The Mexican coastline is currently struggling with water problems due to extreme weather conditions. Rainfall and storm surges can cause a lot of damage in cities along the coastline, because of insufficient protection and regulation. On one side, these cities are vulnerable to threats coming from the sea. On the other side, water accumulation in these cities is a common issue due to heavy rainfall. Water management systems cannot cope with the current rainfall events and are therefore running behind. Due to climate change these extreme weather conditions are being intensified, increasing the risk of damage to the coastal zones. Variations in the climate can result in floods, the need to displace people, damage to infrastructure, salinisation of water sources, the need to dewater the area and coastal erosion. Adaptions of the coastline need to take place in order to secure these cities from future threats.

San Francisco de Campeche can be considered as one of the cities experiencing serious difficulties due to extreme weather conditions. The city has been affected several times by hurricanes in the last decades, resulting in a lot of damage throughout the city. Since Campeche is located in the relatively poor south part of Mexico, this damage has a large impact on the overall economy of the city.

1.2 Strategic objective

The strategic objective of this research is as follows:

"Provide solutions to decrease inundation risks due to the combination of rainfall and storm surge, generated by a hurricane which may occur once in fifty years, in the city of Campeche"

Our aim is to provide knowledge that decision-makers can use to ensure the safety of Campeche in the future fifty years. In order to achieve this, we will search for solutions on how to diminish the negative effects of inundations which threaten the city of Campeche.

1.3 Operational objectives

The operational objectives of this research are as follows:

- Analyse the degree and dispersion of vulnerability to inundations in the city of Campeche in the current state.
- Investigate influence factors due to climate change and their impact on the city's vulnerability in the upcoming fifty years.
- Explore, elaborate and evaluate options to diminish the negative effects of these influence factors to reduce the overall inundation risks in the city.

These operational objectives help in order to achieve the strategic objective of this research.

1.4 Concept definitions

1.4.1 Vulnerability

The vulnerability of a community to a flood hazard is commonly measured using socioeconomic indicators or calculating physical flood extents, however, their combined impact is often ignored. Since the current drainage system is not built for projected climate change, it is likely that it overloads more frequently and severely. Therefore, it is important to also take the drainage system into account when assessing vulnerability.

1.4.2 Risk

In this report, risk is defined as the product of vulnerability and probability of a hurricane to occur. Vulnerability is taken into account as described above. The probability of a hurricane to occur is set on once in fifty years. The risk is therefore directly dependent on the vulnerability of a specific area.

2 Analysis

2.1 Location analysis

2.1.1 General

2.1.1.1 History

San Francisco de Campeche is the capital of the state of Campeche, located on the coast of the Yucatán Peninsula. The city was founded in the 16^{th} century by the Spanish conquerors. At that time, the city had a high commercial and military importance, even as the biggest seaport. In the second half of the 16^{th} century it faced a lot of pirate attacks. In response to this, a large-scale military defence system was installed. This fortification, including a hexagonal wall around the city, was constructed between 1686 and 1704. To complete this system, the fortresses of San Miguel and San José, on both ends of the city, along with several bastions along the coastline, were constructed. This construction enhanced the urban growth and city development of Campeche. The walls enclose the city centre. Surrounding areas, called barrios, encompass religious buildings, civil and military architecture. In 1893 a part of the wall was pulled down to create a space with a sea view and the main square was turned into a public garden. The area of historic monuments and the system of fortifications have a high authentic value, because there have been very few interventions and transformations to them. (UNESCO, 1999)

2.1.1.2 City development

As can be seen in Figures A.1 & A.2 the city of Campeche has grown fast in the last decades. The first figure is dated from 1984, where the population laid around 122,000 inhabitants and grew to a number of around 242,000 inhabitants in 2016 (PopulationCity, 2015). A result of this population growth is the paved area of the city and the increase of the use of water. This overload in water distribution towards the sea is resulting in accumulations in water all around the city. Especially when it rains there are places around the city where the drainage system has troubles with distributing the water. It is expected that the number of inhabitants keeps growing in the future. Due to this growth it is important to regulate the water management of the city in order to ensure the safety of the inhabitants against flooding.

2.1.1.3 Climate

The state of Campeche has a tropical climate, with a humid rain season from June to October and two dry seasons, a hot season from March to May and a relatively dry season from November to February. Temperatures in the hot season can reach up to 33°C on daily average, with at least one day with a peak of more than 40°C (World Bank, 2012). The relative humidity can range between 58% and 97% and the hours of sunshine range between 220 hours in December to 320 hours in May (Worlddata.info, 2017).

2.1.1.4 Economy

The state of Campeche is highly dependent on the oil industry. As can be seen in Figures A.3 & A.4 almost 97% of the total gross production of the state is earned in the municipality of Carmen. This is due to the company PEMEX that has several oilrigs near the coast of Ciudad del Carmen. However, the oil industry is not the biggest supplier of jobs in the region. Most of the people of the state Campeche are working in the private non-financial sector, although the amount of companies is the highest in the commerce sector. Besides, the amount of job offers is the highest in the municipality of Ciudad del Carmen. The municipality of Campeche is on the second place with 32% of the total job offers of the state. The total gross production of the municipality of Campeche is 15,723 million pesos. Converted to euros this is about 2,800 euros per year per person (INEGI, 2014). Since the oil price decreased due to the financial crisis, Campeche is having some difficult years. As said earlier, 97% of the total gross production of Campeche is earned in the oil sector. As a result, the state has less money to spent on new projects. This can be an important factor of this research. Since the state and municipality do not have that much money to spent it is necessary to look for smart solutions that are inexpensive to construct.

2.1.1.5 Housing

According to numbers of 2010 the city of Campeche has a total of 71,454 houses with an average occupancy of 3.6 inhabitants per house. In Table B.1 different indicators are given concerning the percentage of these houses are connected with for example the electricity and drainage. The last years some modifications to the drainage system have been done, so it is possible the numbers in the table are slightly changed in comparison with today.

2.1.2 Land

2.1.2.1 Elevation

The city of Campeche is surrounded by hills. Due to the height differences, water naturally flows towards the sea. Especially the Malecón and the area between the inner city hills are low-lying. Logically, water easily flows in the direction of these areas. A detailed height map can be found in Figure A.6.

2.1.2.2 Land reclamation

In the past, land was reclaimed from the sea as can be seen in Figure A.7. Before the land was reclaimed, the boulevard laid, at the widest parts, 500 meters land inwards. During the years, this land is crammed with buildings. This is the main area that is vulnerable for inundations due to storm surges since the elevation is lower in this area in comparison to other parts.

2.1.2.3 Land Value

The value of a square meter land in Campeche differs among the neighbourhoods. The state of Campeche divided the areas in fifteen categories, each having their own land value. Some examples of categories are the commercial historical centre, cafes, traditional neighbourhoods, commercial avenues, etc. In Poder Legislativo del Estado de Campeche (2015), in total 214 neighbourhoods and residential divisions were divided into these fifteen categories. Various neighbourhoods and divisions have multiple categories in one area. To construct one value for the whole area, the average of these values was taken. All the neighbourhoods and divisions are ranked into nine categories depending on the land value as can be seen in Figure 2.1. Clearly the neighbourhoods near the coast and historical centre have the highest land values. Furthermore, the values of southwestern region are reasonably higher than those of the northeast. The represented drainage structures show that neighbourhoods near these structures have higher land values than those not situated near the structures. The lowest land values can be found on hills (in comparison with Figure A.6).

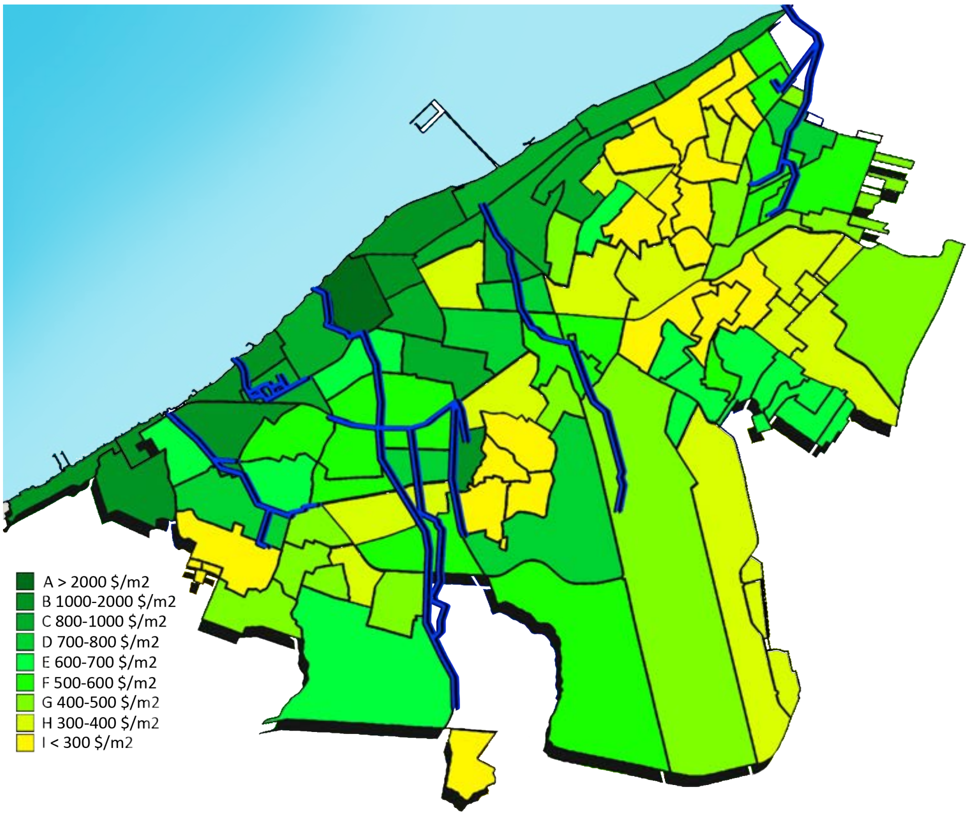

Figure 2.1: Land value of the neighbourhoods of Campeche and the current drainage structure

2.1.2.4 Soil conditions

The soil conditions of the municipality of Campeche can be found in Figure A.9. Although the soil type in the city of Campeche is just characterised as urban, some estimations can be made based on the surrounding soil types. The most dominant type around the city is Phaeozem, a dark soil which is rich in organic matter. This soil type can be encountered in areas with a dry and wet season. At some moments the soil dries out, whereas on others percolation through the soil takes place. Phaeozems have a very permeable, well-aggregated structure and can be used excellently as farmland.

The other dominant soil type surrounding the city of Campeche is formed by vertisol. They can be found on mildly sloping topography in areas with a distinct wet and dry season. The clay content in vertisol is high, which makes the soil type not well suited for cultivation. They are dark-colourd soils, with only moderate humus content, and can also be characterised by salinity and layers of calcium carbonate or gypsum. Contrary to phaeozem, vertisol has a low permeability. (Encyclopædia Britannica, Inc., 2017b)

2.1.2.5 Green space

Green spaces such as parks and sports fields as well as woods and natural meadows, wetlands or other ecosystems, represent a fundamental component in any urban ecosystem. Green urban areas facilitate physical activity, social interaction, recreation and relaxation, and form a refuge from noise. Trees produce oxygen, and help filter out harmful air pollution, including airborne particulate matter. Urban parks and gardens play a critical role in cooling cities, and also provide safe routes for walking and cycling. Recent estimates show that physical inactivity, linked to poor walkability and lack of access to recreational areas, accounts for 3.3% of global deaths. (Black, 2016)

Green spaces also are important to mental health. Having access to green spaces can reduce health inequalities, improve well-being, and aid in treatment of mental illness. Some analysis suggests that physical activity in a natural environment can help remedy mild depression and reduce physiological stress indicators. (Black, 2016)

Ultimately, it is green spaces that contribute to a city's greatness, as John Ruskin professed:

> "*The measure of any great civilisation is in its cities, and a measure of a city's greatness is to be found in the quality of its public spaces, its parks and its squares*"

The World Health Organisation has suggested that every city should have a minimum of 9 m^2 of green space per person. Unfortunately, for Campeche this required minimum is far from met. Merely 1.47% of its area is green, which results in 3.28 m^2 per resident.

As can be seen from Figure A.8, in the biggest part of Campeche the amount of vegetation is decreasing and only at the Malecón it is increasing. The consequence is that precipitation cannot infiltrate easily into the soil, but just flows on the streets. The city has been growing for the last years and seems to keep growing, causing the vegetation to decrease over the next years. This is not a good sign for the vegetation and therefore the flooding.

2.1.3 Sea

2.1.3.1 Bathymetry and Coastal Transects

As can be seen in Figure 2.2, the continental shelf of the Gulf of Campeche stretches out 150-200 km from the coastline of Campeche, where the depth is equal to 100-200 m. The distance to the first 20 m bathymetry line is approximately 50 km, which makes the average continental slope equal to ca. 1:2500.

Figure 2.2: Bathymetry of the Gulf of Campeche (NOAA, 2017)

In order to obtain a good perception of the depth variation across the coastline, some coastal transects are necessary. In Figure A.14 the six locations are given where these transects are obtained. The respective coastal transects are given in Figure A.15-A.20. It becomes clear that the depth gradient at almost every transect is very low, which is in line with the computed continental slope. From the significant wave height in the figures it can be seen that the risk of inundation of the hinterland is pretty high. The mangroves in Figure A.20 clearly form a good buffer zone, protecting the neighbourhood of Imí laying behind.

2.1.3.2 Sea level

The city of Campeche is one of the few major cities in Mexico located at the coast and is therefore one of the most vulnerable cities with respect to sea level rise. According to the National Oceanic and Atmospheric Administration (NOAA) (2013), the mean sea level trend is a rise of 4.67 mm/year with a 95% confidence interval of +/- 0.94 mm/year based on monthly mean sea level data from 1952 to 1990 in 100 years, measured in Progreso (Yucatán, Mexico). Botello, Villanueva-Fragoso, Gutiérrez, and Rojas Galaviz (2011) investigated the sea level rise in Ciudad del Carmen, near San Francisco de Campeche, resulting in an increase of 3.4 mm/year with an interval of +/- 1,0 mm/year. This estimation is more probable to occur in Campeche, because this is located in the same bay.

2.1.3.3 Tidal range

The tidal range of Campeche is influenced by different components. As can be seen in Figure A.21, the tide is dependent on the season, the astronomy and the meteorology. The data of the measurements are obtained between August 2016 and July 2017 and processed with a MATLAB script written by Puc (2017). With the historical data a prediction can be made for the tidal range of the year 2018 for example. As can be seen in Figure A.21, there are two periods where the tidal range is relatively high. The first period is from November until February and the second period is from June until August. The maximum tidal range lays between +0.65 and -0.95. Within a day the tide shows us three peaks of which two are high tides and one is low tide. In Figure 2.3 the tidal variations are presented of a week in July, 2017.

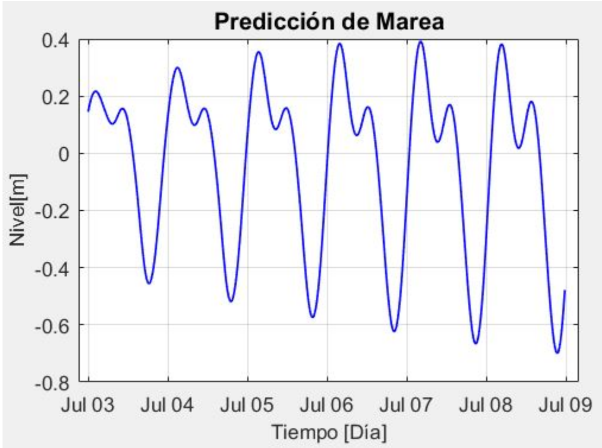

Figure 2.3: Tidal range of a week in July 2017 (Puc, 2017)

2.1.3.4 Wind and wave conditions

The most important period for this research is the period between the months of June until October. These months are warm and have the most of precipitation of the year. The probability of an inundation in this months is higher in comparison with other months.

The wind rose in Figure A.22 indicates the wind is coming from the east direction most of the time. According to Figure A.23 in the months June till September the percentage of the wind coming from the east is even higher. This means the wind is blowing from the land to the sea. As a result of the wind direction the height of the waves is considerably less in comparison with the east coast of the Yucatán peninsula. It was very hard to find usable hard data on wave heights for the coast of Campeche. We assume the waves are considerably low and so negligible for further research.

The wind velocity can increase drastically in the event of a hurricane. The wind velocity of the most severe hurricanes in the last twenty years (Roxanne, Wilma and Emily) have been measured by Instituto Mexicano de Tecnología del Agua (IMTA). The velocity of these hurricanes vary between twenty up to sixty meter per second. At one point the velocity of Hurricane Wilma reached 66.88 m/s (Silva Casarín, Maya Magaña, Posada Vanegas, & Durán Valdéz, 2010).

2.1.3.5 Hurricanes and storms

The frequency of hurricanes has increased since the last forty years. Where in the fifties the occurrence on average was only once every two years it has almost doubled in the last fifteen years (World Bank, 2012). The most harmful hurricanes all occurred in the last 30 years. In addition, the severity of the hurricanes also increased, causing over a billion US dollars in damages in 2005 only (see Table B.2). According to Vecchi and Knutson (2008), the rainfall and storms will continue to increase in occurrence and intensity. The study of Posada-Vanegas, Durán-Valdez, Silva-Casarin, Maya-Magaña, and Salinas-Prieto (2010) concludes that with a return period of 10 years, the sea level rises up to 1.5 meter and with a return period of 50 years up to 2.5 meter due to a storm surge. This sea level rise can have a disastrous consequence to the reclaimed Malecón at the city's coast. The probability that this sea level rise occurs is put into Figure A.24.

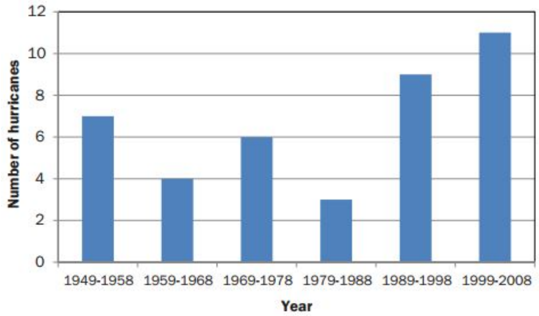

Figure 2.4: Number of hurricanes every 10 years (World Bank, 2013)

2.1.4 Flood risk

2.1.4.1 Drainage system

To avoid inundations in the city, locations of former water accumulation have been investigated and a drainage system has been constructed over the last decades. This system functions properly with the current rainfall and sea level for most neighbourhoods.

In Figure 2.5 the current drainage structure is visible with the assumed coverage areas per drainage pipe. The structure consists of 27 kilometres of drainage pipes (see Appendix F.2). Besides the normal drainage system, there are several natural basins where water is flowing to and can be stored. After a heavy rainfall event water can be pumped from this basins to the sea. These basins are used as buffer zones to cope with the large amount of water that needs to get distributed.

During the first week of the research the most important parts of the drainage system were visited to get an image of the present situation. In Appendix G.1-G.6 some photos are presented that are useful to understand the present drainage system.

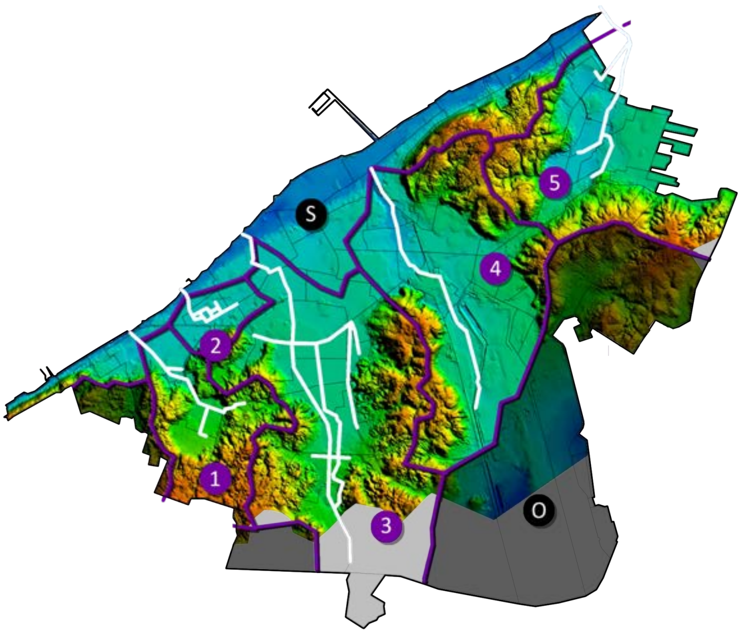

Figure 2.5: Areas per drainage pipe line on elevation map

To get a better insight in the current capability of the drainage system there has been a meeting with Arq. Felipe Jiménez Silva. He is member of the city council and head of the secretary of public works within the municipality of Campeche. Before his term in the city council he was the director of CAPAE (see Subsection 2.2.1). The construction of the mega drainage system project is at the moment still an ongoing process. The progress of the project is dependent on the choices of the municipality on which project they will spend money. In Mexico, generally, buildings or facilities which are not noticeable by the common people are considered less valuable in comparison to facilities which can be noticed. For example, in the city of Campeche, pumps were installed at the drainage system located underneath Av. Lic. Benito Juárez, just for the inhabitants to ensure they could see a result. In reality the pumps are not working at all (see Appendix F.1). Several scenarios of precipitation were discussed during the meeting with Arq. Felipe Jiménez. The new drainage system is capable to cope with rainfall events of 55-65 mm/hr. The main problem with rainfall events is the duration of a certain event. On the 12th of July 2016 a rainfall event of 85 mm in 40 minutes occurred with an accumulation of 120 mm over the night (see Appendix F.2). Even then, the drainage system was able to drain the water away without damage to buildings.

2.1.4.2 Precipitation

Campeche has a dry season with merely six days of rain per month, with a maximum intensity of around 30 mm/day and a rainy season where it rains almost every day with a maximum intensity between 50 and 100 mm/day. (CLICOM, 2017; Servicio Meteorológico Nacional, 2017) Since half a century ago, every decade a major hurricane succumbs the city of Campeche, causing a precipitation intensity of over 200 mm in one day. (World Bank, 2012)

To predict the future development of precipitation, the quantities per day and per year, following from Servicio Meteorológico Nacional (2017), are put into Figure 2.6 and a linear trend line is obtained. It can be concluded that precipitation increases on average 3 mm/day annually. In twenty years the precipitation will be around 1190 mm/year.

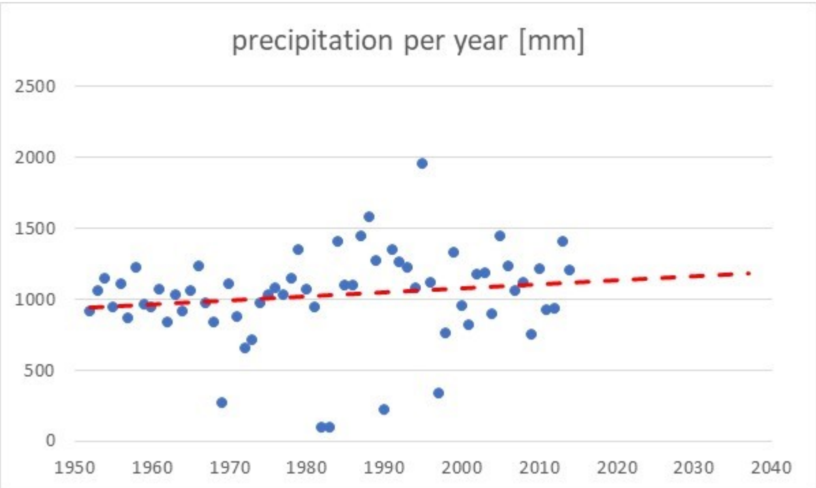

Figure 2.6: Precipitation per year

As the precipitation on short term is governing for the capacity of the drainage system, the precipitation per day is also considered. To obtain a worst case scenario, the maximum daily precipitation per year is presented in Figure 2.7.

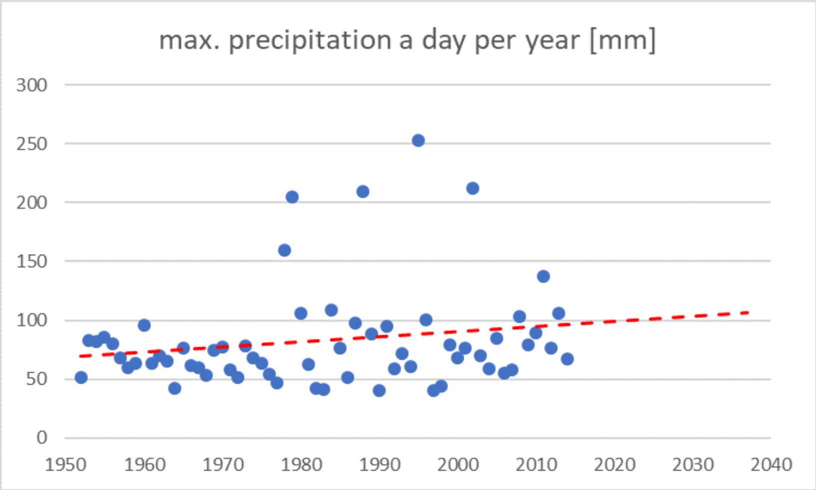

Figure 2.7: Every year's daily maximums of precipitation

From Figure 2.7 it can be concluded that the daily maximums over the last sixty years did increase and therefore it seems likely that this increase will continue linearly, similar to as it did previously. A maximum precipitation in twenty years is likely to reach over 100 mm per day.

A precipitation of over 100 mm per day only occurred fifteen times since the recording in 1952. It can be seen in Figure 2.8 that the number of days with more than 100 mm/day of rainfall increased over the last sixty years. The amount of precipitation also increased. From 1952-1982 there only once fell over 200 mm of rain on one day, whereas this occurred three times in the following thirty years, with even 254.2 mm on one day in 1995. (Servicio Meteorológico Nacional, 2017)

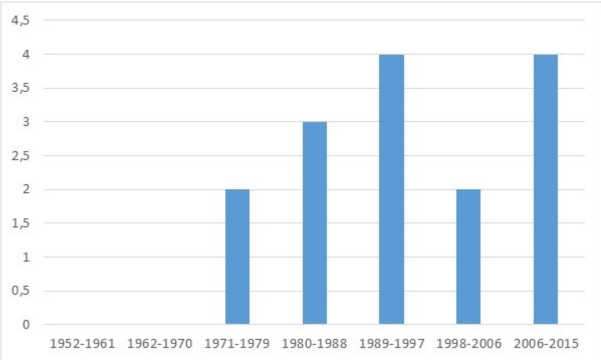

Figure 2.8: Number of days with over 100 mm precipitation

2.1.4.3 Flood risk

Apart from the fact that some areas will be inundated with just high precipitation, most will only be inundated with both heavy precipitation and a risen sea level. This is mostly the case during a hurricane. Water volumes from land can less easily flow into the sea because the drains are partly filled with water. Furthermore, the capacity of the drains is lower due to the smaller height difference. As a result, low-lying areas near the sea and lower situated areas landward will be inundated, as can be seen in Figure 2.9. The principle of this situation is visible in Figure 2.10.

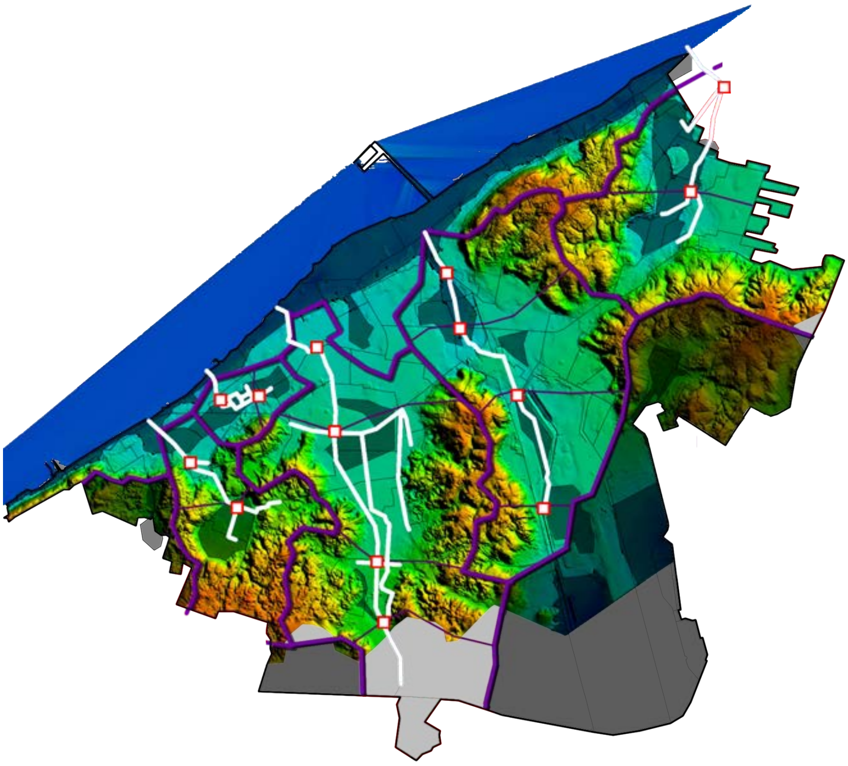

Figure 2.9: Inundation areas in case of a combination of rainfall and storm surge

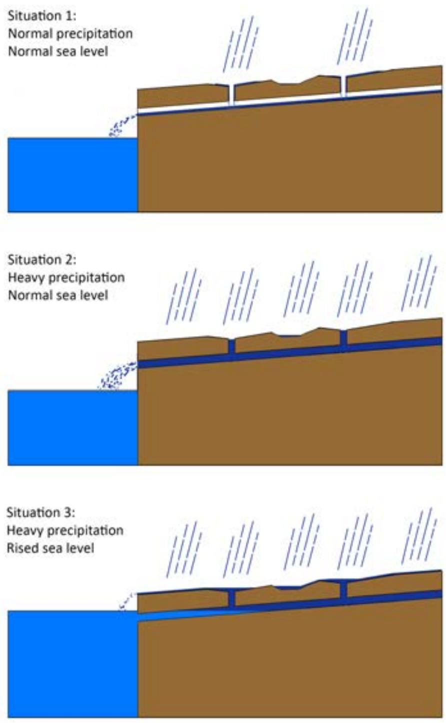

Figure 2.10: Principal sketches of three different situations

2.2 Stakeholder analysis

The stakeholder analysis is made to get a good overview which parties are involved in this project. At first, all the different parties are described shortly. For example what their main activities are and what the relation is between the certain party and the project. After the description of all the parties involved, it is important to divide these stakeholders in order of their interest in this project and the amount of influence they can exert. In this way you get a good overview of groups that are most important to keep satisfied and to keep informed.

2.2.1 Stakeholders

Municipality of Campeche
The municipality of Campeche is one of eleven municipalities in the state of Campeche and has the largest settlement located: San Francisco de Campeche. The municipality has a city council which is led by the mayor. The municipality is closely involved in all projects within the city of Campeche. They are responsible for 50-60% of the execution of the new mega drainage project, according to Arq. Felipe Jiménez (see Appendix F.2). Since the municipality has to make decisions on what projects have to be executed in the city, it is an important stakeholder in this project. Inside the municipality there are two departments that are of importance for this project: the Department of Urban Development and the Department of Public Works, later referred as respectively DDU & DOP. They are responsible for respectively regulations and construction of a certain project (Evelia Rivera Arriaga, 2017).

State of Campeche
The government of the state of Campeche can be divided in 21 secretaries. The ones sharing the most common ground with the project are the Secretary of Urban Development, Public Works and Infrastructure and the Secretary of Social and Human Development. In comparison to the municipality, the state is deciding on problems of a greater scale. However, they also have great influence on projects of this size. Solutions on this problem can probably be used in similar cities in the state near the coast like Champotón or Ciudad del Carmen.

SHCP
The "Secretaría de Hacienda y Crédito Público", later referred as SHCP, is the secretary of finance of the federal government. When a budget is needed for a project there are several possibilities to obtain the required money, as mentioned in Appendix F.3. One way is through the federal budget that is available for every state in each fiscal year. The SHCP is reviewing every project that is presented. After reviewing, the decision is made if the presented project is worth the investment of the federal government. From the SHCP the credit reaches the state through CONAGUA.

UNESCO
The historical city centre of San Francisco de Campeche has been a UNESCO World Heritage site since 1999. UNESCO invests to keep the historical centre in the same quality as it was. Recently the Spanish drainage system was improved, in order to drain the accumulated water more efficiently. The Spanish built the city centre with a small incline towards the sea, so that the rain streams towards the sea. However, in the seventies, the new Malecón was built, causing the rain to stream towards the Malecón instead of the ocean. UNESCO and the municipality of Campeche installed a new drainage system in order to prevent water accumulation in the old and new city centre. With investments like these UNESCO plays a role in the improvement of the city.

Research institutes
In Campeche there are several research institutes that are involved in this research. The most important one is EPOMEX, the host of this research. The institute has as core mission to encourage the application of scientific knowledge to protect the coast of Mexico and abroad. Via research, education and the spread of knowledge EPOMEX has become an institute with strategic partnerships with several universities throughout Mexico, but also in the USA, Canada and France. Since the institute has a lot of knowledge regarding the subjects this project is covering, they are valuable stakeholder.

Universities
The National Autonomous University of Mexico (UNAM) is in collaboration with the University of Granada and the National Laboratory of Civil Engineering of Lisbon to realise a project regarding the coastal infrastructure and climate change. The Malecón and M180 highway are a part of the coastal infrastructure and interesting to do research in. The durability of this route straight through San Francisco de Campeche depends on the durability of the city itself. The Malecón is the lowest part of the city, making it the initial part to flood. However, it is also the main connection with Mérida and Villahermosa. This report is contributing to this project.

The Autonomous University of Campeche (UACAM) is in collaboration with EPOMEX to do research regarding ecology, fisheries and oceanography in the Gulf of Mexico. They investigate the coast of the state of Campeche, giving advice regarding how to deal with inundations.

Inhabitants
During a meeting with Dr. Evelia Rivera Arriaga (EPOMEX), she mentioned inhabitants that do not live directly near the coast do not consider themselves as living in a coastal zone. There are a lot of low educated inhabitants in Campeche of which many do not understand the consequences of living close to the coast and the potential danger the sea brings. This part of the population needs to be informed in a way to understand the potential dangers and realisation of living near the coast. The inhabitants are the ones that are discerning the most of all the water problems that are occurring in the city and will benefit a lot when improvements are made.

CONAGUA
The “Comisión Nacional del Agua”, later referred to as CONAGUA, is the national commission of water in Mexico. Their mission is to preserve and administrate the national water system, even as the guarantee of water safety to the society. CONAGUA has to approve every project concerning the water system in Campeche, but they do only execute projects on higher levels of scale (see Appendix F.2).

SEMARNAT
The “Secretaría del Medio Ambiente y Recursos Naturales de Campeche”, later referred to as SEMARNAT, is the secretary of environment and natural resources of the federal government. They are closely involved in the protection, restoration and conservation of the environment in Mexico and take into account social, economical and sustainable development (Gobierno del Estado de Campeche, 2015). Besides, SEMARNATCAM is the secretary of environment of the state government with practically the same purposes as SEMARNAT, only on state level.

CAPAE
The “Comisión de Agua Potable y Alcantarillado del Estado de Campeche”, later referred to as CAPAE, is the drinking water and sewage commission of the state of Campeche. Their mission is to improve facilities in these areas throughout the entire state (Gobierno de Campeche, 2015).

CONANP
The “Comisión Nacional de Áreas Naturales Protegidas”, later referred to as CONANP, is the national commission of protected natural areas in Mexico. Their mission is to preserve the most representative ecosystems of Mexico, together with their biodiversity. The “Reserva de la Biósfera Los Petenes”, later referred to as Los Petenes, is recognised by CONANP as a biosphere reserve. This reserve is characterised by so-called ‘petenes’, a Mayan name given to ecosystems consisting of vegetation islands on the Yucatán peninsula. They are exposed to permanent inundation and the dominant vegetation species is mangroves. Los Petenes stretches out north of Campeche along the coastline to the state of Yucatán and also encompasses a sea section consisting of a part of the sea in front of Campeche, crossing the pier (see Figure A.26). CONANP mainly acts as a restricting organ, since Los Petenes is a protected natural area. However, the part of the reserve which is directly situated on the seaside of Campeche is not protected, since it only benefits from the protected area of the reserve.

SECTUR & touristic sector
The “Secretaría de Turismo del Estado de Campeche”, later referred to as SECTUR, is the tourist secretary of the state of Campeche. They are involved by all tourism in the city, like hotels, activities, apartment owners and restaurants, but also the public transport is involved in the touristic sector. This sector will benefit from a safe city that is resistant against flooding due to less costs of damage of buildings and infrastructure and the related delays.

Fisheries
In Campeche still a lot of men work in fishery. There are two shrimp seasons in Mexico, the first is located in the north during winter and at summertime there are shrimp fisheries in the south, as well as in front of the city. Any modifications in front of the coast of Campeche can cause problems with the fisheries.

Shipping transport
There are several shipping harbours near the coast of Campeche. The most important one is the harbour of the oil company PEMEX. Solutions along the coastline can affect the harbours or the shipping routes. This can result in the modification of navigation routes. PEMEX is an important company in the area of Campeche and an important source of income for the state of Campeche (see Subsection 2.1.1.4). It is expected that PEMEX will have influence on the decisions that are made by the municipality that can affect the activities of the company.

Commercial sector & health care
This group is formed by the general commercial instances which are located in zones which suffer from flooding. The most important instances are formed by the shopping mall Plaza Galerías, the casino of Campeche and the Walmart. They mostly suffer from flooding since they are less accessible for visitors. Also the IMSS hospitals in Concordia and Área AH experience disadvantages from the inundations, since they always need to be accessible for patients.

Local- and foreign engineering firms
Local engineering firms can benefit of investments that need to be made for small adjustments of the coastal infrastructure or the drainage system of the city. It will create employment opportunities for local workers and will give the local economy a boost. When a solution is proposed with a bigger extent even foreign engineering firms can be of influence to the construction.

2.2.2 Stakeholder summary

Table 2.1 sums up all the different resources and interests from the stakeholders involved. Using this table, Figure 2.11 is made up. In this figure, all the different stakeholders are measured against each other based on the amount of influence and interest they have. Their approximate locations in the figure give a visual representation of their role within the realisation process.

Stakeholders	**Resources**	**Interests**
Municipality of Campeche	• Formal power • Manpower • Skills	• Reduce flood damage • Economic development • Safety
State of Campeche	• Formal power • Manpower • Skills	• Reduce flood damage • Economic development • Safety
SHCP	• Financing	• Economic development
UNESCO	• Legitimacy regarding World Heritage sites	• Historic preservation
Research institutes	• Knowledge • Advice	• Reduce flood risk • Coastal protection
Universities	• Knowledge • Advice	• Reduce flood risk • Coastal protection
Inhabitants	• Protest/resistance	• Safety • Reduce flood damage • Accessibility
CONAGUA	• Authority • Access to SHCP	• Improvement water utilities • Reduce flood risk
SEMARNAT	• Regulation	• Environmental protection
CAPAE	• Manpower • Skills	• Improvement water utilities • Reduce flood risk
CONANP	• Legitimacy regarding protected natural areas	• Environmental protection
SECTUR & touristic sector	• Protest/resistance	• Safety • Better touristic perception • Reduce flood damage
Fisheries	• Protest/resistance	• No reduction in fish quantity
Shipping transport	• Economic value • Protest/resistance	• No transport obstructions
Commercial sector & health care	• Protest/resistance	• Accessibility • Safety • Reduce flood damage
Local- and foreign engineering firms		• Employment opportunities

Table 2.1: Resources and interests per stakeholder

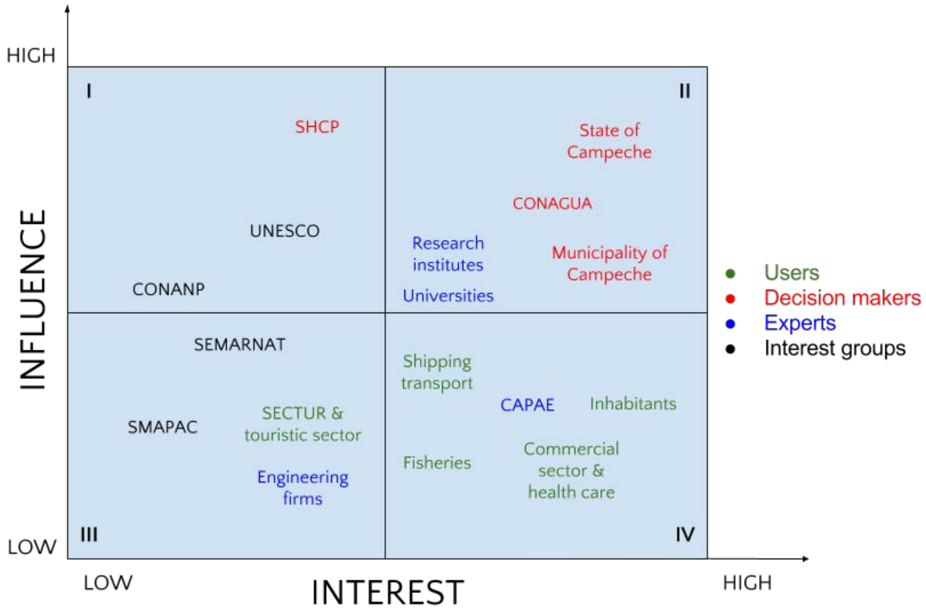

Figure 2.11: Stakeholder summary based on influence and interest

In quadrant I the stakeholders with high influence and low interests can be found. It is important to keep these stakeholders satisfied, since they usually provide boundary conditions in the form of finance, regulations or permissions for the project. Without the support of one of these stakeholders, the project is often impossible to realise.

In quadrant II the stakeholders with high influence and high interests can be found. Full engagement of these key players is crucial. Usually they are in charge of the project execution and are aware of everything relevant for the project.

In quadrant III the stakeholders with low influence and low interests can be found. Stakeholders in this group need to be monitored, because their role can change over time.

In quadrant IV the stakeholders with low influence and high interests can be found. This group does not have the power to make large changes in the project, but the results of it effects them in a significant way. This group needs to be informed adequately, since they may start protests or demonstrations if they are unsatisfied.

2.2.3 Multi-actor systems

In order to get a better insight in the different stakeholders, groups are defined. The groups are established through shared involvement in the project.

Users: shipping transport, inhabitants, commercial sector & health care, SECTUR & touristic sector and fisheries

The users stand closest to the changes to be made. They perceive it the most when the current system is lacking functionality, but they also will benefit most from improvements.

Decision makers: municipality of Campeche, state of Campeche, SHCP, CONAGUA

The decision makers are the authorities which have influence on the policy, execution, license grants and they are the main financial source for the project.

Experts: universities, research institutes, CAPAE, engineering firms

The experts are the ones that have the knowledge of the problem. They are of great importance with respect to the progress of the project.

Interest groups: UNESCO, CONANP, SEMARNAT

Interest group are the parties that are not in direct contact of the decision making process, although they are in a way related to the project. The interest groups differ a lot in interest and influence in the project.

2.2.4 Conclusion

From the stakeholder analysis and the meeting with Dr. Evelia Rivera Arriaga it can be concluded that the three most important parties for the start of this project are the state of Campeche, CONAGUA and the municipality of Campeche. These three parties are crucial for the adoption of the project, since they are responsible for the acknowledgement of problems in the city and have influence on the policy of new projects. Besides these three stakeholders, the SHCP is another important stakeholder regarding the necessary funding of the project. Other options of funding are described in Subsection 2.3.3. There are several stakeholders that have influence on these parties. During our meeting with Dr. Evelia Rivera Arriaga it became clear knowledge in the field of the problem inside the decision makers is of great importance. Therefore research institutes and universities are of high value for the supportive knowledge to the decision makers.

2.3 Political system

2.3.1 General

In Mexico, the political system consists of three branches: executive, legislative and judicial. The executive branch dominates the other two. The president serves a term of six years and he cannot be re-elected. He also has legislative power, since laws can only be enacted after he has signed them. Furthermore, he assigns the cabinet, attorney general, diplomats, the mayor of the Federal District, high-ranked military officers and Supreme Court justices. The legislative branch, a bicameral congress, consists of the Senate (upper chamber) and the Chamber of Deputies (lower chamber). Senators serve the same term as the president, deputies serve a term of three years. Both cannot be re-elected for the successive term. The judicial branch is divided into federal courts and state courts, but federal courts deal with most cases. (Geo-Mexico, 2012; Encyclopædia Britannica, Inc., 2017a; Country Studies, n.d.)

State governments also have an executive, legislative and judicial branch. Since the political system is highly centralised, state governments depend on the federal district of Mexico City (under supervision of the president). This is because most of their revenue comes from there. Mexico is divided into 31 states. In each state, the executive branch is leaded by a governor, serving a six-year term without possibility of re-election. Legislative power is in hands of a unicameral congress, the Chamber of Deputies, with deputies having the same term as those on federal level. Judicial power lays with the tribunals established by the constitution of the respective state. (Photius Coutsoukis, 2004; Wikipedia, 2017)

On municipal level, the government is leaded by a mayor and a municipal council, elected for a three-year term. They mainly rely on transfers from higher levels of government, which form approximately 80% of their revenue (Photius Coutsoukis, 2004). Public services are one of their major responsibilities. However, in the state of Campeche, a lot of this responsibility has been taken over by the state government, due to a list of promises of the former governor, Fernando Ortega Bernés (see Appendix F.3).

The ban on re-election is a returning concept in the political system. It helps to avoid corruption, but at the same moment it hinders the continuity as well as the expertise of the government at all different levels (Geo-Mexico, 2012). For the full government structure, see Figure 2.12.

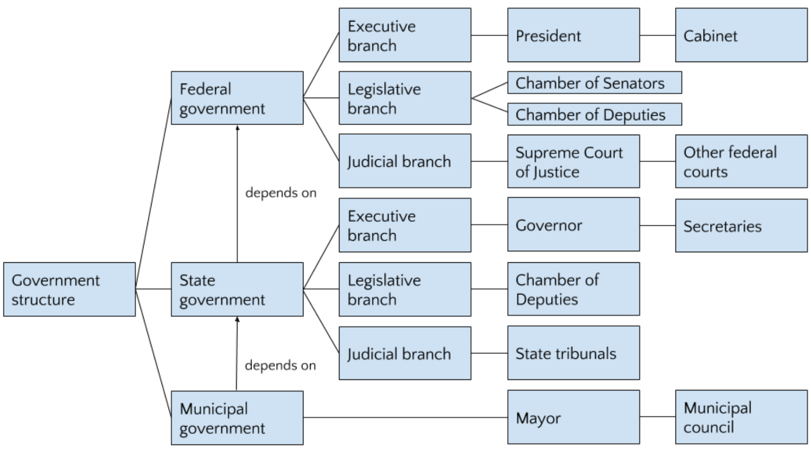

Figure 2.12: Government structure

2.3.2 Decision making

Each division has its own decision maker regarding the areas to concerned, which are flood risk and drainage. On federal level CONAGUA has the role of decision maker, on state level this role is occupied by the governor and on municipal level by the mayor. Approval on all different levels is needed in order to initiate the project.

COPLADE
The "Comité de Planeación del Desarrollo", later referred to as COPLADE, is an executive committee put in place by the federal government to coordinate the national development at state level. For approval of a project plan, it first has to pass the COPLADE of the respective state. Such a plan usually consists of a proposal for investments at state and municipal level and supervises coordination of actions across levels of government. The COPLADEM (respective committee at municipal level) is responsible for a municipality development plan with more specific expenditure proposals. The plan forms the principal framework for policy planning across levels of government, also governing fiscal relations to a large extent. Based on this, municipal development agreements can be conducted, defining shared responsibilities and setting out transferal of resources. (OECD, 2015)

Consejo de Cuenca
The Consejo de Cuenca is a space for conciliation regarding water utility management, put into place by CONAGUA. Institutions and organisations in this branch can point out their priorities in terms of requests or proposals of hydraulic projects. The users also form an assembly and can also give their opinion upon relevant subjects brought to the table. Delegations of the federal government (CONAGUA), state government and municipal government are also present at the conciliation. The Consejo de Cuenca is there to support and advise the different parties involved. The conciliation can come to good use to find public support for a plan. There are also Consejos de Cuenca on a small scale concerning a specific topic. See Figure 2.13 for the functioning of the structure of the Consejo de Cuenca. (Olivares, n.d.; Instituto para la Defensa del Interés Público, 2013)

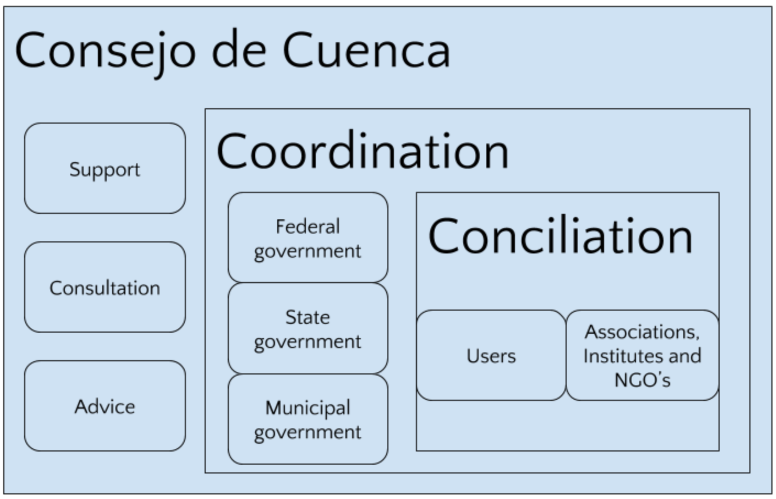

Figure 2.13: Consejo de Cuenca structure (Olivares, n.d.)

2.3.3 Finance

According to Dr. Evelia Rivera Arriaga there are in general four options to get finance for a project (see Appendix F.3). Firstly, there is a federal budget that is available for each state every fiscal year. In order to get a federal credit, the proposal needs to be approved by the SHCP and CONAGUA as mentioned in Subsection 2.2.1. The second option is through the BANOBRAS, which is a development bank that is specialised in giving credits to state and municipal governments. Their mission is to promote investments in infrastructure and public services as well as the financial and institutional strengthening of states and municipalities (Diario Oficial de la Federación, 2014). The bank is regulated by the SHCP. These loans are only granted when the interests of the SHCP can be fulfilled. Besides, the Chamber of Deputies of the state of Campeche needs to give permission to the governor to apply for these loans. Thirdly, there are several development agencies, for example the German/France Development Agency and the Inter-American Development Bank that are in collaboration with Mexico to encourage sustainable cities. These parties are able to arrange funding for particular projects. Note that funding are either investments or shared capital. The fourth option are so called "bags of money", where departments of states can apply for with a project proposal. An important factor for the application is lobbying and convincing people of these department of the federal government. In the period from 2009-2015 these so called "bags of money" were mentioned for environmental projects. Probably the purpose has changed since the new term of the federal government.

2.4 Conclusion

It can be concluded that Campeche has flooding problems from two sides. On one side storm surges cause inundations due to a high sea level and on the other side heavy precipitation causes the same phenomenon. Both events increase in amount due to climate change. If both events occur simultaneously (mostly in case of a hurricane) major flooding may occur with big effects for Campeche's residents.

As a reaction on the frequent inundations, a drainage system has been installed. This system covers precipitation up to 145 mm/day, which is sufficient for the common maximum precipitation per day. Although the system can handle this amount of water, it will take a couple of hours, sometimes even days , until the streets are cleared. Furthermore, streets are used as a buffer for rain water, before it flows into the drain. The amount of precipitation due to a hurricane cannot be handled entirely by the current drainage system. The system is divided into five non-integrated absolute pipelines, where each time adjustments are made locally. Besides, it does not cover the entire city and some neighbourhoods still have inundation problems.

The city has been growing a lot over the last decades. On one side additional land has been obtained by reclaiming it from the sea and on the other side natural areas have been cultivated around the city. The latter one caused a huge decrease in green space, which is anyways scarce in Campeche.

After reviewing the stakeholder analysis and the political system it can be concluded the three levels of decision makers all need to be satisfied before initiation of the project. This means on municipal, state and federal level. Due to the fact that governments are serving a non-renewable term and the new chosen governors and mayors have the authority to cancel an ongoing project, projects of this size are hard to realise. Besides, governors and mayors often want to mark their term with a visible project to the common people to satisfy voters. This can be time and cost consuming projects at the expense of important projects like this for the safety and health of the people.

3 Boundary conditions

The necessary background information to start searching for possible solutions has been retrieved in the previous chapter. However, in order to be able to set up solutions, the hurricane occurring once in fifty years has to be defined. Besides, since its probability is already known, only the vulnerability of the affected area still has to be defined when examining its inundation risk. Following from Section 1.4, vulnerability should be measured using socioeconomic indicators and physical flood extents. The socioeconomic indicators are considered in the multi-criteria analysis (see Section 5.2). The physical flood extents can be expressed in water accumulation per area. For the current drainage system, this is summarised in Figure 3.5. The water accumulation per area (and therefore the vulnerability) of the options is given in Figure 4.19.

3.1 Situation characterisation

Out of the data received in the analysis a hurricane - called Raúl - is simulated, with a probability of occurring once every fifty years. This hurricane induces a storm surge with a period of five days and a wave height of 2.67 meters on the second day. After reaching the maximum, the water level slowly reduces to mean sea level until day five as can be seen in Figure 3.1. The simulation is based on the data of hurricane Opal (see Figure A.27), which had the biggest impact with regard to precipitation and storm surge. The maximum wave height due to the storm surge induced by hurricane Raúl is based on a report of Posada-Vanegas et al. (2010), adding the sea level rise due to climate change. To calculate a probable value of precipitation during a hurricane in the future fifty years (see Figure 3.2), the amounts of precipitation of former hurricanes are analysed and values have been obtained by multiplying the amounts of precipitation of the worst hurricane by a factor 1.11. This factor is obtained by analysing the increase of the daily maximum precipitation per year (see Figure 2.7).

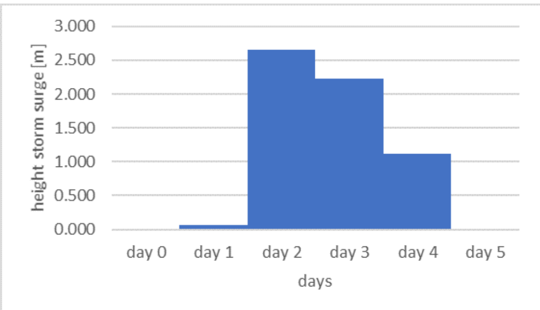

Figure 3.1: Wave height of storm surge during hurricane Raúl

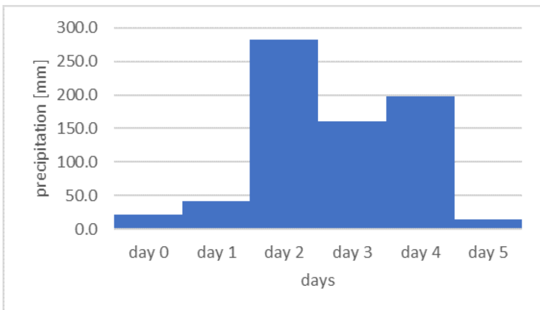

Figure 3.2: Precipitation per day during hurricane Raúl

It is assumed that the drainage system only has a limited amount of inlets (see Figure 3.3). In this way it is possible to set the locations at which flooding can occur. Next, the water accumulation without drainage, infiltration, evaporation or any other way of water getting cleared out from Campeche's soil surface, has to be estimated. Since the city is divided into coverage areas, the increase of water volume per area per day can be calculated by multiplying the amount of precipitation (m/day) with the surfaces of the different areas (m^2). When these daily values are summed up, a cumulative water volume is obtained (see Figure 3.4).

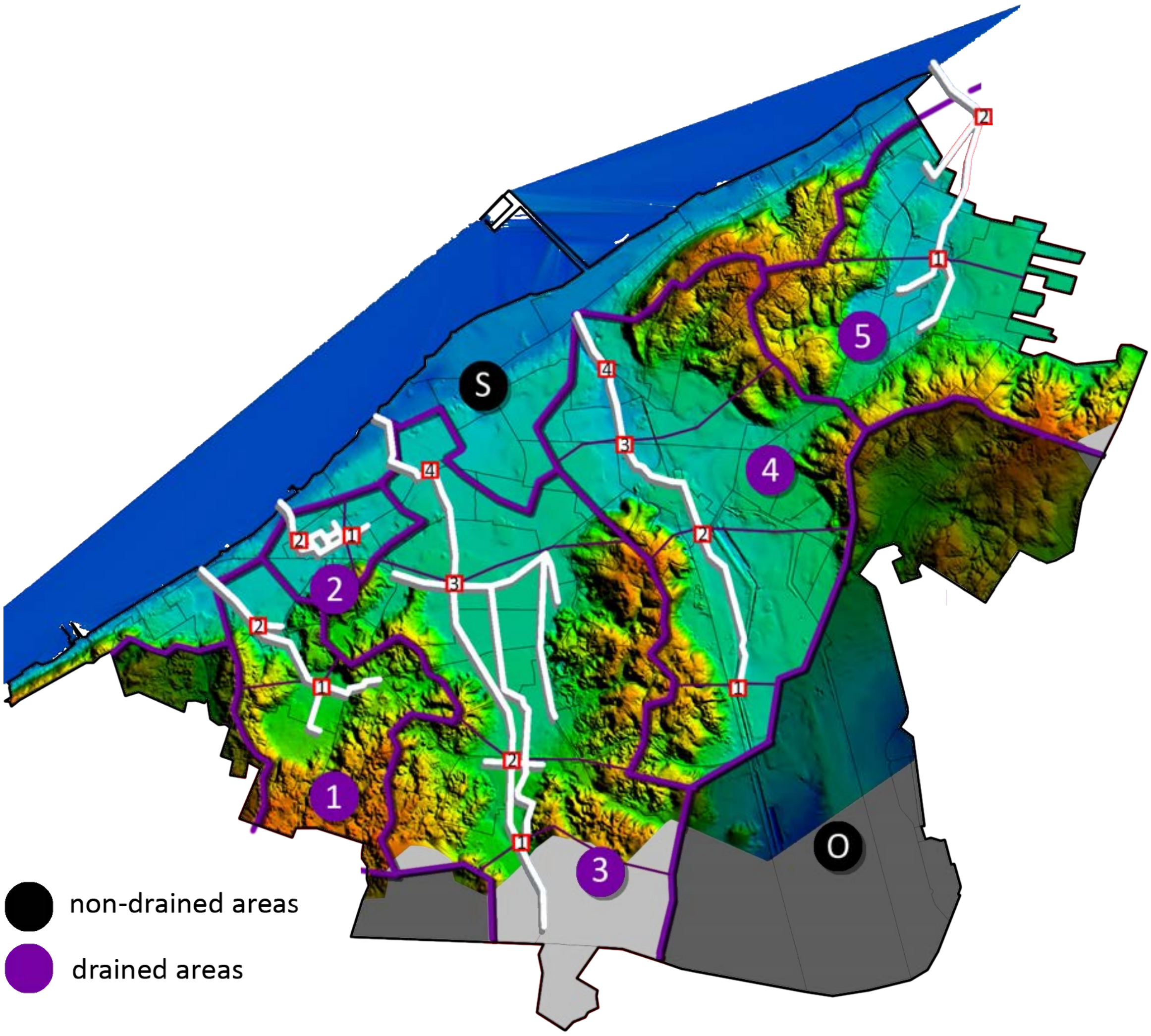

Figure 3.3: Assumed coverage areas and inlets drainage system

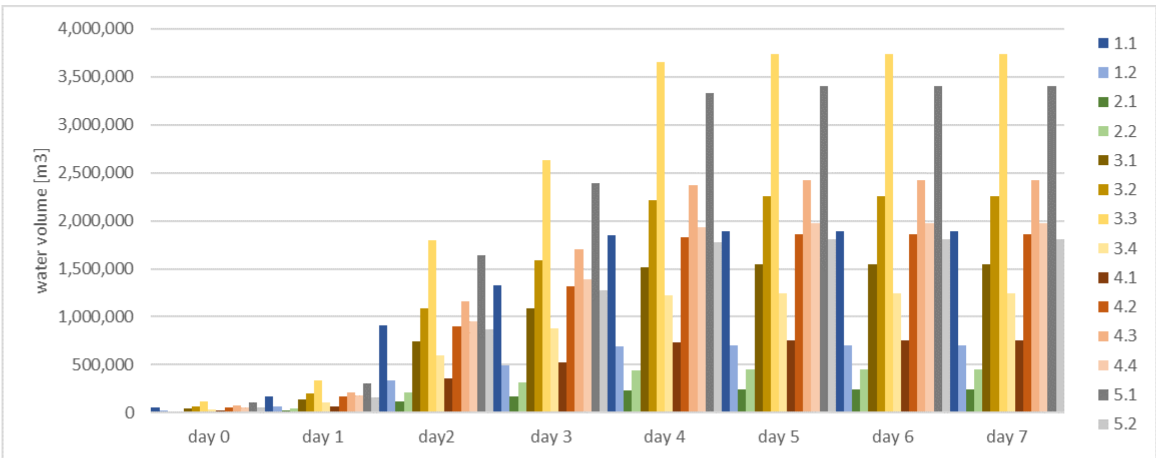

Figure 3.4: Cumulative water accumulation per area due to precipitation, without draining

To compute the daily water accumulation per area due to precipitation, taking into account the current drainage system, the drainage capacity has to be retrieved. Using Figure 3.1 & 3.4, a capacity calculation can be made up. After this calculation, the total water accumulation per area for hurricane Raúl can be computed when draining (see Figure 3.5). These calculations can be found in Appendix C.1.

A few conclusions can be made when observing this figure. Firstly, the areas which have to be drained by the mega drainage (area 3) encounter the longest inundation times. This is mainly due to the relatively small drainage capacity of the mega drainage system. Besides, the seaside pit of the Ría (4.4) cannot drain the area around it when a storm surge occurs, as it is beneath storm surge level, causing large water accumulation. Lastly, the drainage capacity of pipeline 5 is not enough to drain the neighbourhood of Presidentes de México when heavy rainfall takes place.

From Figure 3.3 some other conclusions can be made up as well. The entire area S needs to drain excessive water directly to the sea. When a storm surge takes place as depicted in Figure 3.1, a large part of this area is flooded and therefore excessive water cannot leave the area before the end of the storm surge. Furthermore, the outer areas (depicted as O in Figure 3.3) are not connected to the drainage system. Especially in the neighbourhood of Ciudad Concordia this causes a lot of water accumulation. Lastly, neighbourhoods like Cumbres, Esperanza and Quinta de los Españoles lay in between drainage areas (for example in the gorge in between drainage area 4 and 5). These neighbourhoods cannot drain as efficiently as other neighbourhoods, which makes inundation times over here somewhat larger.

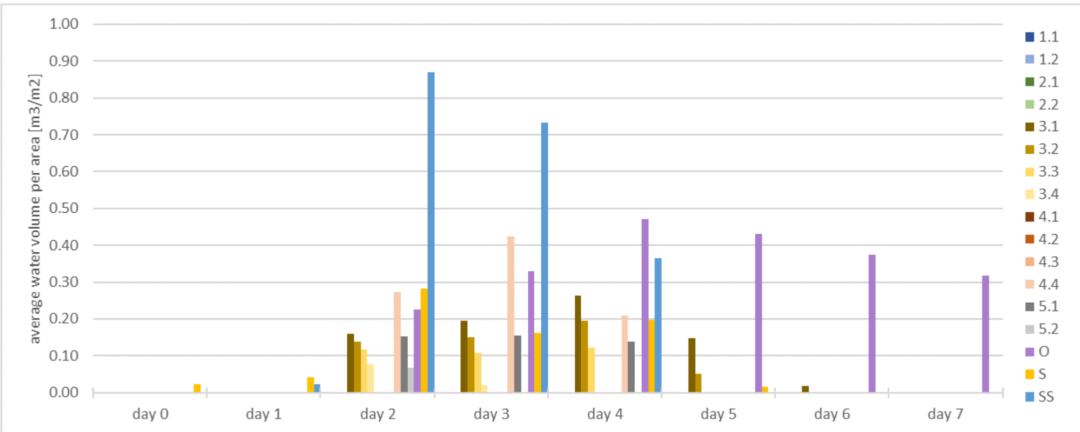

Figure 3.5: Average water volume per area due per day due to hurricane Raúl with draining and soil infiltration

3.2 Program

From the analysis various aspects emerged that need attention when elaborating possible solutions. Some of these aspects are seen as necessities and some as aspirations. The necessities are described as program requirements and the aspirations as program preferences. They are stated below.

3.2.1 Program requirements

- The solution is either a retaining, storing or draining solution.
- The solution reduces the total amount of water accumulation in either a specific location or throughout the city.
- The solution does not cause negative effects elsewhere.
- Safety, social-cultural, political, ecological and economical values have been taken into account for the solution.

3.2.2 Program preferences

- The solution can count on political support.
- The solution is economical; giving good value to the amount of time, money or effort spent.
- The solution contributes in a social-cultural manner to the city and its residents.
- The solution increases the safety of inhabitants and goods against flooding.
- Given the result of the aforementioned preferences, the solution is realistic.
- The solution contributes to the ecological environment.

4 Options

4.1 Alternatives brainstorm

After analysing and setting boundary conditions a brainstorm was done to come up with solutions. These solutions were summarily elaborated (see Appendix D) and subsequently placed in a decision matrix regarding effort and effect (see Figure 4.1).

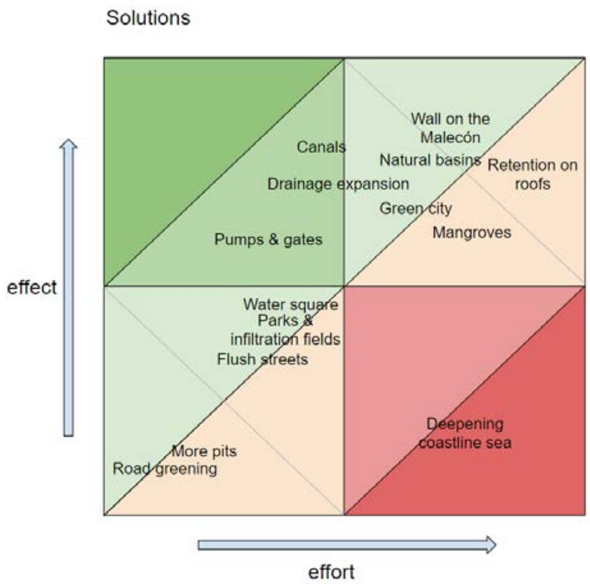

Figure 4.1: Decision matrix

As the matrix did not include side effects, these were written down per solution and solutions with significant negative side effects were stripped off. Some of the remaining solutions would not fit well to our knowledge or responsible people in Campeche would have better knowledge about these specific subjects. For example, the drainage expansion probably is one of the most realistic solutions, but plans are already made by the municipality on how to implement this. Consequently, the following solutions will be thoroughly elaborated:

- Parks & infiltration fields
- Wall on the Malecón
- Natural basins (including pumps; later referred as infiltration basin)
- Water squares

4.2 Elaborated solutions

In this section the different solutions are elaborated. As the solutions have to be compared afterwards, the solutions all have a similar structure.

4.2.1 Parks and infiltration fields

As been told in the elaboration of the alternatives (Appendix D), vegetation does have the ability to temporally store water and therefore delay water from entering drains. Generally parks can take 50% of precipitation, where cities without parks can only take 15%. In a city like Campeche, with only 1.47% of green area, 55% (instead of 10%) of the water runs off and needs to be stored otherwise.

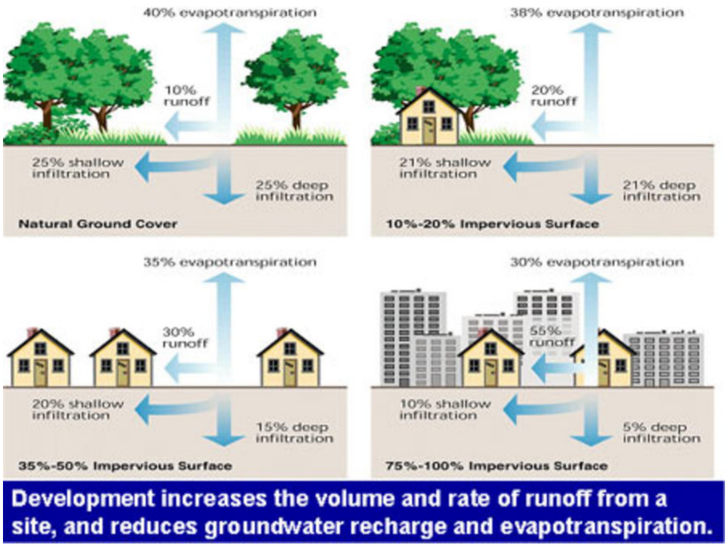

Figure 4.2: Water storage decrease due to impervious surface

So, parks have a significant water storing capacity per square meter and therefore reduce inundations in the city. However, the amounts of Figure 4.2 are determined for an unknown subsoil. In order to know how parks can be a solution to inundations in Campeche, one has to know the storing capacity and therefore the type of soil and the groundwater level.

4.2.1.1 Design

The amount of volume that can be taken per square meter park per day (mm/day) depends on the amount of infiltration in the soil and the amount of evapotranspiration, which consists of evaporation from the soil and transpiration from vegetation.

Infiltration
Soil type is of big interest, because some types of soil will be less suitable to be used as a subsoil for a water storing park (d'Ursu, 2017). To avoid inundations the soil has to be permeable. Permeability is highly depending on grain size; a bigger grain size is usually more permeable. This means that clay lets little water through and even retains water above groundwater level and that sand easily lets water through and is dry above groundwater level. Hence clay soil is more suitable for draining above ground and storing, where sand is more suitable for infiltration.

Due to precipitation the groundwater level will rise. The amount with which it will rise depends on the storage coefficient, which usually is between five and ten percent. This means that the soil can take a water volume of five till ten percent of its total volume. This results in a risen groundwater level of 10 respectively 20 times the precipitation. So, a soil with a low storage coefficient and a high ground water level will be saturated in a short time.

Evapotranspiration
Next to infiltration, plants and soils lose water due to evapotranspiration. Evapotranspiration is the sum of evaporation and plant transpiration from earth's land to the atmosphere. Evaporation is the movement of water to the air from soil, canopy interceptions and water bodies. Transpiration is the movement of water within a plant and the subsequent loss of water as vapour through stomata in its leafs (USGS, 2016).

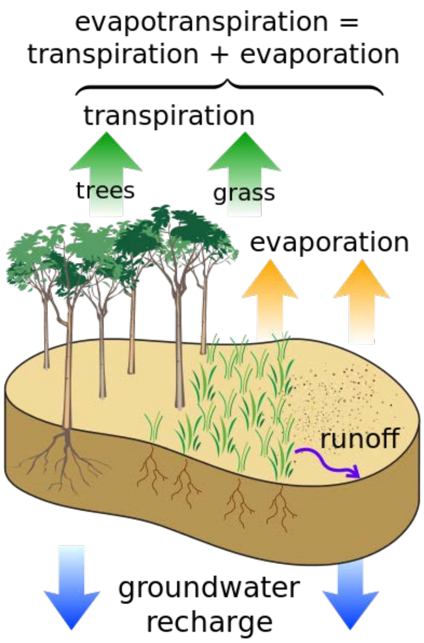

Figure 4.3: Conceptual diagram of near-surface hydrology (Toews, 2007)

Factors that affect evapotranspiration include the plant's growth stage or level of maturity, percentage of soil cover, solar radiation, humidity, temperature, and wind (Jasechko et al., 2013).

Evapotranspiration is usually no greater than precipitation, with some buffer in time depending on the soil's ability to hold water. An exception is areas with high water tables, where capillary action can cause water from the groundwater to rise through the soil matrix to the surface. In order to know what the volume of water is that will be evapotranspirated, the potential evapotranspiration (PET) has to be calculated. The Thornthwaite equation for PET[1] is:

$$PET = 16\left(\frac{L}{12}\right)\left(\frac{N}{30}\right)\left(\frac{10T_\alpha}{I}\right)^\alpha \tag{4.1}$$

Where PET is estimated potential evapotranspiration (mm/month), T_α is the average daily temperature of the calculated month (degrees Celsius), N is the number of days in the month being calculated, L is the average day length (hours) of the month being calculated.

[1]Thornthwaite is chosen because few information was available and it is the most basic equation

$$\alpha = (6.75 \cdot 10^{-7})I^3 - (7.71 \cdot 10^{-5})I^2 + (1.792 \cdot 10^{-2})I + 0.49239 \tag{4.2}$$

$$I = \sum_{i=1}^{12} \left(\frac{T_{\alpha i}}{5} \right)^{1.514} \tag{4.3}$$

The data of average day lengths and temperatures per month were obtained and are visible in Table B.4.

The total capacity of a park regarding the withdrawal of water as the sum of infiltration and evapotranspiration in Table 4.1.

Capacity	**August**	**September**	**October**
Infiltration	1100	1100	1100
Evapotranspiration	14.9	11.5	8.7
Total	1115	1112	1109

Table 4.1: Infiltration capacity parks (mm/day/m^2)

The next step is to determine for which areas parks will be of great benefit and how parks can be applied in these areas.

4.2.1.2 Locations

As the inundation problem has to be solved, it makes sense to create parks in areas with high inundation risk. There are four kinds of high risk inundation areas in Campeche:

A. Low-lying areas near the sea particularly due to a risen sea level;

B. Areas that are drained, but the drainage capacity is not sufficient during high precipitation;

C. Areas with sufficient drainage capacity, but somehow inundations do still occur;

D. Non-drained areas.

Logically, parks in areas that are below sea level (or not far above) during the storm, do not make a difference, because the groundwater level will be too high and the soil would not absorb any water. Therefore only for areas of category B, C and D, opportunities of creating parks will be suitable[2].

Since the capacity with regard to water infiltration is highly dependent on the soil type, parks should be placed on soils with the best infiltration characteristics. As mentioned before it is assumed the soil consists of phaeozem. Since this is an assumption, soil samples need to be taken to ensure the characteristics are similar or at least suitable for water infiltration. Furthermore the elevation of the park in relation with its surroundings is important, as water can only be absorbed when it is on the surface of the park.

Determination of specific suitable locations for parks in problem areas in Campeche is hard due to the yet unknown development plans of specific areas and the current state and use of buildings and spaces. Therefore, only examples are given which are possible to execute at any location determined by the municipality.

[2]If in combination with a surge retaining structure, parks can be a solution in A.

Transform currently paved squares into parks with more green space
Present squares consist for the largest part out of paved area where water is not able to infiltrate. An increase in green space contributes to an increase of the infiltration capacity of a park. In Campeche there are a lot of these paved squares that can be easily adjusted into infiltration parks.

Transform locations without a clear function into parks/green space
Dilapidated buildings are not always suitable for creating a park, however every part of green space can contribute to an increase of water infiltration. Besides dilapidated buildings, there are a lot of unused areas which will become garbage dumps if they do not have a clear function. When these areas are transformed into parks or green spaces it generates a positive impact on the view and contributes to infiltration of water during rainfall events.

These options are both changes in land use on relatively small scale. In order to reduce the water problems in the city, these measures need to be executed at several locations to ensure the decrease of accumulation is noticeable. Besides, these parks and green spaces function as local solutions. Since it is difficult to ensure water from the surrounding areas is going to the parks, locations need to be handpicked for the several areas.

4.2.1.3 Calculations

To determine the catchment area of a park, an example park is made up with an area of 40x30 m. In Appendix C.2, this catchment area is calculated, which is equal to 5.3 times its own size. From the calculation also can be concluded that the capacity of the example park almost gets tripled when made impervious for 90%. Lastly, when meeting the green space requirements from the WHO, the catchment area of the supplementary green space is equal to about 13.5% of the city area. The total infiltration capacity will build up to 855,000 m^3/d in this case. This results in a total water volume reduction of 7.4 million m^3 (see Appendix C.6.1).

4.2.1.4 Possibilities

When looking at possibilities in order to improve public services or city image using the parks and infiltration fields, a few options can be made up. At first, parks can be used to introduce new types of flora and fauna into the city boundaries. Since Campeche is the capital of the state carrying the same name, some typical types of vegetation could be brought to the city. Besides, parks attract animals, which are hard to encounter in the city at the moment.

Parks and infiltration fields can also improve recreational facilities. Playgrounds and open-air fitness areas are some examples of improvements. It must be kept in mind that these facilities should not increase the percentage of imperviousness at location. Since parks are usually central places in a neighbourhood, the citizens could be involved by giving them the opportunity to come up with own ideas.

4.2.1.5 Construction & maintenance

For ecological purposes it is important to use mainly local and diverse vegetation to create a good habitat to different species and make the park as good as self-sufficient. Parks can most easily be constructed on the existing soil type, as in this way no soil has to be transported.

Irrigation
Next to a rain season Campeche also knows a dry season with March as driest month, with only two days of precipitation. The amount of precipitation in the driest month is even expected to decrease (from 0.35 mm/day in 2017 to 0.23 mm/day in 2067). Consequently, parks need to be irrigated for approximately six months a year, since in that period the rainfall is very limited.

Gardening
Where irrigation can be done automatically, parks need gardeners to keep vegetation in the right size. The amount of man hours needed is highly depending on the kind of vegetation and the size of the park.

4.2.1.6 Risks

The main risk in the catchment calculations (see Appendix C.2) is the current pattern on micro-level. To reach the calculated catchment area, the park has to be placed at the lowest location and even then it is possible that runoff flows somewhere else due to the micro-elevation. Furthermore, there are not many locations available, since the city is for its majority densely packed. However, by implementing parks and infiltration fields, there is no risk that the affected neighbourhood undergoes negative consequences. If the solution does not fulfil its function, the situation just remains unchanged.

4.2.1.7 Costs

By far the largest cost is that of the land. Furthermore, there could be costs related to accommodating the park or infiltration area in its surroundings, for example to make more runoff flow towards the park area. Minor costs are related to seeding plants, create recreational or aesthetic supplements and maintenance.

4.2.1.8 Conclusion

Creating parks and infiltration fields to increase the amount of green space in the city and therewith reducing inundation impact is a relatively simple step to implement. The costs are low and so is the amount of effort and time to accomplish it. However, searching for suitable locations can be a drawback, due to differences in micro-elevation and the limited amount of space. Nevertheless, a start can be made by making existing parks impervious, which almost triples their capacity. Besides, when succeeding to construct as many parks as prescribed by the WHO, they can play a large part in the overall reduction of inundation impact (covering a supplementary 13.5% of the city area when allowing a maximum water height of 0.5 m). In addition, parks and infiltration fields can have a lot of positive side effects in recreational, aesthetic and ecological field.

4.2.2 Wall on the Malecón

As mentioned in Appendix D, the wall on the Malecón needs to be seven kilometers, of which 2 kilometers in front of the mangroves, to protect the biggest part of Campeche near the coast that has an elevation under the expected storm surge of 2.67 meters. During the design of a wall on the Malecón it is of great importance to keep several influence factors in mind such as safety, costs, feasibility and aesthetics.

There are several possibilities to protect Campeche against a storm surge where the wall is one option. A wall seems not a popular solution, creating a blockage in sight without any additional use. The expected storm surge occurs once every fifty years. Hence, the wall will not used that often. The construction of a plain wall on the Malecón gives the view a severe impact and will likely create public resistance. Therefore two options are designed in SketchUp: elevating the walking path or the cycling path, with two versions for the cycling route.

The first option is an elevated bicycle path with at every 500 meters a ramp to the level of the pedestrian path and road. The part where the cycling path descents, a gate needs to be installed which can slide in front of the wall to ensure the water is not able to get through (see Figures A.28 & A.29). This is mainly done to keep the sea visible from main routes towards the Malecón. Another advantage is that the pedestrian path can be reached without crossing the elevated bicycle path. It also brings a disadvantage: the need for the installation of a gate every 500 meters. This is a complicated construction and therefore will cost more in comparison with a continuous elevated bicycle path.

The second option is also an elevated cycling path, but with a continuous elevation of the wall and every 500 meters a ramp on the side of the bicycle path as can be seen in Figure A.30. The advantage here is the continuous elevation where gates are not needed. On the other hand the view from both sides of the wall will be affected for five kilometers which creates a separation which is not desirable for the aesthetics and accessibility of the Malecón. Beside the ramps, stairs will be placed every 250 meters to be able to cross the wall.

The third option is an elevation of the pedestrian path in combination with the current Malecón wall as can be seen in Figures A.31 & A.32. Every 100 meters there will be stairs to access the pedestrian path of the Malecón. An advantage of this design is in comparison with the other options that it does not separate the Malecón into two parts.

4.2.2.1 Design

Out of the three designs the accessibility and aesthetics of the cycling lane with descends at the walk crossings was the most suitable thus will be further elaborated. The cycling lane will be constructed with an average height of 1.2 m and raised up to 1.5 m at locations below +1.2 m MSL. There are nine crossings, where the path will be descended so the Malecón can be easily reached, which can be seen in Figure A.33.

A part of the wall is protecting the area behind the mangroves ‘Los Petenes’. The length of this part is two kilometers. At that part the wall will not have an cycling path on top of it. This is because of in the current situation the cycling- and pedestrian path stops at the point ‘Los Petenes’ starts. The connection where the cycling route ends and the wall starts is at the location where the path descends and a sliding wall comes into place at the connection between Pedro Sainz de Baranda and Adriano Chino Wong (see Figure A.34). This wall will have another opening for the entrance of the parking lot at the restaurants at the Malecón (see

Figure A.35).

Another notation that needs to be made is the connection canal of the retention area, located at the end of the Ría, with the sea. In an event of a storm surge, water can find his way through this part of the Malecón, flooding the basin and the land behind the Malecón. For this particular passage a one-way opening gate needs to be constructed to withhold the water. An option is the lock gate used at the Rideau canal, where the water can always flow through but can also be closed (see Figure A.36).

Another important consideration for the design are the both ends of the wall. The locations where the wall stops are not high enough to withhold the storm surge thus an elevated carriageways on both sides of the wall are required to ensure the water is not able to bypass the wall. These carriageways are required to be elevated land inwards until the elevation reached 2,67 meter.

The construction of the retention wall at the ramp of the path is the complicated part of the retention. To reduce the costs, the walls are able to move manually over a rails. The walls must be slid, therefore they are separated into sections of 2.5 meter wide each. Another advantage is that the span of the slab will not be large and therefore the maximum deflection will be small. The consequence is that every 2.5 meter a column will be placed (see Figure 4.4).

The walls will be moved by wheels attached to the construction on rails. To prevent seepage of water underneath and between walls rubber strips will be attached (see Figure 4.5). To prevent any unnecessary use, the walls need to be stored in a way that only people allowed to move them, can move them. A construction in front of the rails which can be locked and unlocked would be a solution.

The construction connection between the slope and the cycling path is complicated, because it is not all in one line next to each other. On the part of the rails where the sliding walls are slid away from the construction is behind the line of the wall of the rest of the construction (see Figure A.37).

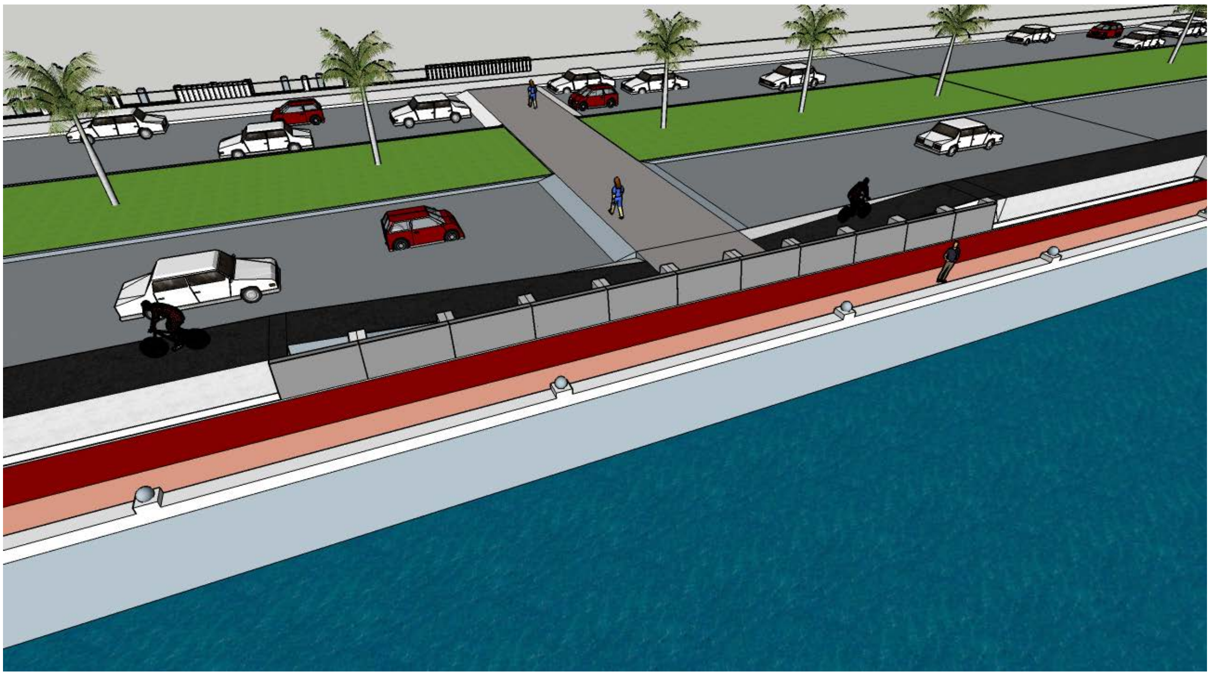

Figure 4.4: Wall construction in SketchUp

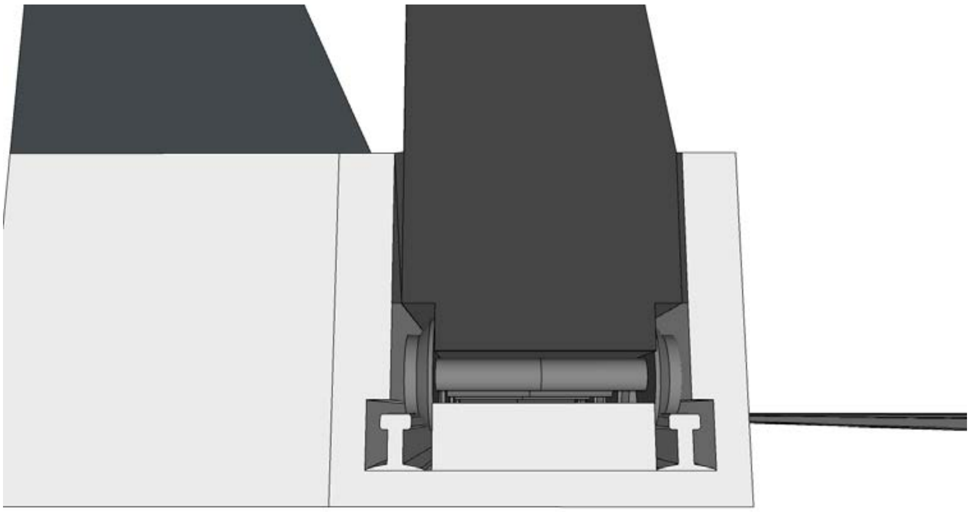

Figure 4.5: Wall construction detail in SketchUp

4.2.2.2 Inundation prevention

The construction of a wall at the Malecón protects an area of 2.174 km^2 against a storm surge. This area is measured by using Global Mapper and the height of the storm surge as calculated in Section 3.1. A calculation was executed with Global Mapper to find out the volume of water that is being held back by the wall. This is done by calculating the volume of sea water that would go into land with the expected storm surge level of 2.67 m. The outcome of this rough estimation is 1,89 million m^3. From this calculation it can be concluded the average elevation in this area is around 1.85 m. In this calculation the presence of buildings in this area is not taken into account. The actual volume reduction of water due to the storm surge is therefore less. Furthermore, for the first two options, there is a stroke in front of the elevated cycling path that still gets flooded, although this is less then 1% of the total and is negligible within this rough estimation. In Appendix C.6.2 the volume reduction over the five days of storm surge is calculated, preventing a volume of 4.33 million m^3.

4.2.2.3 Calculations

The construction of the wall needs to be able to withstand the pressure created by the storm surge. Therefore hydraulic and structural calculations need to be done.

Hydraulic calculations
When a storm surge hits the wall at the Malecón several forces are acting on the wall. These forces are described by numerous design codes, the formulas are based on H. Yeh and I. Robertso and J. Peuss (2005):

1. Hydrostatic force: The pressure difference between both sides on the structure, increasing over depth.
$$F_h = \frac{1}{2} \cdot \rho \cdot g \cdot h^2 \cdot w \tag{4.4}$$

2. Hydrodynamic force: A force induced by the flow of the mass of water. It is a function of

the flow velocity and geometry of the structure.

$$F_d = \frac{1}{2} \cdot \rho \cdot C_d \cdot A \cdot u_p^2 \tag{4.5}$$

3. Surge force: A variety of hydrodynamic force caused by the leading edge of the surge. Storm Surge increases with the depth.

$$F_{surge} = \frac{9}{2} \cdot \rho \cdot g \cdot h^2 \cdot w \tag{4.6}$$

4. Breaking wave load: Another variety of the hydrodynamic force caused by the wave breaking on against the structure. This force is a combination of hydrostatic force and dynamic force.

$$F_{wave} = (1.1C_p + 2.4) \cdot \gamma_{sea} \cdot d_s^2 \cdot w \tag{4.7}$$

5. Impact force: Debris transported by the storm surge from sea, for example boats, striking the structure. The impact force is a point load, which will be located on the top of the water level, because debris will flow on top of the water. With a concrete wall the impact time will be between 0.2-0.4 seconds (O'Brien, Christodoulides, Renzi, Dutykh, & F.Dias, 2012). The weight of the impact will be assumed to be 500 kg.

$$F_i = \frac{W \cdot u}{g \cdot \Delta t} \tag{4.8}$$

According to the calculations in Appendix C.3, the largest hydrodynamic impact will be the storm surge force, therefore for the construction calculation the surge force, hydrostatic force and impact force will be accounted for.

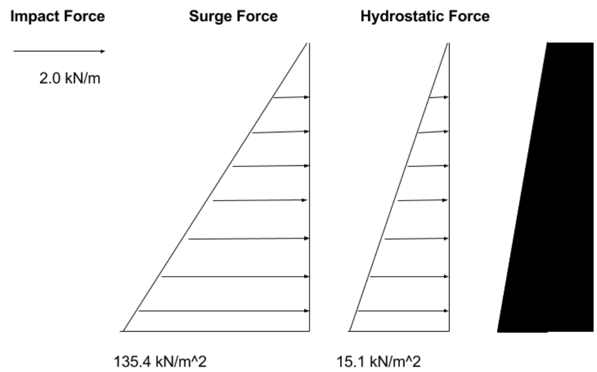

Figure 4.6: Hydraulic forces on the wall

Structural calculations
The wall element was modelled as a concrete slab in a finite element program, with three hinged sides. To calculate the resistance of the slab, the obtained values from the hydraulic calculation were put in the program. This resulted in stresses per coordinate. These stresses were used to calculate the needed longitudinal reinforcement. After that the slab was calculated on shear resistance. The slab is divided in beams for checking the shear resistance.

As concrete cracks perpendicular to the highest stresses, from the obtained stresses (σ_{xx}, σ_{yy}, σ_{xy}), the principal stresses were calculated (σ_1, σ_2) and those have been compared to concrete characteristics. On locations where the stresses were above the tensile strength, longitudinal reinforcement was calculated. After that the shear resistance was checked and shear reinforcement was calculated. The results of these calculations are visible in Appendix B.5 & C.3 and Figure 4.7.

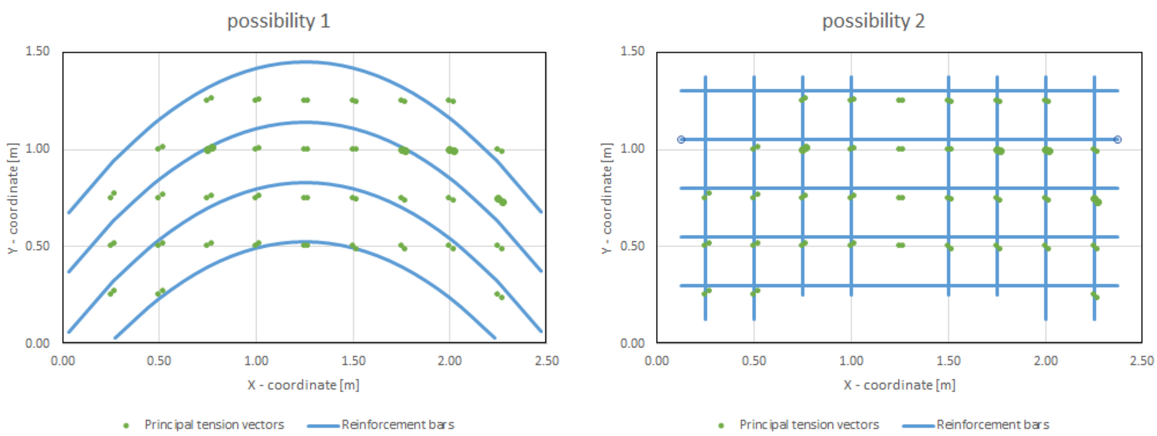

Figure 4.7: Principal tension vectors and possible reinforcement

The slabs are supported by two columns of 0.5x0.5x1.5 m^3. The slab transfers forces to the columns (see Figure A.38). With these forces the reinforcement due to bending and shear has to be evaluated. For bending the resisting moment needs to be larger than the applied moment of 177.2 kNm (see Figure A.39). According to the calculations in Appendix C.3, bending reinforcement of 4xϕ16 mm is necessary.

For shear reinforcement, the shear in the column needs to smaller than the shear resistance $V_{Rd,c}$ of the column. According to the calculations (see Appendix C.3), it does not, so shear reinforcement needs to be applied as well. To apply horizontal shear reinforcement, rebars at both sides are required. These will be 4xϕ12 mm with stirrups of ϕ8 mm (see Appendix C.3).

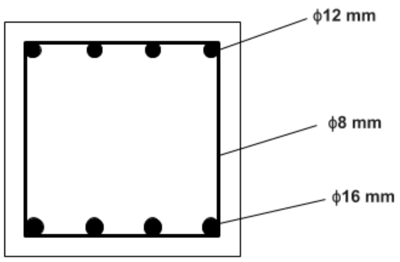

Figure 4.8: Reinforcement column

4.2.2.4 Possibilities

With an increasing sea level and increasing severity of storm surges, something has to be done to withstand this. A wall at the Malecón seems inevitable, although the rarity of the storm surge makes a wall seem rather radical. An elevated cycling route could be the mark on the Malecón of Campeche. This inventive solution against storm surge could become a model to other coastal locations in Mexico.

The recreational facilities change only for a little part. The cycling path is already located on the Malecón. It might become more popular to use, because of the elevated view, but that impact is not significant.

4.2.2.5 Construction & maintenance

The construction of the wall on the Malecón is a time-consuming process. The Malecón needs to be deconstructed and will be not fully functional for a long time. Next to that the road will be affected as well and the construction will probably occupy a lane of the road during construction.

Hardly any maintenance is necessary, the construction needs to be checked on crack formation from time to time to prevent further damage and the sliding wall needs to be tested, but it does not need any other maintenance.

4.2.2.6 Risks

With the construction of a wall there are several risks that need to be taken into account. Although safety factors were taken into account, there is always a chance a part of the wall is not strong enough to retain the force of the water due to a construction error. In the situation of failure at a part of the wall the consequences are very high for the area behind the Malecón with an elevation under the expected storm surge height. Even though the probability of occurrence is small, the consequence of large inundations create a risk that needs to be taken into account.

4.2.2.7 Costs

Due to the long construction period, the labour and equipment costs will be large. Also huge amounts of reinforcement and concrete will be used for the construction of the walls. The walls and columns all have the same dimensions, thus can be prefabricated in large amount. Repetition reduces the costs largely. On the other hand the movable wall construction is an complicated process and therefore will take a lot of time. On top of this all the extend of the construction is large, generating a substantial total cost item.

4.2.2.8 Conclusion

The wall on the Malecón is a construction that can prevent a large area with a couple of the most valuable parts of the city, with a lot of business and commerce, from inundations. Shaping the wall into a cycling route can create an interesting design against the rare storm surges that can submerge the city. On the other hand, it is a large construction where if only one part fails, the construction loses its function. Also the length of the construction makes it a costly solution. Hence the elevated cycling route is an effective solution with a large price-tag.

4.2.3 Infiltration basins

Infiltration basins are stormwater management systems constructed in areas of highly permeable soil that provide temporary storage of stormwater runoff and can help to reduce increases in both the peak rate and total volume of runoff caused by land development. Pollutants in runoff are treated through the processes of filtration through and biological and chemical activity within the soil. The infiltration rate is dependent on the permeability of the underlying soil, the distance separating the lowest basin elevation from the seasonal high water table (SHWT) and the area of the basin bottom. (Blick, Kelly, & Skupien, 2004)

4.2.3.1 Design

Loss of subsoil permeability is a concern due to soil compaction, but also the transport of dissolved pollutants through highly permeable subsoil is of concern. High pollutant or sediment loading is unfavourable for the functioning of the system. No standing water may remain in the infiltration basin 72 hours after a rain event (using the lowest design permeability rate) in order to allow for sufficient storage for the next rain event. Besides, storage in excess of 72 hours may lead to anaerobic conditions, odour and both water quality and mosquito breeding issues. The design permeability rate of the subsoil should lie between 0.5 and 10 inches/hour ($\approx$ 1.3-25 cm/hour). (Blick et al., 2004)

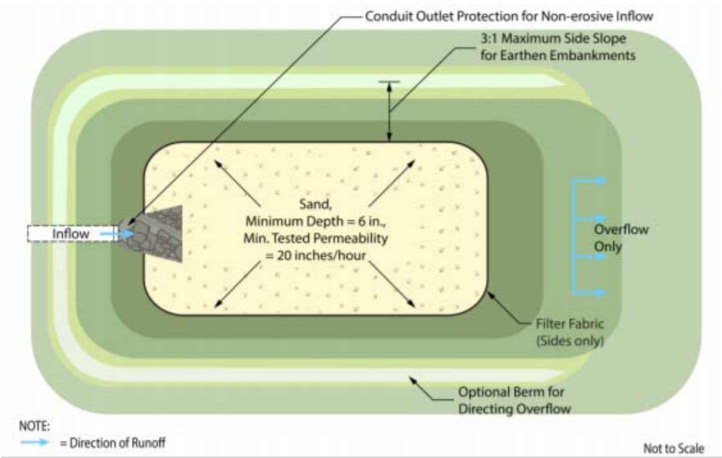

Figure 4.9: Example plan view of surface infiltration basin (Blick et al., 2004)

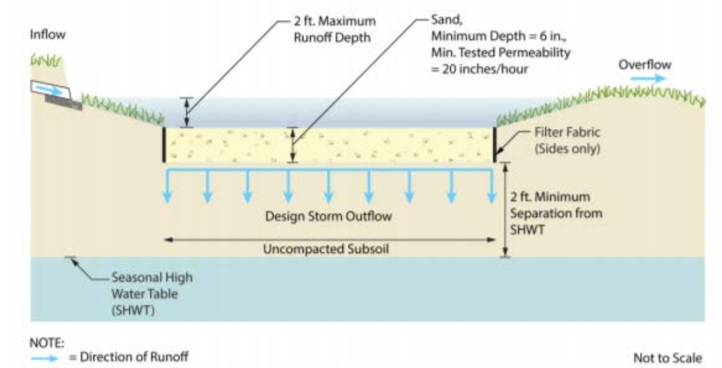

Figure 4.10: Example cross-section of surface infiltration basin (Blick et al., 2004)

From Figure 4.9 & 4.10 it follows that the maximum runoff depth of the infiltration basin is equal to 2 ft. (≈ 61 cm). The maximum interior slope of the embankment is equal to 3:1. A sand layer with a minimum depth of 6 inches (≈ 15 cm) is required to ensure a constant design permeability rate over time. Filter fabric needs to be placed along the sides of the sand layer to prevent migration of fine particles from the surrounding soil. The maximum percentage of fines in the sand layer is 15% and the minimum separation distance from the sand layer to the SHWT is equal to 2 ft. (≈ 61 cm). (Blick et al., 2004)

4.2.3.2 Locations

It is beneficial to make the infiltration basin as large as possible. In this way, investments can be turned into effective results most easily. Besides, the basin has to fulfil the demands of the catchment area it is serving. Since yet undeveloped areas have lower costs of land, it is best to search for location possibilities around the city. The most important inundation areas which are situated at the outer edge of the city are Ciudad Concordia and Presidentes de México. These neighbourhoods could benefit from an infiltration basin in the vicinity. For each of these districts, a possible location will be discussed. In order to find a suitable location for an infiltration basin it is of importance it consists of a flat area. There will always be minor elevation differences which are needed to be excavated to a flat area. With the aid of Google Earth for the location characteristics and Global Mapper for elevation differences the possible locations were determined. In Figure 4.11, the suitable locations are given whereas Table 4.2 indicates the characteristics of these locations such as area and elevation differences of the location borders in cardinal directions.

Ciudad Concordia
The neighbourhood of Ciudad Concordia lays on the outer eastern edge of the city, surrounded by hills. Rainwater collects in the district and almost has no escape routes, leading to intense inundations with heavy rainfall. There are plans to connect Ciudad Concordia via the drainage system to the Ría, therewith reducing the impact of rainwater on the neighbourhood in case of severe storms. Another option would be to construct an infiltration basin which can handle (part of) the surface runoff. There can be found several low-lying areas in the vicinity of Ciudad Concordia. Some of them are close to the Ría, which makes their use redundant, because the Ría already has enough capacity to handle the supplementary rainwater from Ciudad Concordia (following from Appendix C.1). Another option would be to find a suitable location in eastward direction, close to the airport. There can be found a lot of agriculture over here, but also possibilities for areas to inundate, as can be seen in Figure A.43. From Ciudad Concordia to the possible infiltration area the land only leads downhill, as shown in Figure A.42, which makes the construction of the necessary drainage pipelines relatively simple. Besides, the length of the pipeline is less than the one for the expansion of the Ría network. The total catchment area of Ciudad Concordia is 2.07 km^2, as can be seen in Figure A.41. Assuming a total runoff of 60% of the rainfall, the capacity can be calculated, which is done in Appendix C.4.

Presidentes de México
The neighbourhood of Presidentes de México is located on the outer northern edge of the city. It is already connected to the drainage system, which nevertheless cannot deal with the large amounts of rainwater. It would be possible to expand the current drainage system with some supplementary pipelines, however it might be also a good solution to look for another storage area which is closer to some parts of the district. Since Presidentes de México lies rather low, this implies most of the time that pumps are needed to reach the basin. A flat area of

10.8 hectares is found which possibly could be flooded and act as an infiltration basin. Rather than in Ciudad Concordia, this basin functions as a removal of the load from drainage pipeline 5. At the crossing between Av. Lic. Benito Juárez and Lázaro Cárdenas an intersection can be installed, from where the new pipeline sets course for the infiltration basin (under guidance of pumps). The path that the pipe should follow is drawn in black. Most of the path is along the present drainage system. The elevation difference between the proposed pump location and inlet of the infiltration basins is about two meter with a maximum elevation difference of four meter at one part along the pipe. This option of infiltration basin under the guidance of pumps implies that the capacity of the original drainage system increases downstream of the intersection. The infiltration basins cannot cope with all the surface runoff from Presidentes de México, but it can give a hand in the overall reduction of inundations in the neighbourhood. The infiltration capacity of the basins has been calculated in Appendix C.4, for an inflow of 1.5 m^3/s.

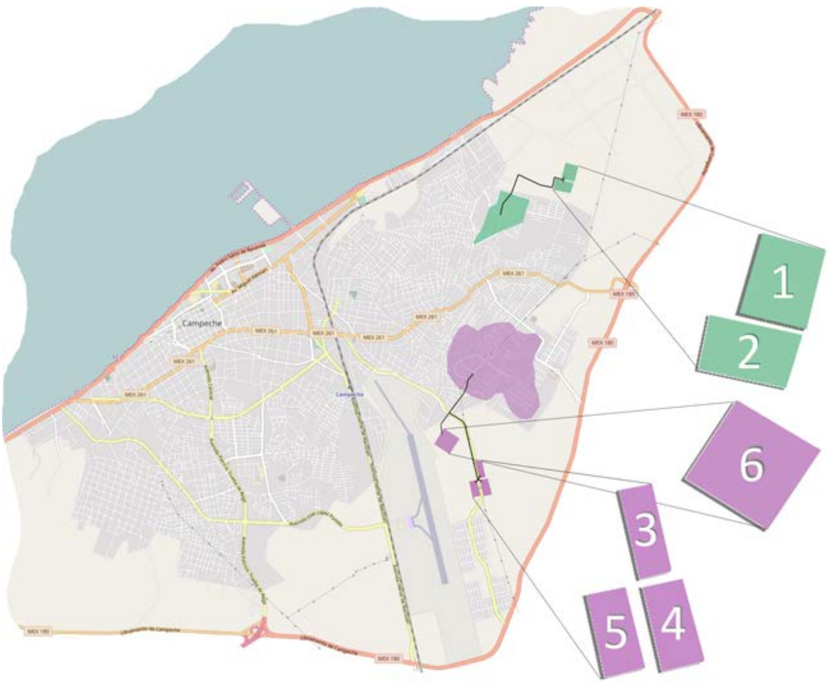

Figure 4.11: Infiltration basin options

Infiltration area	Area (m^2)	Elevation north(m)	Elevation south(m)	Elevation east(m)	Elevation west(m)
Basin 1 (Presidentes)	52,788	4.5	5	5	4.2
Basin 2 (Presidentes)	50,150	5.3	6	5.9	5.8
Basin 3 (Concordia)	22,410	4.8	2	3.4	3
Basin 4 (Concordia)	33,150	1.6	1	2	1.7
Basin 5 (Concordia)	31,200	2.3	1.1	1.8	2
Basin 6 (Concordia)	104,160	9.9	9	10.8	9

Table 4.2: Characteristics of infiltration basin areas

4.2.3.3 Drainage canals and pipelines

Ciudad Concordia

In order to collect the water in the neighbourhoods and transport it to the infiltration basins, a drainage system is required. The catchment area of Concordia can be divided into two parts, a northwest part and a southeast part. Due to the shape of the hills, all the water is accumulated around the sports fields which are located at the lowest part of the area. At the southeast side of these sports fields an existing drainage canal is already in use, which can be seen in Figure 4.12. With some extensions of this canal the southeast catchment area is covered. This drainage canal is running parallel to Av. Concordia in the direction of the airport. Between Concordia and the airport there is an option to construct an infiltration basin (Basin 6 in Figure 4.11). For the northwest area of Concordia a whole new drainage canal system need to be constructed. The proposed locations for the drainage canal do all have an area between the carriageways, except the parts where other roadways are crossing. These parts need to be covered and are indicated in orange in Figure 4.12. The drainage canal will eventually run parallel to the Siglo XXI from Concordia to the other basins (Basins 3, 4 and 5 in Figure 4.11). For both catchment areas, the open drainage canal will be of the same design as the current drainage canal that is present in a part of Ciudad Concordia which is a U-shape concrete canal. The locations of inlets and pits of the drainage canals need to be placed so that the water flowing from the hills is captured as much as possible.

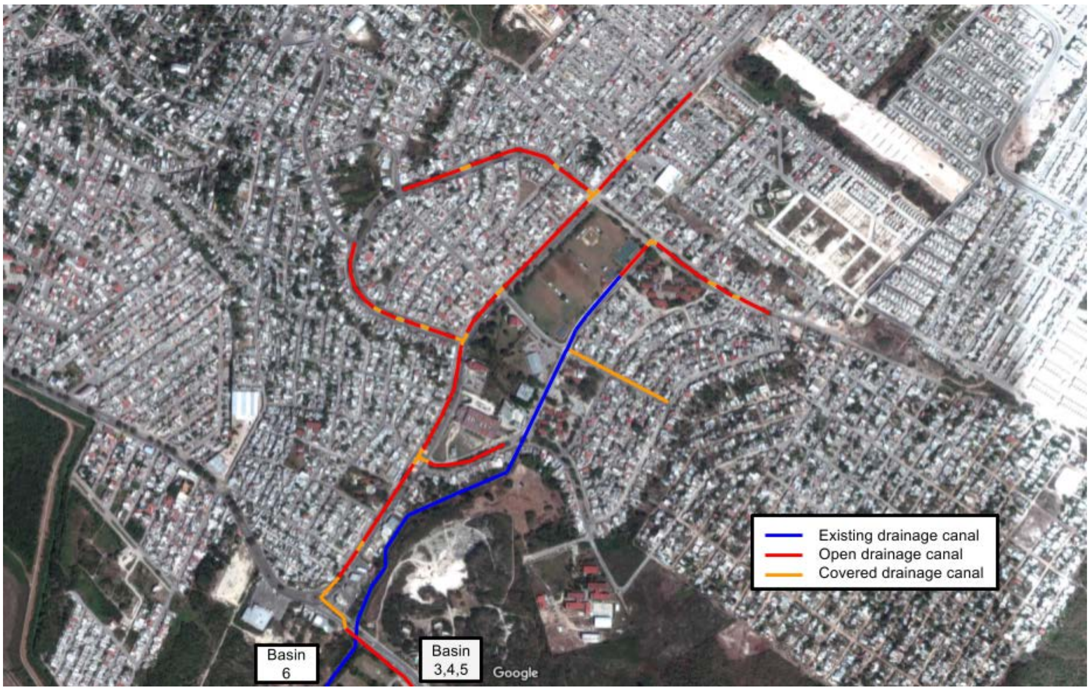

Figure 4.12: Drainage canals in Ciudad Concordia

Presidentes de México

As mentioned earlier, the infiltration basin for the area of Presidentes will only function as removal of load of the existing drainage system that runs underneath Av. Lic. Benito Juárez. The proposed pipeline and pump will be for the largest part along the existing drainage system. When the pipeline is at the height of the inlet of the infiltration basin it will turn into east direction. In this final part, the pipeline needs to overcome the most elevation. The capacity of the pump will be 1.5 m^3/s since that value is to the maximum capacity which the infiltration basin is able to infiltrate without exceeding the boundary conditions. The pump capacity is about 15% of the current drainage system capacity of Presidentes de México. Basin 1 in Figure 4.11 will function as overflow basin when Basin 2 is not able to cope with the intensity of the rainfall which will definitely occur during hurricane Raúl. As can be seen in Table 4.2 the elevation is lower in Basin 1 therefore no pumps are needed here.

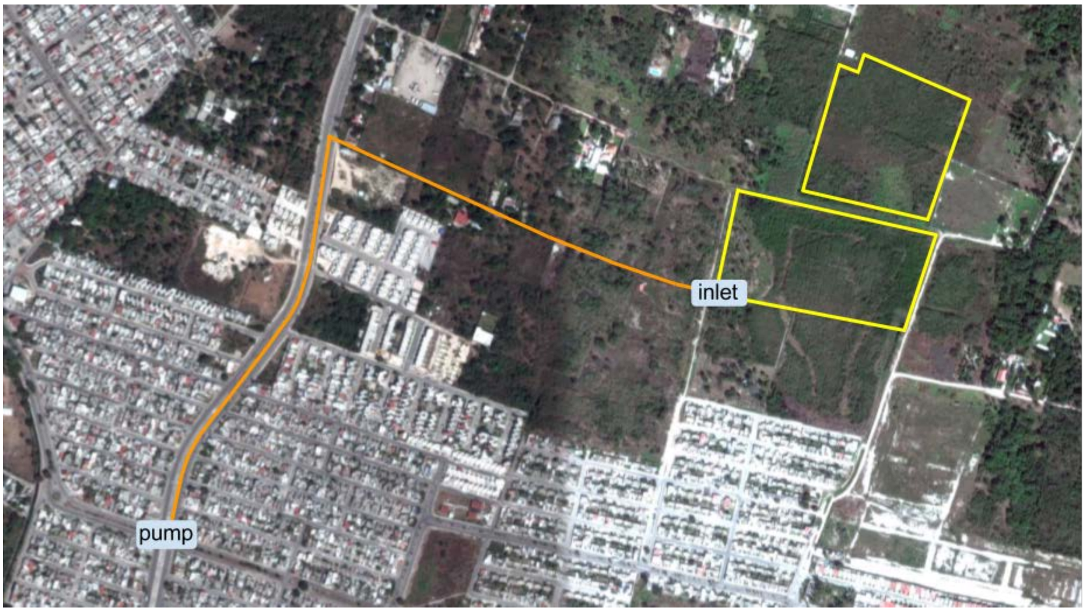

Figure 4.13: Pump and pipeline to infiltration basins in Presidentes de México

4.2.3.4 Possibilities

Since standing water can attract mosquitoes and can result in odour pollution, citizens should be kept away from the infiltration basin as much as possible. The amount of possibilities which can be created in and around the basin is therefore limited. Besides, the infiltration basins lay on the edges of the city, so the locations are not very attractive to pay a visit to.

4.2.3.5 Construction & maintenance

In the construction phase, soil compaction should be eliminated at the location of the basin. Furthermore, equipment should always be placed outside the basin limits. The contributing drainage area has to be completely stabilised prior to using the infiltration basin. The final step always has to be the excavation until the final design elevation of the infiltration basin bottom. (Blick et al., 2004)

Only minimal maintenance is needed, but erosion, cracking, subsidence, spalling and deterioration should be avoided. Inlets should be checked regularly and dredging is needed in order to maintain the basin on its required capacity (only when the basin bed is dry). Disposal of the dredged material (debris, trash and sediments) should take place at suitable disposal locations in compliance with the applicable waste regulations (Dublin Drainage, 2005; Blick et al., 2004).

4.2.3.6 Costs

After analysing reference projects in the United States and the United Kingdom it can be concluded the costs of an infiltration basin lay between \$13 and \$19.50 USD per m^3 infiltration basin capacity (Waelti & Spuhler, 2012; JBA Consulting, 2015). Although, it needs to be taken into account that these reference projects are constructed in more developed areas. This means, the costs to develop an infiltration area in Campeche are expected to be \$13 USD or even less due to the material costs and labour. Besides the costs of the infiltration basin, costs will be present for the construction of the drainage canals, pipelines and pumps. Also maintenance costs should be taken into account.

4.2.3.7 Risks

An infiltration basin is strongly dependent on the characteristics of the soil and water table at a specific location. In a storm event there is a possibility the soil is responding different then expected. As a result, the capacity of an infiltration basin can be less then expected with an overflow of water as consequence. Another risk for an infiltration basin is clogging of the drainage canals and the inlet. Clogging can be caused by garbage or bad maintenance of the drainage canals and basin. The infiltration basins in Presidentes de México are highly sensitive to pump failure. When in an event of heavy rainfall the pumps are not working, the infiltration basin cannot be used at all. This means, operation and maintenance of the pumps is of high importance to ensure the pumps are functional.

4.2.3.8 Conclusion

According to Appendix C.4, the infiltration basins can handle a drainage inflow of 1.5 m^3/s for three days in Presidentes de México and can relieve the entire catchment area of Ciudad Concordia when the upper basin is linked with one of the lower basins. This results in a total volume reduction of about 3.8 million m^3 over the entire time span of hurricane Raúl (Appendix C.6.3). However, the condition that the SHWT should lie at least 61 cm below the sand layer is not met. Some basins even have their bottom on groundwater level. This means that there should be done something in order to satisfy the conditions. Several options are possible:

- Searching for another possible basin location which is situated at least a few meters above mean sea level. Besides, the basins should be made less deep (to remain at a sufficient distance from the SHWT), so more area is needed. Locations just outside the city boundaries can also be considered if necessary.
- Elevating the lower basin sides. In this way, the infiltration basin can be as deep as before without reaching as far into the subsoil. This results in a longer side slope and therewith a reduction in the bottom area. Excavated soil can be used for the elevation.

Using one of these options probably results in higher costs and effort coming along. However, in this way, this option still is realistic to execute.

4.2.4 Water squares

A water square combines water storage with the improvement of the quality of urban public space. Water squares can be used as a twofold strategy. On one hand, they make water storage facilities visible and enjoyable. On the other hand, they generate opportunities to create environmental quality and identity to central spaces in neighbourhoods. Generally, a water square stores rainwater until the water system in the city has enough capacity to drain the water.

Water squares are a quite new option as a solution of water storing in cities. Only few of them were established and mostly on a small scale. Furthermore most of them are established in the Netherlands, which has a different climate and elevation. Although the application of a water square is still in a pioneering phase, it could be a good solution to Campeche's water problem.

Generally there are three types of cisterns:

- A closed collecting cistern: redundant water from drains flows into the cistern during high precipitation and the water flows back into the drains if the drains are emptied.
- An open collecting cistern: water from surrounding areas flows into the cistern and flows into the drains when they are empty.
- An open local cistern: precipitation that falls down on the cistern is absorbed and gets infiltrated or drained above ground.

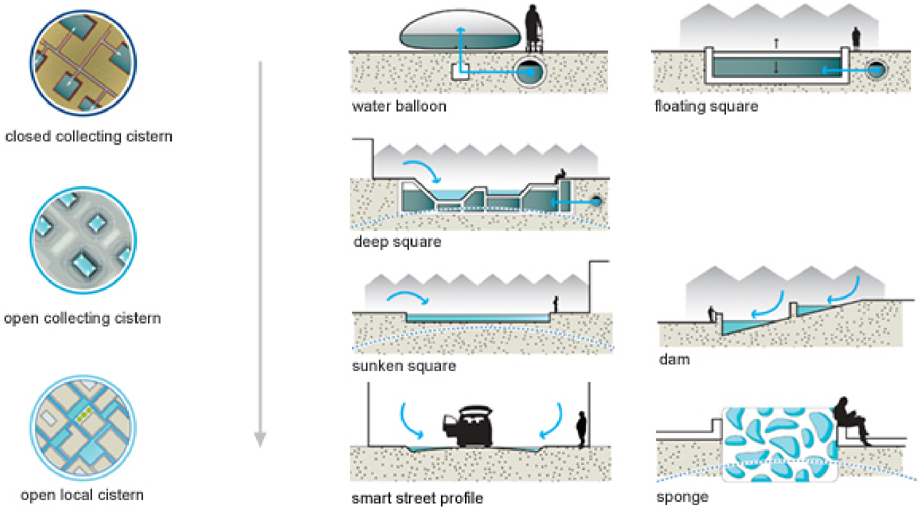

Figure 4.14: Different typs of water squares

Floating squares, deep squares and dams seem to be the most likely solutions for Campeche as they can store high volumes of water. However, the drainage system of Campeche is a mixed system. This means that the drains also serve as sewerage and that water in the drains can be very contaminated.

Reference project
One of the few water squares among the world is the Benthem square in Rotterdam. This square is located between a couple of schools, a theatre and a church and has been designed with input of many stakeholders. Multiple principles of Figure 4.14 are applied.

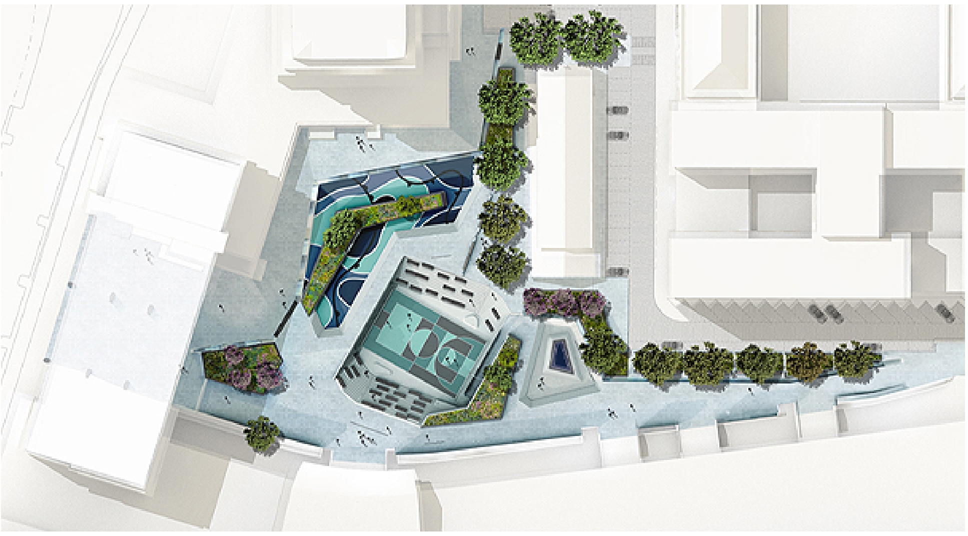

Figure 4.15: Benthem square in Rotterdam

The design consists of three basins which collect the rain water: two shallow basins that are filled with rain from close surrounded areas and a deeper basin that is filled during high precipitation. The water flows through open gleaming gutters to the shallow basins. The areas that are to be inundated are painted in blue.

After the rain, the water of the two shallow basins flows into an underground infiltration device and from there gradually seeps back into the ground. Thereby the ground water balance is kept at level and can also cope with dry periods. This helps to keep the city trees and plants in good condition which helps to reduce the urban heat island effect. The water of the deep basin flows back into the open water system of the city after a maximum of 36 hours to ensure public health (De Urbanisten, 2013).

The capacity of the square is around 1700 m^3 and costed five million euros, which is around 100 million pesos.

4.2.4.1 Types

As already mentioned, there are four distinguishable types of areas with regard to inundation:

A. Low-lying areas near the sea particularly due to a risen sea level.

B. Areas that are drained, but the drainage capacity is not sufficient during high precipitation.

C. Areas with sufficient drainage capacity, but somehow inundations do still occur.

D. Non-drained areas.

Of the four types of inundations areas, three of them are applicable for a water square: B, C and D. As the remaining areas have different problems, each category requires another solution. Consequently three scenarios have been elaborated.

For a category B area, a delayed draining and a large storing capacity is needed. In this way, the water square fills up during the peak of the precipitation and discharges the stored volume when the drainage system is operating on full capacity. Therefore, a floating square or a deep square seems applicable in this case (see Figure 4.14).

A category C area asks for a different storage. The water does not correctly flow towards the drainage system and therefore the water square has the main function to collect the precipitation and discharge it to the drainage system. In this case, a small capacity is sufficient and therefore a sunken square connected to the drainage system would be a good solution.

A non-drained area (D) needs a large storing capacity, in that case the natural drainage is unburdened and therefore reducing the inundations. A floating square or deep square would be a good solution.

4.2.4.2 Locations

The very recent storm Franklin (8/8/2017) caused inundations at several locations due to its 124.8 mm rainfall in one day (Servicio Meteorológico Nacional, 2017). These places can be possible locations of the water square. The neighbourhoods that were inundated during Franklin are: Flor de Limón, Ciudad de Concordia, Quinta de los Españoles, Dzarbay, Plan Chac, Presidentes de México, El Carmelo and Samulá (Tribuna Campeche, 2013). At almost all neighbourhoods there was an area that could be changed in a water square. The locations can be seen in Figure 4.16.

Franklin was a smaller storm than the expected hurricane Raúl, therefore more neighbourhoods will be flooded when Raúl occurs. According to our analysis these will be Servidor Agrario, Lindavista, Las Flores, Fracciorama 2000, San José and Guadalupe. For these areas, the positions of the water squares are not located, because determining positions of water squares on specific locations is not possible with our knowledge about the neighbourhoods. Therefore, from now on, a standard solution will be presented that can be scaled to the according area.

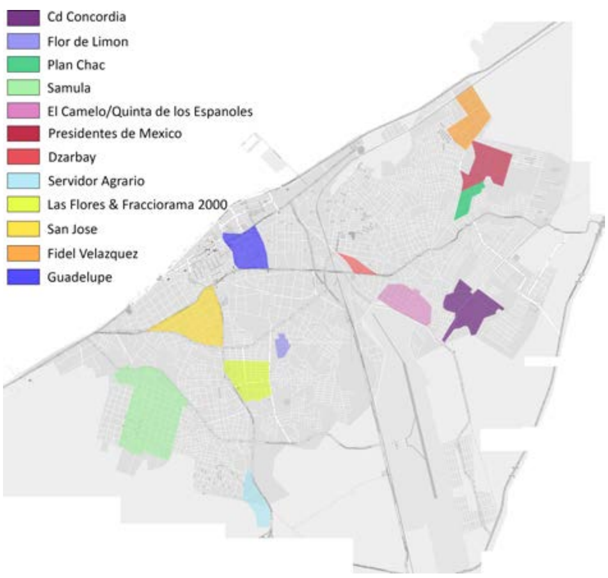

Figure 4.16: Flooded neighbourhoods by Franklin (8/8/2017)

For the neighbourhoods that were flooded by the storm Franklin, possible locations of water squares were investigated. The sites for water squares have to be low-lying, large open spaces, with possible adaptability in order to make construction easier and the square beneficial, with regard to the ability of collecting water. These places are sports fields, playgrounds and/or open fields (see Figures A.44 - A.49).

Neighbourhoods	**Area (m^2)**	**Category**	**Water square (m^2)**
Ciudad Concordia	532,400	D	36,400
Flor de Limón	81,000	B	6,063
Plan Chac	159,060	B	3,150
Samulá	1,326,000	C	6,020
El Carmelo & Quinta de los Españoles	754,420	C	3,375
Presidentes de México	448,200	B	14,560
Dzarbay	41,580	C	4,235
Servidor Agrario	64,600	B	-
Las Flores	122,500	B	-
Fracciorama 2000	376,340	B	-
San José	741,600	B	-
Fidel Velázquez	424,700	B	-
Guadalupe	406,600	D	-

Table 4.3: Flooded neighbourhoods and reduction due to water square

4.2.4.3 Design

The three categories have three different designs. Chosen is to use a deep square for category B, a sunken square for category C and a deep square for category D, the latter one with storage on top of the square (see Figure A.50). With the possible areas from Table 4.3, it is concluded to use a unit size of 80x40 m^2. If the possible areas are larger, more of these water squares can be placed next to each other or placed as one big square. Water squares are designed to store water at the moment of the most precipitation. Therefore, when the precipitation decreases and the drainage system is not operating at its full capacity, the water of the squares can be drained. In this way, the peaks can be reduced and the drainage can cope with the daily precipitation. The designs for the water squares are a simplified version.

In areas of type B with a lack of drainage capacity, a water square can store the polluted water during heavy rainfall. A connection between the water square and the drainage system lets water flow towards the underground tank (see Figure A.51). This tank has a capacity of 10,664 m^3. Las Flores has an area of around 122,500 m^2, causing a water accumulation of 10,428 m^3 with 125 mm/h of precipitation (see Appendix C.5). This volume can temporarily be stored in the water square and be discharged when the precipitation decreases. To prevent the water square from overflowing a gate needs to be constructed between the connection of the drainage system and the storage. This gate is closed when the storage is at its maximum capacity.

For the areas with sufficient drainage capacity (C) the water square can have the function of a skate-park. This skate-park is designed to capture the rainfall with a slope towards an opening underneath the bench where the drainage system is connected to (see Figure A.52 & A.53). For areas like Samulá and Dzarbay, where the drainage system has enough capacity but is not located perfectly, a water square prevents inundations if located properly.

Areas without a drainage system (D) need a large storage water square, but the water only consists out of rainwater and therefore can be stored on top of the construction. The design for this water square consists of deepened football fields with two rings around the fields, where the initial rainfall flows towards the areas around the football fields (see Figure A.54). The rainfall that precipitates on top of the fields travels via the grill to a tank underneath the fields with a depth of 25 mm (see Figure A.55). In this way, little rainfall does not make the fields unplayable. The areas around the football field have a total capacity of 681 m^3. The maximum capacity of the water square is 10,542 m^3. So, with the assumed maximum precipitation of 125 mm/h, an area of 84,336 m^2 can become flood-free due to one water square (see Appendix C.5).

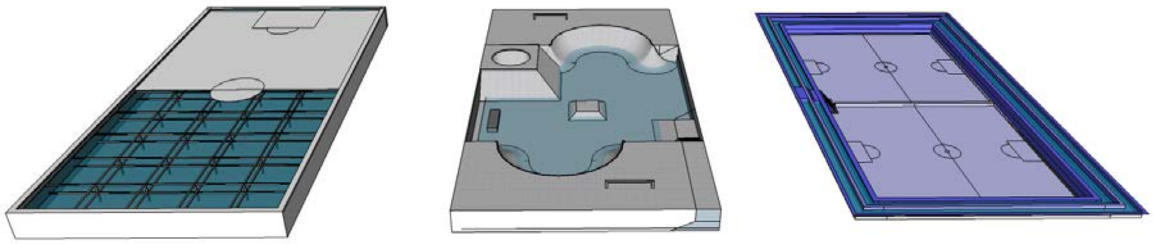

Figure 4.17: Prototypes of the water squares (from left to right: B, C, D)

The catchment area of Ciudad Concordia is around 2.0 km^2, therefore one water square unit can only store 4.2% of the 125 mm/h precipitation. The possible area for a water square of Ciudad Concordia is about eleven times the area of one water square. Thus, there is a possibility to reduce the total volume of precipitation with 46%.

After the heaviest precipitation the stored water volume can be pumped towards the flushing street Avenida Concordia. The current 'drainage system' of Ciudad Concordia consits of water accumulation at Avenida Concordia, where it starts flowing towards the low-lying green lands southwest of Concordia. To reduce the accumulation in this street, the water square can store a large part and, when the precipitation reduces, slowly pump the water into the Avenida. The water square can then be used again and the accumulation will not be too severe. An alternative is letting the water flow into an underground infiltration device and from there gradually letting it seep back into the ground water, keeping the ground water balance at level and coping with dry periods.

4.2.4.4 Calculations

For the three prototypes different calculations have been made.

- Category B - the soccer field with storage basement: one long side slab, the top slab, the bottom slab and the columns were tested and for these components longitudinal and shear reinforcement were calculated.

- Category C - the skate park: no calculations have been made as the skate park is made by excavating soil and pouring concrete on it, so no big soil forces are executed onto concrete.
- Category D - the deepened soccer field: one long side slab and bottom slab were tested and longitudinal and shear reinforcement were calculated.

The slabs were modelled in DIANA and loads were applied as specified in Appendix C.5. The soil load increases by depth and therefore blocks of increasing stresses were applied on the model.

From these stresses the principle stresses were calculated, similar to the calculations of the wall. The principle stresses were then compared to the tensile stress and, if necessary, longitudinal reinforcement was calculated. Also shear resistance and shear reinforcement were calculated (Appendix C.5).

Cat.	**Slab type**	**dimensions**	**Reinforcement**
B	side slab	$80 \cdot 4.67 \cdot 0.50$	stirrups with $d = 10\ mm$, $s = 213.7\ mm$, at $(x = 8k\ m, y = -2.5\ m)$
B	top slab	$80 \cdot 40 \cdot 0.35$	rebars with $d = 10\ mm$, $s = 500\ mm$
B	bottom slab	$80 \cdot 40 \cdot 0.67$	-
B	columns	$3.3 \cdot 0.20 \cdot 0.20$	-
B	struts	$8.0 \cdot 0.20 \cdot 0.20$	-
D	side slab	$80 \cdot 4.67 \cdot 0.60$	stirrups with $d = 18\ mm$, $s = 65.4\ mm$, at $(x = 4k\ m, y = -1.5\ m)$
D	anchors	-	$d = 25\ mm$, $A_s = 479\ mm^2$
D	bottom slab	$80 \cdot 40 \cdot 0.67$	-

Table 4.4: The amount of reinforcement needed per slab

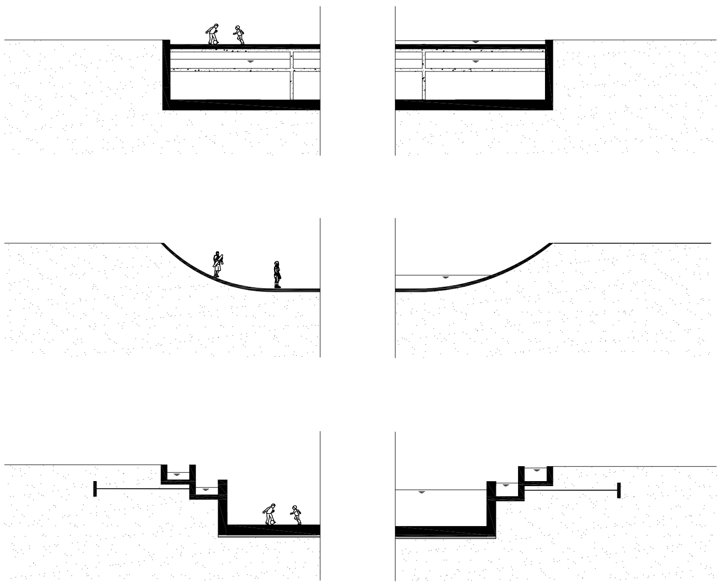

Figure 4.18: Cross sections of the three water squares

To make the volume reduction comparable to the amount of volume of the boundary conditions, it has been decided to place an amount of water squares relative to the total amount of an area. In total 42 water squares are to be placed at locations with water accumulation. The total amount of 42 water squares gives a reduction of 2.3 million m^3, which is obtained from Appendix C.6.4.

Area	**Surface (km^2)**	**Category**	**Amount of water squares**
3.1	2.15	B	4
3.2	3.13	B	5
3.3	5.18	B	6
3.4	1.73	B	4
5.1	4.72	B	6
5.2	2.51	B	4
O	12.88	D	13

Table 4.5: The amount of water squares per area to be placed

In the calculations, no water squares in category C areas have been assumed, since the drainage capacity in these areas is sufficient and therefore the model determines the water accumulation in these areas to be zero.

4.2.4.5 Possibilities

The water squares are all build for recreational use and increase the amount of recreational area in the city, which also improves the health of the youth by creating locations to play sports. Next to that, water squares are a revolutionary solution for inundations. Squares for water storage are at the moment only used in the Netherlands. The climate of Campeche creates a possibility for playful use of the cooling rainwater in water squares.

Since the Benthem square is 'promoting the well-being of humanity', it got a contribution from the Rockefeller Foundation of one million euros (20 million pesos). There are opportunities to request a similar fund, when realising a water square in Campeche.

4.2.4.6 Construction & maintenance

The construction of water squares is rather straightforward. A large area needs to be excavated and poured with concrete to create base and side slabs. The excavation becomes harder when the groundwater level is reached, because then the area needs to be pumped or underwater concrete needs to be used. The largest construction problem will be the anchoring of the prototype D. Finding a location that is not obstructed by any foundation or underground system may be difficult.

A large part of maintenance of a water square is to minimise pollution, which flows along with rainwater. Mud, leafs, branches and especially garbage will pollute the water square. Therefore regular cleaning is mandatory for the use of the square. Especially during the rainy season this might become a daily burden, because of the often occurring rainfall. The ring around the football fields forms a great solution to prevent frequent cleaning. Constructing a grill with an inclination creates a flow towards one location where the garbage congregates and simplifies the cleaning and prevents garbage in the football fields. Other maintenance will be low, every once in a while the sand and trash need to be extracted from the area and the pump.

As the construction of Benthem square - from preliminary design to realisation - took three years, it is likely that a construction of a water square in Campeche also takes a couple of years.

4.2.4.7 Risk

Water squares are low-risk structures, the probability of failure of construction is low and their is little consequence of that failure. However, this slightly differs within the prototypes.

With prototype B, gate failure can cause a too large inflow of water and therefore an overflow on the water square. This can cause:

1. inundations on top of the water square
2. an upwards pressure on the top slab

The first scenario creates a local but large inundation around the water square, which can constitute in heavy nuisance in that specific neighbourhood, especially as it is sewage water that flows to the square. The second scenario can create a rather large consequence, creating cracks in the top slab and making the field unusable. The probability that the second scenario occurs is nevertheless low, because if the pressure increases the water flows out of the inflow at the sides of the square, resulting in the first scenario. When using good filters, the harm due to the first scenario is minimised (see Figure A.51).

Prototype C has no noteworthy risks. A constipated drain, resolves into a flooded water square. This makes the square temporarily nonfunctional, but is easy to fix and will clear the water square.

An overflow into the water square prototype D has an ever-occurring probability that needs to be taken into account every time heavy rainfall occurs. The consequence is that the area will be flooded, this risk is always present and needs to be taken into account when the water square is constructed in non-drained areas. Nevertheless this is not a failure in the construction just a flaw of this solution.

Failure of the column strut construction (B) or the anchor construction (D) in the water squares leads to major deformations and cracks. This reduces the safety of the square, especially when failure of the construction under the top slab of the square occurs, because this causes a collapse of four meters.

4.2.4.8 Costs

The costs of the water square depend on what prototype is used and the scale of the solution. Prototype B and D do have very different constructions compared to prototype C. A skate-park has a smooth construction method and is low on costs. The construction costs are way larger for the other prototypes, due to the complicated construction. Especially the anchor construction needs a lot of preparation time, due to the fact that decent locations of the anchors are hard to find. A large anchor length is necessary without any obstructions in the soil.

4.2.4.9 Conclusion

A water square is a unique solution which can be a great addition to solve local inundations. Especially for areas with a drainage system, a water square will be a convenient solution. Water squares will not be a solution to the city's inundation problem, since a huge amount of water squares is required. As an addition to the drainage system (prototype C) or as a storage during heavy rainfall to unburden the drainage system (B), a water square is a suited solution. When a water square is not attached to a drainage system (D), the water square only unburdens a neighbourhood for a small part. In that case the square's capacity is very low. Consequently, it can be stated that a water square is a good solution in addition to a drainage system, but it is not a very well self-containing solution.

4.3 Conclusion of the elaborated solutions

For all the solutions a volume reduction has been calculated in Appendix C.6. These results have been put together and a chart has been obtained, which makes it easier to understand the effect of each solution over time and makes it possible to compare them (see Figure 4.19).

It is clearly visible that all of the elaborated solutions have a small impact compared to the total amount of water which will be present during the simulated hurricane. From the chart, also the different nature of each solution, is visible. At a certain moment, water squares operate at full capacity and cannot withdraw any more water from their surroundings or from the drainage system, whereas parks and basins are still able to withdraw water, although reduced. Furthermore, the wall has only a retaining function and therefore merely keeps the water out of the city.

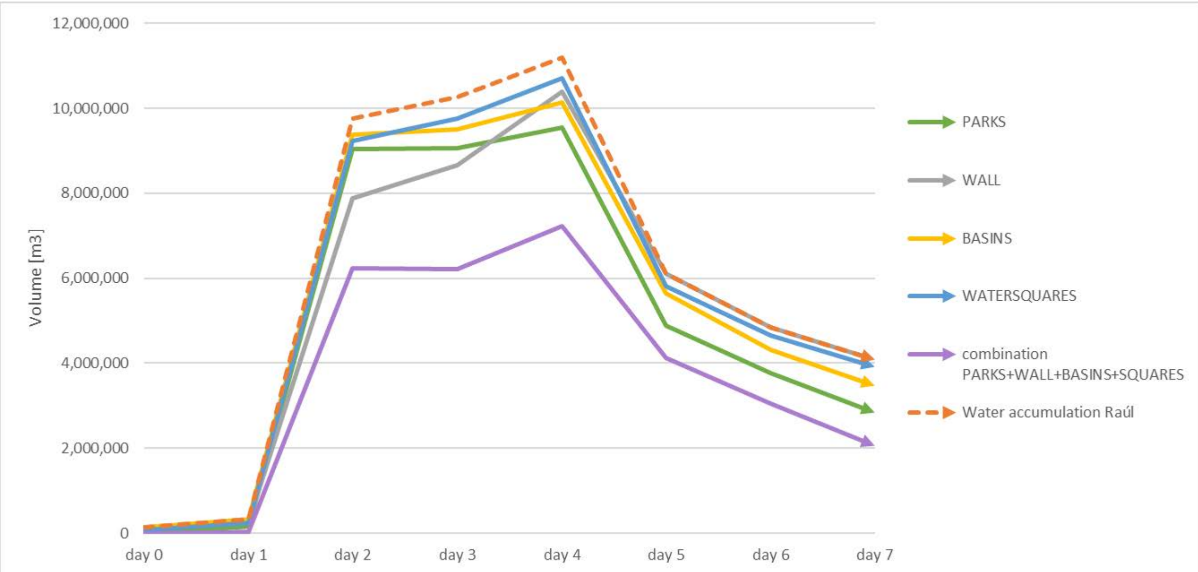

Figure 4.19: The amount of water in the city over time and remaining volume per option

5 Evaluation

5.1 Criteria

The criteria needed to make up the multi-criteria analysis follow from the program preferences. Some of the preferences are criteria on their own, others need to be subdivided in order to be able to compare the different alternatives in an objective way. Every criteria has its own weight factor, based on its relative importance (also taking into account stakeholder influence/interests).

- The solution can count on political support.
  - City image:
    In what way does the solution contribute to the way people see the city of Campeche?
  - Voters: Can the solution be justified to the voters?
  - Aesthetics:
    Is the aesthetics of the construction positive or negative for the surroundings?
- The solution is economical; giving good value to the amount of time, money and effort spent.
  - Time/money/effort spent per unit reduced volume
  - Operations and maintenance
- The solution contributes in a social-cultural manner to the city and its residents.
  - Recreation:
    Grade of improvement of recreational facilities and grade of increase of the amount of recreational facilities.
  - Is the solution in a way beneficial to the mental/physical health?
- The solution increases the safety of inhabitants and goods against flooding.
  - Reduction in the amount of casualties and damage to buildings/infrastructure alongside the global amount of volume reduction
  - Amount of risk induced by the solution.
- The solution contributes to the ecological environment.
  - Biodiversity:
    Growth or loss in amount of flora and fauna in the city.
  - Green space:
    Amount of green space added to/removed from the current situation.
  - Water quality:
    Grade of improvement of current water quality in the city.
- Given the results of the aforementioned preferences, the option is realistic as a solution to the problem.

5.2 Multi-criteria analysis

In order to get an overview on the strengths and weaknesses of the options a multi-criteria analysis has been performed. In this multi-criteria analysis the elaborated options are subjected to the aforementioned criteria factors. At first the scores are given of the solutions for every criteria factor in Table 5.1. The scores are given on the basis of the analysis and elaboration of the solutions in this report.

	++	= Very positive
	+	= Positive
Weighing clarification:	0	= Neutral
	-	= Negative
	- -	= Very negative

	City image	**Voters**	**Aesthetics**	**Effort***	**O & M**	**Recreation**	**Health**	**Damage***	**Risks**	**Biodiversity**	**Green space**	**Water quality**	**Realistic**
Parks & infiltration fields	+	+	++	- -	0	+	++	+	0	+	++	0	+
Wall on the Malecón	-	-	-	-	+	0	-	+	-	-	-	-	-
Infiltration basins	0	0	0	-	-	- -	0	0	0	0	0	+	-
Water squares	+	+	+	0	0	++	+	-	0	-	-	0	0

Table 5.1: Criteria factors per option

* = Criteria factors as mentioned in Section 5.1

The second step is ranking the importance of the factors. As elaborated in Section 2.2.1 the stakeholders can be divided in four groups that all have a different view and opinion on the problem. In order to determine the ratio of importance between the criteria factors according to the stakeholder groups, four different matrices are made for every stakeholder group. In these matrices, all the criteria factors are compared to each other which are shown in Appendix E.

Since the stakeholders have different interests and influences, the scores were multiplied by a weight factor elaborated in Appendix E.

In order to get calculable numbers from Table 5.1 the characters are transformed in numbers from 1 to 5, where 1 is equal to - - and 5 is equal to ++. Using these table and the weighed criteria factors shown in Table E.5, the total score can be determined for the different options shown in Table 5.2.

	City image	Voters	Aesthetics	Effort*	O & M	Recreation	Health	Damage*	Risks	Biodiversity	Green space	Water quality	Realistic	Total score
Parks & infiltration fields	1.3	2.3	1.0	0.9	0.8	0.8	3.3	3.7	2.0	0.3	1.4	1.8	2.4	21.9
Wall on the Malecón	0.7	1.1	0.4	1.8	1.1	0.6	1.3	3.7	1.3	0.1	0.6	1.3	1.6	15.5
Infiltration basins	1.0	1.7	0.6	1.8	0.6	0.2	2.0	2.8	2.0	0.2	0.8	2.5	1.6	17.6
Water squares	1.3	2.3	0.8	2.6	0.8	0.9	2.7	1.8	2.0	0.1	0.6	1.8	2.4	20.2

Table 5.2: Multi-criteria analysis results

* = Criteria factors as mentioned in Section 5.1

From Table 5.2 it can be concluded 'Parks & infiltration fields' is the most suitable option for the city of Campeche. Although, these results do not give the assurance the water problem will be solved with this single option. Besides, many other options were not elaborated in this report as can be seen in Appendix D which might be more suitable solutions for the city.

6 Discussion

In this study, solutions are provided to reduce the overall inundation risks in the city of Campeche. To achieve this, a characteristic hurricane occurring once in fifty years is simulated. Using the precipitation rates and storm surge levels following from this hurricane, named Raúl, the given solutions are tested on the amount of water volume they can reduce in this situation. Besides, all solutions are evaluated based on a multi-criteria analysis, as can be found in Section 5.2. Following from this, the parks and the water squares are found to be better solutions than the wall on the Malecón and the infiltration basin. However, the results of the multi-criteria analysis do not tell instantly that parks and water squares are the best solutions for the given problem.

6.1 Evaluation assessment

'Parks and infiltration fields' is a realistic option when looking at the feasibility and the cost-benefit relationship of a single unit. Furthermore, when meeting the standards from the WHO, the amount of supplementary green space reduces more water volume during the inundation provoked by hurricane Raúl than any other option. However, the realisation of over a thousand parks is an incredibly time-consuming job, which takes an enormous amount of effort. In a lot of neighbourhoods (especially those with inundation problems), buildings are densely packed, making it a tough challenge to construct parks and infiltration fields at suitable locations. This does not mean that the option should not be executed, it only means that implementing this option on a smaller scale (say a few hundred parks) is more realistic. In this way, the decrease in inundation risk will obviously be smaller.

As mentioned earlier, several options are not taken into account by this study. A distinction was made between three different kinds of solutions, namely retaining, draining and retention solutions. In order to protect the city against the storm surge some kind of retaining solution needs to be constructed. From the solutions that were elaborated in this study, only the wall on the Malecón is a suitable option for protecting the city against a storm surge. Although the wall scores worst in the multi-criteria analysis, it therefore should still be considered when solving the overall problem. Especially because ecological solutions do not prevent water from entering the city in case of water levels as high as those generated by the particular storm surge. However, the wall on the Malecón is a solution for very rare occasions. The impact to the Malecón is great but the function of this alteration will hardly be seen. When comparing the wall with other solutions, the water squares and parks are an addition as well in recreation as in water storage and infiltration. The citizens notice that adaptation on daily basis.

When looking at the multi-criteria analysis, the infiltration basins almost do not stand out on any criteria. Since the infiltration basins lay at the city borders, it is not an attractive option for the majority of the stakeholders due to the low amount of possibilities it generates. However, when considering the reduction in inundation risks, the infiltration basins can relieve all of Ciudad Concordia and a part of Presidentes de México. The overall reduction of risks is therefore lower, but locally it can generate large effects. Besides, Concordia and Presidentes are two of the most important neighbourhoods to start acting as soon as possible.

The most important criteria used in the evaluation would be the reduction in the amount of casualties and damage to buildings/infrastructure. The water squares clearly have the lowest score on this criteria, which therefore could be interpreted as having the lowest contribution in reducing inundation risks. Nevertheless, water squares only reduce inundation risks in the areas where it is most needed, making them very efficient. Furthermore, the total score of water squares resulting from the multi-criteria analysis is very good, due to the large amount of possibilities they can create in a neighbourhood.

6.2 Integral considerations

From Section 4.1, it follows that some other options are also worth considering, but were not chosen to elaborate due to a lack of knowledge or better and more specific knowledge of the responsible people in Campeche. One of these options is the expansion of the current drainage system. Following from Section F.2, there are already plans to extend the Ría network over Av. Hidalgo and Av. Concordia, to connect it with the neighbourhoods of El Carmelo, Quinta de los Españoles and Ciudad Concordia. When choosing for example to connect Ciudad Concordia with infiltration basins and place water squares in all these neighbourhoods, the drainage expansion will have less priority. Av. Gobernadores, on the other hand, collects surface runoff from two sides and is one of the places in the city where the most severe inundations occur. Over here, all the runoff gets accumulated on the street, so therefore the proposed solutions are not suitable to use. On the other hand, an expansion of the drainage network from two sides, namely the Ría and the network in Presidentes, could deal with the water accumulation. However, the drainage capacity of the network in Presidentes at the moment is not enough to deal with a larger catchment area. Therefore, supplementary pipelines in this area will be necessary to construct.

Most of the proposed options only solve a part of the problem. The wall on the Malecón only protects the area directly laying behind it. The infiltration basins can only be used for some neighbourhoods at the city borders. Water squares only solve local inundations and parks still allow half a meter of water. Even expanding the drainage system will not cover the whole city. Consequently, it is necessary to combine these individual options to an integral plan when dealing with the entire city.

It should be made clear that results following from this study only account for the worst case scenario with a return period of once in fifty years. Therefore, less severe situations probably are in need of other solutions.

7 Conclusions and recommendations

7.1 Conclusions

Due to climate change, hurricanes will intensify in the future. For San Francisco de Campeche, this means that water accumulation due to rainfall and storm surges gets more severe. Current drainage systems only cover common maximum precipitation rates up to 145 mm/day, which means the city will have problems with extreme weather conditions. Flooding may occur and induces water excess in the city up to several days. Water management systems should be adapted to cope with more intense situations and be able to get an excess of water out of the city as soon as possible. Therefore, the following objective was defined in the introduction of this report:

"Provide solutions to decrease inundation risks due to the combination of rainfall and storm surge, generated by a hurricane which may occur once in fifty years, in the city of Campeche"

An important limiting factor in the realisation of solutions is the political system. A project like this, which covers the entire city, needs a lot of support from different levels of scale. It needs to be approved on municipal, state and federal level. Besides, the fact that governments serve a non-renewable term makes it a simple task for new authorities to cancel ongoing projects or even erase all developments made in this area. Therefore, all different groups of stakeholders (e.g. users, decision makers, experts and interest groups) should be kept satisfied in order to maintain support even if one of the stakeholders fails to deliver. Awareness amongst citizens and visibility of progress consequently are crucial tools in order to make the project into a success.

A hurricane with a probability of occurrence of once in fifty years was simulated in order to retrieve workable data for a characteristic situation, like storm surge heights and precipitation. The current drainage system has been tested when exposed to such a hurricane and fails to keep some neighbourhoods (which are currently connected to the drainage system) free from floods. Besides, a large part of the city is still not connected to any drainage system, which results in a lot of water accumulation in unconnected neighbourhoods. This makes the difference between neighbourhoods large, which is why various specific solutions are needed rather than one global solution.

Some proposals for solutions have been set up, elaborated and evaluated using a multi-criteria analysis. All solutions reduce a considerable amount of excess water, and all have their own strengths and weaknesses. A summary is given in Table 7.1.

Solution	**Score**	**Comments**
Parks & infiltration fields	21.9	More realistic to construct on a smaller scale, reducing the decrease of inundation risk
Wall on the Malecón	15.5	Only option which actually retains water induced by a storm surge; only used in rare occasions
Infiltration basins	17.6	Causes severe water volume reduction in critical neighbourhoods
Water squares	20.2	Low score in overall damage reduction, but very efficient at specific locations

Table 7.1: Summary of solutions

7.2 Recommendations

7.2.1 Project recommendations

Following from the conclusions set up in the previous section, some recommendations can be done with respect to future measures in order to limit inundation risks in the upcoming fifty years.

- The entire process of preparation, design and construction of the solution needs to be possible within a municipality's term.
- Create awareness among citizens, since solutions with public support are more likely to be constructed.
- The drainage network needs to be connected to Avenida Gobernadores.
- Presidentes de México and Ciudad Concordia are the neighbourhoods with the highest vulnerability to inundations, which makes a solution on short term necessary.
- The amount of green space and inundation risks have to be kept in mind when expanding the city.

7.2.2 Recommendations for further research

During the project different subjects came forward that are in need of further research. More knowledge on these subjects increases the reliability of results, reduces uncertainties in the project and makes the solutions realistic to implement. Recommendations are elaborated below.

In the design of the proposed solutions, there principally has not been accounted for any costs, due to uncertainties and a lack of data on this topic. Since costs are an excellent way of expressing solutions in a quantitative way, retrieval of cost-related information would be of great help in evaluating the solutions.

From the elaboration of the infiltration basins it becomes clear that some locations of the proposed infiltration basins are very low with a short distance to the water table as a consequence. In order to get a functional infiltration basin a minimum distance is required. Since the water table in this research is assumed due to a lack of information on the water table it is of great importance that further research will be done with respect to the behaviour of the water table in the different areas within the city of Campeche. Besides, for the parks & infiltration fields it can also be useful to get more information on the water table.

Since some of the infiltration basins almost are situated on the groundwater table, elevation should take place. Due to large differences in elevation between one side and another, it could suffice to only elevate some side walls with the excavated material. It has to be checked for if a basin with elevated side walls would still have the same capacity and if the minimum distance from the groundwater table until the basin bottom is met.

The type of subsoil is assumed as phaeozem for the whole area of Campeche, since this type of subsoil is present for the biggest part around the city of Campeche. In every solution the type of soil has a high impact on the construction and its effect on water volume reduction. In the case of the infiltration basin, the infiltration rate differs a lot between the soil types. To be sure of which soil types the subsoil is composed, probings need to be executed on the various locations of the proposed locations.

In Section 3.1 the hurricane is simulated with a probability of occurring of once every fifty years. This is done using the data of the most severe hurricanes in the region of Campeche. If information of all the past hurricanes would be available, a statistic calculation could be made to retrieve a more accurate representation of a characteristic hurricane occurring once every fifty years.

When considering the maximum precipitation rate per hour of hurricane Raúl, an assumption has been made. Further research should be done in order to find a more accurate maximum precipitation rate per hour and the course of the precipitation rate throughout the day. Using this, design volumes of proposed solutions can be made more representative for the situation.

There can be further investigated for green space area currently present in the city. When having this data at disposal, an accurate calculation can be made on the current infiltration by parks and infiltration fields. Besides, the possible areas to construct new green space should be studied in order to locate parks and infiltration fields. Using both present and future analysis, a well-based conclusion can be made on a realistic amount of parks and infiltration fields that can be constructed.

As mentioned in Section 2.3 it is very difficult in Mexico to get the full support from authorities for large-scale projects like this. This is because the municipality and state governments have a non-renewable term and every government has other thoughts on problems. Besides, a new mayor or governor is allowed to cancel ongoing projects. Therefore, it is important to find out in what way all the stakeholders can be kept satisfied on the long term.

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A Figures

A.1 Analysis

Figure A.1: Map of Campeche, dating from 1984

Figure A.2: Map of Campeche, dating from 2016

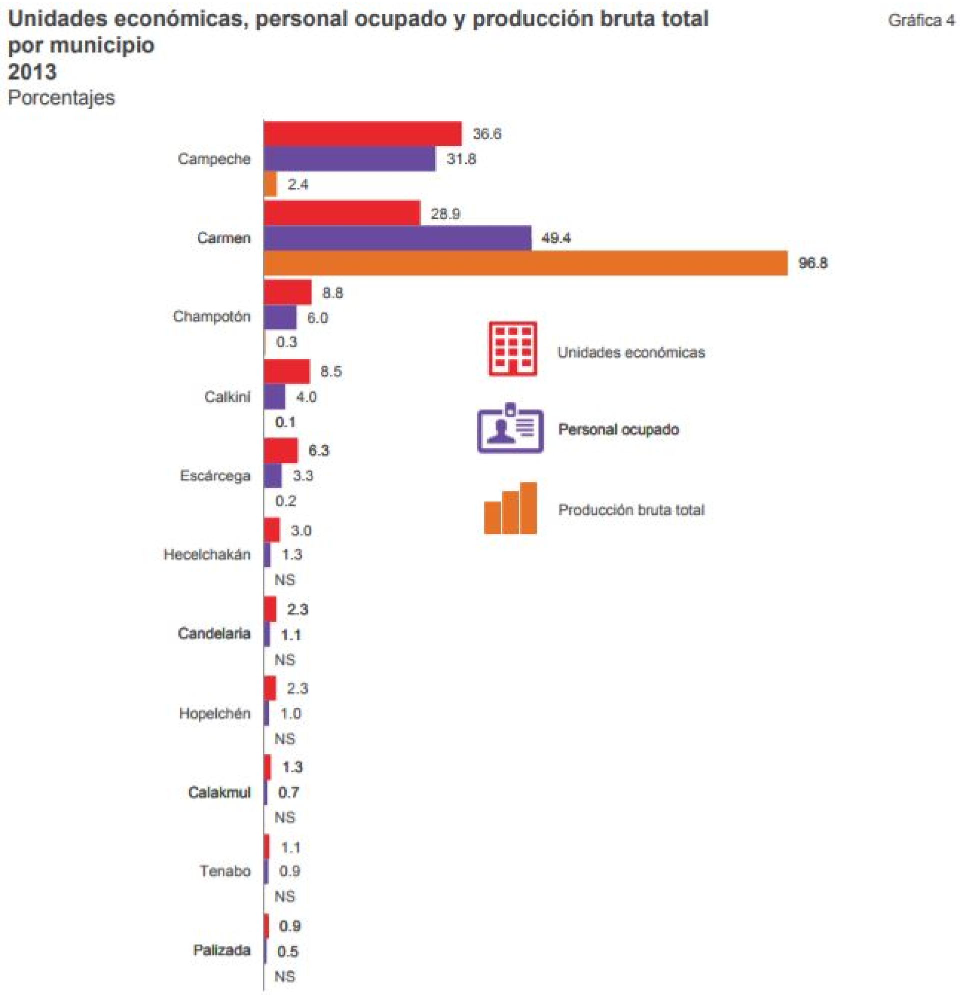

Figure A.3: Economic units, employed persons and total gross production per municipality (INEGI, 2014)

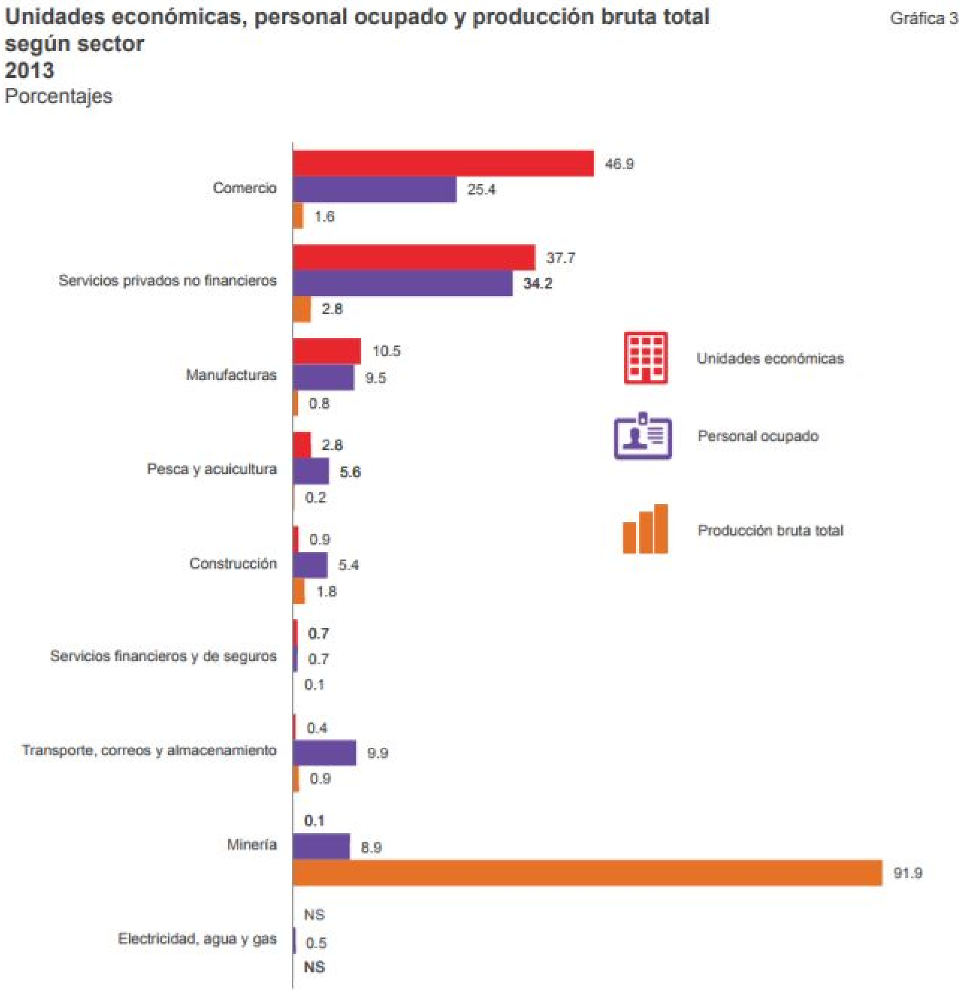

Figure A.4: Economic units, employed persons and total gross production per sector (INEGI, 2014)

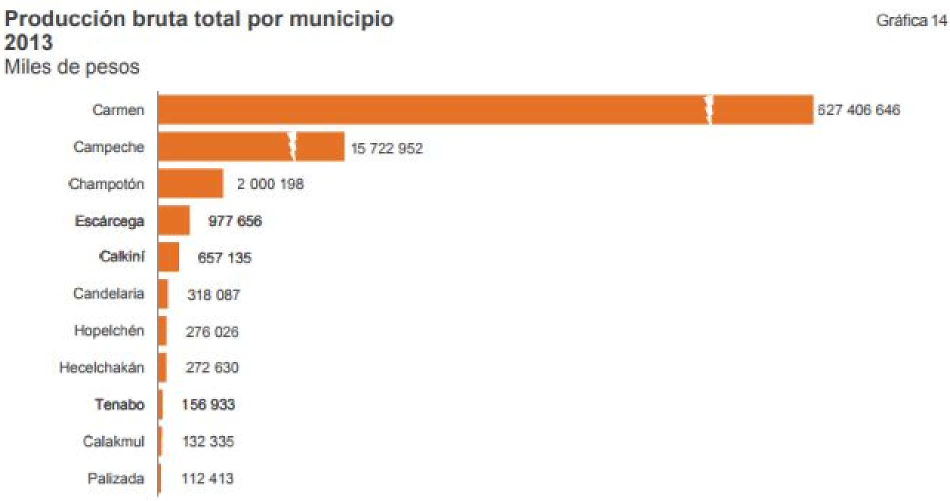

Figure A.5: Total gross production per municipality (INEGI, 2014)

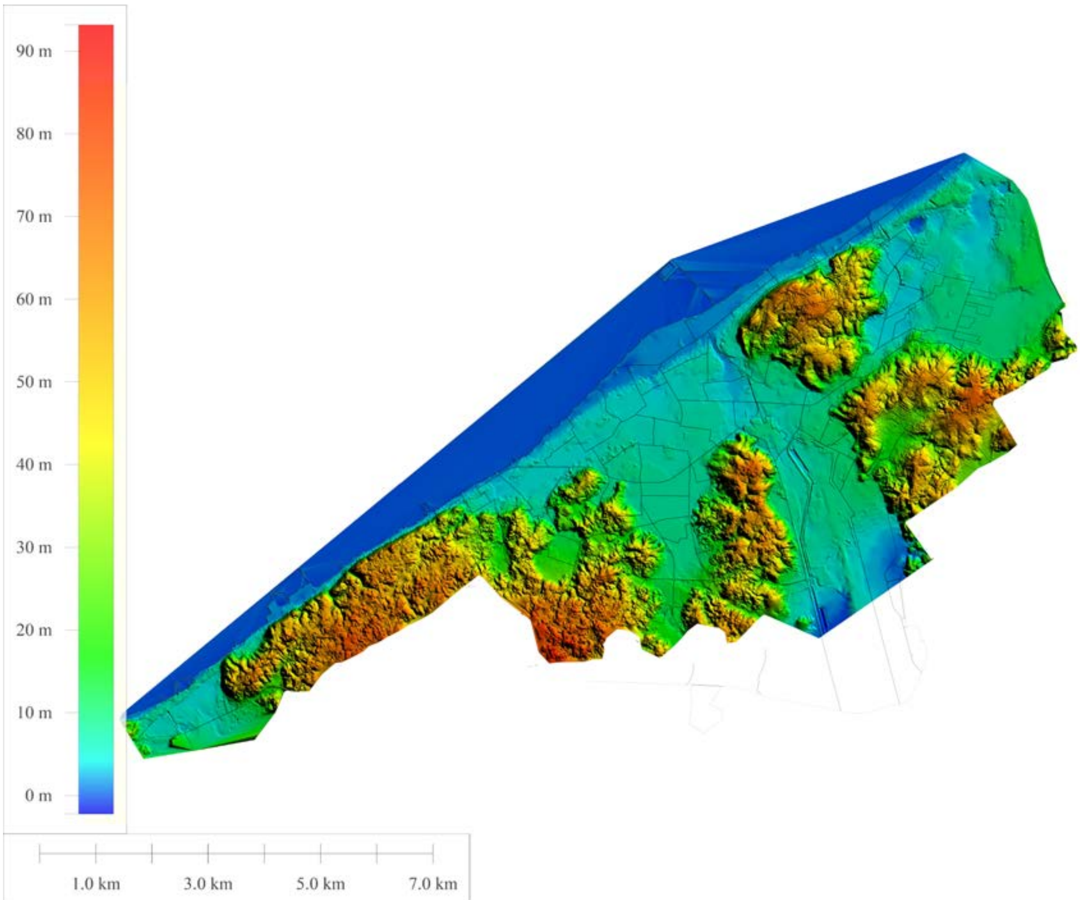

Figure A.6: Elevation map city of Campeche and surroundings


Figure A.7: Land reclamation

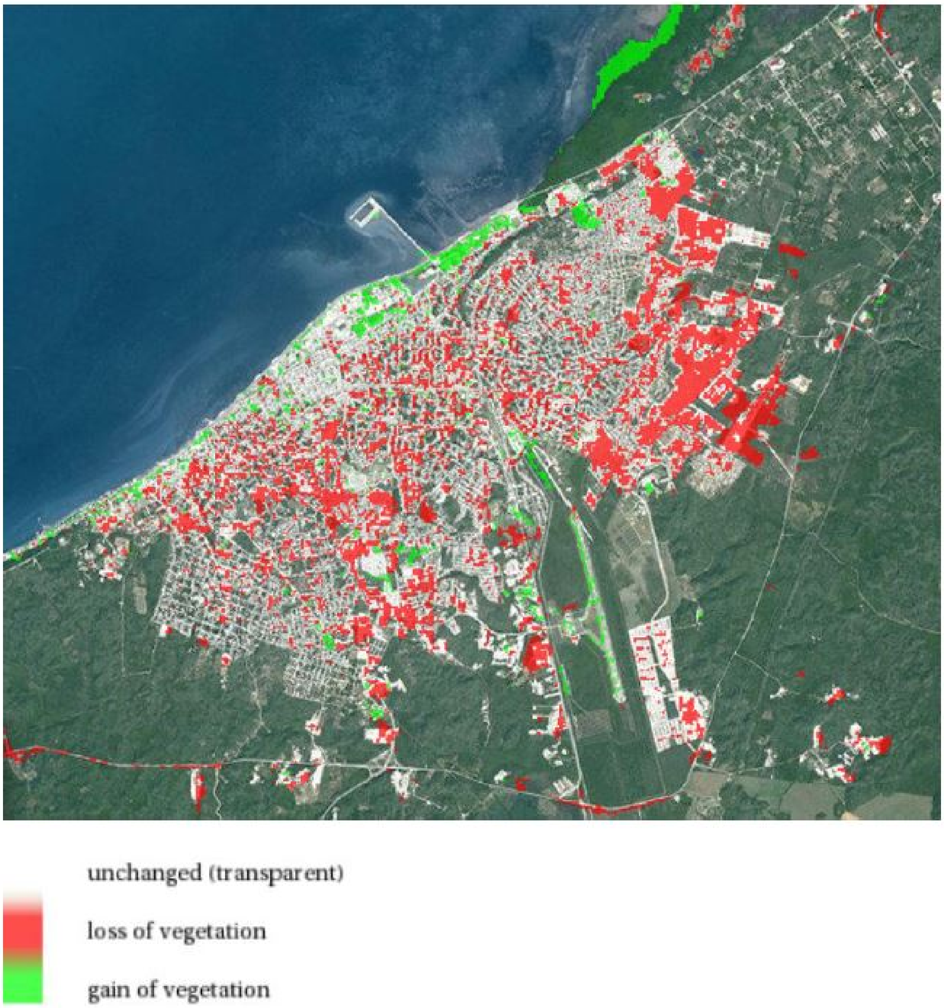

Figure A.8: Change in vegetation

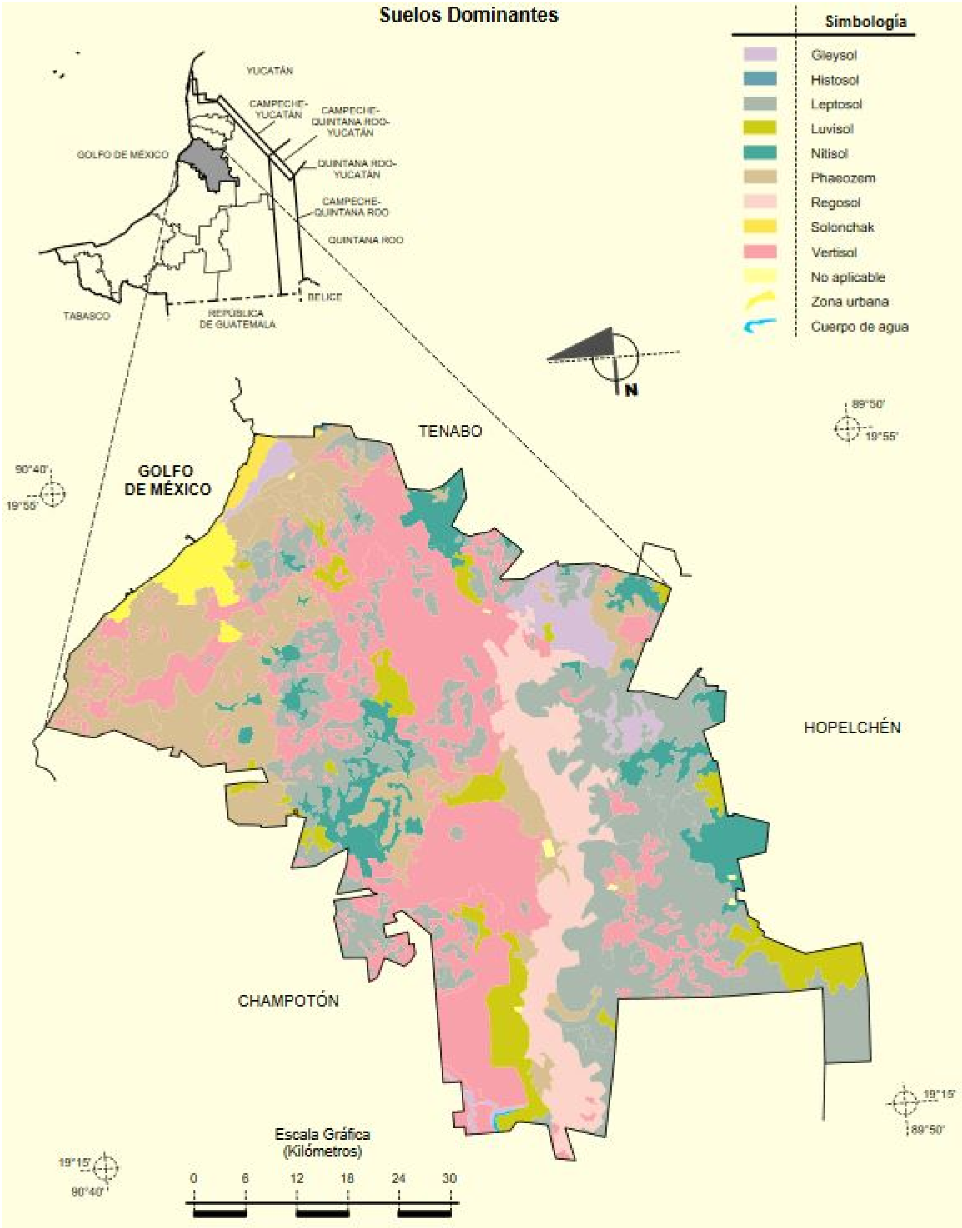

Figure A.9: Dominant soil types in the municipality of Campeche (INEGI, 2009)

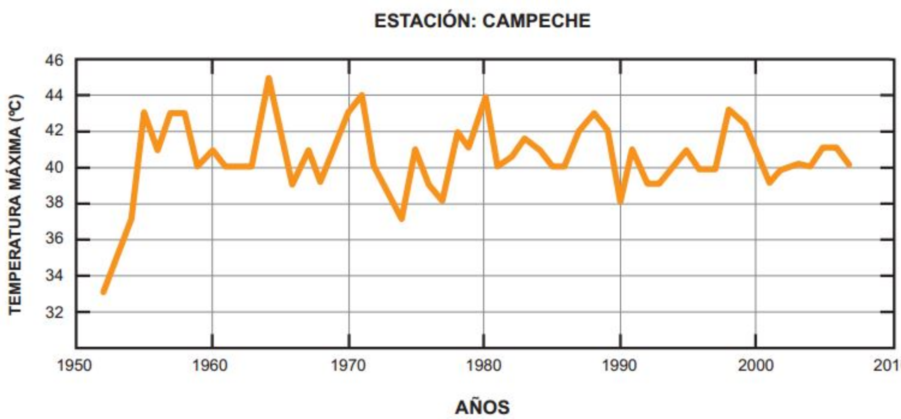

Figure A.10: Maximum annual temperature in Campeche (World Bank, 2012)

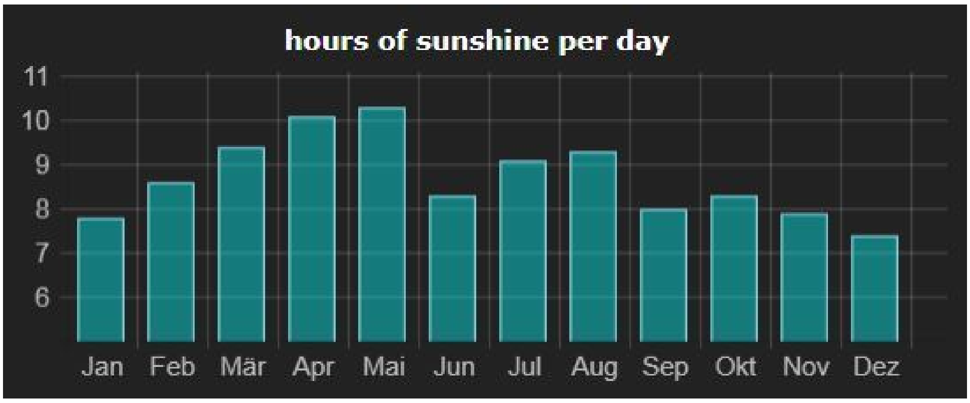

Figure A.11: Hours of sunshine annually in Campeche (Worlddata.info, 2017)

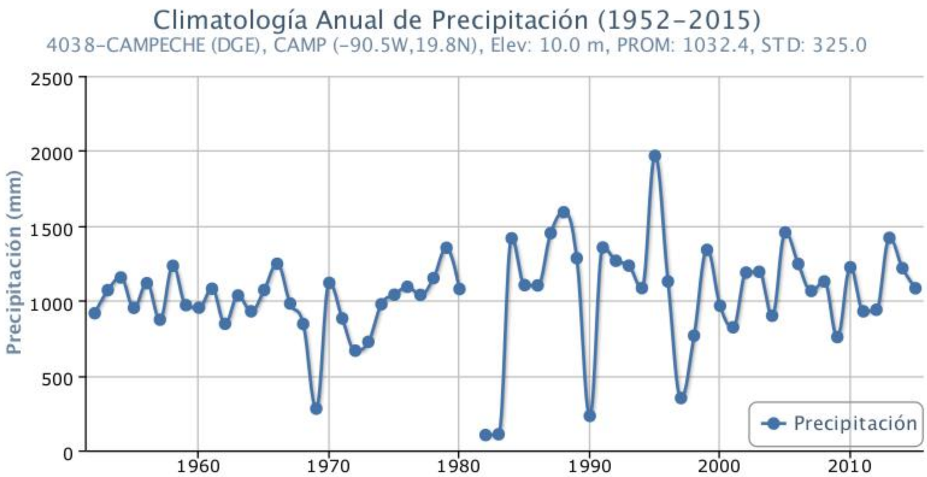

Figure A.12: Annual precipitation in Campeche (CLICOM, 2017)

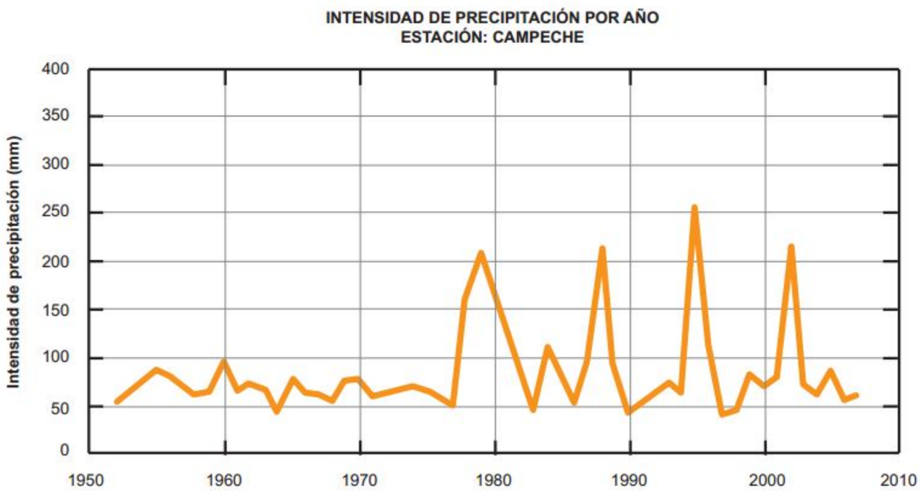

Figure A.13: Intensity precipitation throughout the years

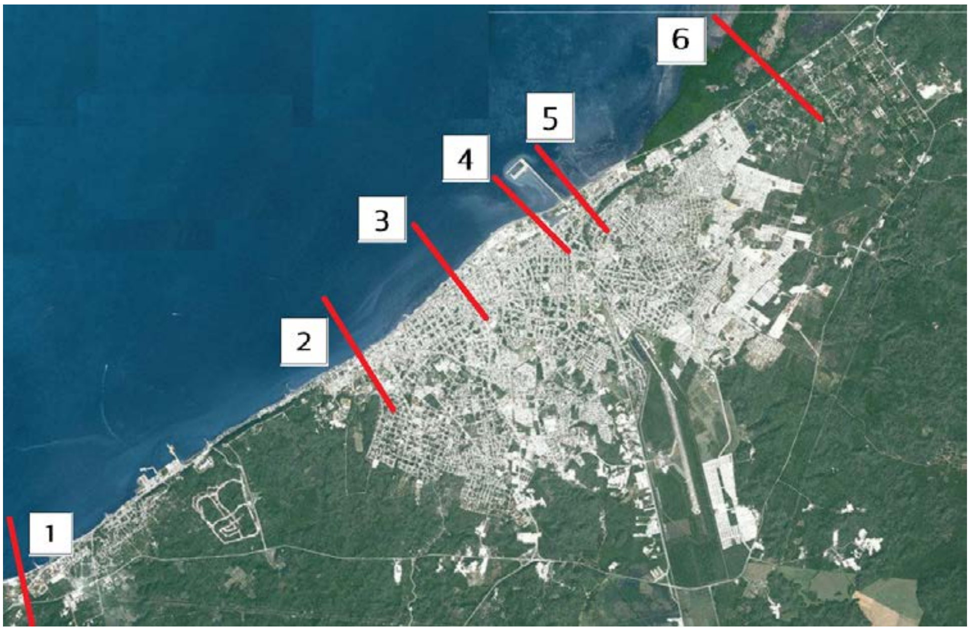

Figure A.14: Coastal transects at six different locations (Deltares & FAST, 2017)

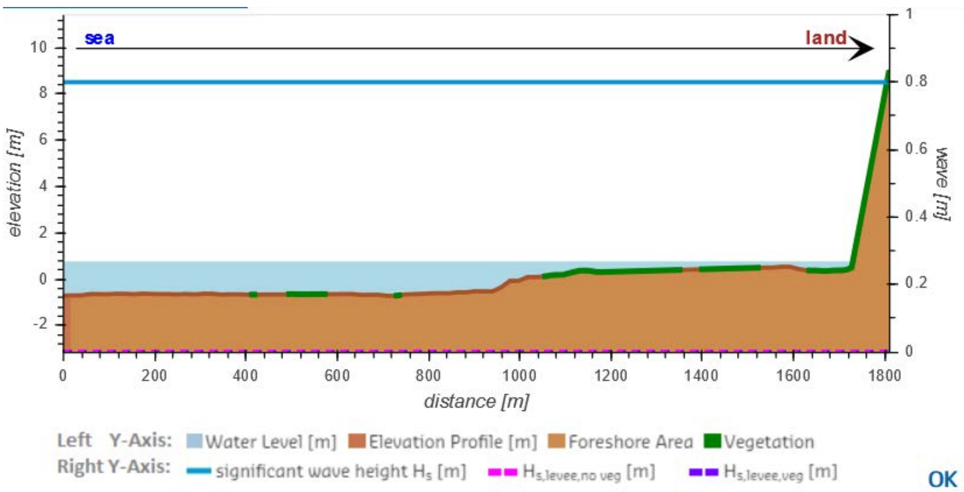

Figure A.15: Coastal transect at location 1, Playa Bonita (Deltares & FAST, 2017)

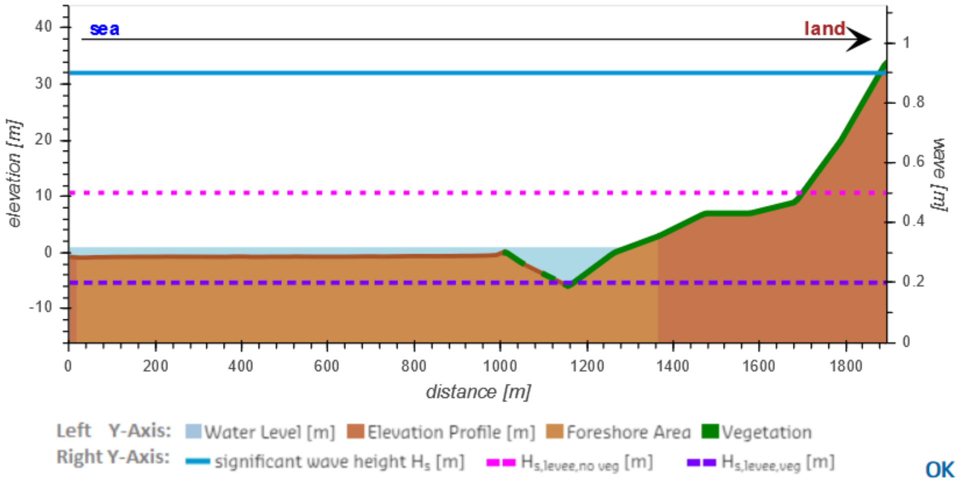

Figure A.16: Coastal transect at location 2, University (Deltares & FAST, 2017)

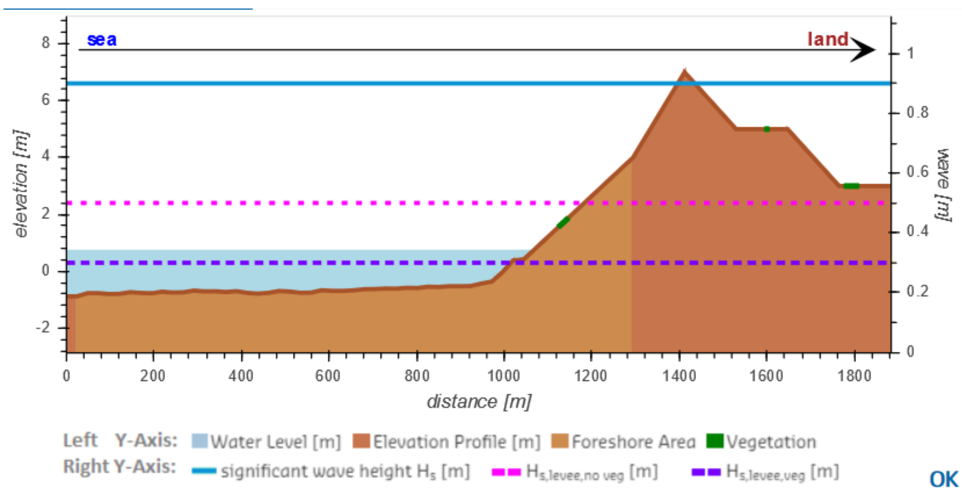

Figure A.17: Coastal transect at location 3, Historic City Centre (Deltares & FAST, 2017)

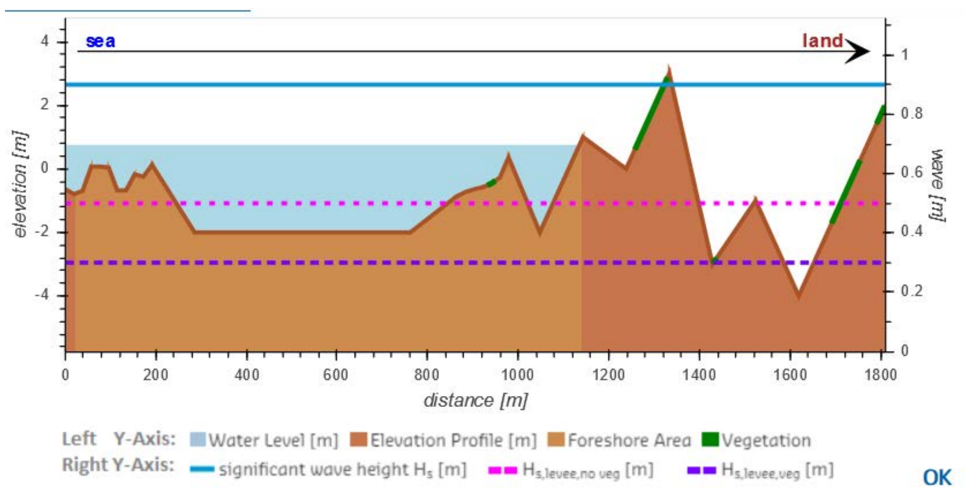

Figure A.18: Coastal transect at location 4, Pier SW Side (Deltares & FAST, 2017)

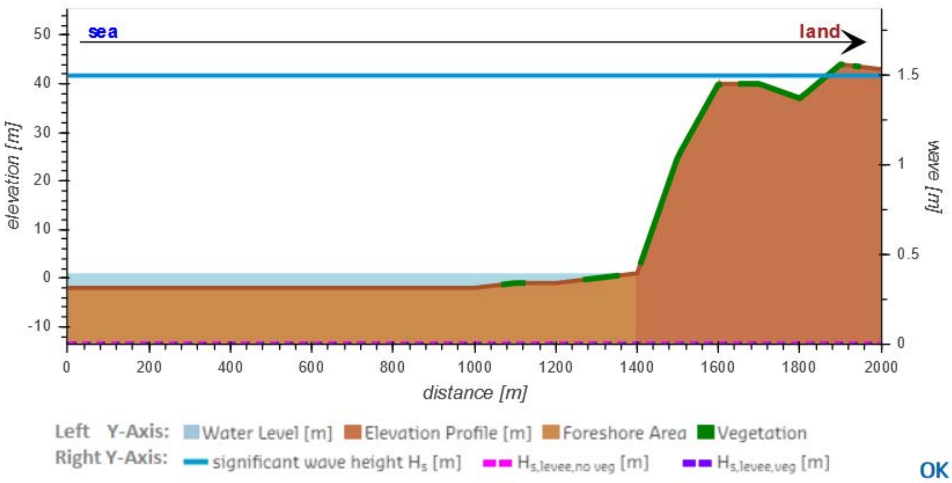

Figure A.19: Coastal transect at location 5, Pier NE Side (Deltares & FAST, 2017)

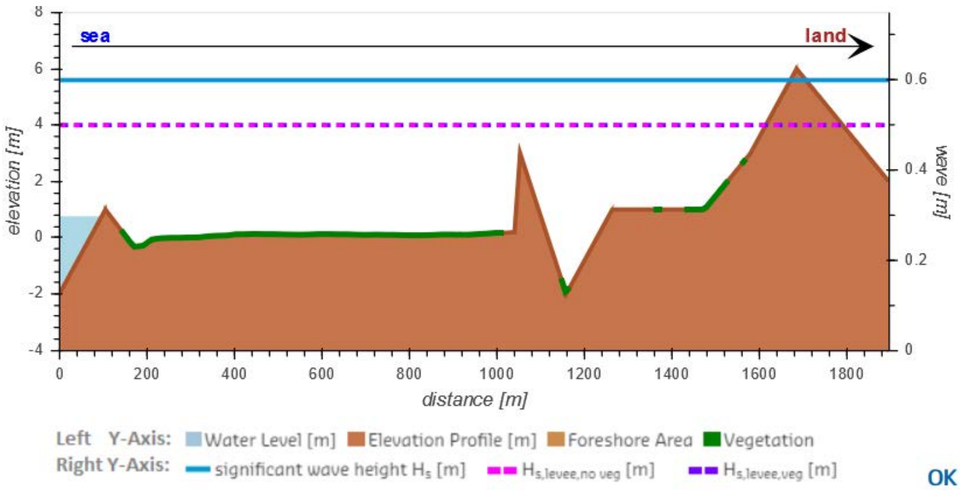

Figure A.20: Coastal transect at location 6, Mangroves-Imí (Deltares & FAST, 2017)

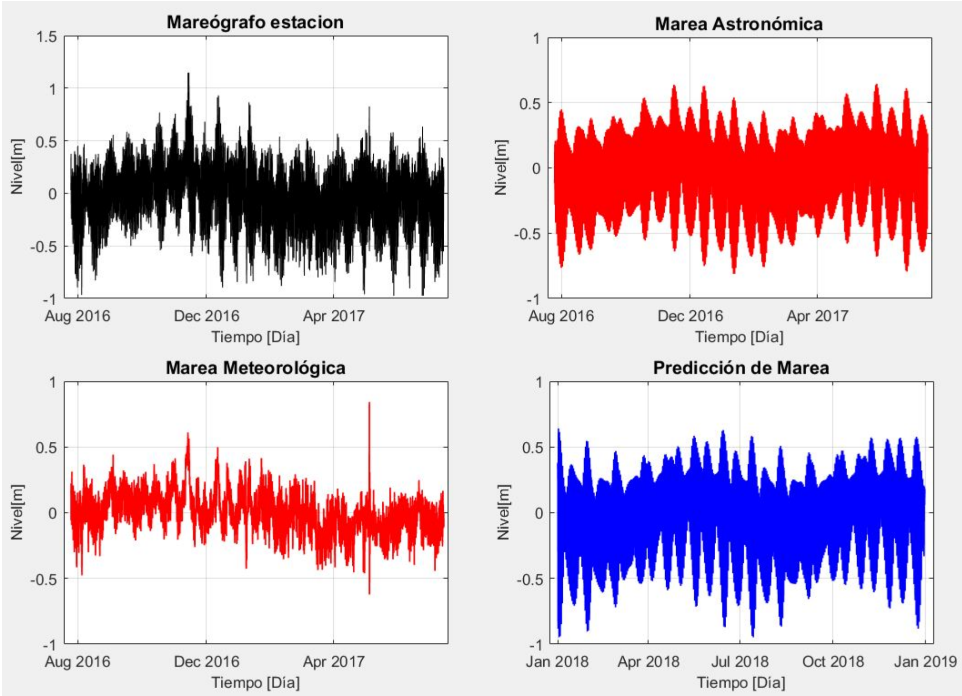

Figure A.21: Tidal range Campeche (Puc, 2017)

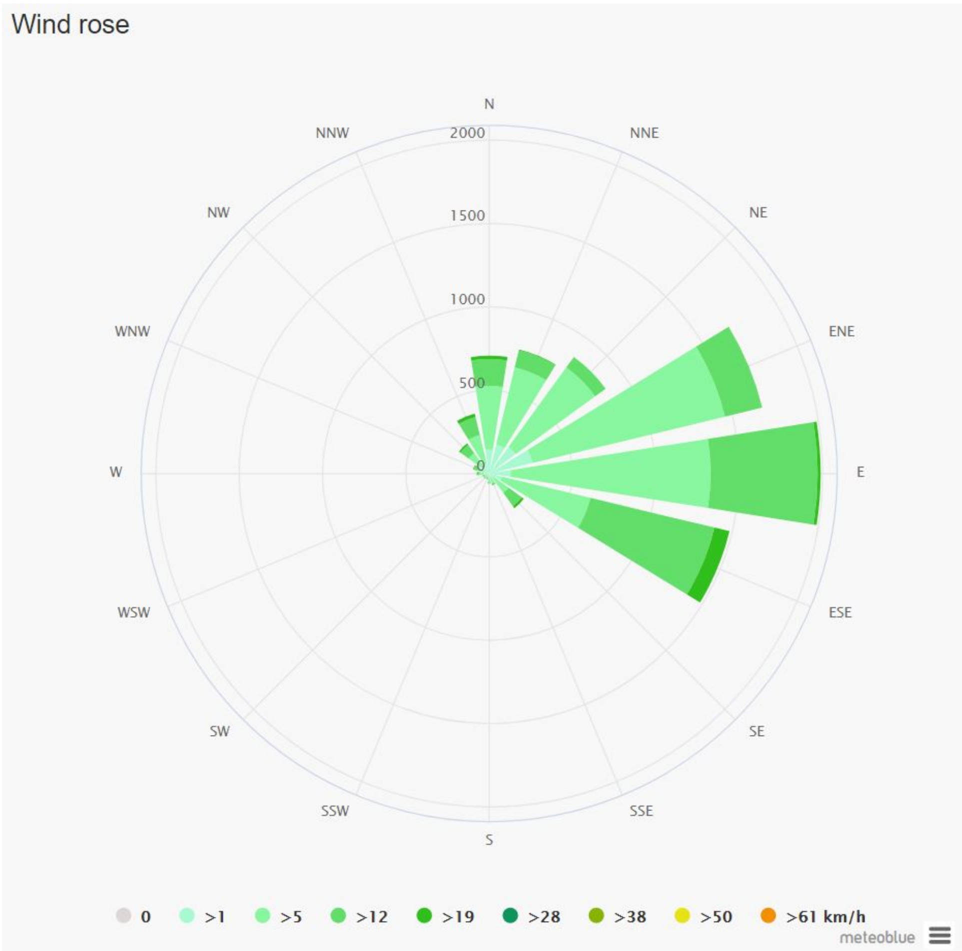

Figure A.22: Average annual wind rose of Campeche (Meteoblue, 2015)

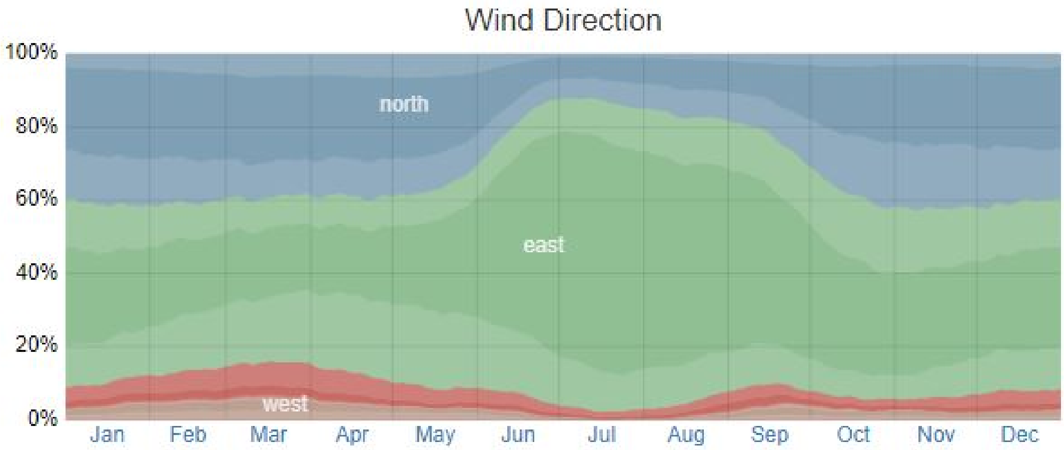

Figure A.23: Annual wind direction Campeche (Meteoblue, 2015)

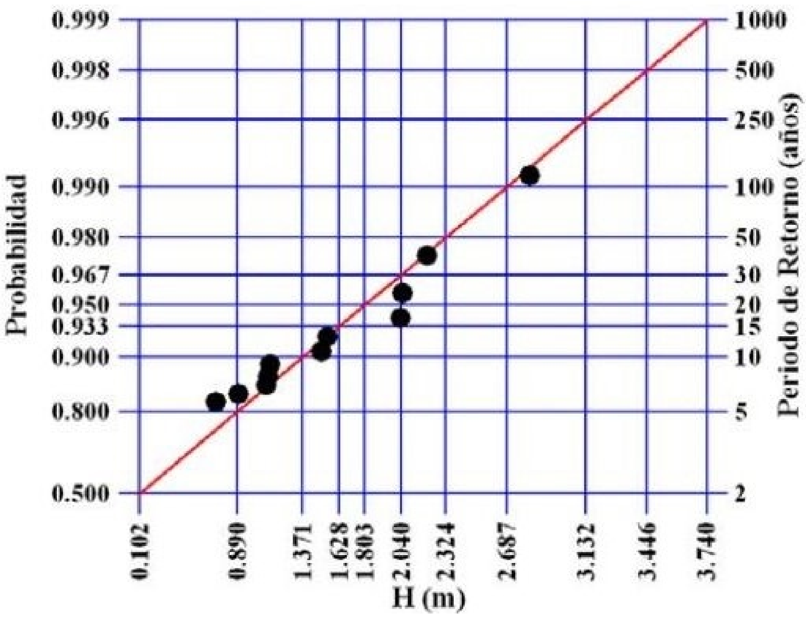

Figure A.24: Storm surge probability and height (Vecchi & Knutson, 2008)

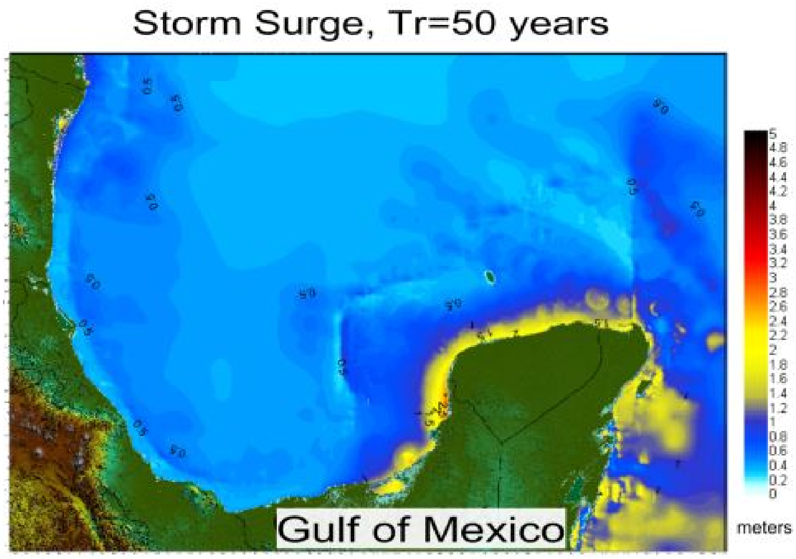

Figure A.25: Storm surge, return period = 50 years (Vecchi & Knutson, 2008)

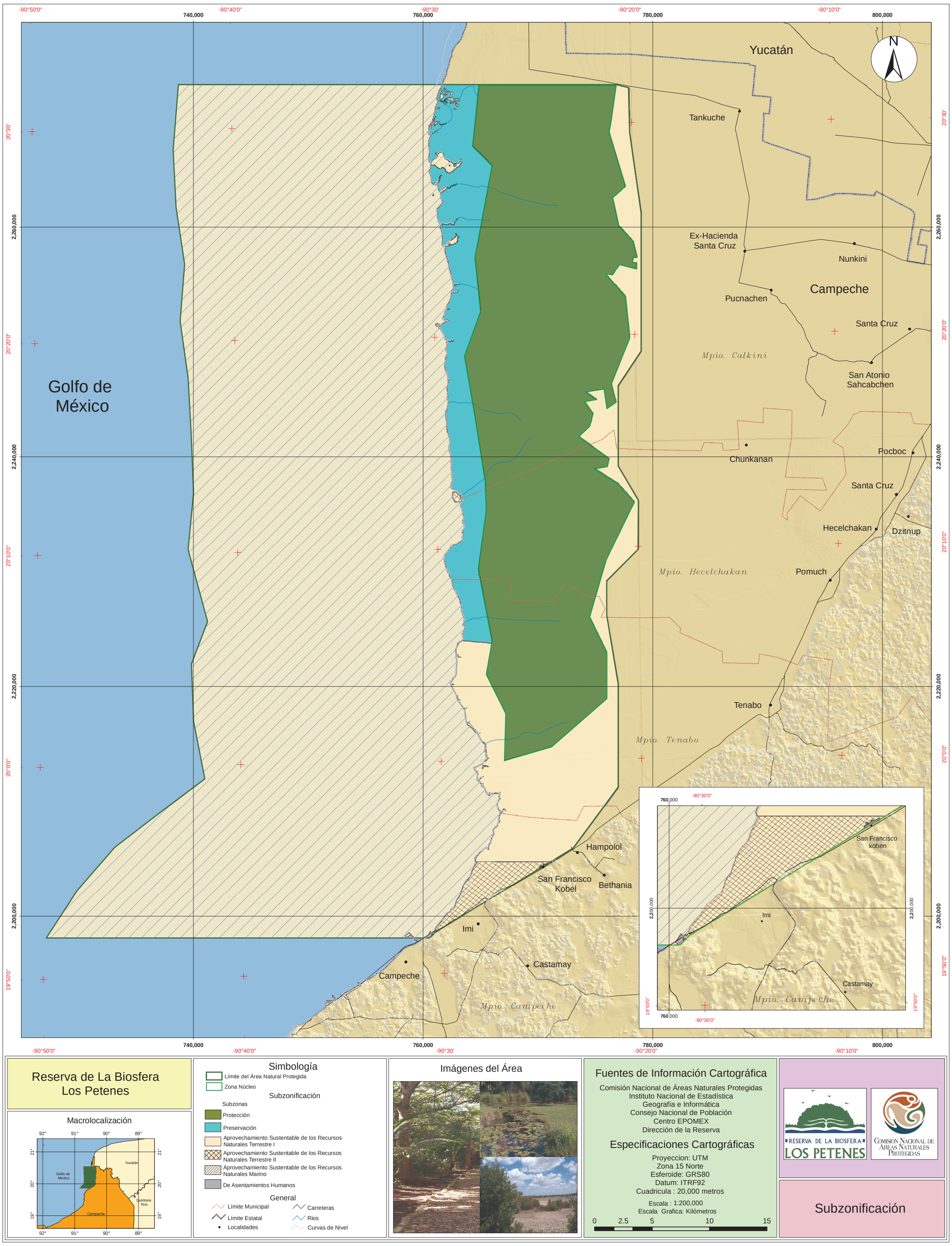

Figure A.26: Biosphere reserve Los Petenes

A.2 Boundary conditions

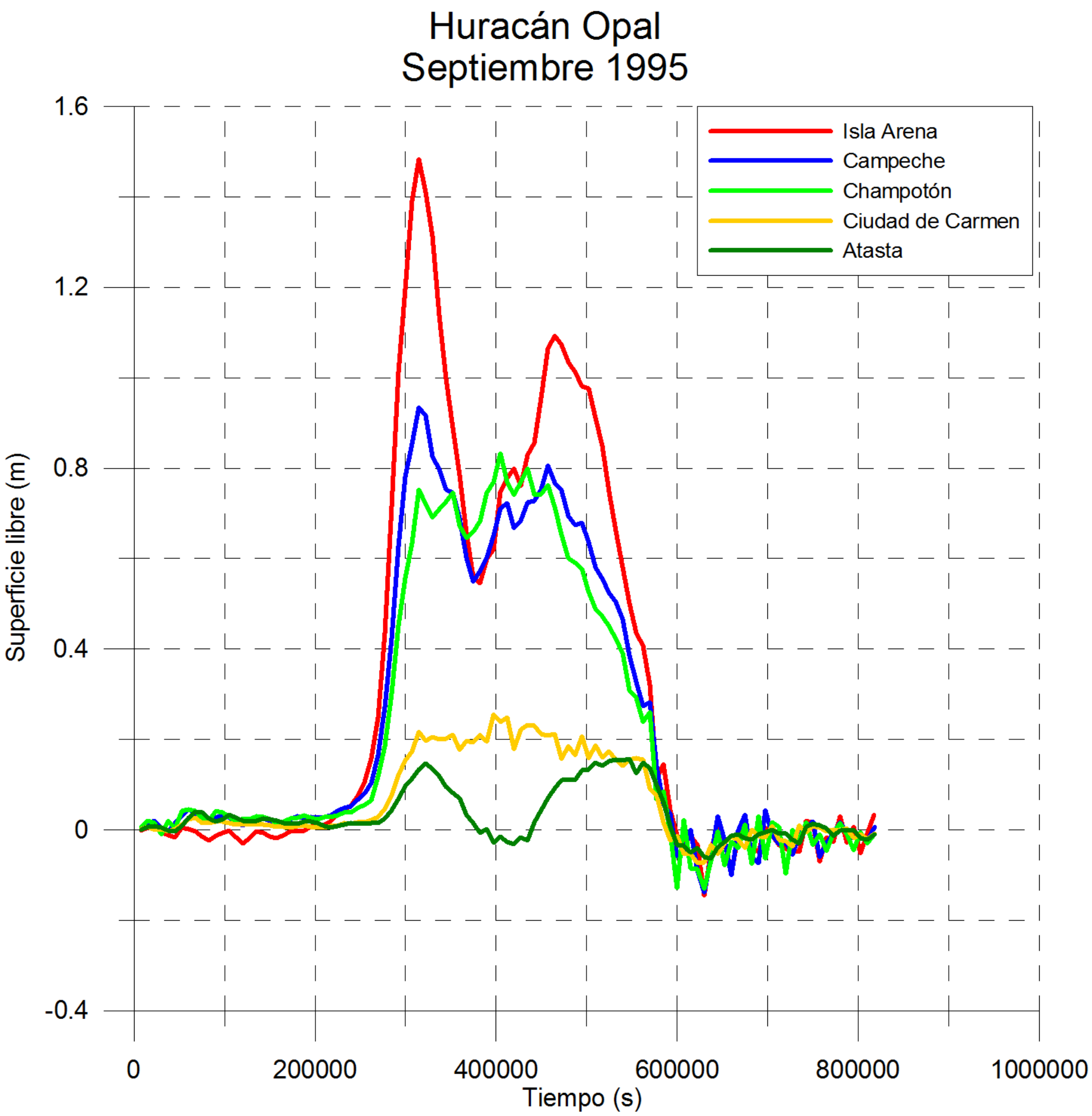

Figure A.27: Storm surge of Opal (1995)

A.3 Options

Figure A.28: Raised cycling path seen from crossing (SketchUp, version 1)

Figure A.29: Raised cycling path seen from Malecón (SketchUp, version 1)

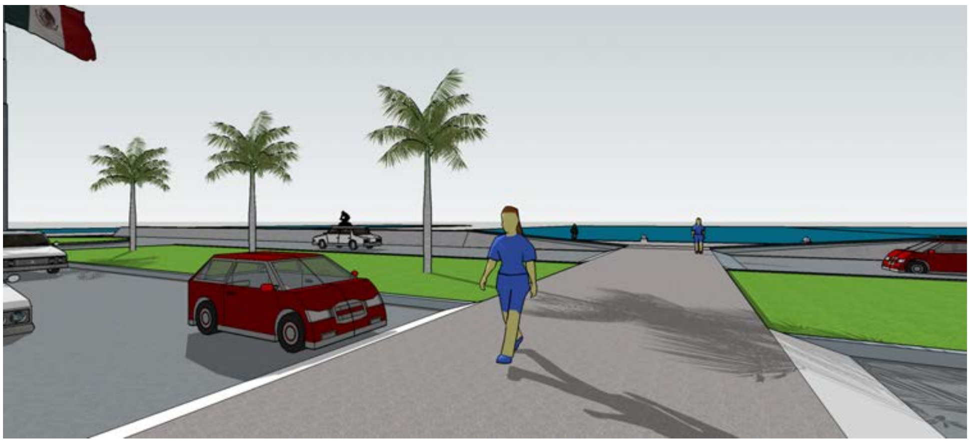

Figure A.30: Raised cycling path seen from crossing (SketchUp, version 2)

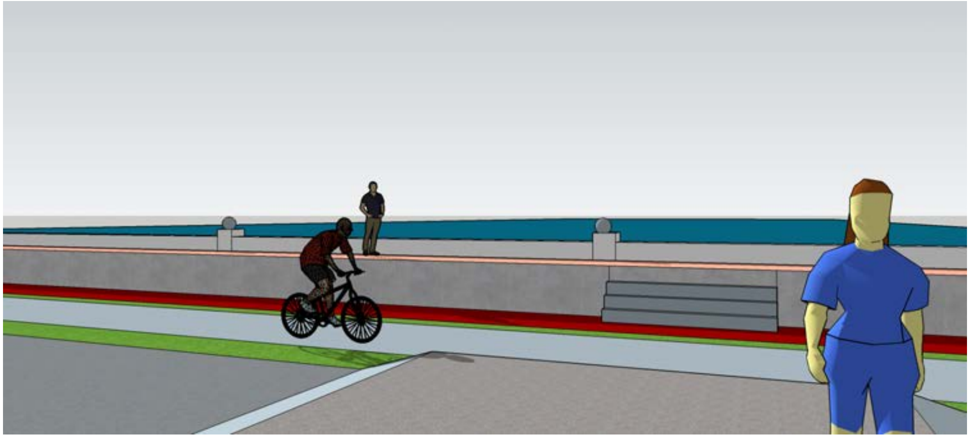

Figure A.31: Raised walking path seen from crossing (SketchUp)

Figure A.32: Raised walking path seen from Malecón (SketchUp)

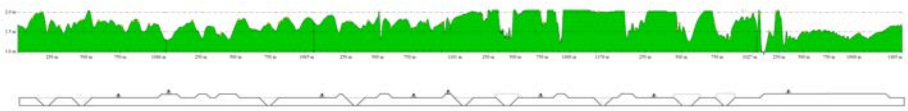

Figure A.33: Cross section over the length of the heights and the new cycling path

Figure A.34: Location #1 for sliding walls, the exit of the parking lot

Figure A.35: Location #2 for sliding walls, the entrance of the parking lot

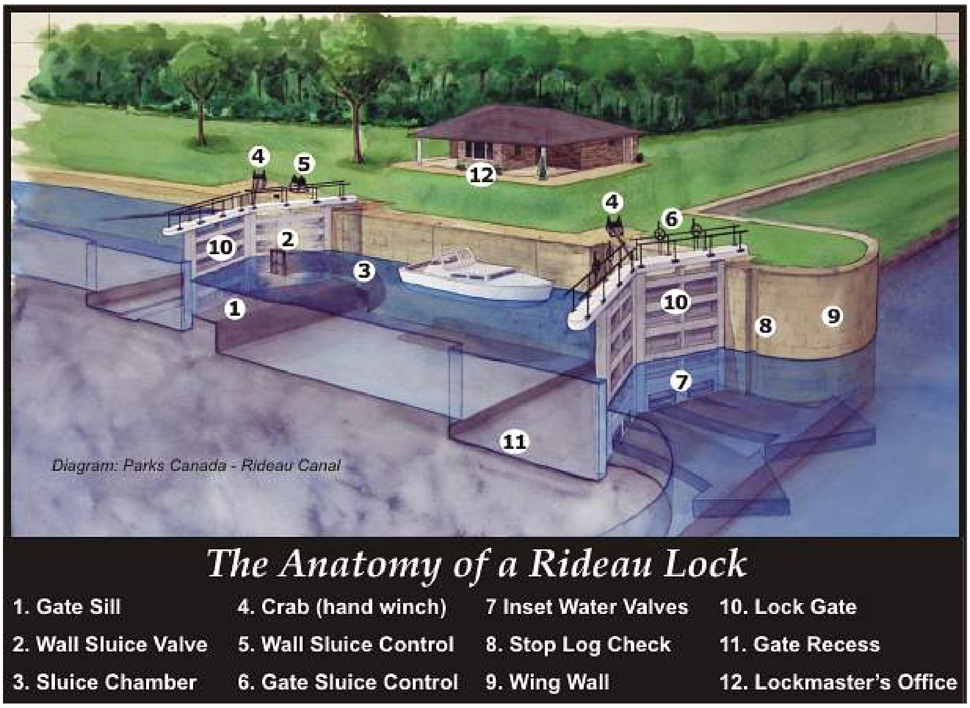

Figure A.36: Rideau lock gate

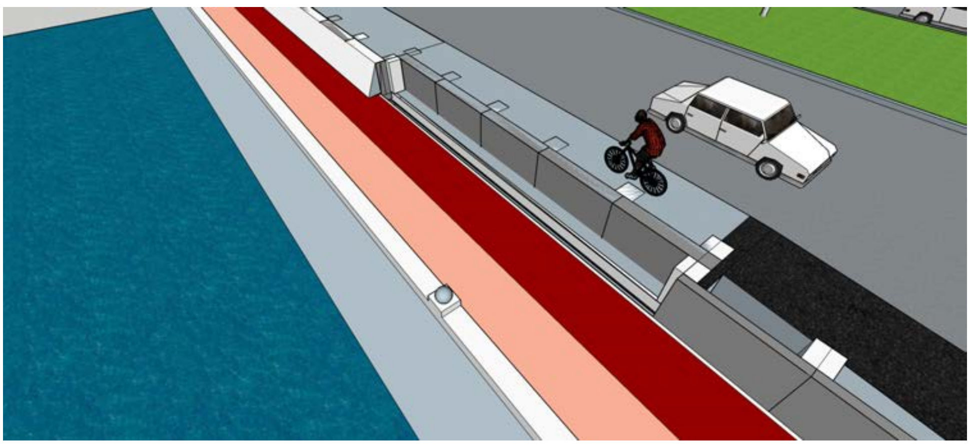

Figure A.37: Construction before, at the end of and after the rails

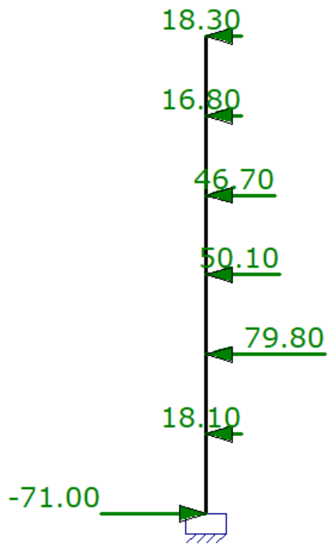

Figure A.38: Forces on column

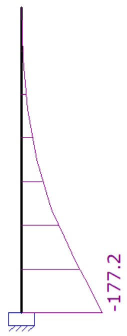

Figure A.39: Moment line of column

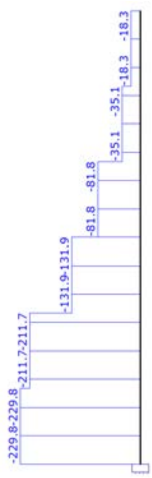

Figure A.40: Shear force column

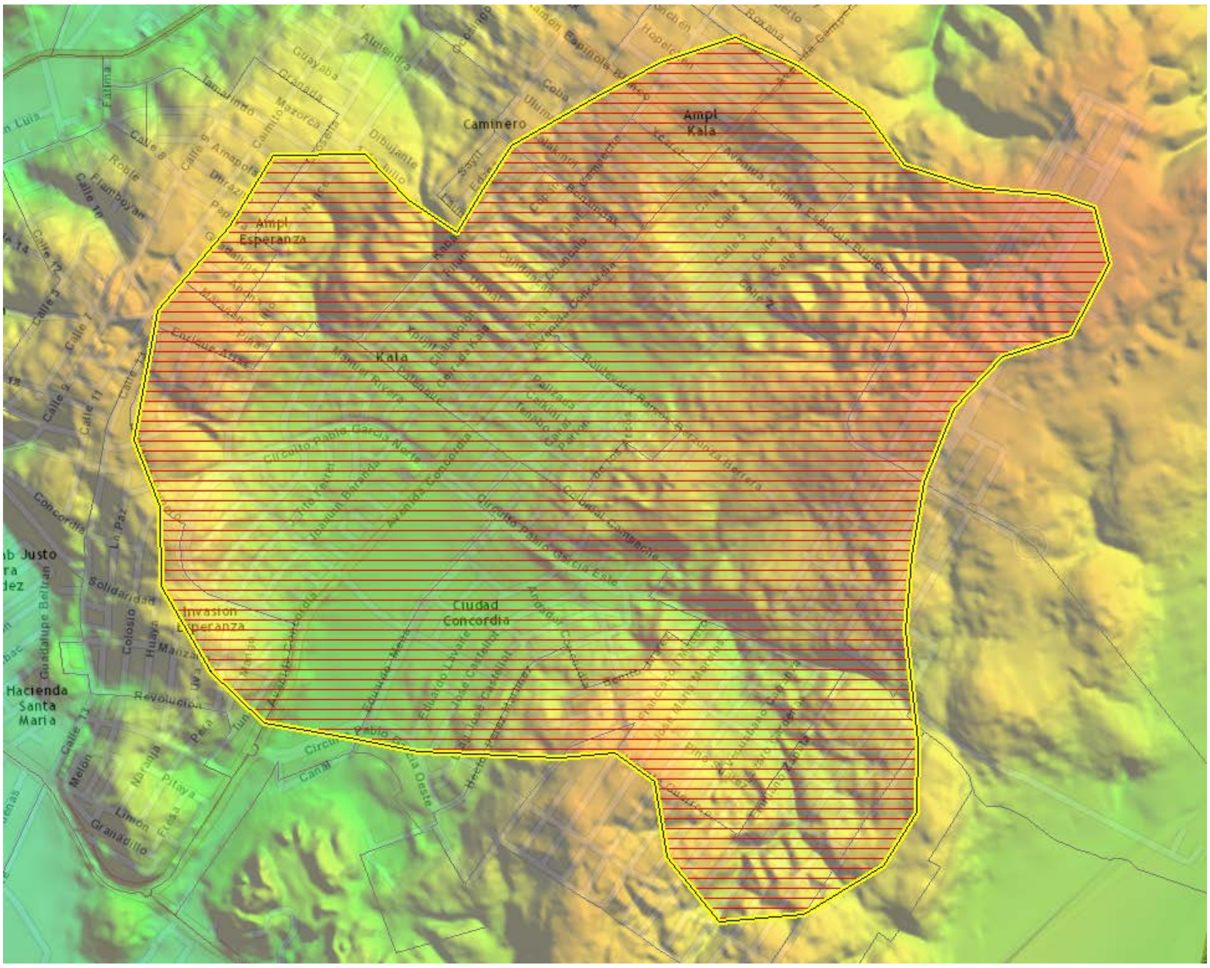

Figure A.41: Catchment area Ciudad Concordia

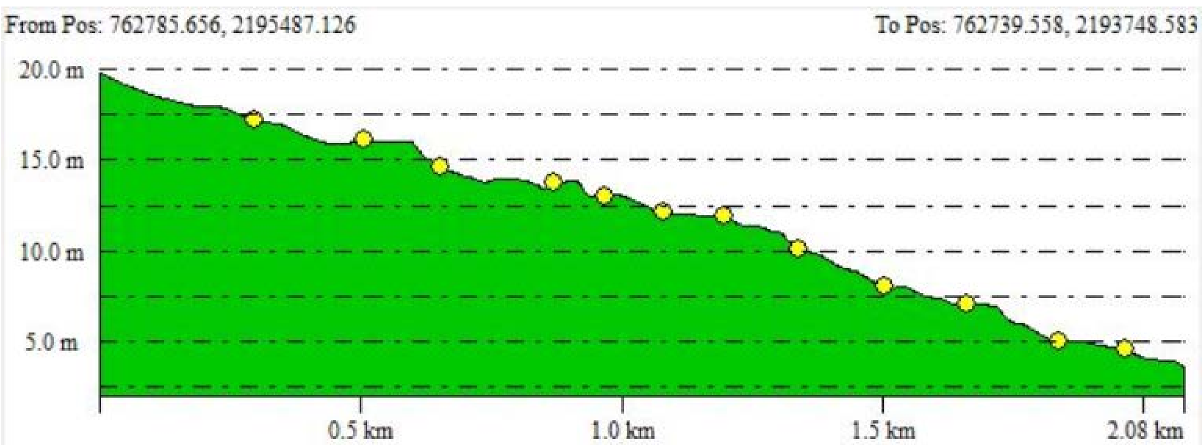

Figure A.42: Elevation course to infiltration basin area at Concordia

Figure A.43: Current view of possible infiltration basin area near Concordia

Figure A.44: Location water square Ciudad Concordia

Figure A.45: Location water square Dzarbay

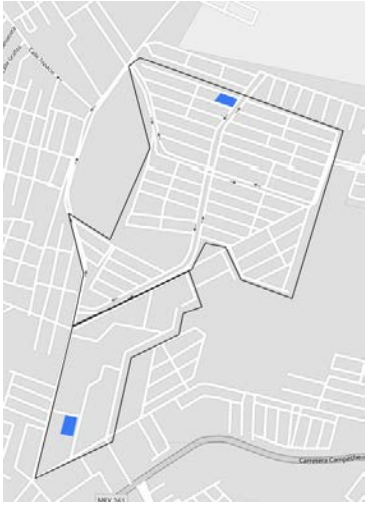

Figure A.46: Location water squares Presidentes de México and Plan Chac

Figure A.47: Location water square Flor de Limón

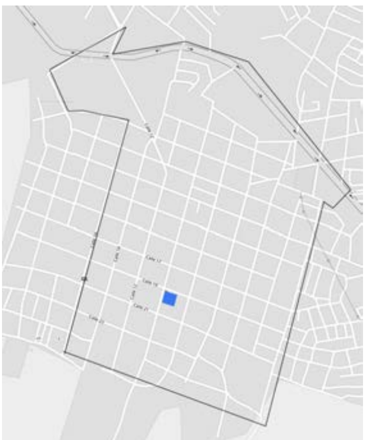

Figure A.48: Location water square Samulá

Figure A.49: Location water square El Carmelo & Quinta de los Españoles

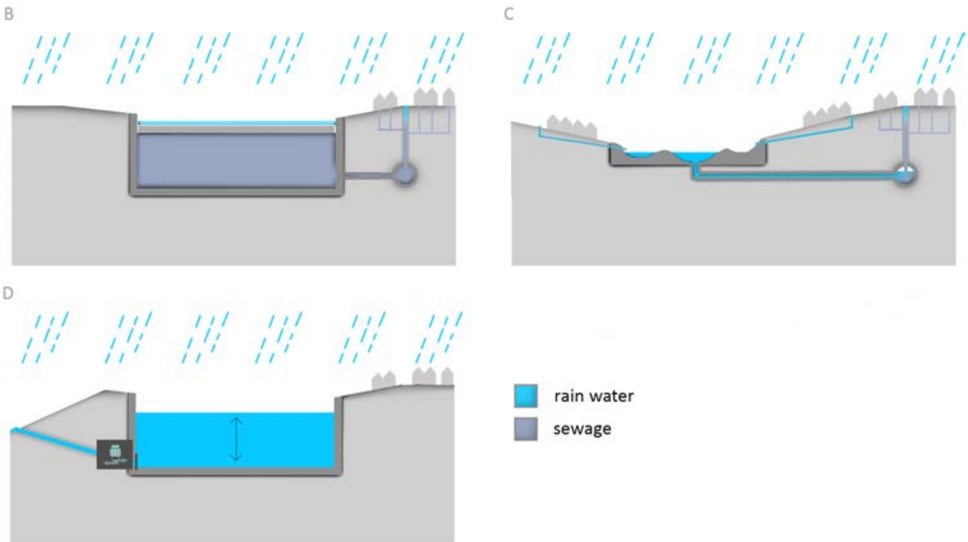

Figure A.50: The principles of the applied squares per category

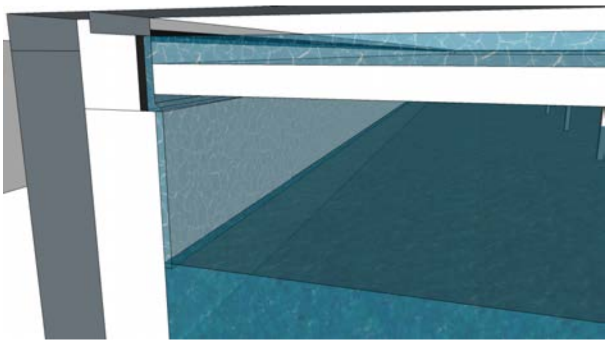

Figure A.51: Detail water square inflow from the top into the tank

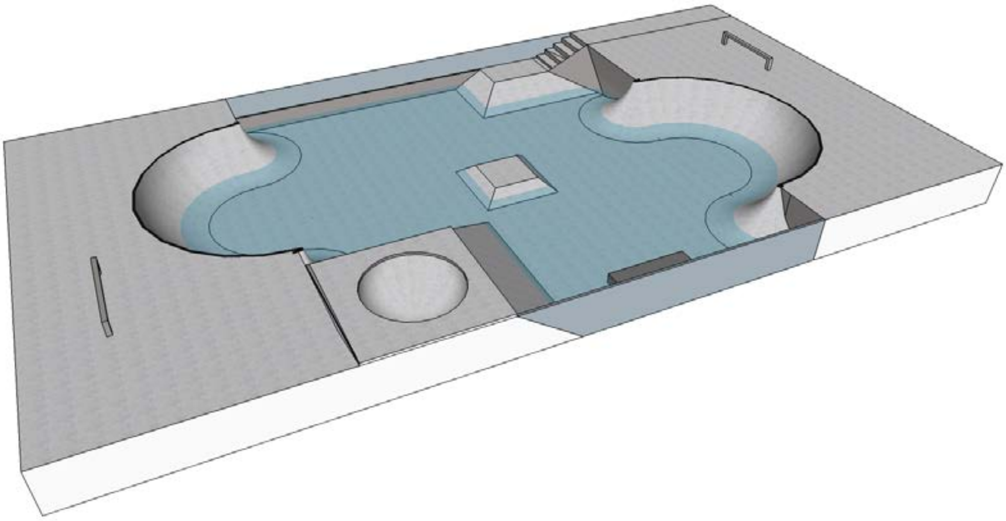

Figure A.52: Water square design for type C: skate-park

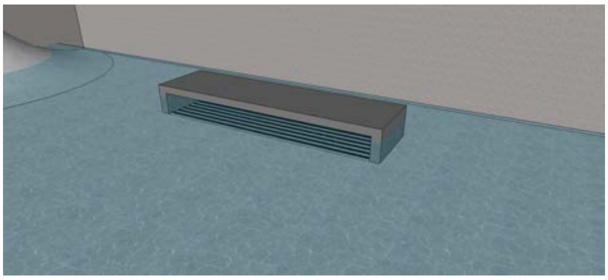

Figure A.53: Detail of water square type skate-park

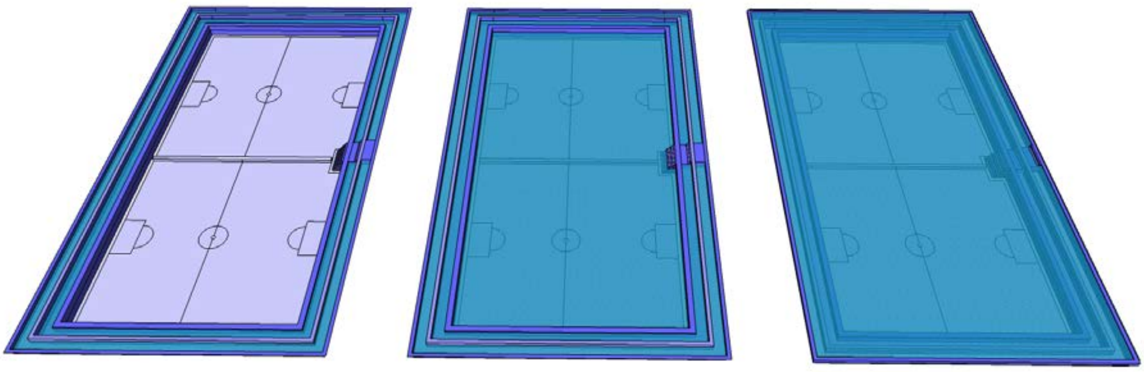

Figure A.54: Water square type D in three different situations

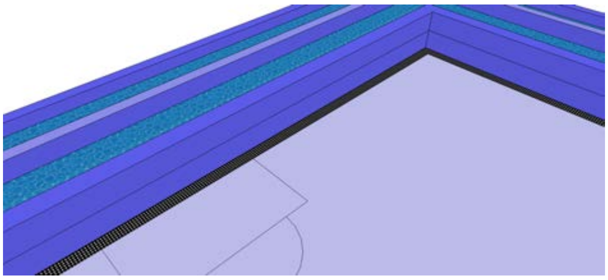

Figure A.55: Water square type D grid detail

B Tables

Inhabited housings with available electricity, 2010 Housing	70,030
Inhabited housings with available water from public net, 2010 Housing	68,351
Inhabited housings that have drainage, 2010 Housing	67,824
Inhabited housings that have toilet, 2010 Housing	68,780
Inhabited housings that have a washing machine, 2010 Housing	55,400

Table B.1: Housing indicators (INEGI, 2010)

Disaster	Damage (million US$)
Floods in Tabasco and Chiapas (2007)	3,000
Hurricane Wilma (2005)	1,782
Hurricane Gilberto (1988)	567
Hurricane Isidore (2002)	308
Hurricane Emily (2005)	302
Hurricane Stan (2005)	228
Hurricane Kenna (2002)	176
Hurricane Juliette (2001)	90
Hurricane Pauline (1997)	62

Source: Bitran 2001, and Comisión de Recursos Hídricos 2008.

Table B.2: Costs of damage due to hurricanes (World Bank, 2013)

Neighbourhoods and Residential Divisions	Land Value (per m2 according to State of Campeche)					Category
	#1	#2	#3	#4	Average	
COLONIA CENTRO	$2.246,00				$ 2.246,00	A
CAMPECHE NUEVO	$1.346,00				$ 1.346,00	B
ÁREA AH-KIM-PECH SECTOR FUNDADORES	$1.346,00				$ 1.346,00	B
BARRIO GUADALUPE	$1.346,00				$ 1.346,00	B
40 FRACC. GUADALAJARA B	$1.346,00				$ 1.346,00	B
ÁREA AH-KIM-PECH - SECTOR METROPOLITANO, FRACC. VILLAS DE AH-KIMPECH	$1.346,00	$1.234,00			$ 1.290,00	B
FRACC. TABACHINES	$1.234,00				$ 1.234,00	B
FRACC. BUGAMBILIAS	$1.234,00				$ 1.234,00	B
FRACC. RESID. CASA BLANCA	$1.234,00				$ 1.234,00	B
VILLAS AH-KIM-PECH - SECTOR FUERTES	$1.346,00	$ 899,00	$1.234,00		$ 1.159,67	B
FRACC. LOMAS DEL CASTILLO	$1.346,00	$ 899,00			$ 1.122,50	B
AV. RESURGIMIENTO	$1.346,00	$1.234,00	$ 674,00		$ 1.084,67	B
BOSQUES DE CAMPECHE	$1.346,00	$1.234,00	$ 899,00	$674,00	$ 1.038,25	B
FRACC. BRISAS	$1.346,00	$ 674,00			$ 1.010,00	B
BARRIO SAN ROMÁN, PENSIONES	$1.346,00	$ 899,00	$ 617,00		$ 954,00	C
CAMINO REAL	$1.346,00	$ 561,00		$953,50	$ 953,50	C
FRACC. PRADO, FRACC. RESIDENCIAL DEL SOL, FRACC. RINCONADA DEL PRADO	$1.234,00	$ 899,00	$ 674,00		$ 935,67	C
FRACC. NARCISO MENDOZA	$ 899,00				$ 899,00	C
FRACC. RESIDENCIAL RESURGIMIENTO	$ 899,00				$ 899,00	C
FRACC. RESIDENCIAL LOMAS DE REY	$ 899,00				$ 899,00	C
LOS ALMENDROS	$ 899,00				$ 899,00	C
FRACC. MISIONES UNIVERSIDAD	$ 899,00				$ 899,00	C
FRACC. LA LOMA	$ 899,00				$ 899,00	C
FRACC. CAMPECHE HILLS	$ 899,00				$ 899,00	C
FRACC. RESIDENCIAL DEL BOSQUE	$ 899,00			$899,00	$ 899,00	C
SECTOR PRIVADA VALLARTA	$ 899,00				$ 899,00	C
21 FRACC. PRIVADA SANTA ANA D	$ 899,00				$ 899,00	C
23 FRACC. LA NORIA D	$ 899,00				$ 899,00	C
36 FRACC. EL DORAL D	$ 899,00				$ 899,00	C
38 FRACC. VILLAS SANTA ANA D	$ 899,00				$ 899,00	C
41 CONDOMINIO SANTA ANA D	$ 899,00				$ 899,00	C
INF. LAS PALMAS I, II Y III	$ 449,00	$1.346,00		$897,50	$ 897,50	C
FRACC. VILLA MERCEDES	$ 449,00	$1.346,00		$897,50	$ 897,50	C
FRACC. RESIDENCIAL VILLAMAR	$ 449,00	$1.346,00		$897,50	$ 897,50	C
FRACC. SAN MIGUEL	$ 449,00	$1.346,00		$897,50	$ 897,50	C
U.H. SOLIDARIDAD NACIONAL	$ 449,00	$1.346,00		$897,50	$ 897,50	C
BARRIO SAN FRANCISCO	$1.346,00	$ 674,00	$ 617,00		$ 879,00	C
COL. PRADO (C.F.E.)	$1.346,00	$ 674,00	$ 561,00		$ 860,33	C
BARRIO ERMITA	$1.346,00	$ 674,00	$ 561,00	$860,33	$ 860,33	C
FRACC. RINCONADA DEL VALLE	$1.234,00	$ 674,00	$ 899,00	$449,00	$ 814,00	C
FRACC. KANISTÉ, FRACC. RINCÓN DEL VALLE KANISTÉ	$1.234,00	$ 674,00	$ 899,00	$449,00	$ 814,00	C
FRACC. 18 DE MARZO	$ 899,00	$ 674,00			$ 786,50	D
FRACC. VILLAS DEL RÍO	$ 899,00	$ 674,00			$ 786,50	D
FRACC. HACIENDA REAL CAMPECHE “EL FÉNIX”	$ 899,00	$ 674,00			$ 786,50	D
FRACC. FRACCIORAMA 2000	$ 899,00	$ 674,00			$ 786,50	D

22 FRACC. COLONIAL CAMPESTRE D-E	$ 899,00	$ 674,00			$ 786,50	D
FRACC. MONTE BELLO	$ 899,00	$ 674,00			$ 786,50	D
FRACC. LOMAS DE LAS FLORES I	$ 899,00	$ 674,00			$ 786,50	D
FRACC. MILITAR	$ 899,00	$ 674,00			$ 786,50	D
FRACC. LOMAS DE LAS FLORES II	$ 899,00	$ 674,00			$ 786,50	D
FRACC. LAS QUINTAS	$ 899,00	$ 674,00			$ 786,50	D
FRACC. MONTE REAL, FRACC. RESIDENCIAL PEDREGAL	$ 899,00	$ 674,00			$ 786,50	D
35 FRACC. COLINAS DEL SUR D-E	$ 899,00	$ 674,00			$ 786,50	D
BARRIO SAN JOSÉ	$ 899,00	$ 674,00	$ 561,00		$ 711,33	D
BARRIO SANTA LUCÍA	$ 899,00	$ 561,00	$ 674,00		$ 711,33	D
BARRIO SANTA ANA	$ 899,00	$ 674,00	$ 561,00		$ 711,33	D
FRACC. HOLLYWOOD	$ 899,00	$ 674,00	$ 561,00		$ 711,33	D
PRIV. GUADALUPANA	$ 899,00	$ 674,00	$ 561,00		$ 711,33	D
FRACC. LA HUERTA	$ 899,00	$ 674,00	$ 561,00		$ 711,33	D
U.H. ADOLFO LÓPEZ MATEOS	$ 674,00				$ 674,00	E
FRACC. JARDINES DEL PEDREGAL, FRACC. LOMAS DEL PEDREGAL	$ 674,00				$ 674,00	E
FRACC. IX-LOL-BE	$ 674,00				$ 674,00	E
FRACC. VILLAS DALIAS	$ 899,00	$ 449,00			$ 674,00	E
FRACC. VILLAS ALLENDE	$ 674,00				$ 674,00	E
FRACC. VILLAS COLOSIO	$ 674,00				$ 674,00	E
FRACC. SAN FRANCISCO	$ 674,00				$ 674,00	E
FRACC. LA ARBOLEDA II	$ 674,00				$ 674,00	E
FRACC. HÉROES DE CHAPULTEPEC	$ 674,00				$ 674,00	E
FRACC. BELLO HORIZONTE	$ 899,00	$ 449,00			$ 674,00	E
COLONIA EL HUANAL	$ 899,00	$ 449,00			$ 674,00	E
INF. JUSTO SIERRA MÉNDEZ	$ 899,00	$ 449,00			$ 674,00	E
FRACCIONAMIENTO COLONIA MÉXICO, FRACC. JUSTICIA SOCIAL	$ 899,00	$ 449,00			$ 674,00	E
U.H. CONCORDIA	$ 899,00	$ 449,00			$ 674,00	E
AMPLIACIÓN CONCORDIA	$ 899,00	$ 449,00			$ 674,00	E
CONJ. HAB. MURALLAS F.S.T.S.E.	$ 899,00	$ 449,00			$ 674,00	E
FRACC. BUENOS AIRES	$ 674,00				$ 674,00	E
FRACC. SOTAVENTO	$ 674,00				$ 674,00	E
FRACC. HACIENDA SANTA MARÍA	$ 899,00	$ 449,00			$ 674,00	E
FRACC. QUINTA LOS ESPAÑOLES	$ 899,00	$ 449,00			$ 674,00	E
LA MURALLAS	$ 674,00				$ 674,00	E
FRACC. ALTAMIRA	$ 674,00				$ 674,00	E
FRACC. FLOR DE LIMÓN	$ 674,00				$ 674,00	E
U.H. LAS FLORES	$ 674,00	$ 449,00	$ 899,00		$ 674,00	E
FRACC. LA ROSA	$ 674,00	$ 449,00	$ 899,00		$ 674,00	E
FRACC. GUADALUPE	$ 674,00				$ 674,00	E
25 FRACC. LOS SAUCES E	$ 674,00				$ 674,00	E
FRACC. VILLA DEL SOL	$ 674,00				$ 674,00	E
FRACC. VILLA JAZMÍN	$ 674,00				$ 674,00	E
42 FRACC. PUERTA REAL E	$ 674,00				$ 674,00	E
43 FRACC. VALLE DEL AGUILA E	$ 674,00				$ 674,00	E
FRACC. VILLA LAURELES	$ 899,00	$ 674,00	$ 449,00		$ 674,00	E
COL. BUENAVISTA	$1.234,00	$ 90,00			$ 662,00	E

U.H. BICENTENARIO	$ 449,00	$ 674,00			$ 561,50	F
FRACC. LA ARBOLEDA	$ 674,00	$ 449,00			$ 561,50	F
U.H. FIDEL VELÁZQUEZ	$ 674,00	$ 449,00			$ 561,50	F
U.H. PLAN – CHAC	$ 449,00	$ 674,00			$ 561,50	F
FRACC. VALLE DORADO	$ 674,00	$ 449,00			$ 561,50	F
U.H. PRESIDENTES DE MÉXICO - FRACC. VILLA NARANJOS, FRACC.	$ 674,00	$ 449,00			$ 561,50	F
GUADALUPE VICTORIA, PASEOS DE CAMPECHE Y FRACC. REFORMA	$ 674,00	$ 449,00			$ 561,50	F
U.H. FOVISSSTE BELÉN	$ 674,00	$ 449,00			$ 561,50	F
FRACC. LAURELES	$ 674,00	$ 449,00			$ 561,50	F
FRACC. LINDA VISTA	$ 674,00	$ 449,00			$ 561,50	F
FRACC. SAN JUAN I Y II	$ 674,00	$ 449,00			$ 561,50	F
FRACC. TULIPANES.	$ 674,00	$ 449,00			$ 561,50	F
FRACC. LA QUINTA	$ 561,00				$ 561,00	F
COLONIA TEPEYAC	$ 899,00	$ 674,00	$ 90,00		$ 554,33	F
COL. AMPL. MIGUEL HIDALGO	$ 899,00	$ 674,00	$ 90,00		$ 554,33	F
COLONIA VICENTE GUERRERO, CERRO DE LA EMINENCIA	$ 674,00	$ 90,00	$ 899,00		$ 554,33	F
COLONIA LA PAZ	$ 899,00	$ 90,00	$ 674,00		$ 554,33	F
COLONIA DELICIAS	$ 899,00	$ 90,00	$ 674,00		$ 554,33	F
COLONIA AVIACIÓN	$ 899,00	$ 674,00	$ 90,00		$ 554,33	F
COLONIA ESPERANZA, FRACC. CRISANTEMO, FRACC. VILLA LUISA	$ 899,00	$ 90,00	$ 674,00		$ 554,33	F
COLONIA CARMELO	$ 899,00	$ 674,00	$ 90,00		$ 554,33	F
FRACC. SAN RAFAEL, COL. SAN ANTONIO, COL. NUEVA ERA, COL. AMPL. SAN ANTONIO	$ 899,00	$ 674,00	$ 449,00	$ 90,00	$ 528,00	F
COLONIA SASCALUM	$ 899,00	$ 674,00	$ 449,00	$ 90,00	$ 528,00	F
FRACC. 4 CAMINOS	$ 899,00	$ 90,00			$ 494,50	G
COLONIA HÉROE DE NACOZARI	$ 899,00	$ 90,00			$ 494,50	G
COL. AMPL. ESPERANZA - KALÁ III	$ 899,00	$ 90,00			$ 494,50	G
COL. AMPL. 4 CAMINOS	$ 899,00	$ 90,00			$ 494,50	G
COLONIA DELICIAS	$ 899,00	$ 90,00			$ 494,50	G
AEROPUERTO	$ 79,00	$ 899,00			$ 489,00	G
INFONAVIT SAMULÁ	$ 449,00				$ 449,00	G
FRACC. LOMAS DE SAN RAFAEL	$ 449,00				$ 449,00	G
FRACC. SAN CAYETANO	$ 449,00				$ 449,00	G
FRACC. LOMAS DE ZARAGOZA	$ 449,00				$ 449,00	G
FRACC. RESIDENCIAL PEDREGAL	$ 449,00				$ 449,00	G
FRACC. VILLA LAURELES II	$ 449,00				$ 449,00	G
FRACC. VILLA ESMERALDA	$ 449,00				$ 449,00	G
FRACC. MONTE VERDE	$ 449,00				$ 449,00	G
FRACC. LA CAÑADA	$ 449,00				$ 449,00	G
U.H. MÁRTIRES DEL RÍO BLANCO	$ 449,00				$ 449,00	G
FRACC. EDUARDO LAVALLE URBINA	$ 449,00				$ 449,00	G
FRACC. TULA - LA CAÑADA	$ 449,00				$ 449,00	G
U.H. SANTA BÁRBARA	$ 449,00				$ 449,00	G
U.H. KALÁ	$ 449,00				$ 449,00	G
FRACC. TULA	$ 449,00				$ 449,00	G
FRACC. HACIENDA SAN ANTONIO	$ 449,00				$ 449,00	G
FRACC. VIVEROS	$ 449,00				$ 449,00	G

PRIVADA RESIDENCIAL CAMPESTRE	$ 449,00				$ 449,00	G
FRACC. LOS CEDROS	$ 449,00				$ 449,00	G
FRACC. VILLA TURQUESA	$ 449,00				$ 449,00	G
FRACC. VILLAS LA HACIENDA	$ 449,00				$ 449,00	G
FRACC. PALMA REAL	$ 449,00				$ 449,00	G
FRACC. QUINTA HERMOSA	$ 449,00				$ 449,00	G
RESIDENCIAL TERRANOVA	$ 449,00				$ 449,00	G
FRACC. EL VERGEL	$ 449,00				$ 449,00	G
FRACC. LOS CAMINEROS	$ 449,00				$ 449,00	G
FRACC. LOS REYES	$ 449,00				$ 449,00	G
FRACC. URBANO AMBIENTAL EX HACIENDA KALÁ	$ 449,00				$ 449,00	G
FRACC. LAS ARBOLEDAS	$ 449,00				$ 449,00	G
FRACC. LOS ALAMOS	$ 449,00				$ 449,00	G
RESIDENCIAL LA HACIENDA	$ 449,00				$ 449,00	G
MAQUILADORAS, COMP. HAB. RAMÓN ESPÍNOLA BLANCO	$ 449,00				$ 449,00	G
FRACC. VILLAS DE KALÁ	$ 449,00				$ 449,00	G
RESIDENCIAL COLONIAL	$ 449,00				$ 449,00	G
FRACC. COLONIAL CAMPECHE	$ 449,00				$ 449,00	G
FRACC. VISTA HERMOSA	$ 449,00				$ 449,00	G
FRACC. MONTECARLO	$ 449,00				$ 449,00	G
RESIDENCIAL DELICIAS H	$ 449,00				$ 449,00	G
34 FRACC. ALTA VISTA H	$ 449,00				$ 449,00	G
37 FRACC. VILLA REAL H	$ 449,00				$ 449,00	G
39 TACUBAYA H	$ 449,00				$ 449,00	G
SECTOR LAS FLORES, FRACC. SANTA CECILIA	$ 899,00	$ 674,00	$ 90,00	$ 79,00	$ 435,50	G
FRACC. AVES DEL PARAÍSO, SAN JORGE	$ 899,00	$ 674,00	$ 90,00	$ 79,00	$ 435,50	G
COLONIA SAMULÁ, AMPL. SAMULÁ	$ 674,00	$ 449,00	$ 90,00		$ 404,33	G
FRACC. RINCONADA DEL VALLE	$ 674,00	$ 449,00	$ 90,00		$ 404,33	G
FRACC. SAN LUIS, FRACC. VILLAS SAMULÁ	$ 674,00	$ 449,00	$ 90,00		$ 404,33	G
FRACC. SAN ANDRÉS	$ 674,00	$ 449,00	$ 90,00		$ 404,33	G
FRACC. GIRASOLES	$ 674,00	$ 449,00	$ 90,00		$ 404,33	G
FRACC. PASEO DEL SEMINARIO	$ 674,00	$ 449,00	$ 90,00		$ 404,33	G
FRACC. LA VISTA, FRACC. EDZNÁ	$ 674,00	$ 449,00	$ 90,00		$ 404,33	G
COL. Y AMPL. IGNACIO ZARAGOZA, FRACC. RESIDENCIAL TEPEYAC	$ 674,00	$ 90,00			$ 382,00	H
COLONIA MIGUEL HIDALGO	$ 674,00	$ 90,00			$ 382,00	H
COLONIA PABLO GARCÍA	$ 90,00	$ 674,00			$ 382,00	H
COLONIA REVOLUCIÓN, COLONIA PEÑA	$ 90,00	$ 674,00			$ 382,00	H
COLONIA CUMBRES I Y II	$ 674,00	$ 90,00			$ 382,00	H
COLONIA MINAS	$ 674,00	$ 90,00			$ 382,00	H
COLONIA FÉNIX	$ 90,00	$ 674,00			$ 382,00	H
COLONIA TOMÁS AZNAR	$ 674,00	$ 90,00			$ 382,00	H
COL. SAN JOSÉ ESCALERA, SECTOR SANTA MARGARITA	$ 899,00	$ 79,00	$ 46,00		$ 341,33	H
FRACC. SIGLO XXI	$ 449,00	$ 90,00			$ 269,50	I
FRACC. VIVAH	$ 449,00	$ 90,00			$ 269,50	I
FRACC. ALAMEDA	$ 449,00	$ 90,00			$ 269,50	I
COLONIA KANISTÉ	$ 90,00				$ 90,00	I
COLONIA LÁZARO CÁRDENAS	$ 90,00				$ 90,00	I

PRIVADA RESIDENCIAL CAMPESTRE	$ 449,00				$ 449,00	G
FRACC. LOS CEDROS	$ 449,00				$ 449,00	G
FRACC. VILLA TURQUESA	$ 449,00				$ 449,00	G
FRACC. VILLAS LA HACIENDA	$ 449,00				$ 449,00	G
FRACC. PALMA REAL	$ 449,00				$ 449,00	G
FRACC. QUINTA HERMOSA	$ 449,00				$ 449,00	G
RESIDENCIAL TERRANOVA	$ 449,00				$ 449,00	G
FRACC. EL VERGEL	$ 449,00				$ 449,00	G
FRACC. LOS CAMINEROS	$ 449,00				$ 449,00	G
FRACC. LOS REYES	$ 449,00				$ 449,00	G
FRACC. URBANO AMBIENTAL EX HACIENDA KALÁ	$ 449,00				$ 449,00	G
FRACC. LAS ARBOLEDAS	$ 449,00				$ 449,00	G
FRACC. LOS ALAMOS	$ 449,00				$ 449,00	G
RESIDENCIAL LA HACIENDA	$ 449,00				$ 449,00	G
MAQUILADORAS, COMP. HAB. RAMÓN ESPÍNOLA BLANCO	$ 449,00				$ 449,00	G
FRACC. VILLAS DE KALÁ	$ 449,00				$ 449,00	G
RESIDENCIAL COLONIAL	$ 449,00				$ 449,00	G
FRACC. COLONIAL CAMPECHE	$ 449,00				$ 449,00	G
FRACC. VISTA HERMOSA	$ 449,00				$ 449,00	G
FRACC. MONTECARLO	$ 449,00				$ 449,00	G
RESIDENCIAL DELICIAS H	$ 449,00				$ 449,00	G
34 FRACC. ALTA VISTA H	$ 449,00				$ 449,00	G
37 FRACC. VILLA REAL H	$ 449,00				$ 449,00	G
39 TACUBAYA H	$ 449,00				$ 449,00	G
SECTOR LAS FLORES, FRACC. SANTA CECILIA	$ 899,00	$ 674,00	$ 90,00	$ 79,00	$ 435,50	G
FRACC. AVES DEL PARAÍSO, SAN JORGE	$ 899,00	$ 674,00	$ 90,00	$ 79,00	$ 435,50	G
COLONIA SAMULÁ, AMPL. SAMULÁ	$ 674,00	$ 449,00	$ 90,00		$ 404,33	G
FRACC. RINCONADA DEL VALLE	$ 674,00	$ 449,00	$ 90,00		$ 404,33	G
FRACC. SAN LUIS, FRACC. VILLAS SAMULÁ	$ 674,00	$ 449,00	$ 90,00		$ 404,33	G
FRACC. SAN ANDRÉS	$ 674,00	$ 449,00	$ 90,00		$ 404,33	G
FRACC. GIRASOLES	$ 674,00	$ 449,00	$ 90,00		$ 404,33	G
FRACC. PASEO DEL SEMINARIO	$ 674,00	$ 449,00	$ 90,00		$ 404,33	G
FRACC. LA VISTA, FRACC. EDZNÁ	$ 674,00	$ 449,00	$ 90,00		$ 404,33	G
COL. Y AMPL. IGNACIO ZARAGOZA, FRACC. RESIDENCIAL TEPEYAC	$ 674,00	$ 90,00			$ 382,00	H
COLONIA MIGUEL HIDALGO	$ 674,00	$ 90,00			$ 382,00	H
COLONIA PABLO GARCÍA	$ 90,00	$ 674,00			$ 382,00	H
COLONIA REVOLUCIÓN, COLONIA PEÑA	$ 90,00	$ 674,00			$ 382,00	H
COLONIA CUMBRES I Y II	$ 674,00	$ 90,00			$ 382,00	H
COLONIA MINAS	$ 674,00	$ 90,00			$ 382,00	H
COLONIA FÉNIX	$ 90,00	$ 674,00			$ 382,00	H
COLONIA TOMÁS AZNAR	$ 674,00	$ 90,00			$ 382,00	H
COL. SAN JOSÉ ESCALERA, SECTOR SANTA MARGARITA	$ 899,00	$ 79,00	$ 46,00		$ 341,33	H
FRACC. SIGLO XXI	$ 449,00	$ 90,00			$ 269,50	I
FRACC. VIVAH	$ 449,00	$ 90,00			$ 269,50	I
FRACC. ALAMEDA	$ 449,00	$ 90,00			$ 269,50	I
COLONIA KANISTÉ	$ 90,00				$ 90,00	I
COLONIA LÁZARO CÁRDENAS	$ 90,00				$ 90,00	I

Table B.3: Calculation land value neighbourhoods and divisions

		jan	feb	mrt	apr	may	june	july	aug	sep	okt	nov	dec
daily temperature	°F	84.0	85.5	89.0	93.0	94.0	92.5	92.0	91.5	90.0	88.0	85.5	94.0
	°C	28.9	29.7	31.7	33.9	34.4	33.6	33.3	33.1	32.2	31.1	29.7	34.4
day length	hours	11:05	11:31	12:00	12:37	13:06	13:18	13:12	12:45	12:15	11:40	11:11	10:58

Table B.4: Average day length and temperature per month in Campeche (Spark, 2017)

INPUT from DIANA					calculations					
x [m]	y [m]	σxx [kN/m2]	σyy [kN/m2]	σxy [kN/m2	M [kN/m2]	R [kN/m2]	σ1 [kN/m2]	σ2 [kN/m2]	θ [rad]	θ [°]
0.00	0.00	99.3	114.5	807.7	106.9	814.7	921.6	-707.8	0.4692	26.8812
0.00	0.25	-189.91	27.31	889.34	-81.30	893.05	811.75	-974.35	-3.37	-193.28
0.00	0.50	-414.97	-220.89	958.58	-317.93	1014.05	696.12	-1331.98	0.13	7.45
0.00	0.75	-438.60	-342.24	803.26	-390.42	894.50	504.08	-1284.92	-0.79	-45.19
0.00	1.00	-484.00	-294.79	644.95	-389.39	755.23	365.84	-1144.62	-0.56	-32.29
0.00	1.25	-389.86	-181.43	527.19	-285.65	599.95	314.30	-885.60	1.26	72.31
0.00	1.50	-457.3	-99.7	466.2	-278.5	543.0	264.5	-821.5	0.2956	16.9370
0.25	0.00	-24.46	-106.01	878.17	-65.24	881.88	816.64	-947.12	2.57	147.04
0.25	0.25	-364.08	-211.84	1002.59	-287.96	1044.97	757.01	-1332.93	-0.21	-11.98
0.25	0.50	-642.62	-359.67	1116.96	-501.14	1233.61	732.47	-1734.76	-0.35	-20.00
0.25	0.75	-726.99	-332.12	921.15	-529.55	1079.42	549.87	-1608.97	-5.35	-306.32
0.25	1.00	-746.79	-244.11	717.64	-495.45	886.29	390.84	-1381.74	-0.11	-6.50
0.25	1.25	-657.17	-121.07	561.36	-389.12	698.86	309.74	-1087.98	-0.38	-21.63
0.25	1.50	-724.00	-22.64	463.61	-373.32	605.72	232.40	-979.04	-0.19	-10.92
0.50	0.00	-284.20	-191.92	827.78	-238.06	862.40	624.34	-1100.45	0.31	17.61
0.50	0.25	-559.54	-301.38	974.47	-430.46	1065.89	635.44	-1496.35	-0.12	-6.92
0.50	0.50	-883.62	-495.26	1110.86	-689.44	1309.27	619.83	-1998.71	-0.70	-40.04
0.50	0.75	-1150.52	-493.74	914.81	-822.13	1234.49	412.36	-2056.62	-0.60	-34.56
0.50	1.00	-1124.97	-364.40	701.59	-744.69	1026.79	282.10	-1771.48	-0.18	-10.39
0.50	1.25	-1087.95	-216.74	530.19	-652.35	845.90	193.55	-1498.24	0.11	6.09
0.50	1.50	-1147.64	-83.08	418.59	-615.36	744.24	128.88	-1359.60	-0.51	-29.22
0.75	0.00	-501.95	-256.96	567.37	-379.46	684.59	305.13	-1064.05	-6.72	-385.25
0.75	0.25	-644.08	-370.34	672.04	-507.21	845.04	337.83	-1352.26	1.28	73.50
0.75	0.50	-934.83	-593.93	771.53	-764.38	1088.98	324.60	-1853.36	5.84	334.75
0.75	0.75	-1311.14	-591.82	643.77	-951.48	1151.39	199.91	-2102.87	-0.52	-30.01
0.75	1.00	-1276.18	-436.32	498.17	-856.25	994.09	137.84	-1850.35	0.61	35.08
0.75	1.25	-1298.35	-272.82	378.11	-785.58	873.76	88.17	-1659.34	-0.53	-30.18
0.75	1.50	-1372.26	-110.32	302.03	-741.29	800.83	59.54	-1542.13	-0.26	-14.80
1.00	0.00	-556.65	-283.11	285.28	-419.88	517.44	97.56	-937.32	-0.65	-37.20
1.00	0.25	-677.64	-400.57	338.23	-539.11	644.71	105.61	-1183.82	0.62	35.61
1.00	0.50	-972.38	-641.81	393.06	-807.10	902.86	95.77	-1709.96	0.02	0.97
1.00	0.75	-1381.30	-639.83	331.17	-1010.57	1066.37	55.81	-2076.94	-0.37	-21.12
1.00	1.00	-1362.79	-473.39	258.53	-918.09	956.67	38.58	-1874.76	-0.47	-27.01
1.00	1.25	-1403.01	-299.93	197.86	-851.47	875.59	24.12	-1727.06	-0.18	-10.56
1.00	1.50	-1501.70	-128.10	157.35	-814.90	831.20	16.30	-1646.10	-0.12	-6.65
1.25	0.00	-565.39	-288.73	0.00	-427.06	444.22	17.16	-871.28	0.00	0.00
1.25	0.25	-687.31	-409.06	0.00	-548.18	561.45	13.27	-1109.63	0.00	0.00
1.25	0.50	-985.74	-656.19	0.00	-820.97	827.70	6.73	-1648.66	0.00	0.00
1.25	0.75	-1404.58	-654.51	0.00	-1029.55	1032.80	3.25	-2062.35	0.00	0.00
1.25	1.00	-1388.65	-484.88	0.00	-936.76	939.33	2.56	-1876.09	0.00	0.00
1.25	1.25	-1437.11	-308.84	0.00	-872.98	874.42	1.44	-1747.39	0.00	0.00
1.25	1.50	-1538.79	-132.93	0.00	-835.86	837.42	1.56	-1673.28	0.00	0.00
1.50	0.00	-556.65	-283.11	-285.28	-419.88	518.30	98.41	-938.18	0.56	32.03
1.50	0.25	-677.64	-400.57	-338.23	-539.11	645.40	106.29	-1184.51	-0.22	-12.44
1.50	0.50	-972.38	-641.81	-393.06	-807.10	903.34	96.24	-1710.43	-0.16	-8.98
1.50	0.75	-1381.30	-639.83	-331.17	-1010.57	1066.84	56.27	-2077.40	0.37	21.12
1.50	1.00	-1362.79	-473.39	-258.53	-918.09	957.10	39.01	-1875.19	0.53	30.34
1.50	1.25	-1403.01	-299.93	-197.86	-851.47	876.00	24.53	-1727.47	0.19	10.66
1.50	1.50	-1501.70	-128.10	-157.35	-814.90	831.62	16.72	-1646.52	0.12	6.77
1.75	0.00	-501.95	-256.96	-567.37	-379.46	688.32	308.86	-1067.78	0.08	4.57
1.75	0.25	-644.08	-370.34	-672.04	-507.21	846.29	339.08	-1353.51	0.06	3.69
1.75	0.50	-934.83	-593.93	-771.53	-764.38	1089.77	325.39	-1854.15	0.56	32.12
1.75	0.75	-1311.14	-591.82	-643.77	-951.48	1152.37	200.89	-2103.85	0.52	29.95
1.75	1.00	-1276.18	-436.32	-498.17	-856.25	995.55	139.30	-1851.80	7.19	412.01
1.75	1.25	-1298.35	-272.82	-378.11	-785.58	874.45	88.87	-1660.04	0.75	42.78
1.75	1.50	-1372.26	-110.32	-302.03	-741.29	802.69	61.40	-1543.98	0.27	15.24
2.00	0.00	-284.20	-191.92	-827.78	-238.06	869.75	631.69	-1107.80	-0.34	-19.55
2.00	0.25	-559.54	-301.38	-974.47	-430.46	1066.26	635.81	-1496.72	-0.30	-17.40
2.00	0.50	-883.62	-495.26	-1110.86	-689.44	1309.63	620.19	-1999.07	0.70	40.02
2.00	0.75	-1150.52	-493.74	-914.81	-822.13	1235.26	413.13	-2057.39	0.60	34.52
2.00	1.00	-1124.97	-364.40	-701.59	-744.69	1028.98	284.29	-1773.66	0.17	9.70
2.00	1.25	-1087.95	-216.74	-530.19	-652.35	846.75	194.40	-1499.10	-0.12	-6.93
2.00	1.50	-1147.64	-83.08	-418.59	-615.36	748.40	133.04	-1363.76	0.54	31.21
2.25	0.50	-642.62	-359.67	-1116.96	-501.14	1229.90	728.76	-1731.04	-0.71	-40.95
2.25	1.00	-746.79	-244.11	-717.64	-495.45	881.99	386.54	-1377.43	-0.59	-33.55
2.25	1.25	-657.17	-121.07	-561.36	-389.12	698.68	309.56	-1087.79	2.30	131.61
2.25	1.50	-724.00	-22.64	-463.61	-373.32	607.23	233.91	-980.55	-0.43	-24.45
2.50	0.00	99.3	114.5	-807.7	106.9	814.7	921.6	-707.8	-0.4692	-26.8812
2.50	0.25	-189.91	27.31	-889.34	-81.30	893.05	811.75	-974.35	3.37	193.28
2.50	0.50	-414.97	-220.89	-958.58	-317.93	1014.05	696.12	-1331.98	-0.13	-7.45
2.50	0.75	-438.60	-342.24	-803.26	-390.42	894.50	504.08	-1284.92	0.79	45.19
2.50	1.00	-484.00	-294.79	-644.95	-389.39	755.23	365.84	-1144.62	0.56	32.29
2.50	1.25	-389.86	-181.43	-527.19	-285.65	599.95	314.30	-885.60	-1.26	-72.31
2.50	1.50	-457.3	-99.7	-466.2	-278.5	543.0	264.5	-821.5	-0.2956	-16.9370

Table B.5: Amounts and directions of stresses per node (averaged)

C Calculations

C.1 Drainage capacity current drainage system

To calculate the drainage capacity of the current drainage system the following assumptions are made:

- The drainage system is divided into five areas. These areas are divided in two to four drainage sections. Each drainage section drains to a single pit with assumed locations as depicted in Figure 3.3.
- Each drainage pit is connected to a separate pipeline. The amount of pipelines at the outlet is therefore equal to the amount of assumed drainage pits. Therefore, the actual amount of pipelines per area can differ from the assumed amount. Besides, widening of the separate pipelines does not take place.
- All the pipelines in the same area have the same dimensions. Area 3 (mega drainage) forms an exception to this assumption. Due to its complex subdivision of pipelines, the drainage pits deal with large differences in area of the respective drainage sections. The proportion of pipeline dimensions is therefore equal to the approximate section to be drained by the respective pit (pit 3.1 : pit 3.2 : pit 3.3 : pit 3.4 = 1 : 1.5 : 2.5 : 1).
- The drainage system is always operating on full capacity. This implies that the drainage pipelines are entirely filled up at all times.
- Every pipeline is located one meter below ground level.
- Water can only leave an area by drains.

At first, water accumulation without draining was calculated. In order to do so, accumulation areas were estimated, based on elevation it was determined were water would flow. The surfaces of the areas were multiplied with the amount of rain per day and the daily amounts were summed up. This generated a cumulative water volume per area.

The drainage capacity is retrieved using the data from the fictive hurricane Raúl. Consequently, a storm surge takes place as depicted in Figure 3.1 and the precipitation is equal to Figure 3.4. Drainage capacity (Q) can be calculated using Equation C.1.

$$Q = \frac{A\sqrt{2gH}}{\sqrt{1 + K_e + K_c L}} \tag{C.1}$$

where:

Q = drainage capacity of pipeline (m^3/s)

A = pipe cross-sectional area (m^2)

g = gravitational acceleration (m/s^2)

H = energy head (m)

K_e = entrance loss ($-$)

K_c = friction loss (m^{-1})

L = pipeline length (m)

In case of a submerged outlet of a drainage pipeline (when a storm surge takes place), Figure C.1 can be used when determining the energy head (H). In case of a free outlet, Figure C.2 should be used.

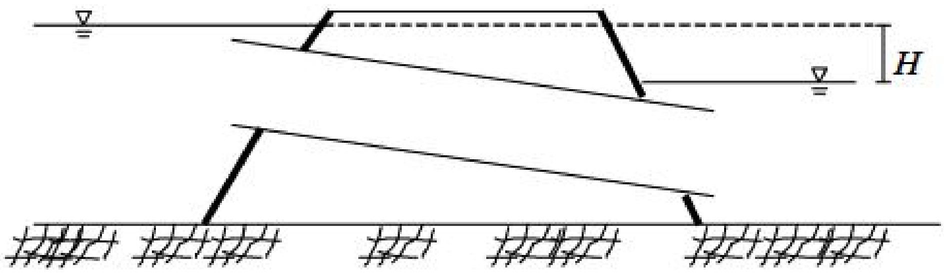

Figure C.1: Example of energy head determination for submerged outlet (Todd Walter, 2008)

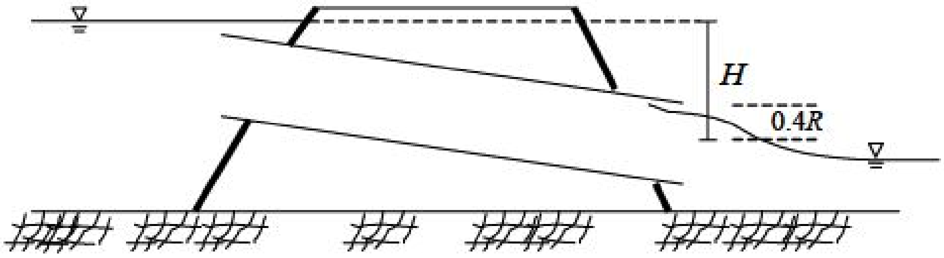

Figure C.2: Example of energy head determination for free outlet (Todd Walter, 2008)

Measurements have been done at location to retrieve the necessary dimensions of the pipelines per area (width, height and water height at a specific moment in a tidal cycle). Global Mapper was used to achieve the heights of the drainage pits (needed when computing the energy head) and the pipeline lengths. The gravitational acceleration is set to 9.81 m/s^2 and the entrance loss to 0.5, assuming a hood drop inlet (Todd Walter, 2008). The friction loss can be calculated using Equation C.2 (Colebrook-White).

$$K_c = \frac{0.25}{R \cdot (log(\frac{k_s}{3.7R} + \frac{5.74}{Rey^{0.9}}))^2} \tag{C.2}$$

where:

R = hydraulic radius pipeline (m)

k_s = roughness coefficient = 0.0015 m (concrete pipeline)

Rey = Reynolds number ($-$) = $\frac{U_e \cdot R}{\nu}$

where:

U_e = entrance velocity (m/s) = $\sqrt{\frac{2gH}{K_e}}$

ν = kinematic viscosity = $1 \cdot 10^{-6}$ m^2/s

The computations have been executed in Maple 2016. The results of these computations can be found in Table C.1. Using this table, the total water accumulation due to hurricane Raúl can be made up per area (see Figure 3.5).

Pit	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5
1.1	17.7	17.7	17.1	17.4	17.7	17.7
1.2	19.2	19.2	18.1	18.7	19.2	19.2
2.1	1.7	1.7	1.3	1.5	1.7	1.7
2.2	2.7	2.7	2.0	2.2	2.7	2.7
3.1	3.0	3.0	2.8	2.9	3.0	3.0
3.2	5.4	5.4	4.9	5.0	5.3	5.4
3.3	10.7	10.7	9.3	9.6	10.5	10.7
3.4	5.0	5.0	3.9	4.2	4.9	5.0
4.1	17.9	17.9	16.2	16.9	17.9	17.9
4.2	19.2	19.2	16.7	17.8	19.2	19.2
4.3	19.6	19.6	14.8	16.9	19.6	19.6
4.4	12.8	12.8	0.0	0.0	12.8	12.8
5.1	16.7	13.4	6.6	8.1	11.2	16.7
5.2	11.2	9.4	6.0	6.7	8.2	11.2

Table C.1: Drainage capacity per pipeline (in m^3/s)

The discharge (m/s) was multiplied by 86,400 to obtain it in m/day. Then the accumulated water volumes per area were calculated by applying Equation C.3. Results can be found in Table C.2 on the next page.

$$V_{acc,n.n,m} = max(V_{acc,n.n,m-1} + V_{prec,n.n,m} - V_{cap,n.n,m} - V_{inf,n.n,m}; 0) \tag{C.3}$$

where:

$V_{acc,n.n,m}$ = the accumulated volume in area $n.n$ on day m (m^3)

$V_{acc,n.n,m-1}$ = the accumulated volume in area $n.n$ on day $m-1$ (m^3)

$V_{prec,n.n,m}$ = the volume of precipitation in area $n.n$ on day m (m^3)

$V_{cap,n.n,m}$ = the volume capacity of pit $n.n$ on day m (m^3)

$V_{inf,n.n,m}$ = the infiltration capacity volume in area $n.n$ on day m (m^3)

Pit	**Day 0**	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**
1.1	0	0	0	0	0	0	0
1.2	0	0	0	0	0	0	0
2.1	0	0	0	0	0	0	0
2.2	0	0	0	0	0	0	0
3.1	0	0	344	419	567	319	40
3.2	0	0	431	473	607	158	0
3.3	0	0	609	564	636	0	0
3.4	0	0	136	35	0	0	0
4.1	0	0	0	0	0	0	0
4.2	0	0	0	0	0	0	0
4.3	0	0	0	0	0	0	0
4.4	0	0	746	1,160	571	0	0
5.1	0	0	717	732	656	0	0
5.2	0	0	167	0	0	0	0
O	0	0	2,906	4.249	6,079	5,541	4,813
S	143	271	1,817	1,036	1,279	96	0
SS	0	50	1,891	1,592	796	0	0

Table C.2: Water accumulation per area ($V_{acc,n.n,m}$ in 10^3 m^3)

C.2 Catchment area: Parks & infiltration fields

To compute the catchment area of an average park or infiltration field, firstly an estimation should be made of an example which is representative for such a park or infiltration field. Assumptions for this example park can be found below:

- The area should be small enough to be able to incorporate the example park at different locations. Therefore, an area of 30x40 meters is taken, which is approximately the size of Guadalupe park.

- The example park is pervious for 90% and has a subsoil fully consisting of phaeozem, which is considered as a sandy loam. The infiltration rate (f) of the phaeozem follows from Table 4.1. Evapotranspiration is neglected, since the estimations do not allow for such a high significance.

- A rainfall event of three days is assumed with an average precipitation rate (P_{avg}) of 0.2 m/d (based on Figure 3.2). It is assumed that water may rise up to half a meter (since treating with an extreme event).

- A runoff coefficient (CF_{runoff}) of 0.8 is assumed, since most of the rainfall already falls in the park. For the other part of the rainfall, the biggest part turns into runoff due to impervious infrastructure and medium to high-populated areas.

Using the estimated infiltration rate of the subsoil, the discharge into the subsoil can be computed. Firstly, the infiltration capacity should be corrected, regarding aspect ratio, biofouling and siltation. The correction factor for biofouling and siltation ($CF_{silt/bio}$) is set to 0.6, due to probable contamination of surface runoff and location of the soil beneath vegetation. Equation C.4 describes the calculation of the correction factor for aspect ratio (CF_{aspect}). Equation C.5 gives the calculation for the corrected infiltration rate (f_{corr}).

$$\begin{aligned} CF_{aspect} &= 0.02 \cdot \frac{L}{W} + 0.98 \\ &= 0.02 \cdot \frac{40}{30} + 0.98 \approx 1.01 \end{aligned} \tag{C.4}$$

$$\begin{aligned} f_{corr} &= CF_{silt/bio} \cdot CF_{aspect} \cdot f \\ &= 0.6 \cdot 1.01 \cdot 1.1 \approx 0.66 \ m/d \end{aligned} \tag{C.5}$$

The effective infiltration area of the park is assumed to be 90% of the total area. The infiltration discharge (Q) follows from Equation C.6.

$$\begin{aligned} Q &= 0.9 \cdot A \cdot f_{corr} \\ &= 0.9 \cdot 1200 \cdot 0.66 = 718 \ m^3/d \end{aligned} \tag{C.6}$$

Using the infiltration discharge, the catchment area of the example park can be computed. The incoming discharge (Q_{in}) is given by the sum of the infiltration discharge and the supplementary discharge (Q_{supp}) due to the allowable ponding height (y_s), see Equation C.7. The catchment area (A_{catch}) for the example park follows from Equation C.8.

$$\begin{aligned} Q_{in} &= Q + Q_{supp} = Q + \frac{y_s \cdot A}{t} \\ &= 718 + \frac{0.5 \cdot 1200}{2} = 1018\ m^3/d \end{aligned} \tag{C.7}$$

$$\begin{aligned} A_{catch} &= \frac{Q_{in}}{CF_{runoff} \cdot P_{avg}} \\ &= \frac{1018}{0.8 \cdot 0.2} = 6360\ m^2 \end{aligned} \tag{C.8}$$

This means that the catchment area of the example park is about 5.3 times its own size. Also, looking at the proportion between the supplementary discharge and the incoming discharge, the capacity of a park gets more than tripled when made impervious. If satisfying the minimum requirement of amount of green space from the World Health Organisation, the green area in the city has to increase with about 1.4 km^2 (almost tripling the initial amount of green space). Such an increase therefore leads to approximately 7.3 km^2 of supplementary catchment area (when accounting for a maximum ponding height of 50 cm), which is about 13.5% of the total city area. This results in 1200 new parks of 1200 m^2, of which approximately 10% (assumption) can be extracted when turning impervious parks into pervious parks. The total infiltration capacity of this amount of parks is equal to about 855,000 m^3/d.

C.3 Wall on the Malecón

Hydraulic calculations

The depth of the surge or wave will be equal to the height, because the structure is located inland. Therefore there are no difference between these values. The formula for the design flood velocity will be used:

$$u_p = \sqrt{gd_s} = \sqrt{9.81 \cdot 1.5} = 7.67\ m/s \tag{C.9}$$

The combined force on the structure will be one of the hydraulic forces combined with the hydrostatic force and impact force. The hydrostatic and impact force are equal to:

$$F_h = \frac{1}{2} \cdot 1027 \cdot 9.81 \cdot 1.5^2 \cdot 2.5 = 11,334\ N \tag{C.10}$$

$$F_i = \frac{500 \cdot 7.67}{9.81 \cdot 0.2} = 1995\ N \tag{C.11}$$

Of all the hydrodynamic forces the one with the largest impact will be used in the construction calculation of the structure.

$$F_d = \frac{1}{2} \cdot 1027 \cdot 1.5 \cdot 3 \cdot 7.67^2 = 170,013\ N \tag{C.12}$$

$$F_{surge} = \frac{9}{2} \cdot 1027 \cdot 9.81 \cdot 1.5^2 \cdot 2.5 = 253,884\ N \tag{C.13}$$

$$F_{wave} = (1.1 \cdot 1.6 + 2.4) \cdot 10030 \cdot 1.5^2 \cdot 2.5 = 234,702\ N \tag{C.14}$$

Name	**Symbol**	**Value**	**Units**
Density	ρ	1027	kg/m^3
Gravitational acceleration	g	9.81	m/s^2
Volumetric weight	γ_{sea}	10,030	N/m^3
Width	w	2.5	m
Area	A	3	m^2
Water height	h	1.5	m
Surge depth	d_s	1.5	m
Drag coefficient	C_d	1.5	-
Dynamic pressure coefficient	C_p	1.6	-

Table C.3: Characteristics and values

Structural calculations

The wall of the malecón exists of repeating movable modules of 2.5x1.5 meter. The modules restricted in translation in x-,y- and z-direction on the bottom, left and right side. The thickness at the bottom side is 0.4 meter and at the top 0.2 meter.

C45/55 is used with: f_{ctd} = 1777 kN/m^2; f_{cd} = 30,000 kN/m^2.
S355 is used with: f_{yd} = 355,000 kN/m^2.
b_{el} = 250 mm (element size)

Tensile reinforcement

The values of the hydraulic calculation were multiplied by the variable load factor (x1.5) and were put in a finite element model program and stresses were obtained per node. Neither σ_{xx}, nor σ_{yy} exceeded the tension strength of the chosen concrete, but principle stresses were calculated on the 70 nodes and these stresses did exceed the tension strength on 35 nodes.

For each node the principle stresses were obtained with Mohr's circle. For the stresses that exceeded the tension stress, the angle (θ) was calculated (see Table B.5). The stress vectors were then put in an coordinate system and the most efficient places for the reinforcement were determined.

As slabs are most often reinforced with an orthogonal grid of bars, also an orthogonal grid was designed and calculated.

Possibility 1	**Possibility 2 - horizontal**	**Possibility 2 - vertical**
$\sigma_{max} = 2340\ kN/m^2$	$\sigma_{max,xx} = 1656\ kN/m^2$	$\sigma_{max,yy} = 839\ kN/m^2$
$b_{tens} = 0.350\ m$	$b_{tens} = 0.360\ m$	$b_{tens} = 0.383\ m$
$h_{tens} = 0.139\ m$	$h_{tens} = 0.139\ m$	$h_{tens} = 0.139\ m$
$A_c = 0.048\ mm^2$	$A_c = 0.050\ mm^2$	$A_c = 0.053\ mm^2$
$F = \sigma_{max} \cdot A_c = 57\ kN$	$F = \sigma_{max} \cdot A_c = 41\ kN$	$F = \sigma_{max} \cdot A_c = 22\ kN$
$A_{s,req} = \frac{F}{f_y} = 160\ mm^2$	$A_{s,req} = \frac{F}{f_y} = 116\ mm^2$	$A_{s,req} = \frac{F}{f_y} = 63\ mm^2$
$d_{req} = \sqrt{\frac{A_{s,req}}{\pi}} = 14.3\ mm$	$d_{req} = \sqrt{\frac{A_{s,req}}{\pi}} = 12.2\ mm$	$d_{req} = \sqrt{\frac{A_{s,req}}{\pi}} = 8.9\ mm$
$d = 16.0\ mm$	$d = 14.0\ mm$	$d = 10.0\ mm$
$A_s = 201\ mm$	$A_s = 154\ mm$	$A_s = 79\ mm$
$\frac{A_s}{A_s} = 0.004 < 0.02\ OK$	$\frac{A_s}{A_s} = 0.005 < 0.02\ OK$	

Table C.4: Results of slab reinforcement calculations

So, in case of the curved reinforcement, bars with a diameter of 16 mm are needed and in case of the orthogonal reinforcement, horizontal bars with a diameter of 14 mm are needed and vertical bars of 10 mm diameter.

Shear reinforcement

The slab is also checked on shear. Due to the support forces, shear is the highest at the edges, as can be seen in Table C.5.

X-coordinate	y=0.00	y=0.25	y=0.50	y=0.75	y=1.00	y=1.25	y=1.50
0.00	35.50	-9.07	-39.91	-25.07	-23.33	-8.39	-9.16
0.25	-4.48	-	-	-	-	-	-
0.50	-28.28	-	-	-	-	-	-
0.75	-34.97	-	-	-	-	-	-
1.00	-36.97	-	-	-	-	-	-
1.25	-37.48	-	-	-	-	-	-
1.50	-36.97	-	-	-	-	-	-
1.75	-34.97	-	-	-	-	-	-
2.00	-28.28	-	-	-	-	-	-
2.25	-4.48	-	-	-	-	-	-
2.50	35.50	-9.07	-39.91	-25.07	-23.33	-8.39	-9.16

Table C.5: Shear forces on slab edges (kN)

The shear capacity is calculated by assuming the slab exists of multiple beams of 0.25 m wide, using Equation C.15.

$$V_{Rd,c} = max\big(C_{Rd,c} \cdot k \cdot (100 \cdot \rho_1 \cdot f_{ck})^{\frac{1}{3}} \cdot b \cdot d;\ (v_{min} + k_1 \cdot \sigma_{cp}) \cdot b_w \cdot d\big) \tag{C.15}$$

where:

$$f_{ck} = 45\ N/mm^2$$

$$k = 1 + \sqrt{\frac{200}{d}} < 2.0$$

$$\rho_1 = max(\tfrac{A_s}{b \cdot d}; 0.02)$$

$$C_{Rd,c} = 0.12$$

$$v_{min} = 0.035 \cdot k^{\frac{3}{2}} \cdot f_{ck}{}^{\frac{1}{2}}$$

As there is no reinforcement near the lower edge the value for ρ_1 is set to zero for all nodes with Y=0. The results are presented in Table C.6.

X (m)	Y (m)	d (mm)	k	ρ_1	A_s (mm^2)	v_{min}	$V_{Rd,min}$ (N)	$V_{Rd,tr}$ (N)	V_{Ed} (N)	UC
0.00	0.50	303.3	1.812	0.00128	106.9	0.573	43,428	29,580	39,910	0.92
2.50	0.50	303.3	1.812	0.00128	106.9	0.573	43,428	29,580	39,910	0.92
1.25	0.00	370.0	1.735	0.00000	0.0	0.537	49,624	0	37,478	0.75
1.00	0.00	370.0	1.735	0.00000	0.0	0.537	49,624	0	36,986	0.74
1.50	0.00	370.0	1.735	0.00000	0.0	0.537	49,624	0	36,986	0.74
0.00	0.75	270.0	1.861	0.00143	106.9	0.596	40,223	28,003	25,075	0.62
2.50	0.75	270.0	1.861	0.00143	106.9	0.596	40,223	28,003	25,075	0.62
0.00	1.00	236.7	1.919	0.00160	106.9	0.624	36,937	26,332	23,326	0.63
2.50	1.0	236.7	1.919	0.00160	106.9	0.624	36,937	26,332	23,326	0.63

Table C.6: Results shear reinforcement calculations

As all unity checks are below 1.00, no shear reinforcement is needed.

Column bending calculations
Concrete class: C45/55: $f_{ck} = 45\ N/mm^2$, $f_{cd} = 30\ N/mm^2$, $c = 30\ mm$. $b = h = 500\ mm$
Steel class: B500B: $f_{yd} = 435\ N/mm^2$, $\phi = 16\ mm$ (assumed)

$$\begin{aligned}
117.2kNm = M_{Ed} < M_{Rd} &= N_s z \\
N_s &= A_s f_{yd} \\
A_s &= n\frac{1}{4}\pi\phi^2 \\
A_c &= bh \\
&= 250,000\ mm^2 \\
k &= \frac{f_{yd}}{f_{cd}} = 11.83 \\
d &= h - c - \frac{1}{2}\phi_{r1} - \frac{1}{2}\phi_{r2} - \phi_s \\
&= 448\ mm \\
\rho &= \frac{A_s}{A_c} \\
&= \frac{A_s}{250,000} \\
x_u &= \frac{3d\rho k}{4} \\
&= 0.0283A_s \\
z &= d - \frac{7}{18}x_u \\
&= 448 - 0.011A_s
\end{aligned} \tag{C.16}$$

The only unknown is A_s and thus the amount of reinforcement (n), if M_{Ed}=M_{Rd} the amount of reinforcement is 3.74. Therefore four rebars of ϕ16mm are used.

Column shear calculations
Concrete class: C45/55: $f_{ck} = 45\ N/mm^2$, f_{cd} =30 N/mm^2, $c = 30\ mm$. $b = h = 500\ mm$
Steel class: B500B: $f_{yd} = 435\ N/mm^2$

$$\begin{aligned}
229.8kN = V_{Ed} < V_{Rd,c} &> V_{min} \\
V_{Rd,c} &= [0.12k(100\rho f_{ck})^{\frac{1}{3}}] \cdot bd \\
&= 109.3\ kN \\
V_{min} &= [0.035k^{\frac{3}{2}} f_{ck}^{\frac{1}{2}}] \cdot bd \\
&= 113.3\ kN \\
k &= 1 + \sqrt{\frac{200}{d}} < 2.0 \\
&= 1.67
\end{aligned} \tag{C.17}$$

The shear resistance is smaller, so shear reinforcement is necessary. Stirrups are chosen with a diameter of 8 mm, so the only unknown is the spacing between the stirrups (s).

$$
\begin{aligned}
V_{Ed} &= 229.8kN < V_{Rd,s} \qquad \text{(C.18)}\\
V_{Rd,s} &= \frac{A_{sw}}{s} z \cdot f_{ywd} \cdot cot(\theta)\\
s &= \frac{A_{sw}}{V_{Rd,s}} \cdot z \cdot f_{ywd} \cdot cot(\theta)\\
\theta &= 21.8^{\circ}\\
f_{ywd} &= 435\ N/mm^2\\
s &> 170.7\ mm
\end{aligned}
$$

So the maximum distance between stirrups is 171 mm over the first 0.5 m and may become larger over the next parts due to a smaller applied shear force. For the stirrups also rebar on the other side of the column is required. For the construction of the column four rebars would come in handy.

$$
\begin{aligned}
F_{cd} &= \sqrt{(V_{Rd,s}^2 cot(\theta)) - V_{Rd,s}^2} \qquad \text{(C.19)}\\
&= 527\ kN\\
A_s &= \frac{F_{cd}}{f_{yd}}\\
&= 1486\ mm^2\\
\phi &= \sqrt{\frac{A_s}{n\pi}}\\
&= 10.9\ mm
\end{aligned}
$$

Therefore 4 rebars of ϕ12 mm will be used.

C.4 Infiltration basin capacity

When computing the capacity of the infiltration basins to relieve Presidentes de México and Ciudad Concordia from their rain burden, a few assumptions have to be made:

- The maximum depth of an infiltration basin usually equals 61 cm. However, due to the large differences in rain intensities throughout the year and the fact that hurricane Raúl only occurs once in fifty years, anaerobic conditions may take place during the largest storms. Furthermore, high water depths will only be present for short time periods and the areas around the basins are low populated. Therefore, water depths can be higher than usual. The specific water depths are also dependent on the groundwater table.

- The water in the infiltration basins will reach until the lowest side of the basin when completely filled. The basin bottom is flat, which results in longer side slopes at the higher basin sides (integrated in Table C.8 & C.11).

- The assumption is made that the soil underneath the basins consists of phaeozem. Nevertheless, the properties for vertisol are also given, which can be used if the soil turns out to have different properties.

- It is assumed that vertisol is a silty clay with a little sand (80% silty clay, 20% sandy clay). Besides, it is assumed that phaeozem is a sandy loam.

- In reality, a sand layer is applied on top of the subsoil to stimulate infiltration. For simplicity, this layer is not taken into account. Its properties are still given.

- The groundwater table (GWT) lies at 3.0 m below ground level. If this means the groundwater table lies below mean sea level, it is assumed that it lies on mean sea level.

- Based on Figure 3.2, a rainfall event of three days is assumed with an average precipitation rate of 0.2 m/d.

Besides, some general soil properties should be known. The three used soil types are sand, vertisol and phaeozem (see Subsection 4.2.3). The soil properties are obtained according to Section Water Control TU Delft (2017). The properties can be found in Table C.7, where n is the porosity, K_s is the saturated hydraulic conductivity, θ_r is the irreducible water content, ψ_b is the displacement pressure head, λ is the pore size distribution index and y_f is the water pressure at the wetting front.

Soil type	n $(-)$	K_s (m/d)	θ_r $(-)$	ψ_b (m)	λ $(-)$	y_f (m)
Sand	0.43	7.1	0.045	0.069	1.68	-0.04
Vertisol	0.36	0.01	0.076	1.67	0.12	-1.45
Phaeozem	0.41	1.1	0.065	0.13	0.89	-0.08

Table C.7: Soil properties

When determining the capacity of the infiltration basin, firstly the infiltration rate (f) should be obtained. This is done by making use of the Green-Ampt infiltration model (see Equation C.20).

$$f = K_s \cdot i = K_s \left[1 + \frac{y_s - y_f}{L_f}\right] \tag{C.20}$$

where:

f = infiltration rate (m/d)

i = hydraulic gradient (m/m)

y_s = water height in infiltration basin (m)

L_f = depth of wetting front below the bottom of the pond (m)

y_f = water pressure at wetting front $(m) = -(\psi_b/2)(2+3\lambda)/(1+3\lambda)$

The infiltration rate of the subsoil is dependent of time and can be illustrated by the curve in Figure C.3. It can be seen that the infiltration curve tends to approach the saturated hydraulic conductivity of the soil type (meaning that the wetting front reached the groundwater table and the hydraulic gradient equals 1). Since the infiltration basin has to deal with a long-lasting hurricane, it is likely that the infiltration rate will reach this value very soon and can therefore be assumed to be equal to the hydraulic conductivity the entire time until all the water has infiltrated. However, this has to be demonstrated first. This can be done by comparing the time water starts ponding on the surface (t_p) with the duration of the hurricane. At t_p, the infiltration capacity (f_c) is equal the inflow per basin area (I), according to Figure C.3. Using Equation C.20, the depth of the wetting front (L_f) can now be computed at t_p. Using this value, t_p can be calculated with Equation C.21.

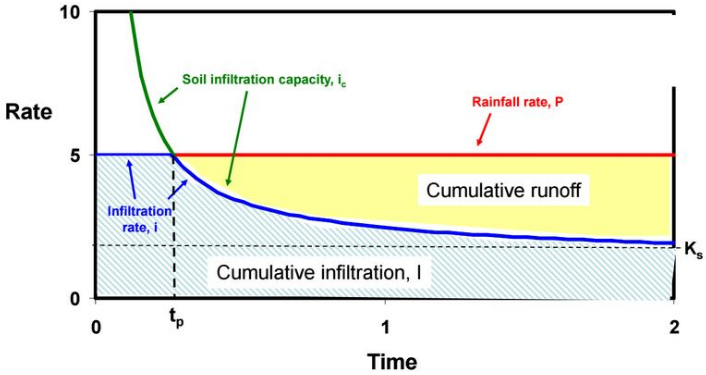

Figure C.3: Infiltration excess curve (Section Water Control TU Delft, 2017)

$$t_p = \frac{K_s(y_s - y_f)(n - \theta_i)}{I(I - K_s)} \tag{C.21}$$

where:

t_p = time when water starts ponding on basin surface $(days)$

θ_i = initial soil moisture content $(-) = \theta_r + (n - \theta_r)\left(\frac{\psi_b}{|y|}\right)^{\lambda}$

where: $|y|$ = water pressure head (distance above water table) (m)

I = inflow per basin area (m/d)

Long-term infiltration rates may be reduced significantly by factors such as biofouling and siltation. Besides, computer simulations also suggest that basins with high aspect ratios (A_{ratio} = length/width) have higher infiltration rates. The correction factor for biofouling and siltation

($CF_{silt/bio}$) is set to 0.7 for all basins, because these conditions are approximately the same at either location. Siltation may occur due to contamination of surface runoff and biofouling is less likely to occur, because the basins are not located in shaded areas nor beneath vegetation. Furthermore, long-term maintenance can turn out to be below average. The correction factor for aspect ratio (CF_{aspect}) is given by Equation C.22. The corrected infiltration rate (f_{corr}) can be computed using Equation C.23.

$$CF_{aspect} = 0.02A_{ratio} + 0.98 \tag{C.22}$$

$$f_{corr} = CF_{silt/bio} \cdot CF_{aspect} \cdot f \tag{C.23}$$

When the corrected infiltration rate is obtained, the flow out of the sides and bottom of the basin (Q) can be computed using Equation C.24.

$$Q = f_{corr}(A_{sides} + A_{bottom}) \tag{C.24}$$

where:

Q = total flow rate of infiltration basin (m^3/d)

A_{bottom} = cross-sectional area of the bottom of the basin in a horizontal plane (m^2)

A_{sides} = cross-sectional area of the submerged basin sides in a vertical plane (m^2)

After three days (T_{event}), the rainfall event comes to an end. At this moment, the basins should be checked on overflow (see Condition C.25). The basins should be empty again after the required draining time (T_{req}) of 72 hours (see Subsection 4.2.3.1). This can be checked using Condition C.26.

$$Q \cdot T_{event} + V_{basin} \geq V_{design} \tag{C.25}$$

$$Q \cdot (T_{event} + T_{req}) \geq V_{design} \tag{C.26}$$

where:

V_{basin} = maximum volume of infiltration basin (m^3)

V_{design} = design volume of infiltration basin (m^3)

The infiltration capacity calculations as described above are based on J.W. Massmann (2003).

Presidentes de México

The following parameters are necessary:

Runoff coefficient = 75% (high-density residential area, concrete infrastructure)

Angle of side slopes = 1 : 3

The inflow per basin area (I) can be determined by assuming a pump discharge for the pipeline which leads to basin 1 and 2. This discharge is set at 1.5 m^3/s which is about 15 % of the current discharge capacity of the Presidentes de México drainage system. Using the basin volume proportions, the inflow per basin area can be computed.

Basin	*Total area* (m^2)	*Bottom area* (m^2)	y_s (m)	I (m/d)	CF_{aspect} ($-$)	A_{sides} (m^2)
1	52,788 (249 × 212)	46,179 (234 × 198)	2.0	1.39	1.00	1844
2	50,150 (295 × 170)	42,766 (280 × 153)	2.0	1.40	1.02	1860

Table C.8: Parameters per infiltration basin (Presidentes de México)

Using the equations introduced above, the intermediate results in Table C.9 can be retrieved.

Basin	GWT (m)	L_f (m)	y (m)	θ_i ($-$)	t_p ($days$)
1	-1.0	7.89	6.89	0.41	0
2	-1.0	7.63	6.63	0.41	0

Table C.9: Intermediate results per infiltration basin (Presidentes de México)

The theoretical wetting front reaches out under the groundwater table (GWT). Therefore, the initial soil moisture content (θ_i) is equal to the porosity of the subsoil. This results in immediate ponding on the basin surface (since $t_p = 0$). The infiltration rate always equals the saturated hydraulic conductivity in this case. Using this, the final results can be made up, illustrated in Table C.10.

Basin	f_{avg} (m/d)	f_{corr} (m/d)	Q (m^3/d)	V_{design} (m^3)	V_{req} (m^3)	V_{basin} (m^3)
1	1.1	0.77	37,110	200,939	111,329	95,124
2	1.1	0.78	34,898	187,861	104,694	88,322

Table C.10: Final results per infiltration basin (Presidentes de México)

Condition C.25 and C.26 are met in both basins.

Ciudad Concordia

The following parameters are necessary:

Catchment area = 2.07 km^2

Runoff coefficient = 60% (medium-density residential area, concrete infrastructure)

Angle of side slopes = 1 : 3

The inflow per basin area (I) can be determined by multiplying the precipitation rate with the catchment area and the runoff coefficient and divide it proportionally over the basin volumes.

Basin	*Total area* (m^2)	*Bottom area* (m^2)	y_s (m)	I (m/d)	CF_{aspect} ($-$)	A_{sides} (m^2)
3	22,410 (270 × 83)	15,924 (250 × 64)	2.0	1.42	1.05	1412
4	33,150 (255 × 130)	29,392 (247 × 119)	1.0	1.12	1.02	770
5	31,200 (260 × 120)	27,344 (250 × 109)	1.0	1.12	1.02	760
6	104,160 (336 × 310)	90,365 (315 × 287)	3.0	1.70	1.00	3876

Table C.11: Parameters per infiltration basin (Ciudad Concordia)

Using the equations introduced above, the intermediate results in Table C.12 can be retrieved.

Basin	$GWT\ (m)$	$L_f\ (m)$	$y\ (m)$	$\theta_i\ (-)$	$t_p\ (days)$
3	0.0	7.15	7.15	0.41	0
4	0.0	59.4	59.4	0.41	0
5	-0.1	59.4	59.3	0.41	0
6	0.0	5.65	5.65	0.41	0

Table C.12: Intermediate results per infiltration basin (Ciudad Concordia)

For all basins, the theoretical wetting front reaches out under the present groundwater table (GWT). Therefore, the initial soil moisture content (θ_i) is equal to the porosity of the subsoil. This results in immediate ponding on the basin surface (since $t_p = 0$). The infiltration rate always equals the saturated hydraulic conductivity in this case. Now, the final results, as shown in Table C.13, can be made up.

Basin	$f_{avg}\ (m/d)$	$f_{corr}\ (m/d)$	$Q\ (m^3/d)$	$V_{design}\ (m^3)$	$V_{req}\ (m^3)$	$V_{basin}\ (m^3)$
3	1.1	0.81	14,027	73,820	42,081	33,967
4	1.1	0.79	23,698	101,345	71,093	30,547
5	1.1	0.79	22,171	94,428	66,512	28,484
6	1.1	0.77	72,699	480,504	218,096	276,909

Table C.13: Final results per infiltration basin (Ciudad Concordia)

Condition C.25 is met for all basins, so no overflow will occur during the considered rainfall event. However, Condition C.26 is not met for Basin 6, which means it will not be drained entirely within 72 hours after the rainfall event. This can be counteracted when installing a drainage pipeline to one of the lower located basins. Opening this pipeline after the rainfall event will allow all the water to infiltrate within the required drainage time.

C.5 Water squares

Volume of water square

In the following calculations it is assumed that the groundwater level lies at three meters below ground level. Another assumption that is made is that the maximum precipitation in one hour is equal to 125 mm.

Water accumulation in Las Flores

Volume of prototype B:

$$\begin{aligned} V &= Total\ volume\ tank - construction\ parts \\ &= 80 \cdot 3.35 \cdot 40 - 4 \cdot 8 \cdot (3.35 \cdot 0.2^2) \\ &- 2 \cdot 8 \cdot 40 \cdot 0.2^2 - 2 \cdot 4 \cdot 80 \cdot 0.2^2 \\ &= 10,664\ m^3 \end{aligned} \tag{C.27}$$

When the water height exceeds the 0.3 m in the top of the tank, the water flows towards the tank underneath it (see Figure A.51). When including this 0.3 m, the total capacity is:

$$\begin{aligned} V_{total} &= 10,654 + 0.3 \cdot 40 \cdot 80 \\ &= 11,654\ m^3 \end{aligned} \tag{C.28}$$

Water accumulation in Las Flores after one hour of peak precipitation:

$$V_{acc,Flores} = \gamma \cdot \frac{A_{Flores}}{A_{3.2}} \cdot \rho \cdot V_{Acc,3.2} \tag{C.29}$$

$$= 1.5 \cdot \frac{122,500}{3,130,884} \cdot 0.44 \cdot 401,142$$

$$= 10,428\ m^3 \tag{C.30}$$

γ is a factor related to the catchment area of Las Flores. A_{Flores} is the area of the neighbourhood Las Flores, $A_{3.2}$ is the area of the total inlet 3.2 where Las Flores is part of. The ρ is the ratio between the rain of 125 mm/h and the total rain on day 2 of Raúl: 282.2 mm/day. This total rainfall creates an accumulation of 401,142 m^3 (=$V_{acc,3.2}$).

Capacity of water square type D

Volume capacity of the areas around the field:

$$V_{ring,1+2} = 681\ m^3 \tag{C.31}$$

$$\begin{aligned} V_{ring,1} &= (A_{total} - A_{inside,1}) \cdot d = (80 \cdot 40 - 77 \cdot 37) \cdot 1 \\ &= 351\ m^3 \\ V_{ring,2} &= (A_{inside,1} - A_{inside,2}) \cdot d = (76.5 \cdot 36.5 - 73.5 \cdot 33.5) \cdot 1 \\ &= 330\ m^3 \end{aligned}$$

Total volume capacity:

$$\begin{aligned} V_{total} &= V_{field} + V_{ring,1+2} + V_{ring,extra} \\ &= 10,542\ m^3 \end{aligned} \tag{C.32}$$

$$\begin{aligned} V_{field} &= b \cdot l \cdot d = 72.5 \cdot 32.5 \cdot 3 \\ &= 7068.5 m^3 \\ V_{ring,extra} &= b \cdot l \cdot d = 76.5 \cdot 36.5 \cdot 1 \\ &= 2794.5\ m^3 \end{aligned}$$

Catchment area:

$$\begin{aligned} A_{storage} &= \frac{V_{total}}{h_{precipitation}} \\ &= \frac{10,542}{0.125} = 84,336\ m^2 \end{aligned} \tag{C.33}$$

$$\begin{aligned} Reduction &= \frac{A_{storage}}{A_{Concordia}} \\ &= \frac{84,336}{2,000,000} = 4.2\% \end{aligned} \tag{C.34}$$

$$Total\ possible\ reduction = 11 \cdot 4.2\% = 46\% \tag{C.35}$$

Structural calculations

Loads are specified as follows:

Variable loads:

$$q_{people} = 2.94\ kN/m^2$$
$$q_{rainwater} = 3.00\ kN/m^2$$

Permanent loads:

$$q_{topslab} = 25.0\ kN/m^3$$
$$q_{soil,hor,0.00m} = 0.0\ kN/m^3$$
$$q_{soil,hor,3.00m} = 33.0\ kN/m^3$$
$$q_{soil,hor,4.67m} = 58.2\ kN/m^3$$

As it is very unlikely that the squares will be full of water and full of people at the same time, the variable loads are in turn multiplied by a combination factor.

$$LC1 : 1.2 \cdot (q_{topslab} + q_{soil,hor}) + 1.5 \cdot q_{people} + 0.2 \cdot 1.5 \cdot q_{rainwater} \tag{C.36}$$
$$LC2 : 1.2 \cdot (q_{topslab} + q_{soil,hor}) + 0.2 \cdot 1.5 \cdot q_{people} + 1.5 \cdot q_{rainwater} \tag{C.37}$$

Prototype category B, the football field with water storage in the basement

Side slab
Characteristics:

$$L = 80.00\ m$$
$$h = 4.67\ m$$
$$t = 0.5\ m$$
$$E = 36 \cdot 10^6\ kN/m^2$$
$$\nu = 0.2$$
$$f_{ck} = 45 \cdot 10^3\ kN/m^2$$

From DIANA: $\sigma_{1,max} = 853.1\ kN/m^2$ and $\sigma_{2,min} = -571.6\ kN/m^2$. From these stresses it can be concluded that no longitudinal reinforcement is needed.

From DIANA: $V_{Ed,x=8k,y=-2.5} = 178.8\ kN$ and $V_{Rd,min} = 115.4\ kN$ (method Appendix C.3). So shear reinforcement is needed. With a diameter of 10 mm, the spacing between the bars has to be 213.7 mm around all points with coordinates $x = 8k$ and $y = -2.5$.

Top slab
The top slab is 80x40 m^2 with a column grid beneath it, with a distance of 8.0 m, and the side slabs as supports. For calculation this slab is calculated as one element, clamped at all sides.

Characteristics:

$$L = 8.00\ m$$
$$b = 8.00\ m$$

$t \quad = 0.35\ m$

$E \quad = 36 \cdot 10^6\ kN/m^2$

$\nu \quad = 0.2$

$f_{ck} \quad = 45 \cdot 10^3\ kN/m^2$

From DIANA: $\sigma_{1,max} = 1963.0\ kN/m^2$ and $\sigma_{2,min} = -1060.0\ kN/m^2$. From these stresses it can be concluded that longitudinal reinforcement is needed.

It is chosen to apply an orthogonal grid of reinforcement. The reinforcement is calculated by considering parts of the slab as tensile members of separate beams of 0.5 m width. With a height of the slab of 0.35 m and a compression height of 0.12 m, the tensile member is 0.23 m. As the the concrete cracks when the stress is over 1777 kN/m^2, only the part that cracks times the width is taken as area on with the maximum stress is assumed.

$\sigma_{max} \quad = 1963.0\ kN/m^2$

$b \quad = 0.5\ m$

$h_{tens+} \quad = 0.022\ m$

$A_{c,tens+} \quad = 0.011\ m^2$

$F \quad = 21.7\ kN$

$f_y \quad = 355{,}000\ kN/m^2$

$A_{s,req} \quad = 61.13\ mm^2$

$d_{req} \quad = 8.82\ mm$

$d \quad = 10\ mm$

$A_s \quad = 78.54\ mm^2\ per\ 0.5\ m$

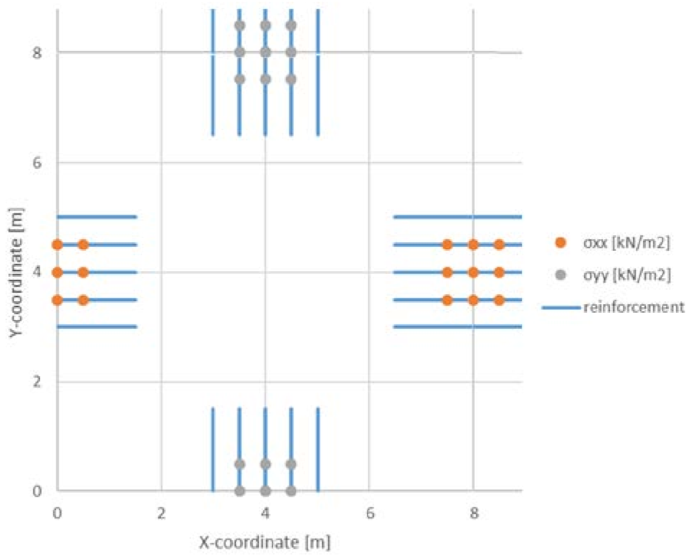

Figure C.4: Result reinforcement calculation top slab

$V_{Ed,max} = 27.13\ kN$ and $V_{Rd} = 88.12\ kN$ (method Appendix C.3). Since $V_{Ed,max} < V_{Rd}$, no shear reinforcement is needed.

Bottom slab
The bottom slab needs to withstand the groundwater pressure, by doing so the slab will be in balance and will not have any bending. The water pressure due to the large amount of water on top of the slab will be withstand by the soil underneath, which is assumed to be infinitely stiff. The groundwater level is assumed to be 3.0 m below ground level. Therefore the formula for the thickness of the slab will be:

$$\gamma_{concrete} \cdot t = \gamma_{water} \cdot ((4-3)+t) \tag{C.38}$$

$$\begin{aligned} t &= 0.67\ m \\ \gamma_{concrete} &= 25\ kN/m^3 \\ \gamma_{water} &= 10\ kN/m^3 \end{aligned}$$

Thus a slab of 0.67 m will be sufficient.

Columns
The columns of the construction have to be checked on two different capacities: buckling and collapse due to pressure. The columns are designed with a grid of 8.0x8.0 meters, thus have to carry an area of 64 m^2 with a water load of 0.3 m and people. According to Evenementenveiligheid (2013) the maximum allowable amount of persons on a square meter is four. The total load on the column comes down to:

$$\begin{aligned} F_{Ed} &= 64 \cdot (1.2 \cdot q_{selfweight} + 1.5 \cdot q_{people} + 1.5 \cdot 0.2 \cdot q_{rainwater}) \\ &= 1017\ kN \end{aligned} \tag{C.39}$$

$$\begin{aligned} q_{people} &= 2.94 kN/m^2 \\ q_{rainwater} &= 3\ kN/m^2 \\ q_{selfweight} &= \gamma_{concrete} \cdot t \\ &= 25 \cdot 0.35 = 8.75\ kN/m^2 \end{aligned}$$

The buckling capacity is calculated by Euler's formula:

$$\begin{aligned} F_k &= \frac{\pi^2 EI}{l_k^2} \\ &= \frac{\pi^2 \cdot 36,000 \cdot 1.33 \cdot 10^8}{1.675^2} = 4217\ kN \end{aligned} \tag{C.40}$$

$$\begin{aligned} I &= \frac{bh^3}{12} = \frac{0.2^4}{12} = 1.33 \cdot 10^8\ mm^4 \\ l_k &= \frac{1}{2} l = 1.675\ m \end{aligned}$$

The collapse load due to pressure:

$$\begin{aligned} F_{collapse} &= f_{cd} \cdot A \\ &= 30,000 \cdot 0.2^2 = 1200\ kN \end{aligned} \tag{C.41}$$

Both resisting forces are larger than the applied force, therefore columns of 200x200 mm^2 will be sufficient.

Struts
The struts supporting the side slabs can also succumb due to buckling and pressure. The formulas are the same as for the columns, only the length of the struts is 8.0 m and the struts are clamped at the connection. The height and width of the struts are equal to the column: 0.2x0.2 m^2. According to the calculations of DIANA, the compressing force is equal to 178.76 kN.

The buckling capacity:

$$\begin{aligned} F_k &= \frac{\pi^2 EI}{l_k^2} \\ &= \frac{\pi^2 \cdot 36,000 \cdot 1.33 \cdot 10^8}{5.6^2} = 1509\ kN \\ I &= \frac{bh^3}{12} = \frac{0.2^4}{12} = 1.33 \cdot 10^8\ mm^4 \\ l_k &= 0.7 \cdot l = 5.6\ m \end{aligned} \tag{C.42}$$

The collapse load due to pressure:

$$\begin{aligned} F_{collapse} &= f_{cd} \cdot A \\ &= 30,000 \cdot 0.2^2 = 1200\ kN \end{aligned} \tag{C.43}$$

Both resisting forces are larger than the applied force, therefore beams of 200x200 mm^2 will be sufficient.

Prototype category D, the deepened soccer field

Side slab
The side slab of the deepened soccer field is similar to the side slab of the football field with water storage in the basement, except that the slab is not horizontally supported at the top and halfway by horizontal struts, but by anchors at $x = k \cdot 4\ m$ and $y = -1.5\ m$.

Characteristics:

$L = 80.00\ m$

$h = 4.67\ m$

$t = 0.60\ m$

$E = 36 \cdot 10^6\ kN/m^2$

$\nu = 0.2$

$f_{ck} = 45 \cdot 10^3\ kN/m^2$

From DIANA all stresses are far below the tension strength of concrete, so no longitudinal reinforcement is needed.

There are two typical shear locations: shear at the edges (similar to previous calculation with regard to shear resistance) and punching shear due to the anchors.

From DIANA: $V_{Ed,max} = 64.65\ kN$ and $V_{Rd} = 134.46\ kN$ (method Appendix C.3). Since $V_{Ed,max} < V_{Rd}$, no shear reinforcement is needed at the edges.

For the locations where the anchors are attached, reinforcement may be necessary. $V_{Ed} = 208.50\ kN$ at the anchors. Punching shear has to be calculated. The following dimensions are assumed:

$$\begin{aligned} l_{plate} &= 300\ mm \\ b_{plate} &= 300\ mm \\ d &= h/2 - c - d_x - 1/2 \cdot d_y = 252\ mm \end{aligned}$$

From the known acting shear force the needed amount of reinforcement is calculated with the following formulas:

$$F_{sd} = 0.12 \cdot \xi \cdot (100 \cdot \rho \cdot f_{ck})^{\frac{1}{3}} \cdot u_1 \cdot d = 208.50\ kN \tag{C.44}$$

$$\xi = 1 + \sqrt{\frac{200}{d}} = 1.89 \tag{C.45}$$

$$u_1 = 2 \cdot l_{plate} + 2 \cdot b_{plate} + 2 * \pi \cdot 2 \cdot d = 4366.73\ mm \tag{C.46}$$

From this it can be concluded that a ρ of 1.29% is required and with $\rho = \sqrt{\rho_x \cdot \rho_y}$ and the fact that the slab consists of square elements, $\rho_{x,req} = \rho_{y,req} = 1.29\%$. With an area of $A_{cx} = A_{cy} = 784,800\ mm^2$, this results in bar diameters of 18 mm with a spacing of 65.4 mm.

Anchors

The tensile forces applied to the anchors have to be less than the resisting anchor wall force, which is given in the slab calculations: The design value for the resisting anchor force is:

$$F_{Rd,wall} = 1.1 \cdot F_T \tag{C.47}$$

$$\begin{aligned} F_{R,wall} &= K_p \cdot \frac{1}{2} \cdot \gamma' \cdot h^2 \cdot w - K_a \cdot \frac{1}{2} \cdot \gamma' \cdot h^2 \cdot w = (K_p - K_a) \cdot \frac{1}{2} \cdot \gamma' \cdot h^2 \cdot w \\ &= (3 - \frac{1}{3}) \cdot \frac{1}{2} \cdot 19 \cdot 2^2 \cdot w \end{aligned} \tag{C.48}$$

Therefore, the only unknown is the width of the anchor wall:

$$w = \frac{1.1 \cdot 208.5}{(3 - \frac{1}{3}) \cdot \frac{1}{2} \cdot 19 \cdot 2^2}$$

$$w = 2.3\ m$$

The soil is unknown, so the assumption is made that it is vertisol, with an effective volumetric weight of 19 kN/m^3 and an angle of internal friction of 30 degrees. This results in an active and passive soil pressure coefficient of:

$$K_a = \frac{1 - sin(\phi')}{1 + sin(\phi')} = \frac{1}{3}$$

$$K_p = \frac{1}{K_a} = 3$$

The anchor wall and water square wall are held together by tie rods. These tie rods are from steel and have to be able to withstand the tension force generated by the soil:

$$A_s = \frac{F_T}{f_{yd}} = \frac{208.5 \cdot 10^3}{435} = 479\ mm^2$$

$$\phi = \sqrt{\frac{479}{\pi \cdot \frac{1}{4}}} = 25\ mm$$

Thus, tie rods of 25 mm are used in the anchor construction.

Symbol	**Value**	**Units**	**Description**
F_T	208.5	kN	Tensile anchor force applied
K_p	3	-	Passive soil pressure coefficient
K_a	$\frac{1}{3}$	-	Active soil pressure coefficient
γ_{soil}	19	kN/m^3	Effective volumetric weight
h	2	m	Depth of the bottom of anchor wall below ground level
w	2	m	Width of anchor wall

Table C.14: Characteristics and Values

Bottom slab

The bottom a tie-rod slab of category D is at the same depth as that from category B and therefore has the same thickness, namely 0.67 m.

C.6 Comparison options

In order to make it possible to compare the different solutions, the amount of volume that each solution reduces over the total period of the hurricane is calculated.

The volumes of the 0-scenario, described in Chapter 3, are taken as start volumes and the capacities calculated in the different options are subtracted from these start volumes.

C.6.1 Parks

To calculate the remaining water volumes in the city if parks are applied, the capacity per square meter park from the calculations is multiplied with the surface of created park per area. As parks withdraw each day a specific amount of water from their surroundings (see Equation C.8), the obtained value is subtracted each day. The volumes are calculated by the following formula:

$$V_{acc,parks,n.n,m} = max(V_{acc,n.n,m-1} + V_{prec,n.n,m} - V_{cap,n.n,m} - V_{inf,n.n,m} - V_{parks,n.n}; 0) \quad \text{(C.49)}$$

where:

$V_{acc,parks,n.n,m}$ = the accumulated volume in area $n.n$ on day m when applying parks(m^3)

$V_{acc,n.n,m-1}$ = the accumulated volume in area $n.n$ on day $m-1$ (m^3)

$V_{prec,n.n,m}$ = the volume of precipitation in area $n.n$ on day m (m^3)

$V_{cap,n.n,m}$ = the volume capacity of pit $n.n$ on day m (m^3)

$V_{inf,n.n,m}$ = the infiltration capacity volume in area $n.n$ on day m (m^3)

$V_{parks,n.n}$ = the extra infiltration capacity volume in area $n.n$ per day due to parks

Area	**Day 0**	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	$V_{parks,n.n}$
1.1	0	0	0	0	0	0	0	42
1.2	0	0	0	0	0	0	0	16
2.1	0	0	0	0	0	0	0	5
2.2	0	0	0	0	0	0	0	10
3.1	0	0	310	350	463	181	0	35
3.2	0	0	380	372	456	0	0	50
3.3	0	0	525	397	386	0	0	84
3.4	0	0	108	0	0	0	0	28
4.1	0	0	0	0	0	0	0	17
4.2	0	0	0	0	0	0	0	42
4.3	0	0	0	0	0	0	0	54
4.4	0	0	702	1,072	439	0	0	44
5.1	0	0	641	579	428	0	0	76
5.2	0	0	127	16	0	0	0	41
O	0	0	2,698	3,834	5,456	4,710	3,775	208
S	0	109	1,652	871	1,114	0	0	104
SS	0	50	1,891	1,592	796	0	0	0

Table C.15: Water accumulation per area if parks are applied ($V_{acc,parks,n.n,m}$ in 10^3 m^3)

The total reduced water volume due to parks is $7432 * 10^3\ m^3$ over the time the hurricane is present.

C.6.2 Wall on the Malecón

To calculate the remaining water volumes in the city if a wall on the Malecón is applied, the volumes of Area SS are set to zero. This results in the following table:

Area	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
1.1	0	0	0	0	0	0	0
1.2	0	0	0	0	0	0	0
2.1	0	0	0	0	0	0	0
2.2	0	0	0	0	0	0	0
3.1	0	0	344	419	567	319	40
3.2	0	0	431	473	607	158	0
3.3	0	0	609	564	636	0	0
3.4	0	0	136	35	0	0	0
4.1	0	0	0	0	0	0	0
4.2	0	0	0	0	0	0	0
4.3	0	0	0	0	0	0	0
4.4	0	0	746	1,160	571	0	0
5.1	0	0	717	732	656	0	0
5.2	0	0	167	0	0	0	0
O	0	0	2,906	4.249	6,079	5,541	4,813
S	143	271	1,817	1,036	1,279	96	0
SS	0	0	0	0	0	0	0

Table C.16: Water accumulation per area if a wall is applied ($V_{acc,wall,n.n,m}$ in $10^3\ m^3$)

The total reduced water volume due to the wall is $4329 * 10^3\ m^3$ over the time the hurricane is present.

C.6.3 Infiltration basins

To calculate the remaining water volumes in the city if infiltration basins are applied, the daily volume capacities (Appendix C.4 & C.4) are subtracted from the 0-scenario volumes. This is done by applying the following formula:

$$V_{acc,basins,n.n,m} = max(V_{acc,n.n,m-1} + V_{prec,n.n,m} - V_{cap,n.n,m} - V_{inf,n.n,m} - V_{b,n.n,m}; 0) \quad (C.50)$$

where:

$V_{acc,basins,n.n,m}$ = the accumulated volume in area $n.n$ on day m when applying infiltration basins(m^3)

$V_{acc,n.n,m-1}$ = the accumulated volume in area $n.n$ on day $m-1$ (m^3)

$V_{prec,n.n,m}$ = the volume of precipitation in area $n.n$ on day m (m^3)

$V_{cap,n.n,m}$ = the volume capacity of pit $n.n$ on day m (m^3)

$V_{inf,n.n,m}$ = the infiltration capacity volume in area $n.n$ on day m (m^3)

$V_{b,n.n,m}$ = the extra infiltration capacity volume in area $n.n$ per day due to infiltration basins

Area	Day 0	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	$V_{b,n.n,0-4}$	$V_{b,n.n,5-6}$
1.1	0	0	0	0	0	0	0	0	0
1.2	0	0	0	0	0	0	0	0	0
2.1	0	0	0	0	0	0	0	0	0
2.2	0	0	0	0	0	0	0	0	0
3.1	0	0	344	419	567	319	40	0	0
3.2	0	0	431	473	607	158	0	0	0
3.3	0	0	609	564	636	0	0	0	0
3.4	0	0	136	35	0	0	0	0	0
4.1	0	0	0	0	0	0	0	0	0
4.2	0	0	0	0	0	0	0	0	0
4.3	0	0	0	0	0	0	0	0	0
4.4	0	0	746	1,160	571	0	0	0	0
5.1	0	0	467	231	0	0	0	250	133
5.2	0	0	167	0	0	0	0	0	0
O	0	0	2,776	3,990	5,690	5,080	4,280	130	72
S	143	271	1,817	1,036	1,279	96	0	0	0
SS	0	50	1,891	1,592	796	0	0	0	0

Table C.17: Water accumulation per area if basins are applied ($V_{acc,basins,n.n,m}$ in 10^3 m^3)

The total reduced water volume due to infiltration basins is $3783 * 10^3$ m^3 over the time the hurricane is present.

C.6.4 Water squares

The amount of water volumes reduced by water squares is calculated by multiplying the amount of applied water squares with their volumes. Since water squares have an limited capacity and will not withdraw any water from their surroundings when they are filled, the reduced volume is the total accumulated volume minus the volume of the applied water squares. The following formula is applied until the squares are filled:

$$V_{acc,sq,n.n,m} = max(V_{acc,n.n,m-1} + V_{prec,n.n,m} - V_{cap,n.n,m} - V_{inf,n.n,m} - V_{sq,n.n}; 0) \quad (C.51)$$

When the squares are fully filled, the following formula is applied:

$$V_{acc,sq,n.n,m} = max(V_{acc,n.n,m-1} + V_{prec,n.n,m} - V_{cap,n.n,m} - V_{inf,n.n,m}; 0) \quad (C.52)$$

where:

$V_{acc,sq,n.n,m}$ = the accumulated volume in area $n.n$ on day m when applying squares (m^3)

$V_{acc,n.n,m-1}$ = the accumulated volume in area $n.n$ on day $m-1$ (m^3)

$V_{prec,n.n,m}$ = the volume of precipitation in area $n.n$ on day m (m^3)

$V_{cap,n.n,m}$ = the volume capacity of pit $n.n$ on day m (m^3)

$V_{inf,n.n,m}$ = the infiltration capacity volume in area $n.n$ on day m (m^3)

$V_{sq,n.n}$ = the extra capacity volume in area $n.n$ due to water squares

Area	**Day 0**	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	$V_{sq,n.n}$
1.1	0	0	0	0	0	0	0	0
1.2	0	0	0	0	0	0	0	0
2.1	0	0	0	0	0	0	0	0
2.2	0	0	0	0	0	0	0	0
3.1	0	0	319	394	541	294	0	26
3.2	0	0	392	434	579	119	0	38
3.3	0	0	545	500	572	0	0	64
3.4	0	0	110	9	0	0	0	26
4.1	0	0	0	0	0	0	0	0
4.2	0	0	0	0	0	0	0	0
4.3	0	0	0	0	0	0	0	0
4.4	0	0	707	1,121	533	0	0	38
5.1	0	0	653	668	593	0	0	64
5.2	0	0	129	0	0	0	0	38
O	0	0	2,739	4,083	5,912	5,375	4,646	166
S	66	197	1,740	959	1,202	19	0	77
SS	0	50	1,891	1,592	796	0	0	0

Table C.18: Water accumulation per area if water squares are applied ($V_{acc,sq,n.n,m}$ in 10^3 m^3)

The total reduced water volume due to applying 42 water squares is $2330 * 10^3$ m^3 over the time the hurricane is present.

D Elements of solutions

During the initial brainstorm for possible solutions we came down to thirteen realistic options within three different fields: draining, retaining and storing. These options were evaluated on their state of being realistic, what the plan would look like, their pros and cons and possible side effects.

D.1 Draining solutions

Drainage pipe expansion
The current drainage system is in some areas not sufficient for the expected rainfall of an hurricane. In some neighbourhoods of Campeche there is not even a drainage system at all. With an expansion of the current drainage system, inundations in certain parts of Campeche can be reduced. During one of our meetings it became clear there have been some new plans to expand the drainage system to the parts that are not connected yet. Therefore, our interference in these plans are not of priority.

Flush streets
In the current situation Calle 14 in the historical centre of Campeche is used as a so called 'flush street'. Rainfall from surrounding streets are led to this street through elevation differences. At the beginning of the street, it has a normal elevation in comparison with the sidewalk. At the end, the surface of the street is almost 1.5 meter below the sidewalk. In order to drain the water, there is an inlet of the drainage system as can be seen in Figure G.6. This is an aged solution and far from ideal with traffic and parked cars. Moreover the elevation within the current streets have to be altered, making it an intensive transition.

Pumps & Gates
Within this solution there are two different possibilities to use pumps and gates. Campeche has a lot of elevation differences throughout the city. Due to this, some lower located areas are hard to drain because of the natural flow direction is contradicted to the desirable flow direction. In order to drain lower located areas, pumps can be installed to transport the water to higher located storage areas or dump areas. As a result of pumps, the drainage system is more efficient. The second option is to use pumps with the combination of gates. In an event of high tide, seawater can infiltrate in the drainage system. In order to prevent this, gates can be installed at the outlets of the drainage canals which keep the water from passing through. The drainage function of the pipes can still be fulfilled by placing pumps. In a storm situation the pressure from precipitation within the city will be larger than the pressure from sea. Therefore, gates do not have any function during a storm.

More pits
Local inundations due to micro elevation can be solved with the construction of more pits along the street. The problem with the construction of more pits, is the required connection to the drainage system. Otherwise it has no additional value to the system. This solution is therefore only useful to local inundations area with a connection to the drainage system near the pits. Since the construction of pits is a relatively common solution, it can be executed without a large planning phase.

D.2 Retaining solutions

Mangroves
Along the entire coastline of Campeche, directly on the seaside of the Malecón a muddy coastal stretch with mangroves can be installed forming a connection with the current mangroves of Los Petenes. It has various advantages, it is a natural sea defence causing wave reduction and a buffer against sea-level rise by trapping sediments as well as it forms a habitat to many species and a sequester of large amounts of carbon. It is a cheap solution that needs no maintenance. On the other hand, sufficient amount of fresh water is needed, it may degrade the present ecosystem and it cannot grow with contamination. It affects the view of the Malecón towards the sea gravely and it does not block the storm surge during a hurricane.

Wall on the Malecón
As can be seen in Figure 2.9 there is a large area at the coast that will be inundated in case of a storm surge of 2.67 meter. In order to protect the city from this storm surge a retaining wall can be constructed on the Malecón. The location of the retaining wall can be placed at different parts of the Malecón. On the landside of the Malecón, between the two driver lanes or on the seaside of the Malecón. The height of this wall need to be approximately 1.5 m from the surface level of the Malecón. The total length that it need to cover is approximately 7.0 kilometres. The choice between the locations of the wall on the Malecón can have a lot of influence on the construction, since in the case of a wall on the landside of the Malecón, streets perpendicular to the Malecón, need to be crossed. For every perpendicular street, a particular kind of gate or temporarily wall need to be installed in order to ensure the traffic has no nuisance of the wall during normal use of the Malecón.

Deepening seaside of coastline
The wave height depends on the depth of the coastline. The shallower the coastline, the higher the wave height. Deepening the seaside of the coastline reduces the wave height during storms. The soil near the seaside needs to be excavated all along the coastline of Campeche. This is a time costly project where the result will be for very few moments and also will only make little difference. Therefore this is not a reasonable option.

D.3 Storing solutions

Canal
An option to store a large amount of water throughout the city is to build a canal. The canal can store and discharge large volumes towards the sea. There are several downsides to this idea. There is no river nearby where the canal can be connected to. Therefore it has to be connected on both sides by the sea, creating a non-flowing salt water canal or it is filled with rainwater, forming a canal that it empty a large part of the year. Another downside of a canal is the fact that Campechanos tend to use it as garbage disposal, throwing small and large garbage into the canal knowing this will flow towards the sea. This also occurs in small canals towards the Ría.

Parks and infiltration fields
To locally store water, an option is to sacrifice space of the city to create parks. The amount of green in the city will be increased to acceptable limits (see Subsection 2.1.2.5). Not only parks reduce flood risk as the city offers more permeable spaces, also the groundwater will be cleaner due to its natural filtering. Furthermore parks result in lower burdens on drainage systems. Moreover parks make urban spaces greener, healthier and more enjoyable, which improves quality of life, create more pleasant landscape aesthetics and recreational areas that attract people. This also means increase in land value. And last but not least parks enrich biodiversity and are therefore responsible solutions in ecological view.

Road greening
Roads in Campeche consist for almost 100% of concrete or asphalt and therefore do not let any water pass. Furthermore roads in Campeche are quite wide for how many traffic lanes are on it. These characteristics make it possible to do a road greening improvement in order to make roads more water absorbing. Not often used parts of the road can be paved with grass-concrete paving and parts that are not used at all to ride on can be transformed to water retardant green strips. These solutions will increase the water storing capacity of the city and might increase the street view a little. Both solutions are low-maintenance and can be applied when roads are anyway to be replaced.

Natural basins
Natural basins outside the urban area create extra storage area, for some neighbourhoods it is easier to transport rainwater to the basins than to the sea. To make this possible it is necessary to construct a new pipeline towards these basins and levelling areas for the basin. Natural basins are used at the moment in Campeche therefore easy to implement.

Retention on roofs
To reduce the intensity of the water on the drainage system there is an option to create buffers on the roofs of buildings in the city. The majority of the buildings of Campeche has a flat roof that is ideal for collecting water. In the present situation, rainfall is distributed directly to the street where it gets distributed to the drainage system. Most of the time this is done through gutters along the street or in the case of no gutter by the fully width of the street. It is a common event, streets are accumulated with water due to a normal rainfall event. In the case water is collected in retention tanks, it can cause an intensity peak decrease for the drainage system. Besides, water in the retention tanks can be used as grey water in houses. In order to achieve this, some adjustments need to be made to the 'in-house' water systems. Looking to the capacity of retention tanks that are used in other cities, this solution can only be functional when it is carried out on a large scale. Furthermore, it will be hard for the municipality to convince the inhabitants to install a retention tank on their roof or in their backyard. Especially for poor

and low educated people it will be hard to understand the benefits of a retention tank.

Water square
A water square is a square that is capable to store water. This can be done on two different ways, the first storing it under the square and the second storing it in the square. A water square has been made in Rotterdam, The Netherlands. In Rotterdam it has a basketball field where underneath water can be stored and a steepening play field where water can be stored in. The Benthem square in Rotterdam has the capacity to store 1800 m^3 water.
It is a revolutionary way of storing water, making use of play areas and at the same time using the water to play with. Creating the realisation to the inhabitants about water storage in a playful manner.

E Evaluation

The following matrices weigh the criteria factors elaborated in Section 5.1 against each other for every stakeholder group. This is done to determine the proportion of importance between the criteria factors. In the matrices a '+' indicates the criteria factor in the column is more important compared to the criteria factor in the row according to the stakeholder group in question. With a '-' this is the other way around. When chosen for '0', it means the importance of the criteria factors in question is equal.

	City image	**Voters**	**Aesthetics**	**Effort***	**O & M**	**Recreation**	**Health**	**Damage***	**Risks**	**Biodiversity**	**Green space**	**Water quality**	**Realistic**
City image		+	-	+	0	-	+	+	+	-	0	+	+
Voters	-		-	+	-	0	+	+	0	-	0	0	0
Aesthetics	+	+		+	0	0	+	+	+	-	0	+	+
Effort*	-	-	-		-	-	-	0	0	-	-	-	0
O & M	0	+	0	+		0	+	+	+	-	0	0	+
Recreation	+	0	0	+	0		+	+	+	-	+	+	+
Health	-	-	-	+	-	-		+	0	-	-	0	+
Damage*	-	-	-	0	-	-	-		-	-	-	-	-
Risks	-	0	-	0	-	-	0	+		-	-	+	0
Biodiversity	+	+	+	+	+	+	+	+	+		0	+	+
Green space	0	0	0	+	0	-	+	+	+	0		+	+
Water quality	-	0	-	+	0	-	0	+	-	-	-		+
Realistic	-	0	-	0	-	-	-	0	0	-	-	-	

Table E.1: Criteria factor matrix: Decision makers

* = Criteria factors as mentioned in Section 5.1

	City image	Voters	Aesthetics	Effort*	O & M	Recreation	Health	Damage*	Risks	Biodiversity	Green space	Water quality	Realistic
City image		+	-	+	0	-	+	+	+	-	0	+	+
Voters	+		-	+	-	-	+	+	0	-	0	0	0
Aesthetics	+	+		+	0	0	+	+	+	-	0	+	+
Effort*	-	-	-		-	-	-	0	0	-	-	-	0
O & M	+	+	0	+		-	+	+	+	-	0	0	+
Recreation	+	+	0	+	+		+	+	+	0	+	+	+
Health	-	-	-	+	-	-		+	0	-	-	0	+
Damage*	-	-	-	0	-	-	-		-	-	-	-	-
Risks	-	0	-	0	-	-	0	+		-	-	+	0
Biodiversity	-	0	0	+	+	0	+	+	+		0	+	+
Green space	-	-	-	+	0	-	+	+	+	0		+	+
Water quality	-	-	-	+	0	-	0	+	-	-	-		+
Realistic	-	-	-	0	-	-	-	0	0	-	-	-	

Table E.2: Criteria factor matrix: Interest groups

* = Criteria factors as mentioned in Section 5.1

	City image	Voters	Aesthetics	Effort*	O & M	Recreation	Health	Damage*	Risks	Biodiversity	Green space	Water quality	Realistic
City image		+	-	+	0	-	+	+	+	-	0	+	+
Voters	-		-	+	-	-	+	+	0	-	-	-	0
Aesthetics	+	+		+	0	0	+	+	+	-	0	+	+
Effort*	-	-	-		-	-	-	0	0	-	-	-	0
O & M	0	+	0	+		+	+	+	+	0	0	0	+
Recreation	+	+	0	+	-		+	+	+	-	+	+	+
Health	-	-	-	+	-	-		+	0	-	-	0	+
Damage*	-	-	-	0	-	-	-		-	-	-	-	-
Risks	-	0	-	0	-	-	0	+		-	-	+	0
Biodiversity	+	+	+	+	0	+	+	+	+		0	+	+
Green space	0	+	0	+	0	0	+	+	+	0		+	+
Water quality	-	+	-	+	0	-	0	+	-	-	-		+
Realistic	-	0	-	0	-	-	-	0	0	-	-	-	

Table E.3: Criteria factor matrix: Users

* = Criteria factors as mentioned in Section 5.1

	City image	Voters	Aesthetics	Effort*	O & M	Recreation	Health	Damage*	Risks	Biodiversity	Green space	Water quality	Realistic
City image		+	-	+	0	-	+	+	+	-	0	+	+
Voters	-		-	+	-	-	+	+	0	-	0	0	0
Aesthetics	+	+		+	0	0	+	+	+	-	0	+	+
Effort*	-	-	-		-	-	-	0	0	-	-	-	0
O & M	0	+	0	+		-	+	+	+	-	0	0	+
Recreation	+	+	0	+	+		+	+	+	0	+	+	+
Health	-	-	-	+	-	-		+	0	-	-	0	+
Damage*	-	-	-	0	-	-	-		-	-	-	-	-
Risks	-	0	-	0	-	-	0	+		-	-	+	0
Biodiversity	+	+	+	+	+	0	+	+	+		0	+	+
Green space	0	0	0	+	0	-	+	+	+	0		+	+
Water quality	-	0	-	+	0	-	0	+	-	-	-		+
Realistic	-	0	-	0	-	-	-	0	0	-	-	-	

Table E.4: Criteria factor matrix: Experts

* = Criteria factors as mentioned in Section 5.1

In order to get calculable numbers the +, 0 and - are transformed to 1, 0.5 and 0 respectively. Thereafter, the digits in the columns were summed and averaged using Excel shown in Table E.5.

Since the influence and interest of the stakeholder groups are not equal as can be seen in Figure 2.11, a weight factor needs to be introduced in order to determine the importance of the criteria factors. The following weights were given to the stakeholder groups:

Decision makers	= 0.5
Interest groups	= 0.1
Users	= 0.25
Experts	= 0.15

Every averaged criteria factor is multiplied by the weight factor according to the stakeholders above. Subsequently the averages shown in Table E.5 were obtained.

	City image	Voters	Aesthetics	Effort*	O & M	Recreation	Health	Damage*	Risks	Biodiversity	Green space	Water quality	Realistic
Decision makers	0.33	0.54	0.21	0.88	0.29	0.21	0.67	0.92	0.67	0.04	0.30	0.63	0.80
Interest groups	0.33	0.42	0.13	0.88	0.33	0.08	0.67	0.92	0.67	0.08	0.29	0.63	0.79
Users	0.33	0.63	0.21	0.88	0.21	0.25	0.67	0.92	0.67	0.08	0.30	0.58	0.79
Experts	0.33	0.58	0.21	0.88	0.33	0.08	0.67	0.91	0.67	0.08	0.29	0.63	0.79
Weighed factors	0.33	0.57	0.2	0.88	0.28	0.19	0.67	0.92	0.67	0.06	0.28	0.61	0.79

Table E.5: Weighed factors

The weighed criteria factors obtained in Table E.5 are used to calculate which options are expected to be the most suitable for the city of Campeche. The result are given in Section 5.2.

F Minutes

F.1 Minutes meeting Ing. Segovia Ramírez

Persons present: Evelia Rivera Arriaga, Gregorio Posada Vanegas and Máximo Flavio Segovia Ramírez
Location: EPOMEX
Date: 17/07/2017

Water quality tests
The city can be divided in two parts; east of the line airport and the pier and west of that line. The problems with regard to floating in the west side are as good as solved. However the east part does still have these problems. Around the measure points 3 and 4 a lot of water accumulates. Due to the new pipelines and the steep slope at m7 and m8 water flows easily away there.

There is a water well at m4. There is no or little regulation with respect to filters etc. People do still get sick due to the poor drinking water quality.

From origin people in Campeche have flat roofs. These roofs are used to collect water. This water is filtered by nets?

Sometimes they had water with salt (came into the city from the sea). This gave kidney problems.

Poor houses uphill do not have infrastructures to lead faecal wastewater away and with heavy precipitation, the polluted water flows through the city to the sea.

The local governor should now where to build and where not to. But due to a lack of money, wrong decisions are being made. Because governors are afraid to lose votes, they won't move people out of their houses if that is necessary for ecological, environmental, safety reasons. The social/environmental/risks weighing plays a big role in decision making. It is all about responsibility.

On the question, how the process of installing such a drainage system develops.
There is a book, written in the 80's, about the flooding in Campeche. In that book is a blueprint of the pipeline. The then mayor of the city wanted to start doing something about this problem but did not occur.

Until 1990-1996, when Jorge Salomon came into power. He started a new project to do something about the flooding, but it never finished. He got the money, but did not have the technicians to do the job causing lot seepage in the pipelines. Next to that, after six years was a change in government and they did not finish the plans of Salomon.

Later, due to lack of respect of the natural systems new flooding occurred at several barrios.

The problems remained, there was no integrated large vision for the whole, only small interventions.

In 1995 there were two hurricanes, Roxanne and Opal, almost at the same time flooding the whole city from two different sides. Roxanne from land and Opal from sea, with Roxanne rose the sea level and stayed like that for three days.

After these hurricanes and major flooding the Ría was widened, with first a hydraulic area of 7 m^2 to 14 m^2 and finally up to 21 m^2. This was done by adding five culverts underground, see Figure F.1 .

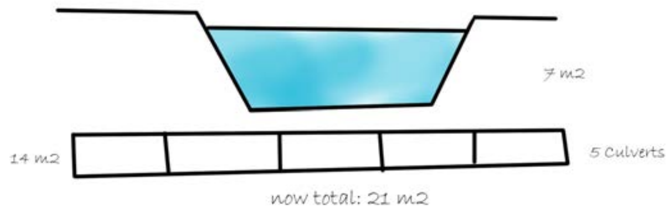

Figure F.1: Adding culverts to increase capacity

In total 25 million pesos was invested into flood prevention but parts of the pipeline does not function now.

Twelve years ago, another 15 million pesos was invested but did not give any result either.

The last fifteen years additional drainage pipelines have been installed to improve the system.

Plans for drainage system
From 2009-2015 the government made plans to sanitise and increase the water quality in the city, this was impossible without regarding what kind of and where pipelines were installed. They had four main points:

1. Pipeline Sanitation
2. Rainwater drainage
3. Portable water
4. Water treatment plans

This project has been designed to work for the next 30 years.

One problem was that there are differences in type and size of pipelines. They are not all the same size and at some locations a circular pipe is connected to a square pipe.

Another problem is that the Central Government distributes the money to different states according to their population. Campeche having very little inhabitants, receives fewer money than needed to put the project into plan.

In 2012 another flooding occurred blocking the main road south and north of the city as well as the airport. The government made a plan to improve the water drainage and sanitary pipeline, there was a pipeline made between Lerma and Campeche. The only problem was that the connection of the pipelines had to be paid by the people, but they did not so the pipeline fails its use.

Areas of the city
The city is divided into five areas with different types of drainage, geographical, shed of drainage etc. Seven studies were done for the new drainage system, one consultant used the information gained with these studies but dropped the project unfinished. The second consultant built the system with the information from the first consultant, but there was a lack of data triggering huge mistakes. For example one street was designed to have the water stream uphill. The

problem of the current drainage system is the inconsistency, due to change in administration every six years a lot of previous information and plans are discarded or lost.

Problems in the past
At the end of 1996 there was a huge problem with flooding in front of the Guadalupe Church. A drain in front of the church should have drained the water towards the sea, but it turned up to be the other way around. The sea level was 1.07 m higher than the level at the Church causing the sea water to go towards the church instead of the other way around.

There are blueprints of the location where the city floods, Mr. Segovia has them and will try to give them to the project group on Thursday.

In Presidentes de México there are two pumps installed to pump the water out, but actually have no function and is only installed to please the public. The drainage system works with gravity, just going downstream.

There are still three major drainage failures.

Rainfall of 45 mm in an hour can cause a flood in the city, combining this with a high tide may arise to a serious problem.

A idea to improve the drainage system, is to use gates at the ends of the drainage systems, preventing the seawater to get in. At the moment when the gates are closed, the rainwater needs to be saved in the reservoir and pumped out later at a lower tide. This could be a useful solution for Victoria street but every different part of the city needs another solution.

The reasons that this plan was not put into action were that the government think that there needs to be one solutions fit to all (different) problems, also the Malecón had to be opened and reconstructed.

Climate change is something that has never been taken into account in models in Mexico. Because of the big scale it is hard to put into account.

Course of events in Campeche
In general a governor or mayor finds a big project like a monument or big skyscraper more interesting than a better working water system. Since the oil price is still relatively low the governor of this term will have problems with the amount of money they can spend on new projects.

Half of the citizens of Campeche have a job or a family member with a job in the government, making them depended on the government. This way the best interest of the government is in the best interest of a large part of the population, causing actually solving problems long term hard.

The current government has big plans to put their reign on the map. There are two different plans, one to construct a monument at the shore located near the UACAM. This would block the drainage exit from the University making this plan impossible. The other plan is to make a 30 story high building at the pier, but it would be impossible to install electricity and water there. So this plan seems not to happen as well.

In the city there are water container installed, but they are not always at the right location or with the right soil above, making them useless. *(unsure)*

F.2 Minutes meeting Arq. Jiménez Silva

Persons present: Evelia Rivera Arriaga, Gregorio Posada Vanegas and Felipe Antonio Jiménez Silva
Date: 18/07/2017

By whom is the mega drainage project executed?
50-60 percent has been built by the municipality and the rest of the work is performed by the state.

Where will the reservoirs be built?
Regulating basins are being built where at a natural way water is flowing through the streets. On top of this basins it is not allowed to build. These basins are abrasive lands and are used as buffers zones. These basins are located around the city in the peripheries.

The water in the Ría is flowing from uphill to the sea to push the water from the hills towards the sea driven by gravity. It starts with a hydraulic area of 15 m^2 and it narrows to 11 m^2 at sea side.

There is one street from the 16 de Septiembre until the Malecón that is kept open to encourage the water flowing through it. Because of the large distance, big amount of water and high pressure/velocity. This is a part of the new mega drainage project.

Mega drainage system
In total the new mega drainage consists of 27 kilometres of drainage pipelines. There are three main outlets of the new mega drainage system. One of those is in the Presidentes neighbourhood coming out to Los Petenes biosphere reserve. This one is flowing into natural habitat which makes outflow into the sea unnecessary.

Where do improvements still have to be made?
Improvements still have to be made in Concordia, Hidalgo, Quinta de los Españoles, Guadalupe.

Why there?
Because of political reasons these areas are still missing. As a reaction on this, a negotiation was started at the beginning of the new governmental term. The mayor was committed to fulfil this project considering the drainage. Criteria were formed by amount of people who could get helped and amount of money which was available and could be created, among others. Especially the amount of money available formed a problem.

Why are the costs so high? Was it a cost problem or an engineering problem?
A cost-benefit analysis was required to be made. Costs were comparable to other projects. In Mexico, generally, if the results of a project are not noticeable to the common people, they do not consider it worthy. Land value increases due to its drainage facilities, so the state government needed to decide where the people would benefit best from these when making priorities. They also accounted for safety and health issues in this analysis.

When the state loans money from the federal government for a certain project, it also has to invest a certain amount of money from their own resources. For this drainage project the state needed 1300 million pesos, but the federal government only assigned 1000 million pesos, because they did not acknowledge enough benefits in the project. The federal government also had influence because of their investments.

Drinking water facilities

The amount of drinking water needed to provide to the population of Campeche is equal to 700-800 l/s. In the present situation, an inflow of 1300 l/s is needed, because of leakage. Due to the big amounts of subsidy the population receives in combination with a very low monthly contribution per household for drinking water (1.5 dollars/month for an unlimited amount), people have no incentive to be thrifty with the use of water. The municipality does not want to increase the drinking water contribution, because they are afraid they will lose voters. Besides, the poor people cannot cope with increments in drinking water contribution due to the lack of money and the water quality is actually to poor to ask the people for money.

The drinking water project also consisted of the construction of five drinking water tanks. Furthermore, it encompassed public space improvements such as underground cable systems and LED illumination throughout the city centre. It would come in handy to improve those things at the same time, because they needed to break up the streets for both. Therefore, changes were very large and investments were too.

In the new administration approach the municipality wants to regulate the water payment. In every single neighbourhood where improvements have to be made the drainage is getting fixed too. When a citizen signs a water contract with the municipality the house will be connected to the drainage system. However, at this moment there are only 80,000 contracts while others just consume water without contracts.

Due to the construction of the peripheral road around the city in combination with other peripheral activities, modifications were generated in the water currents through the valley. A new water treatment plant was constructed in Lerma substituting the former one that was located close to Los Petenes. The new one had a higher capacity and needed less pumping stations. In Campeche there are a total of 24 treatment plants of which seven are active at the moment. Due to required improvements to the chemical cleaning of the water these renovations had to be performed.

Did the municipality think about solutions to the combination of high tide and rainfall?

Mr. Jiménez told us the municipality looked at the available data with a return period of 50 years when designing the drainage system. They also took into account the water levels due to storm surges. They did not consider climate change, but they are aware of this problem and are starting to implement it in their considerations right now. One of the solutions they came up with was the use of gates in combination with pumps.

Campeche lays 3 meters above sea level on average. Because of this low variation the city will flood either way with every major storm event, so the municipality focuses on reducing the inundation time with the current drainage system.

Is the current drainage system able to hold the 200 mm/day of rain generated by the storms?

The drainage system can already cope with 145 mm/day without accumulation. The major problem is the duration of a certain heavy rainfall event, since some events can take up to 7 to 8 hours of rainfall.

Hurricanes can be divided into four quarters of which one generates the heaviest rainfall. The hurricanes can come along with a lot of garbage, trenches, leaves and other stuff. This can cause a lot of additional problems such as damage to buildings but also blocking of the drainage canals.

In the past the city could be flooded for several days whereas now with the new drainage system this is reduced to 2 or 3 hours. With an intensity of 55-65 mm/hr the drainage system is capable to flush the rainwater directly out of the city.

At July 12th 2016 the rainfall was equal to 85 mm in 40 minutes with a total accumulation of 120 mm over the entire night. The current drainage was able to cope with this amount of rainfall without flooding.

In case of a super-moon the sea level can be exceptionally high. The old drainage system fails in this case because the water pressure of the sea drives the water upwards at the Guadalupe church. The new drainage has more capacity and less inclination.

In the Netherlands we use vegetation on the roofs and parks so that the water can infiltrate. Did Campeche also consider this solution already?
In Campeche the natural basins are used as buffers. Furthermore the municipality uses natural paths throughout the city to transport the rainwater. This is a bit different in comparison with the solutions we use in the Netherlands.

What is the role of CONAGUA in the drainage system process?
CONAGUA has only to approve every modification that has to be made to the water system. They only execute projects on inter-regional, inter-state and national level. The federal government manages and approves this kind of projects.

F.3 Minutes meeting Dra. Rivera Arriaga

Persons present: Evelia Rivera Arriaga
Location: EPOMEX
Date: 25/07/2017

Decision making
As a baseline in the decision making of every project, a proposal has to be made to present to the COPLADE, a commission which is set up by the federal government.

The state of Campeche has a low population, so they receive only a small amount of money.

Fernando Ortega Bernés, the former governor of the state of Campeche (2009-2015), made a governmental division on state-level. Instead of keeping the environment department within the social division, he put it in the economic division. Furthermore, he set up a list of legally binding promises resulting from his campaign, which he was obliged to fulfil.

CONAGUA proposed the Consejo de Cuenca as a space for civilians to talk about water issues on federal level. First one was formed for the Yucatán Peninsula, afterwards also smaller ones were formed. Initially it was used for the reorganisation of the coastal waters in the Bay of Campeche, involving all actors.

There are three levels for decision making: federal, state and municipal. The decision maker on federal level for water-regarding projects is CONAGUA, on state level it is the governor and on municipal level it is the mayor.

SMAAS (Secretaría de Medio Ambiente y Aprovechamiento Sustentable), is the former state ministry of environment. Dr. Evelia Rivera was the head of this secretary (2009-2015). This secretary has now been replaced by SEMARNATCAM, although there are major differences in between the former and the current secretary.

When dealing with integrated coastal zone management (ICZM) it is of importance to understand the entire system. For ICZM also money is needed for campaigns in order to convince people of the best way to improve the coastal zone. Some kind of show might be necessary to make people aware of the current situation, because without the participation of the citizens it is impossible to realise a good solution.

Financing
There are several ways to obtain financing for a project:

1. Federal budget
   For every state, a federal credit is available in each fiscal year. In order to receive this credit, the project proposal has to be presented to the secretary of Hacienda (SHCP). From SHCP the credit reaches the state through CONAGUA. The credit is based on a co-investment, which means the state should invest in the project too.

2. BANOBRAS
   BANOBRAS is a bank which is specialised in giving credits to the state governments. The bank is regulated by SHCP and grants a loan if some of their interests can be fulfilled. The House of Representatives of Campeche grants the governor permission to apply for this credit.

3. Promotion sustainable cities
   International organisations like GIZ (German development agency), AFD (French development agency) and IDB (Inter-American Development Bank) are in collaboration with Mexico. They can arrange funding for particular projects. Campeche is taken into consideration because of the opportunities in the drainage system. This funding could either be an investment or shared capital.

4. Bags of money for the state
   The federal House of Representatives decides over these bags, it has everything to do with lobbying and convincing people. Application is only possible if a project meets the requirements. In the past, the bags for projects in the environmental sector contained 1,350 million pesos, but right now the environmental bags are empty and not used anymore. Probably there is still money available for other sectors. For the coastal reorganisation project of Dr. Evelia Rivera a project portfolio was presented, which caused a funding of 1x 8 million pesos, 1x 22 million pesos and 1x 112 million pesos. After Mexico City and the state of Mexico, the state of Campeche received the largest funding.

Drainage
The state government of Campeche took over the drainage project from the municipality, because of the promises ex-governor Fernando Ortega Bernés made. This is legally tricky, since next government administrations can react badly on the former ones. When making accusations all the former work can be wiped out.

Landmark
As mentioned earlier state governments want to put a mark on their term which is visible for the people. Most of the time these projects are a waste of valuable time and money. At the moment the government is planning to put a statue and a fountain in front of the governmental palace in the sea.

G Photos

G.1 Drainage outlets

Figure G.1: Outlet of drainage system in Los Petenes

Figure G.2: Ría of the drainage system near Calle 10

Figure G.3: Outlet of drainage system near Guadalupe

Figure G.4: Outlet of drainage system near San Roman barrio

Figure G.5: Outlet of drainage system near the university


Figure G.6: Inlet of drainage system at the end of Calle 14

G.2 Inundations Franklin

Figure G.7: Inundations by hurricane Franklin, location 1

Figure G.8: Inundations by hurricane Franklin, location 2

Figure G.9: Inundations by hurricane Franklin, location 3

H Timetable

Week	4.11	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8
Meeting: Dr. Edgar Mendoza									
Kick-off: Dr. Gregorio Posada									
Location analysis									
Meeting: Dr. Evelia Rivera									
Stakeholder analysis									
Meeting: Ing. Máximo Segovia									
Meeting: Arq. Felipe Jiménez									
Evaluation analysis									
Boundary conditions									
Brainstorm alternatives									
Set up alternatives									
Elaborate alternatives									
Evaluate alternatives									
Finishing process									
Final deadline									

Table H.1: Project timetable (based on TU Delft time schedule)

I Logbook

In order to give insights in the main tasks performed during the project and the distribution of them between us, a logbook has been made up. This logbook can be found back on the next page.

Week	Activity	Kevin	Ivar	Tessa	Sebastiaan
4.11	• Meeting: Dr. Edgar Mendoza	X			X
5.1	• Kick-off: Dr. Gregorio Posada	X	X	X	X
	• Meeting: Dr. Evelia Rivera	X	X	X	X
	• General info analysis	X	X		X
	• Elevation maps			X	
5.2	• Meeting: Ing. Máximo Segovia	X	X	X	X
	• Meeting: Arq. Felipe Jiménez	X	X	X	X
	• Drainage maps			X	
	• Land value maps	X		X	
	• Stakeholders		X		X
	• Global mapper		X		
	• Elaborating analysis	X	X	X	X
5.3	• Construct logbook/timetable				X
	• Evaluation analysis	X		X	
	• Global mapper		X		
	• Stakeholders		X		X
	• Meeting: Dr. Evelia Rivera		X		X
	• Political system		X		X
	• Flood risk	X		X	
	• Field work	X	X		
	• Precipitation			X	
	• Situation characterisation	X		X	
	• Layout				X
	• Water accumulation model			X	
5.4	• Brainstorm alternatives	X	X	X	X
	• Drainage capacity	X			X
	• Program of requirements/desires	X	X	X	X
	• Elements of solutions	X	X	X	
5.5	• Drainage capacity				X
	• Wall on the Malecón	X	X		
	• Parks & infiltration fields			X	
	• Situation characterisation				X
	• Water accumulation model			X	
5.6	• Wall on the Malecón	X		X	
	• Infiltration basins		X		X
5.7	• Wall on the Malecón	X		X	
	• Infiltration basins		X		X
	• Water squares	X		X	
	• Parks & infiltration fields		X		X
5.8	• Water reduction calculation			X	
	• Evaluation		X		
	• Discussion				X
	• Conclusion & Recommendations	X	X		X
	• Report check/Lay-out	X	X	X	X

Table I.1: Project logbook (based on TU Delft time schedule)