Multidisciplinary Project

A study on reducing flood risk in Cartagena de Indias, Colombia

Cartagena, it's now or never

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Preface

The report –Cartagena, it's now or never– is the result from a research project conducted as a joined effort between Royal HaskoningDHV, Delft University of Technology (TU Delft) and the Universidad Tecnológica de Bolívar (UTB). A group of students from the Delft University of Technology traveled to Cartagena, Colombia, to perform a study on flood risk in the city of Cartagena.

Our project group consists of 6 students. We are all in the final stage of different master degrees within the faculty of civil engineering. During the research we occasionally worked together with a group of 10 students from the UTB who mainly assisted us in finding information from local, Spanish, sources.

This project has been conducted to investigate the current problems caused by inundations in Cartagena, identify their causes and formulate the most efficient integral solution. We sincerely hope that the conclusions formulated in this report are used to solve the problems caused by inundation.

During our time in Cartagena we had close contact with Rutger Perdon, business developer South-America at Royal HaskoningDHV. He helped us tremendously in setting up the scope of the project and identifying the focal points of our research. Rutger's guidance ensured that the project was always heading in the direction which gives it the biggest possible chance to influence the decisions of local politicians. Also we acknowledge the financial support from Royal HaskoningDHV.

Bas Hofland, associate professor of coastal structures at the TU Delft, was supervising the project on behalf of our university. His experience in the field of coastal engineering and the process of doing research in general, were of great help to the completion of this project.

Mauro Antonio Maza Chamorro, associate professor at the UTB, assisted our project in multiple ways. His local knowledge of Cartagena proved useful in our project. We would also like to thank him for making us feel at home and help us adapt to the Cartagenero way of life.

Finally we would like to acknowledge the support supplied by the UTB, especially by the staff of the international office. They helped us to arrange housing, visa's and an office to work from.

Cartagena de Indias, Colombia
April 11, 2017

Abstract

This report is the result of a study which aims to understand both the source and severity of flood risk in Cartagena de Indias, Bolívar, Colombia. Solutions to the problem are proposed accordingly.

The flood risk is found to be severe and urgent enough to demand action. Currently annual damage and negative impact of inundations are severe enough to justify intervention. The problem is considered urgent due to the threat of an extreme event such as a hurricane or La Niña rainfall in combination with a predicted growth in future flood risk due to sea level rise and heavy rainfalls due to climate change, subsidence and increased urbanization. The current proposed solutions do not offer protection against all the causes of the floods and are not effective in the face of climate change. Therefore, a new flood protection plan must be proposed.

An integral solution is proposed for Cartagena at the conceptual level. The solution protects the city from both coastal and pluvial floods in an integral, elegant and efficient manner. The solution provides many opportunities to improve the general well-being of the city.

Executive Summary

Cartagena de Indias (Cartagena) is Colombia's fifth largest city. Due to its location on the Caribbean coast and its UNESCO heritage historic center, it is the country's main tourist destination. Multiple floods a year indicate that the city is coping with a serious flood risk. These floods are caused by both excessive precipitation, high sea level and waves and a combination of these factors. Especially the areas of the peninsula (Bocagrande, El Laguito and Castillogrande), the area South of Ciénaga de la Virgen and the industrial zone of Mamonal suffer from the consequences in a multitude of ways.

The water level in the Ciénaga rises very fast during rainfall as urbanization and deforestation of the upper basin increases discharge peaks. This causes the low-lying neighborhoods to flood and decreases the hydraulic gradient in urban drainage channels. This decreases the capacity of the channels, which is already insufficient; flooding occurs in upstream areas. Unplanned urbanization into the Ciénaga escalates the problem and thus this part of the city is frequently flooded.

The seawalls protecting the coastal areas and inner bay are deteriorating and are not designed for current nor future conditions. Water flows onto the streets during high tide. Due to storm-induced erosion of beaches, coastal protection is reduced. Furthermore, the drainage is limited during high tide as there is small height difference between land and sea. Lastly, rainwater outlets function as seawater inlets during high tide.

In the industrial zone, companies build their own dikes pushing the water back into surrounding residential areas. The channel capacity is reduced with harsh turns and thereby increasing the flooding problems.

The floods impact the city in different ways. The frequent flooding severely impacts the living quality. During the floods, water moving at high velocities and carrying debris, is a direct danger to inhabitants. The water has led to serious injury and even several cases of death. When the flooding is over, pools of stagnant water remain on the streets for days increasing the spread of vector-borne diseases.

The floods also have a big impact on the local economy in Cartagena. It is estimated that the pluvial floods alone cause the urban areas 12.8 million USD in direct damages annually. The indirect damage due to lost income are expected to be higher. The floods cause the traffic system to paralyze, render work spaces unusable and have a negative impact on tourism. In the La Niña year of 2011, total damages in Cartagena are estimated at 540 million USD.

The environment is affected as well. Waste water and sewage overflow worsen the water quality of surrounding water bodies and causes unwanted smells in the city.

Because of the rising water levels in the surrounding water bodies, flooding due to high water levels will become more frequent and intense. Furthermore the drainage of rainwater in higher areas of the city will become even less effective. It is predicted that in 2040, 26.2% of the houses are flooded, there will be an 100% increase of vector-borne diseases, 100% of the historic center is flooded, 28% of the industry is at risk and all beaches will erode.

It is concluded that the flood risk in Cartagena is very high and has a serious impact on the city. It is one of the, if not the, pressing threats in the future. Furthermore, against the backdrop of increased

urbanization trends, subsidence and climate change, the impacts of the floods are expected grow. If action is not taken immediately, the city will suffer from immense damage in the (near) future, damage which could have been prevented. The future looks bleak and the flood protection urgently requires action.

Currently, there are plans to tackle the floods. The most important ones are:

- Pluvial drainage master plan (2007) - A design to solve flooding due to excessive rainfall.
- Coastal master plan (2011) - A master plan to create an attractive zone along the coast with opportunities for economy, tourism and improved infrastructure.
- Plan 4C (2014) - A vision on how to transform Cartagena into a climate compatible and competitive city.

The problem with these proposed solutions is the focus on a single cause of the floods. The pluvial master plan only focuses on increasing the capacity of drainage channels, Plan 4C only considers climate change and the coastal master plan is focused on urbanizing and exploiting the shoreline. The floods in Cartagena are however caused by a complex combination of high water levels, insufficient drainage and poor management. An effective solution should be integral, robust and should consist of no-regret measures to make sure it does not become obsolete or even counteract future developments. Every cause of the floods has to be considered. Otherwise, the city's flood risk management will remain disjointed and vulnerable.

No generally applicable solution exists to manage floods. Each case is unique and requires a tailor-made solution. General strategies for water protection do exist. These strategies can be used to counter flooding caused by excessive rain and rising seawater. The main strategies given to counter flooding due to rain are given as follows:

- *Reduce discharge peaks entering the city* - Lower the discharge peak that enters the city after a heavy rain event by implementing upper basin management (for example, retention, increased infiltration and delayed surface runoff).
- *Increase discharge capacity in the city* - For example, widen, deepen and clean the drainage channels in the city.
- *Increase storage in the city* - Create overflow areas in the city where excessive water can temporarily be stored.

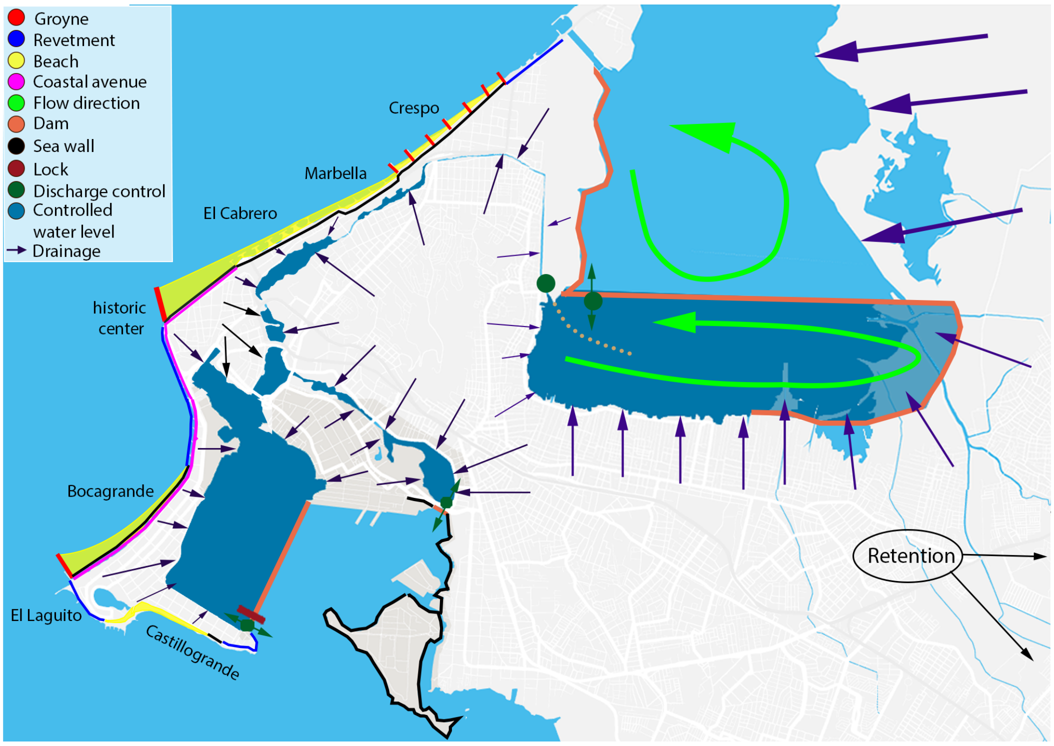
To solve the pluvial flood problems a combination of these strategies must be employed to create a successful flood defense system.

The strategies for providing protection against a rising sea level are presented below:

- *Retreat* - Move the vulnerable areas of the city and its inhabitants landwards.
- *Accommodate* - Accept the sea level rise and erosion and adapt the city so the risk of floods is reduced.
- *Protect* - Take protective measures to counteract the increased probability of flooding.

The only realistic strategy for Cartagena concerning coastal management is to *protect*. The other two strategies will cause too great a loss, both economical as social, to be viable.

Many alternatives were evaluated during the design process and the best one is selected and elaborated upon in the final conceptual design. It is a combination of all three strategies regarding the drainage problems and it offers protection against rising water levels. The core of the solution consists of two closure dams, one in Ciénaga de la Virgen and one in the inner Bay of Cartagena. Together they create a closed water body in which the water level may be regulated. In this way, large parts of the city are protected from high water levels. Besides providing extra storage, it also increases the drainage capacity as the hydraulic gradient in urban channels is increased. The increased storage capacity and the drainage capacity in combination with small-scale measures and upper basin management is expected to be sufficient to deal with extreme rainfall events. The design also guarantees water refreshment in the water bodies of Cartagena. The Caribbean coast is protected by a combination of soft and hard measures. Widened and regularly maintained beaches in combination with a seawall and restored and improved revetments will protect the city against high water levels.



Integral solution for Cartagena

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List of Abbrevations

ANLA	Autoridad Nacional de Licensias Ambientales
CCO	Comision Colombiana del Oceano
CIOH	Centro de Investigaciones Oceanográficas e Hidrográficas
DADIS	Departamento Administrativo Distrital de Salud
DATT	Departamento Administrativo de Transito y Transporte
DIMAR	Direccion General Maritima
ENSO	El Niño-Southern Oscillation
EPA	Estabilicimiento Publico Ambiental
GDP	Gross domestic product
GDPPC	Gross domestic product per capita
HAT	Highest Astronomic Tide
ICZM	Integrated Coastal Zone Management
IDEAM	Instituto de Hidrología, Meteorología y Estudios Ambientales
INVEMAR	Instituto de Investifaciones Marinas y Costeras
IPCC	Intergovernmental Panel on Climate Change
LAT	Lowest Astronomic Tide
M.s.n.m.	Metros Sobre el Nivel del Mar (Colombian national reference level: meters above sea level)
MADS	Ministerio de Ambiente y Desarollo Sostenible
MCA	Multi-Criteria Analysis
MHHW	Mean Highest High Water
MHW	Mean High Water
MHWS	Mean High Water Spring
MLLW	Mean Lowest Low Water
MLW	Mean Low Water
MLWS	Mean Low Water Spring
MSL	Mean Sea Level
SIAB	Sociedad de Ingenieros y Arquitectos de Bolivar
SLR	Sea-level rise
SLS	Serviceability Limit State
TEU	Twenty-foot equivalent unit
UCB	Unidades Comuneras de Gobierno Urbana
ULS	Ultimate Limit State
USACE	United States Army Corps of Engineers
UTB	Universidad Tecnológica de Bolívar

Chapter 1

Introduction

1.1 Background

Colombia has made significant progress in resolving its internal conflicts in the last decade. Although the civil war continues to this day, the violence occurs mainly in remote and isolated areas. This has allowed the government to focus its resources on improving the country's infrastructure and its citizens well-being. As a result investments have gone to flood defense, water management works and road projects like the Crespo tunnel project, Baranquilla's new bridge and the rehabilitation of Canal del Dique.

The Caribbean coast presents interesting challenges for foreign and local engineering firms and contractors. coastal erosion, heavy rainfall, land subsidence, poor maintenance, a lack of urban planning and a chaotic political system have resulted in complex problems.

Cartagena de Indias (henceforth called Cartagena), Colombia's fifth largest city and number one tourist destination, is coping with these problems. The city's historic city center was founded in 1533, which is a UNESCO world heritage site and attracts hundreds of thousands of visitors every year. Many luxurious hotels, shops and restaurants are located on the downtown peninsula.

The Bay of Cartagena is home to the third busiest port in the Caribbean and serves a large industrial zone with a variety of different industries.

Figure 1.1: Location of Cartagena de Indias

1.2 Problem Description

In recent years, it has become increasingly more evident that the city of Cartagena and the surrounding areas are suffering from flood risk related issues. The city is situated between the sea and several terrestrial drainage basins. Parts of the city are below sea level at high tide. This makes the city vulnerable to inundation due to precipitation, as water cannot be drained to the sea by gravity. This results in inundation from sea water that is able to flow into the low-lying areas. In addition, the ongoing urbanization in the basins cause an increase in the discharge peaks of runoff water that reaches the city.

The city is poorly protected against water from the sea. Already at mild sea conditions streets are flooded due to wave overtopping and/or high tide. Considering subsidence and the ongoing rise of sea level, the flood risk related problems in Cartagena are only likely to increase in the near future if nothing is done. It is currently estimated that 27% of the houses in Cartagena are vulnerable to the effects of climate change according to Plan 4C (CDKN et al., 2014).

Adding to the complexity of the problem is the political situation in Colombia. In order to avoid corruption, many political positions are set for a period of four years. This makes it difficult to implement long-term solutions because of the lack of time to build professional relationships and a change in political agendas occurs every four years.

The problem is made more complicated by social and economical inequality between the different districts and peoples of Cartagena. High money earning and prestigious parts of the city are subjected to high investments, where poorer parts of the city seem to be forgotten (Benítez, 2012).

Due to the lack of proper water management and the immediate danger to citizens' life, the environment has slipped to a lower priority. At the moment, the Ciénaga de la Virgen is polluted due to waste and garbage being flushed in. Around the Bay of Cartagena, mangrove forests are dying and large areas of the bay have been pronounced dead due to insufficient oxygen.

Reducing the flood risk in Cartagena is a highly complex issue and will not simply come down to technical solutions. A highly integrated solution has to be sought that fits all technical, social, economic, environmental and political demands.

"We are worried, the floods are getting worse and we do not know when a storm will hit us or trap us."

— Bocagrande community representative

Figure 1.2: Dominoes during inundations after the 2011 La Niña rains, taken by El Tiempo

1.3 Approach

The goal of this study is to understand the source and consequences of floods in Cartagena and investigate the possibilities for a comprehensive solution. This will be done by investigating the source and urgency of the problem, followed by an assessment of the currently implemented and proposed solutions. Finally, a clearly defined philosophy will be defined to help the authorities reducing the high flood risk due to excessive precipitation and seawater entering the city. The proposed solution following from this research will be integral and fits in this philosophy. Within this context 'integral' implies a solution which does not only reduce flood risk from both sources, but a solution which also presents opportunities to tackle other problems such as urban planning and accessibility to name but a few.

The project planning centers around answering three main questions. Question 1 and 2 will be treated as the analysis phase of the project. Question 3 is the synthesis stage.

- Question 1 – What are the causes of the floods in Cartagena and is the associated current or future flood risk urgent enough to demand action?
- Question 2 – Will the current plans work to solve the problem?
- Question 3 – What is the best integral solution to reduce flood risk in Cartagena?

Question 1

The higher level causes and urgency of the flood risk will be explored. In order to obtain a deeper understanding of the nature of the problem, the problem will be divided into manageable pieces. While answering this question the entire city is considered. A deeper understanding of the different causes of the floods will be gained. The cause of floods due to rain- and seawater are analyzed separately to help structure the investigation. The future situation regarding the floods is analyzed by using reports and interviews. The important stakeholders are described and an understanding of the impact the floods have on safety, economical, social and environmental issues will be generated. Understanding the flood impact will be obtained mostly by using news articles, interviews and other qualitative public information. The current and future urgency of the problem will be pointed out and it will be determined whether the problem is sufficiently large to demand action. The interests of several concerned parties will be used to ensure the understanding of the urgency of the problem is not be biased and the later developed solution will take all concerns in consideration.

Question 2

After understanding the problem, it is important to investigate which solutions are already planned. There are two goals behind this question. The first goal is to find out which measures already have been taken to reduce the problem and why these did or did not work. The second goal is to find out if the existing plans are sufficiently capable of solving the problem. It must be understood why these plans work or do not work. The locally formulated solutions will be benchmarked with global flood risk management practices. To do this, a deeper understanding of global flood risk management and the design conditions of planned solutions is gained. Using existing reports, presentations and data, the effectiveness of existing solutions is judged. Possible sources are reports from the UTB, (local) government, contractors and engineering firms.

Question 3

Using various brainstorm techniques, different viable solutions will be identified. The goal is to create a large set of theoretically possible solutions. These solutions are later analyzed and combined in various ways to produce several feasible alternatives. These alternatives will be discussed with experts from RoyalHaskoninngDHV and explained to professors of Universidad Tecnológica de Bolívar. Their expert judgment will reveal whether the list of alternatives is comprehensive and indeed feasible. A multi-criteria analysis (MCA) is used to test set of alternatives along with the existing plans to select the most promising one. The most promising alternative is worked out in more detail up to a conceptual level. This process of generating and evaluating alternatives is in accordance with the generally accepted project methodology and the design loop, which is illustrated in Figure 1.3.

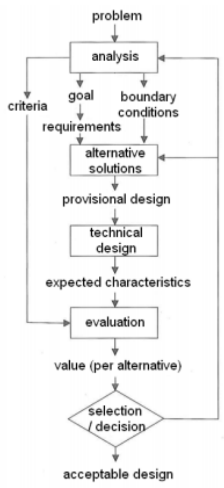


Figure 1.3: Schematic overview of the design process

Partner Cooperation

The project will be conducted in a joint effort between the Delft University of Technology (TU Delft), Universidad Tecnológica de Bolívar (UTB) and RoyalHaskoningDHV (RHDHV). The group from the TU Delft consists of six master students with both Mechanical and Civil Engineering backgrounds. This group of students is responsible for conducting the research and will be reporting to the TU Delft and RHDHV. At the faculty of the UTB an office is made available from where the project is conducted. Professors from the UTB cooperated in the project where possible by providing some local knowledge, contacts and access to previous work. Furthermore, a group of ten undergrad students from the UTB were selected to assisted the project on a part-time basis, as a part of their thesis. During the lifetime of the project this group was gradually reduced to one student.

Project focus

This project is heavily focused bringing the urgency of the situation to the attention of local officials. The client (Royal HaskoningDHV) wants the thought process leading up to the solutions to be clear. For this reason the report contains some unconventional content. The report is complemented with a presentation. This presentation was presented during a closing event at the end of the project. The mayor of Cartagena and many other important stakeholders where present. Sections such as Understanding Flood Impact and Understanding Global Water Management and the chapter *Flood Risk Reduction Strategies* were vital input for this presentation.

1.4 Reading Guide

As described in the project approach, the research is focused on finding the answer to the three main questions. The first two questions are answered in the *Introduction*, *Analysis* and *Program of Requirements* , the last question is addressed in the *Synthesis* and *Evaluation* .

In the *Introduction*, some light is shed on the team, the start of the project, the motivation for conducting the research and the planned project approach.

In the *Analysis*, a research is conducted into the cause, effects and urgency of the inundation problem. Before a solution can be sought, it is crucial to understand the causes of inundations. The main question in this part is: Where is the water coming from now, and how will this change in the future? It is not always evident what negative impacts are caused by the presence of inundation, thus these are examined. Here the consequences of the floods are investigated and divided in social, economic, safety and environmental impacts. In this section, it will be shown whether the city's inundation problem is urgent enough to demand action, followed by an analysis of the current planned solutions.

Additionally, a comparison is made with the water management solutions of other water sensitive city's in the world. This covers research question 2 and establishes whether or not Cartagena's government is doing enough, compared to global practice, to protect its citizens against flood risk. The chapter is concluded with the Section Boundary Conditions where a technical analysis is made of the physical phenomena that influence the solution.

The *Program of Requirements* is a summary of the *Analysis* and translates the causes, effects and impact of the water problem into technical and non-technical requirements that have to be incorporated in the design. Wishes, desirable effects of the solution, are also established.

Flood Risk Reduction Strategies outlines the globally accepted strategies to dealing with flood risk. These strategies for the basis for the solutions proposed in the next chapter. In the *Synthesis*, many alternatives are sought to reduce different aspects of flood risk. With a multi-criteria analysis (MCA) in the *Evaluation*, the most promising alternative is selected. This alternative is worked out to a conceptual design level in the *Final Design*. These three chapters answer research question 3.

The report continues with the *Conclusion* where the research questions are answered. At the end, the *Recommendations* can be found. Advice, based on experiences build up during this project, is given on how to approach this problem and which next steps should be taken in order to reduce the flood risk successfully in Cartagena.

Chapter 2

Analysis

This chapter answers the most important questions one should ask in order to understand the flood risk faced by Cartagena:

- What kind of city is Cartagena?
- What causes the floods?
- Who are the most important stakeholders?
- What is the impact of the floods?
- Are there any solutions in place?
- What are global practices for comparable flood risk?
- What are the design conditions in Cartagena?

The key findings in this chapter are:

– Cartagena is Colombia's fifth largest city, a coastal city situated between various water bodies. The city's economy revolves around its historic center and the industrial zone of Mamonal. Over the last decades Cartagena has experienced rapid and unorganized urban expansion.

– Floods in Cartagena are caused by both rain and seawater. Rainwater does not drain easily from the low-lying city as drainage infrastructure is insufficient or non-existent. Changes in the upper basins increase the discharges entering the city. Poor coastal protection makes the city vulnerable to erosion, wave overtopping and sea level rise.

– Local politics are very complex and difficult to navigate. Many organizations have similar functions and do not communicate well, leading to a disjointed political system. The local government lacks funds. The most important stakeholder is the mayor as he is the head of local government. However, the regional and national government entities are important sources of funding. An integral and regional solution is required to obtain non-local funds.

– Floods in Cartagena cause direct economic damage and casualties. Citizens feel unsafe as they notice an increase in flood frequency and severity. Equally striking are the indirect effects, both economically, socially and environmentally. The economy is crippled, while social inequality and distrust in local government grow. The future prediction looks grim; flood impacts seem to increase with climate change and increase urbanization.

– Several solutions have been proposed by the city. Plan 4C is a general, policy outlining, document which provides guidelines for dealing with climate change. It encourages integral city-wide approaches. Also a pluvial drainage plan is proposed. However, this plan is not considered sufficient as it is a local short term and expensive solution. Limited information is available on the coastal plan which is currently being formulated.

– Comparable cities in the world are investing more in water management and security than Cartagena.

– A technical set of boundary conditions for the design is formulated.

2.1 Area Analysis

Cartagena is a coastal city in the Caribbean located at 10°25' North, 75°32' West. The city was founded in 1533 by the Spanish. It is the fifth biggest city of Colombia and capital of the department of Bolívar. The surface area of the district of Cartagena is 697.24 km^2 of which 12.55 % is considered to be urban area. This urban area houses 95.6% of the 1,013,454 inhabitants of Cartagena in 2016. Cartagena's population has shown a rapid increase in population in recent years, leading to a rapid increase in urbanization (PROColombia, 2016).

A first overview of the surrounding area of Cartagena can be found in Figure 2.1. A more detailed map can be found in Appendix A.

Figure 2.1: Cartagena: an overview

The city is situated between the Caribbean Sea in the West, the Ciénaga de la Virgen (shortly Ciénaga) in the North and the Bay of Cartagena in the South. Due to these natural boundaries, the city's waterline consists of a unique combination of sandy beaches and mangrove forests which offer the city many benefits like coastal safety, attracting tourists and providing recreational possibilities. Mangroves are mainly found in the La Virgen marsh and on Isla Tierra Bomba. To maintain the water quality in the Ciénaga, a structure called La Bocana is built in the connection with the Caribbean sea. Using a breakwater, sluices and a sheet piled wall the circulation driven by the tides is restored (Moor, van Maren, & van Laarhoven, 2002).

The areas around, and especially just south of the Ciénaga de la Virgen, are considered among the poorest areas of Cartagena. Houses are built of waste materials, pallets and corrugated plates. These houses often lack access to running water and electricity and sewage flows in the streets (Forero, 2009). For many years, houses were built closer to and gradually into the Ciénaga de la Virgen swamp. This can be seen in Figure 2.2. Most of these houses are built on top of waste with close to no waterline clearance. Since this urban growth is unorganized no public services exist.

Another densely populated area is the peninsula. The neighborhoods Bocagrande, Castillogrande and El Laguito are located here. It is considered to be the richest part of Cartagena with skyscrapers, exclusive shopping centers and expensive hotels built on the beaches.

The city's historic center is located just North of the peninsula. Getsemani is the neighborhood adjacent to it and both are confined within the city walls. The historic center attracts many tourist every year and has been a UNESCO world heritage site since 1984.

North of the city center a thin urban strip stretches Northwards between the sea and the Ciénaga.

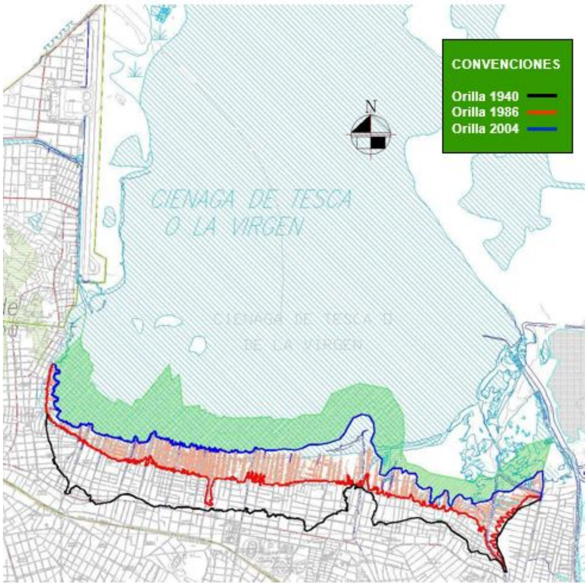


Figure 2.2: Growth of the poorest neighborhoods of Cartagena into the Ciénega de la Virgen (Fonade, 2007)

Here the neighborhoods of Marbella, Crespo and La Boquilla are located. The city's airport is found here and so is La Popa, the monastery situated on the highest hill in Cartagena. The neighborhoods built on and around the hill are low income areas.

The largest part of the upper lower class and middle class live in the area between the Ciénaga and the bay. Neighborhoods such as Socorro, Los Ejecutivos, Calamares, El Bosque and Manga are found here. The most aggressive urban expansion is found in this area as the city expands eastward.

Currently, 80% of the urban development in Cartagena is unplanned (Consultores et al., 2007). This makes it difficult to implement water management solutions on a regional scale, since it is difficult to predict where the city may expand. Though, as seen in the Vía Perimetral project, it is possible to influence city growth by the construction of tactically placed infrastructure. Vía Perimetral is a road placed on a dike which forms a border and stops urbanization of the Ciénaga behind it. The Vía Perimetral only runs along the Western half of the Southern shore and ends at the Olaya neighborhood.

A solution for the inundation problems in Cartagena must thus be designed in such a way that it leaves sufficient room for uncertain city growth, but should also try to influence the city growth according to the city's urban planning guideline. Such a guideline has been developed in 2007. In Figure 2.3, the areas suitable for expansion are identified according to this document. Unfortunately no time horizon is mentioned in this document (Consultores et al., 2007).

The Bay of Cartagena covers an area of 82 km^2 and has a depth of 16 m on average. In the South, Canal del Dique flows into the bay. This channel spills sediments and freshwater into the bay and causes the bay to behave more or less like an estuary. There are plans to build a sluice in Canal del Dique, which will reduce the sediment and freshwater supply. The bay is connected with the Caribbean Sea through multiple channels (DIMAR, 2016).

Many yacht clubs, storage facilities, refineries, the SPRC terminal and the naval base are located in the Northern, sheltered part of the Bay of Cartagena (henceforth called the inner bay) (Figure 2.4). A transfer of the naval base from Bocagrande to Isla Tierra Bomba is planned for capacity and logistic reasons. President Juan Manuel Santos announced in 2013 that this transfer is a point of national interest. Besides benefits for the navy, it also increases the public services and education on Isla Tierra Bomba as a bridge will be built to connect the island (El Universal, 2016b). The president has

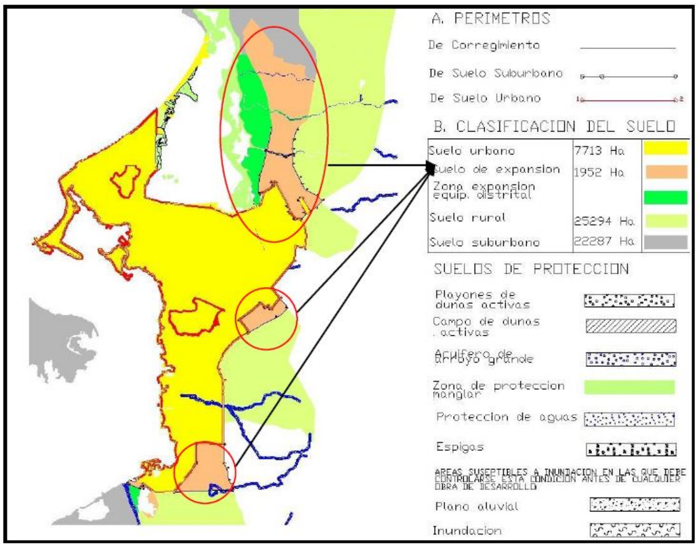


Figure 2.3: Areas identified to be suitable for future expansion -Indicated with red circles (Consultores et al., 2007)

mandated the navy to cover the expenses of the construction of the facilities on Isla Tierra Bomba, including the necessary bridge connection with Bocagrande. It is expected that this will encourage residents to settle there instead of the unplanned urban expansion towards the Ciénaga de la Virgen. The project will be financed with the sale of the naval urban properties in Bocagrande. Neither the national nor local governments want to fund the project with their own treasury. According to the project manager, mangroves and local residents will not be threatened by the project (America Militar, 2016).

The port of Cartagena is Colombia's main sea port and the third busiest port of the Caribbean sea through which 60 % of the Colombian maritime trade passes (CDKN et al., 2014). More than 2.6 million TEU was handled in 2015 by the SPRC terminal alone (ECLAC, 2016). The SPRC terminal, an oil/liquid terminal and a cruise terminal are located within the inner bay (World Port Source, 2016) .

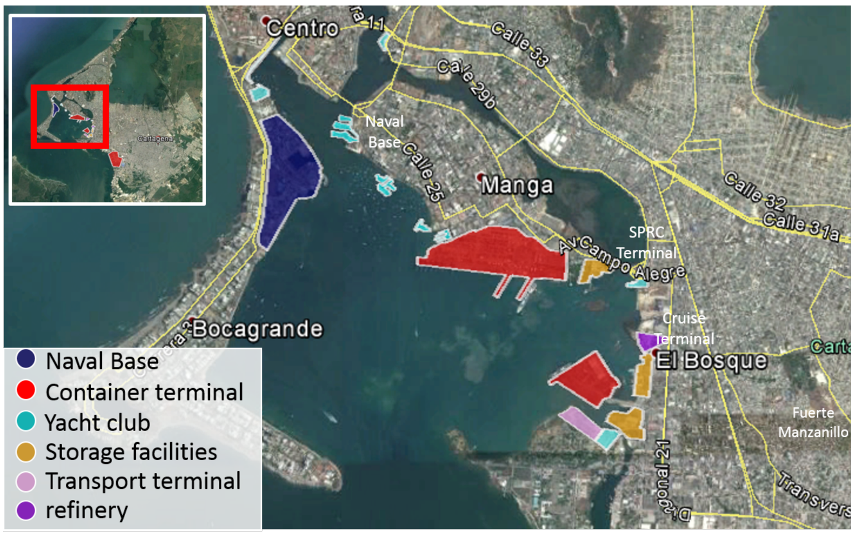


Figure 2.4: Activities in the inner bay

The city's industrial heart and additional quays and jetties are located in the Mamonal zone, East of the Bay of Cartagena (Figure 2.5). More than 2500 companies operate here. Most industrial activities are involved with sea transport, treatment of chemicals, and oil refining.

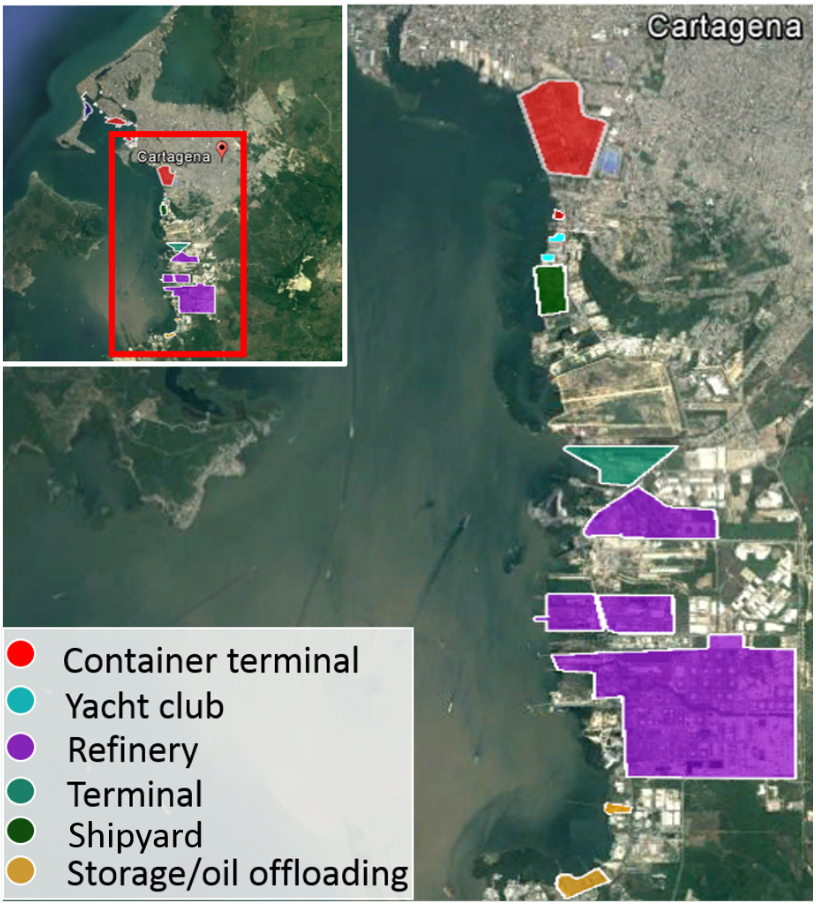


Figure 2.5: Industrial activities in the Mamonal area

Cartagena is considered to be the tourist capital of Colombia. In 1984, UNESCO named the historic center a World Heritage Site, recognizing its cultural and historical value (UNESCO World Heritage Centre, 2016). The touristic sector in Cartagena consists of over 2700 companies.

2.2 Understanding Causes of the Floods

The floods in Cartagena generally occur in the low-lying areas close to intertidal plains, shores or banks of water bodies. Also, the areas surrounding rivers and drainage channels are vulnerable to flooding. To structure the analysis, the cause, are divided into two main categories: flooding due to precipitation and floods caused by a combination of a high sea level or waves. In this chapter, for both types an analysis will be conducted into the causes of these floods. It is crucial to understand that at some locations the floods are caused by a combination of both factors.

2.2.1 Floods due to excessive precipitation

The first cause of the floods is excessive precipitation. Rainfall in the city and runoff from locations higher in the drainage basins cannot be properly discharged into surrounding water bodies, causing floods in the city of Cartagena. Figure 2.6 indicates which areas are vulnerable to flooding due to precipitation. As can be seen, the area just South of Ciénaga de la Virgen is the most at risk. No source exists in which the risk presented in Figure 2.6 is quantified.

Figure 2.6: Flood risk due to precipitation (red is high risk, yellow is medium risk) (Alcaldia Mayor de Cartagena, 2016)

The area south of the Ciénaga de la Virgen is subject to such a high precipitation induced flood risk due to a combination of several factors (Alcaldía Mayor de Cartagena de Indias D.T.C., 2013):

1. Hydrological changes in drainage basins and associated increased surface runoff.
   - Urbanization
   - Deforestation
2. Urban drainage system
   - Drainage structures are missing in low-lying locations
   - Water enters the street via manholes
3. Insufficient capacity of drainage channels and rivers
   - Accumulation of waste in the drainage channels and rivers
   - Sedimentation of the drainage channels and rivers
   - Construction of obstacles in the drainage channels and rivers
   - Modification of topography of drainage channels
   - Lack of maintenance of drainage channels
   - Discharge of waste water
   - High water levels in the Ciénaga

Each category of causes will be further analyzed in this paragraph.

Hydrological changes in drainage basins

The basins which drain into Ciénaga de la Virgen have a total area of 516 km^2. Of this total, 470 km^2 is rural drainage (basins Mesa, Tabacal Hormiga, Chiricoco, Limon and part of Matute-Ternera). The remaining 46 km^2 are urban drainage (Basins Espiga, Popa Norte, Popa Sur, and Ricaurte (indicated with '??' in Figure 2.7)) (Perez & Ramirez, 2004).

In a spatial ordering plan written for the Ciénaga area in 2004 (Perez and Ramirez), the various volumes entering and exiting the Ciénaga are presented. These are summarized in Figure 2.8. It is noteworthy that the urban drainage is much lower than the rural drainage. In addition, the amount of sewage water discharged into the Ciénaga is a factor seven times as high as the amount of urban drainage water. It should be noticed that during an 1/100 year event 188 m^3/s may exit through

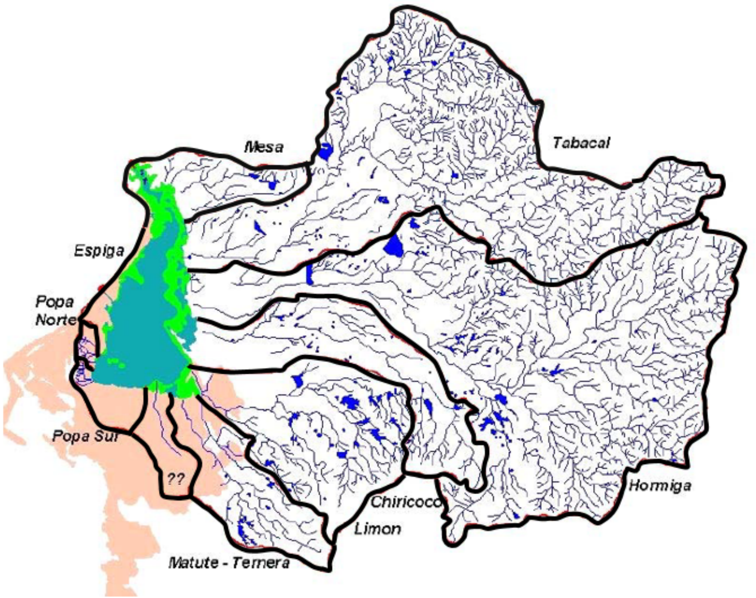


Figure 2.7: Hydrological basins draining into Ciénaga de la Virgen (Perez & Ramirez, 2004)

La Bocana and 38 m^3/s through Caño Juan Angola. However, these numbers are dubious as much more water enters into the Ciénaga than exits, implying an unbalanced situation. Furthermore, this source is over a decade old and these discharges might no longer be true.

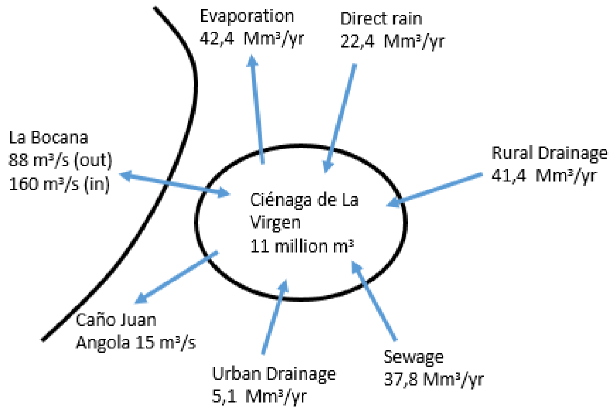


Figure 2.8: Discharges entering and exiting the Ciénaga (Perez & Ramirez, 2004)

According to the UTB (Appendix B.7), changes in the land use of these basins contribute to the increase in flood intensity and frequency. These basins used to be forested. Over the last few decades, these forests have been replaced with pastures for cattle. Many of the towns and cities in the area have expanded rapidly. This has caused water to runoff quicker as infiltration is reduced and more rainwater is drained by surface runoff.

Especially expansion of the city has reduced infiltration over a large area. Very few green zones were incorporated into the city landscape. This has caused nearly all of the urban surface to be either paved or covered in buildings. Currently, most of the urban basins are completely covered by the city. This causes run off to be very fast, leading to short but very high discharge peaks in the city's drainage system.

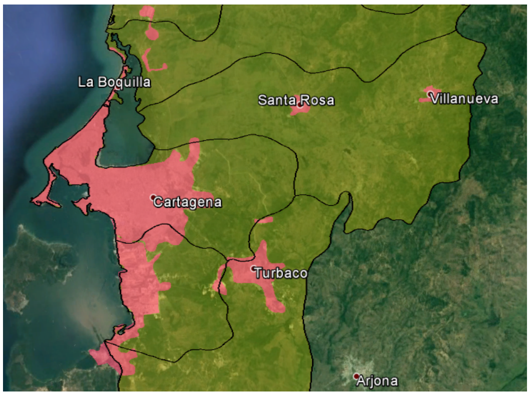


Figure 2.9: Urban areas within the drainage basins are indicated in pink

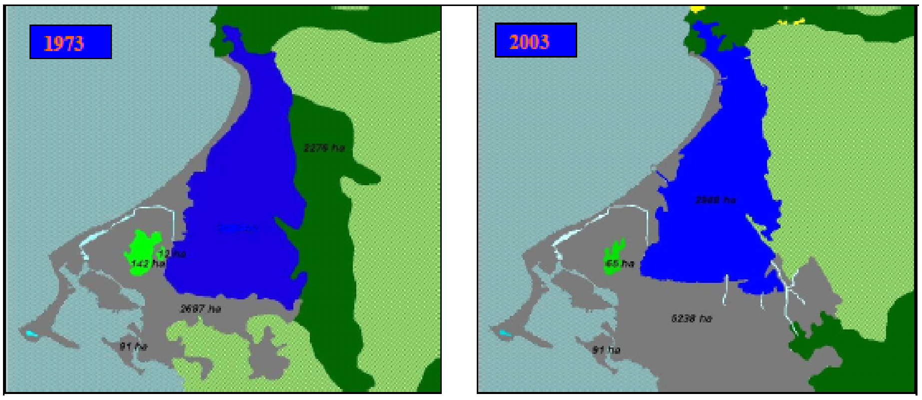


Figure 2.10: Cartagena's urban expansion (Perez & Ramirez, 2004)

Urban sewage system

According to Acuacar (2016), Cartagena has used a separated system for collecting raw sewage and rainwater since 2014. The sewer system in Cartagena is designed to handle the produced raw sewage volume. But in reality, during a precipitation event, rainwater finds its way into the sewage system and mixes with the raw sewage. This can happen due to infiltration through cracks in the pipe and direct inflow from wrong connection of the system (Appendix B.7). During precipitation, the inflow causes the system to overflow, leading to sewage back-flow through manholes and resulting in a mix of rainwater and raw sewage flowing onto the streets and even into houses.

The drainage system for rainwater in the city is limited. The water is supposed to be discharged by drains and channels driven by gravity. But not all areas of the city are incorporated into the pluvial drainage network, resulting in pools of stagnant water that remain long after the rain has passed (Appendix B.7).

Insufficient capacity of drainage channels and rivers

Rainwater from the urban drainage basin are discharged by drainage channels into the Caribbean Sea, Bay of Cartagena or Ciénega de la Virgen. The capacity of the drainage channels is insufficient during heavy rainfall. Due to the small elevation difference and in low-lying areas, the levels in the channels rise and eventually they overflow, causing floods in the low-lying areas South of the Ciénega de la Virgen and in upstream areas. The capacity of the channels is also reduced by accumulation of waste, sedimentation, construction of structures and modification of the topography. Lack of maintenance to the drainage channels is worsening the problem. Furthermore, waste water is discharged in the drainage channel instead of into the sewage system. This decreases the volume the drainage channels are able to discharge.

Figure 2.11 shows the current drainage channels in the city. Many of these channels discharge the rainwater into Ciénega de la Virgen. Combined with the great catchment areas to the East of the Ciénaga, which also discharging into the Ciénaga, the water level of the Ciénaga can rise with a couple of centimeters during a single event. This leads a further reduction discharge capacity of the channels as the available hydraulic gradient diminishes, which in turn adds to the problem of the flooding of the channels in the down and upstream areas.

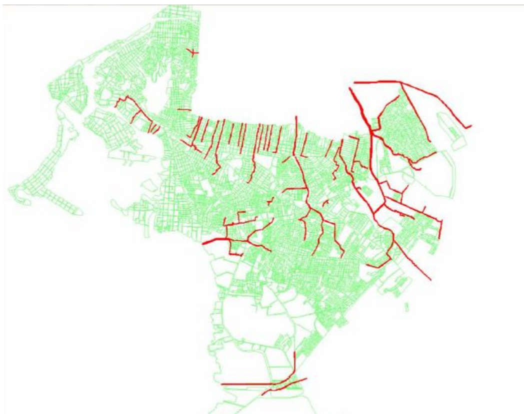


Figure 2.11: Current drainage channels (Consultores et al., 2007)

2.2.2 Floods coming from sea

Figure 2.12 gives an overview of the areas that are expected to flood due to a sea level rise of 15-20 cm as is expected in 2040 (Invemar et al., 2014). It has to be noted that the water level or frequency of the flood is not quantified. The peninsula, the historic center and the entire coastline up to North of Ciénega de la Virgen are vulnerable. Also the industrial zone of Mamonal is at risk. There are different causes and effects for the floods coming from sea, which are explained in this section.

Figure 2.12: Areas flooded in 2040 due to sea level rise (Alcaldia Mayor de Cartagena, 2016)

Coastal erosion

In case of coastal erosion, the coastal safety can be reduced. Along the coast many structures can be found which imply the occurrence of coastal erosion. This is confirmed by Figure 2.13.
According to Wanders et al. 2013, so far there has been no structural erosion near Bocagrande. The groyne built near the mouth of the Magdalena river has partly blocked the sediment supply in the

Figure 2.13: Threat of coastal erosion (CDKN et al., 2014)

coastal system, but coastal erosion near Cartagena has not been observed yet. The relative sea level will however cause structural erosion in the future (see next paragraph).

Local and seasonal erosion is observed around Cartagena. Man-made structures like groynes and breakwaters may prevent local erosion at a certain stretch of beach, but causes erosion at other locations. Also the seasonal variation causes erosion. During the storm season, sand is moved from the upper to the lower shoreface, leading to a coastline retreat, see Figure 2.14. During mild conditions sand is moved back towards the shoreline and the original profile is restored, but this takes time. The beaches near Cartagena are very small, meaning that there is no buffer for the storm season. For example, if after a storm the coastline retreats and sand is moved to the lower shoreface, during the next storm the dissipation of waves at the beaches is less. This leads to stronger coastal currents and bigger impact of the waves on the revetments and buildings near the beaches, resulting in more damage. Observed is that the width of the beaches decreases towards the end of the year and by March beach accretion accretion commences again (Wanders et al., 2013).

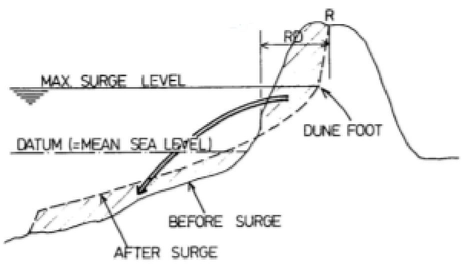


Figure 2.14: Erosion during a storm (Bosboom & Stive, 2015)

Relative sea level rise

Regarding sea level rise it is necessary to make a clear difference between absolute and relative sea level rise. Absolute sea level rise is the rise of the sea level itself. For the relative sea level rise, the rise or fall (for example subsidence) of the land is taken into account. So if the land falls and the sea level rises, the relative sea level rise is greater than the absolute sea level rise (Bosboom & Stive, 2015).

According to Torres (2013), the relative sea level rise near Cartagena has been 5.3mm/year on average. Though it must be noticed that this number is expected to grow. The relative sea level rise also has consequences for the coastal erosion. If the sea level rises, the cross-shore profile adapts to a higher sea level: sand from the shoreline is moved towards the lower shoreface, leading to a coastal retreat.

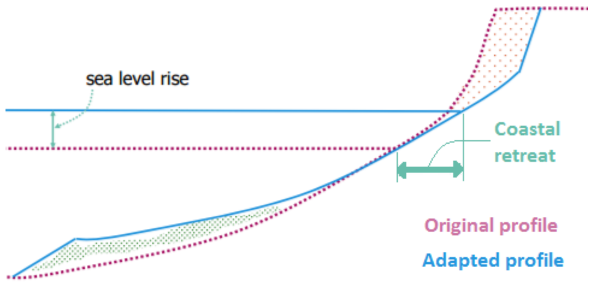
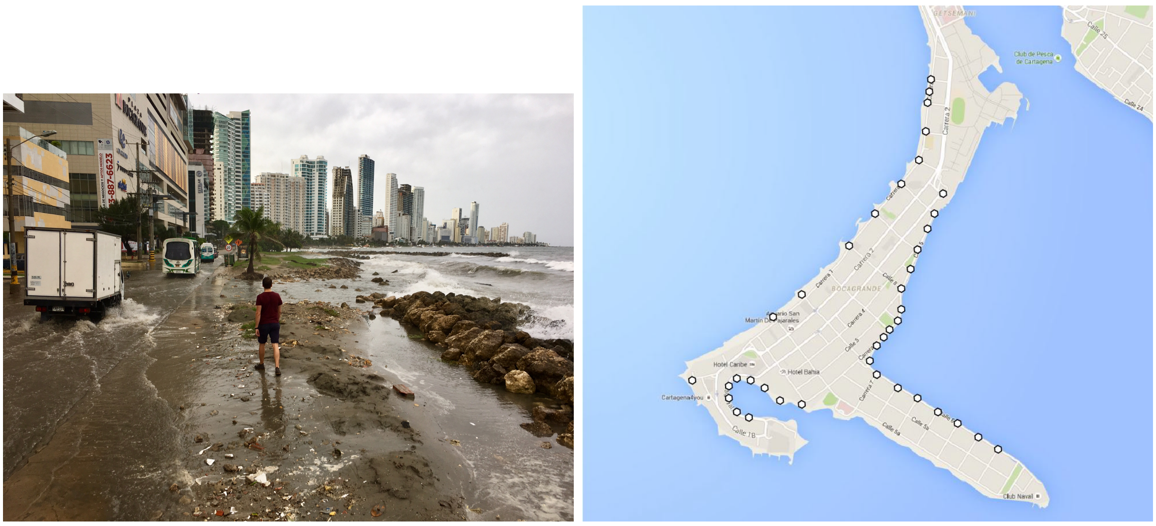


Figure 2.15: Coastal retreat due to sea level rise

Wave overtopping

A seawall is located along the coastal avenue and near the historic city center. It consists of a concrete wall with loose rocks in front of it and (almost) no beach. As seen in Figure 2.16a, the seawall is currently in a bad condition. There are many loose rocks and fine grains on top of the coarse blocks. During mild conditions there is already a significant volume of water overtopping the seawall and flowing onto the streets. It is clearly visible that this is damaging the sidewalk and road. Outlets have been made to let the (rain) water flow into the sea if the roads are flooded. But in practice, during high tide or strong wave action, water flows through the outlets onto the roads.



(a) (b)

Figure 2.16: Clearing made in the sea defense to let the rainwater flow out to sea and an overview of all such locations in the peninsula (Cornelissen et al., 2015)

Current sea defense

To properly design new coastal protection, a good inventory is needed of the current infrastructure. Figure 2.17 gives an overview of the coastal protection of the city. It should be noted that for the most part the coastal protection is in very poor state. As mentioned, in Bocagrande the sea wall has been perforated allowing rainwater to flow into the sea. Reversely, during high tides, high waves, or surges seawater is allowed to freely flow into the city making the sea wall useless. The exact same situation presents itself along the Marbella coast. The revetment in front of the historic center's wall is also not sufficient. Waves often overtop the revetment, hitting traffic with a powerful spray and flooding the street. In some areas the street is covered with bits of rock because the revetment is breaking up. There is a sea wall present, but the height is not sufficient. The only section of the coast which appears to be in good shape is the Crespo area. The large groynes in the north of Figure 2.17 are part of a recent project which combined land reclamation, the construction of a tunnel and coastal defense.

Figure 2.17: Current sea defense infrastructure for the peninsula shoreline

2.2.3 Future expectation

Rainfall and runoff

According to the fifth assessment of the IPCC, it is likely that more heavy precipitation events will occur. Also, there has been an increase in tropical storms since 1970 in the North Atlantic (IPCC, 2013). Whether this is caused by climate change is uncertain (Knutson et al., 2010). But it is likely that the intensity and frequency of floods due to excessive rainfall will increase.

Sea floods

It is expected that by 2100 the sea level will have risen 0.8-1 meter (CDKN et al., 2014). This has direct consequences for the lower parts of the city. The permanently flooded areas are showed in purple in Figure 2.18. Furthermore, the sea level rise will induce coastal erosion. Assuming a equilibrium shoreface, a rough estimate is that the coastal retreat will be about 50-150 meter in case of a relative sea level rise of 1 meter (CDKN et al., 2014).The coastline can be maintained if there is sufficient sediment supply that can keep up with the sea level rise (Bosboom & Stive, 2015). But because sediment is already in short supply, coastal retreat is expected. In 2040 all beaches are at risk of coastal erosion (CDKN et al., 2014).

Taking all this into account, it is likely that the frequency and intensity of the floods will increase in the future. Some areas will even be permanently flooded, including the most dense populated part of the city, the Olaya neighborhood just south of the Ciénaga de la Virgen.

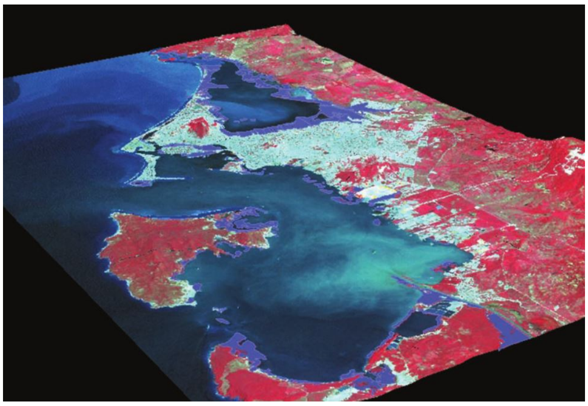


Figure 2.18: The in 2100 permanently flooded areas are shown in purple(Invemar et al., 2014)

In literature, very little information is available about the used methodologies. Most of the information about the floods is qualitative instead of quantitative. Understanding of the causes, intensity and frequency of the floods seems to be lacking.

2.2.4 Overview of causes and effects

Different areas of Cartagena suffer from floods due to various causes. All these causes and effects can be found in Figure 2.19. However, there are some problems which cause floods throughout the city. The drainage system for rainwater in the city is limited, leaving pools of stagnant water. Secondly, there is no responsible party for flood defense and/or pluvial drainage, resulting in a lack of action (see Section 2.3). Furthermore, uncontrolled urbanization causes houses to be build in precarious positions. In the future, all these problems will very likely increase due to climate change related phenomena. It is expected that more heavy precipitation events will occur, in combination with sea level rise, the city will be even more vulnerable to floods.

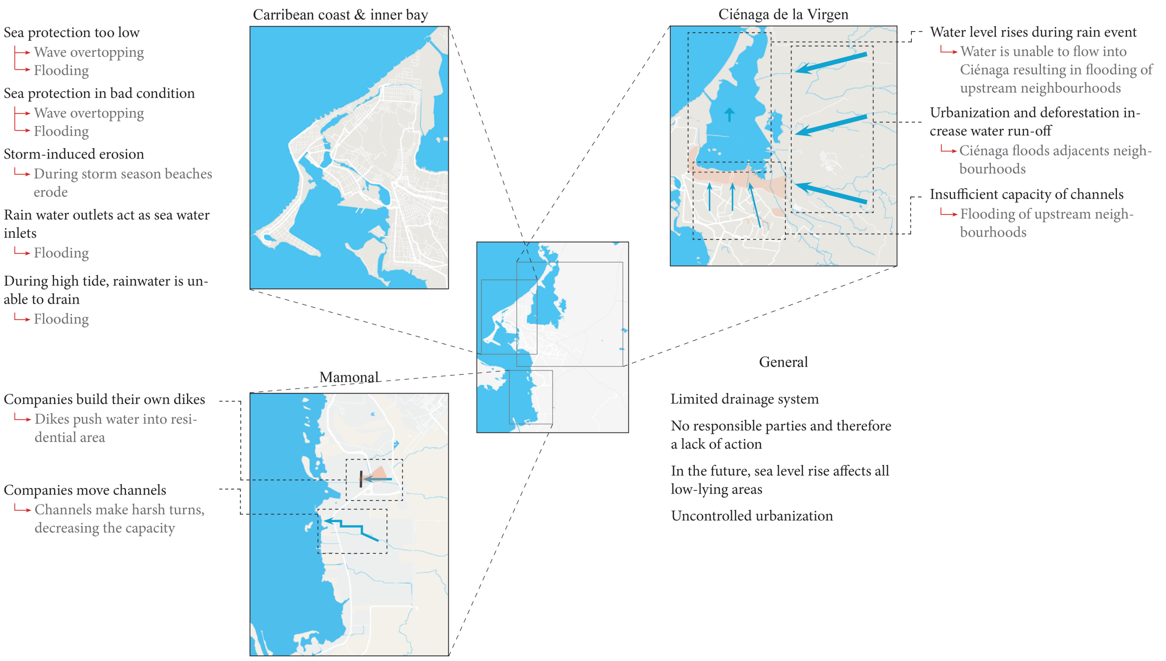


Figure 2.19: Summary causes and effects of floods in Cartagena

The parts of the city at the Caribbean coast and the inner bay mainly encounter problems concerning floods from sea. Most sea walls are too low and in poor state. During high tide seawater also flows into the streets due to the open rainwater outlets, which then acts as seawater inlets. Although structural erosion is not encountered, storm-induced erosion occurs. Lastly, also rainfall is a problem during high tide as it is not able to drain by gravity, since the seawater level is too high. This causes the rainwater to remain in the street.

For Ciénaga de la Virgen, multiple problems result in flooding, which must be addressed to solve the flooding issue. Urbanization and deforestation of the large catchment areas to the East of the Ciénaga, cause the discharge peaks to increase, raising the water level in the Ciénaga. This floods all the neighborhoods adjacent to the Ciénaga. Uncontrolled urbanization also contributes to this problem, as building into the Ciénaga increases the risk. The rise of the Ciénaga level has a secondary effect: the hydraulic gradient in the channels decreases. This results in a reduction of the capacity of the channels. Together with the already limited capacity in the channels, this results in the flooding of the neighborhoods upstream and downstream.

The industrial zone of Mamonal encounters different problems. Companies build their own dikes and moved the channels, causing flooding problems to arise in this area. The dikes push the water back into neighborhoods, such as Policarpa, causing heavy floods. The channels are redirected and are forced to make harsh turns, decreasing the capacity. This increases the severity of the floods (see Appendix B.5).

2.3 Understanding the Stakeholders

The goal of the stakeholder analysis is to identify all parties which are important to the implementation of a solution. These include both parties which have influence on the solution, and parties whom are influenced by the solution. A solution can only be successfully executed once it is clear for whom the solution is made and what their requirements and wishes are.

First, the political system is described on both the national and local level. This provides the legal and political context which must be understood before the stakeholder framework can be understood. Secondly, the top stakeholders are identified. Their relation to the project is elaborated upon, and their interests are described. Stakeholders are ranked by a combination of their power (ability to enable or hinder a solution) and interest in the solution. Below follows the proposed stakeholder management strategy of the most important stakeholders; this strategy is written for the engineering consultant whom is to find a solution.

2.3.1 Political system

Executive government

Colombia is a republic which has three separate branches of government. The president of the Republic is the head of the executive branch. He is supported by the vice-president and ministries at the national level. At the provincial level, the departments are run by a governor whom is elected by popular vote. At local level, mayors are elected to head the executive branch at the municipal level. The mayor answers to the department's governor.

In Colombia, public officials such as governors and mayors are allowed to serve a maximum of four years in office. This law is part of an anti-corruption measure. In addition, these officials may not award projects during the last year of their term. It is not uncommon for a mayor to quit or be impeached before his term is completed.

As head of the local government, the mayor is very powerful within the city. As mayor he is head of not only the city council but also of the organizations such as the EPA (provides licenses), the DATT (transport and traffic policy) and Secretaria de Planeacion (urban planning). The mayor has the power to award projects and also to cancel projects. He may cancel projects that are planned, under construction, or cancel the maintenance budget of completed plans. This causes a discontinuity in policy and encourages a short term philosophy.

Although few people in official positions are willing to admit it, many of the interviews reveal that corruption is a significant problem in Cartagena. Money may disappear within the local government, or projects are awarded not based on their merit, but rather based on social connections. According to the Colombian students, many people feel that some politicians value their ego more than the city. This means that sometimes work is done to create a legacy rather than to solving a problem.

The current mayor is Manuel Duque, a former journalist and sports commentator. He was elected in 2016.

Municipal structure

The city is divided into Unidades Comuneras de Gobierno Urbana (UCB) which resemble administrative districts within the city. Within each UCB neighborhoods are numbered 1 through 6 by so-called estratos. Estrato 6 is the most wealthy section. Here taxes are highest and services are the best. Estrato 1 is the poorest and services are basic to none. UCB's 4-5-6-14 are all completely estrato 1 while UCB 1 is mostly estrato 6.

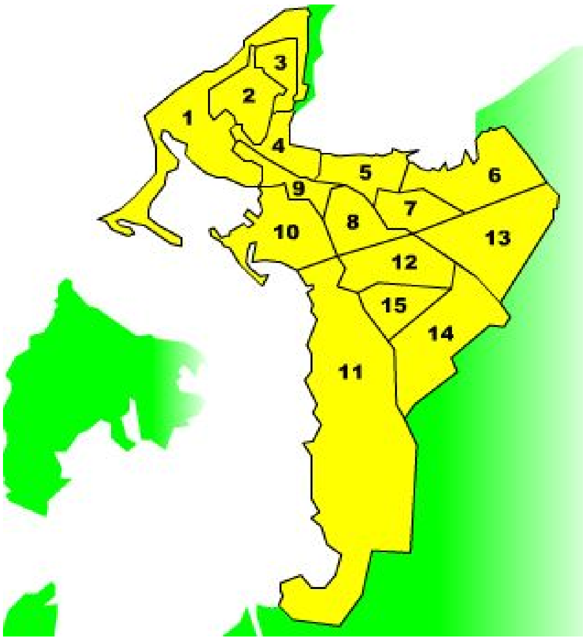


Figure 2.20: Unidades Comuneras de Gobierno Urbano (URBANAS, 2016)

Each UCB receives its own budget for education, infrastructure, recreation, etc. In a calculation of the investment per UCB by (Vides, 2008) it is interesting to note that the budget available for disaster prevention, which is 0.4%, is very small. About 40% of the total budget goes to infrastructure. It is not known whether water management infrastructure is included in this budget. However, since a lot of money is available for infrastructure, solutions which combine urban planning, roads, and other such infrastructure with water management should be explored as they should be easier to finance. A city-wide budgets also exist, please refer to the finance paragraph of this section.

Water management structure

The three national entities are involved in the coastal protection are the MADS, the DIMAR, and the CCO. Within the MADS 4 organizations are in charge of slightly different tasks. These organizations are the ANLA, INVEMAR, CIOH and IDEAM. The roles of these institutions are explained in the Appendix C. According to Royal HaskoningDHV, the MADS focuses on performing studies on coastal ecology. However, it has no funds to implement big projects. Coastal erosion and repairs after events therefore become local responsibilities. Little to no money is invested into prevention.

Important is to note that on the National and Ministerial level several institutions share responsibilities which has resulted in unfulfilled obligations and an inefficient and confusing system which discourages accountability (Anfuso, Rangel-Buitrago, & Williams, 2015). Most noteworthy is that no central organization is responsible for coastal protection.

According to the director of the local engineering firm CARINSA, solely Acuacar provides drinking water and waste water services. This was confirmed in an interview with the Secretaria de Planeacion (see Appendix B.2). Considering the management of flood risk, nobody is responsible. Consequently, no one is willing to pay for the implementation of a solution. Many parties could assumer responsibility, but wait for other parties to pay the bill.

This means no party is in charge of drainage of rainwater nor is anyone responsible for the coast as neither are a waste or drinking water service. According to the Dutch Consulate, Aguacar has very recently signed a contract adding urban drainage to it repertoire.

Finance

The city of Cartagena has a very small budget available for the development of the city. According to the director of CARINSA (see Appendix B.1) the municipality receives very little income. The port only pays 20% of its taxes to the city. The companies which are located in the industrial zone of Mamonal are responsible for 5% of the nations industry, but have their headquarters in Bogota and thus pay their taxes there. Due to tax evasion and a very large unofficial market, the citizens barely contribute to the tax income.

CARINSA estimates that the city has a budget of about 2 million USD per year for flood protection. This budget must cover maintenance, new infrastructure and repairs and thus does not suffice. Additionally, the Consulate mentioned that city does not invest in projects which are not directly profitable. Avoided damage is not seen as a profit either.

The budgets for programs of interest are presented in Table 2.1. These values are obtained from the city's four years plans and are converted to USD. The budgets show that currently 2 million USD is indeed the approximate amount invested and that this amount is due to increase in the future. The monetary units are not specified in the budgets, only numbers are given. Therefore is suspected that numbers for 2014 and 2015 should be multiplied with a factor of 1000 (Duque, 2016; Vélez-Trujillo, 2013). The risk management budget is not subdivided further but should include: inundation prevention, climate change adaptation, fire prevention and mitigation, hurricane preparation, landslides and erosion prevention (Alcaldía Mayor de Cartagena de Indias D.T.C., 2013). For comparison the total annual city budget is also provided. These budgets also indicate a lack of continuity in policy. The coastal protection, for example, disappears completely from the municipal agenda.

Table 2.1: Budget for programs of interest according to 4 year city plans, in USD (Duque, 2016; Vélez-Trujillo, 2013)

Program	2014	2015	2016	2017	2018	2019
Plan Maestro	10,849	11,219	1,421,579	1,481,645	10,405,117	14,318,277
Coastal protection	848	678	-	-	-	-
Risk management	943	948	3,084,443	3,194,395	12,169,450	16,135,210
Total city budget	261,952	277,400	330,512,200	349,864,544	377,700,512	408,717,626

According to the Secretary of Planning (Appendix B.2), it is therefore necessary to obtain funds from the national level. This means that the problem must be solved along the coast as a coastal defense work or as part of the national highway system. New out of the box manners to include the national government are also possible. A regional solution may work, as national funds can be applied.

In June of 2016, law 1784 (Ley del Sitio) was passed. In this law it is stated that the national government is responsible for financing projects in Cartagena concerning coastal protection, rainwater drainage, and local channels and lagoons. This is likely to cause local institutions to become more passive again and to wait for funds from the national government.

2.3.2 Stakeholder map

In order to create an insightful overview of the stakeholders, a map is created which orders stakeholders based on their power and interest. Power is defined as the ability to influence the solution's outcomes. Interest is a scale of how important the outcome of the project is for a party or how important it is to find a solution. This rating is done by comparing the relative power and interest, no values are assigned to quantify these factors.

Parties which poses a lot of power are most important and should be managed closely. Parties with high power but little interest must be convinced of a solution and subsequently be kept satisfied, while parties with high interest and little power should be kept informed. Parties which lack both power and interest should be monitored.

For a full description of each stakeholder refer to appendix C.

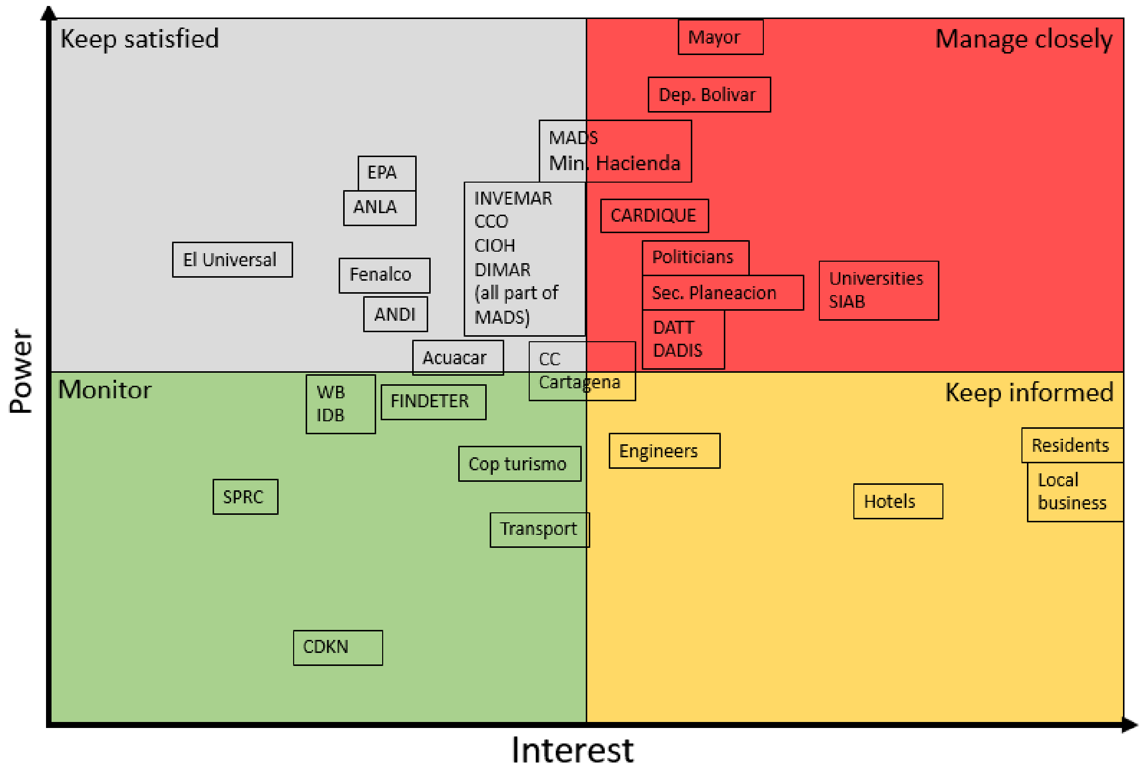


Figure 2.21: Stakeholder map for the project which ranks stakeholders based on their power and interest

2.3.3 Stakeholder management strategy

Based on Figure 2.21 it is concluded that the most important stakeholders are:

1. Mayor of Cartagena
2. Departamento de Bolívar
3. National Ministries (MADS and Ministerio de Hacienda)
4. Respected local knowledge centers (Engineering institutions and universities)

Mayor of Cartagena

The mayor of Cartagena is the most powerful person within the local government. As mentioned he oversees all other local governmental entities such as the DATT, DADIS, Secretary of Planning, EPA, ect. Thus with his approval all these agencies will follow suit.

According to local newspaper El Universal, the mayor is currently seriously considering making investments into rainwater drainage on the basis of the 2007 pluvial drainage plan. This shows that he does want to implement in a solution. However, the lack of action in the past does show that flood safety cannot be considered a true priority. The plan is considered a short-term and local solution (see section 2.5.1 for reasoning). This development has been confirmed by the Universidad Tecnológica Bolívar.

It is important that the mayor is convinced that solution is urgent and that an integral macro scale solution is required. The above mentioned plan could be part of this integral solution. To guarantee the mayor has this mindset, it is vital to convince him of the urgency, scale and future impact of the water-management problem. Therefore, in this report the flood impact description is emphasized. Once the impact of the floods is understood, it should be possible to convince the mayor that solving this issue will bring a positive contribution to many of the city´s objectives (World Bank, 2011).

Based on three documents ((URBANAS, 2016),(Vélez-Trujillo, 2013) and (Duque, 2016)), the city's main priorities and issues are extracted and presented below. Those marked with a star will benefit from proper water management. For the full ranking process refer to appendix C.2:

- Education
- Equality (social, racial, opportunity)*
- Health*
- Sustainable economic growth*
- Transport and mobility*
- Sound and transparent local government
- Environment and Climate change - current water-management plans fall under this category*
- Improved living conditions*
- Safety and Security*
- Public services (drinking water, sewage, waste)*

Once the mayor is convinced that an integrated macro-scale solution is required, he must be convinced that the solution presented in this document is indeed the best. To achieve this, a flood defense philosophy will be presented, which is easily understood and remembered. This should leave a lasting impression. The philosophy should be compared to global practice as it makes it more credible and tangible.

Departamento de Bolívar

As Cartagena is located within this department, it is subjected to the decisions made by the departmental government. In theory, the mayor answers to the governor. Macro-scale solutions implemented in Cartagena will likely impact several other municipalities, and thus departmental approval and guidance is needed.

It is unclear whether the department considers water management an priority. During a seminar the governor declared that preparing Bolívar for climate change, and resulting flood risk, is a main long-term priority. However, they have provided little evidence to support this statement. Assumed is that the department will be very interested in a regional solution, once it is presented to them.
In addition, the regional government can be an important source of funding. If the solution helps the greater Cartagena region, the department is more likely to supply funds. So far, funding seems to be the greatest obstruction for execution of local plans and studies. Attracting regional funds is vital for financing the project. The step from departmental to national government is smaller. Thus the

department can make a stronger appeal for attracting national funds.

As holds for the mayor, the governor must be convinced of the urgency and impact of the flood risk and he must be convinced of the benefits of improvement. Especially the economic benefits to the region and benefits to regional planning must be emphasized. Therefore, he should be approached in the same manner as the Mayor.

National Ministries

The Ministerio de Ambiente y Desarollo Sostenible (MADS, Ministry of Sustainable Development) and the Ministerio de Hacienda (Ministry of Agriculture) are vital to the solutions success for two reasons: the MADS is involved in coastal studies, and Ministerio de Hacienda could be a source of national funds.

The ANLA, INVERMAR, CIOH and IDEAM are all part of the MADS. Even though they are identified as separate stakeholders on the stakeholder map, the MADS does have jurisdiction over them. Thus, it may exert influence on them, once convinced that a solution must be implemented. Although there is no budget available within the MADS, these institutions will likely be involved in any plan regarding coastal defense and their approval and support of a solution is vital to its credibility.

The MADS and the Ministerio de Hacienda are both responsible for the sustainable development of the country. The Ministerio de Hacienda could provide funds on behalf of the national government to finance the project. As an example, Fondo Adaption is an entity within the Ministerio de Hacienda and was created to award and finance infrastructure projects in response to the 2011 La Niña year. They have expressed their interest in financing a solution to Royal HaskoningDHV which indicated some interest in a solution.

In order to involve the national ministries and convince them of the need to reduce Cartagena's flood risk. It is very important that the solution is a marco-scale solution. To let the project succeed, it must be emphasized that the country as a whole will benefit. Therefore, the industrial area of Mamonal and the port, which are of national importance, should also benefit from the solution. The project must improve the livelihood of Colombian citizens significantly and should serve as a example to the rest of the country.

Local knowledge institutions

The SIAB and the universities within Cartagena are the most important bodies having much knowledge about water management. Not only concerning engineering, but also including urban planning, transport and economics. The people within these organizations understand the water management problem and its consequences better than anyone else. These people are respected local experts in their fields and thus have an advisory role towards the (local) government. If they are not convinced of a solution they will not endorse it, which could harm the credibility of a solution to reduce flood risk.

Conversations with the UTB have shown the limited amount of available knowledge about flood risk in Cartagena. It seems that even specialists at universities and local knowledge institutions only partially understand the flood risk that Cartagena faces. They are interested in a solution, not only because of professional interest but also because they are starting to understand the upcoming flood risk.

In order to involve these stakeholders, the solution must be supported by scientific reasoning. These organizations should be involved from an early stage, as is currently done with the UTB. If they are involved with the design process from the start and understand the process, decisions and reasoning, they are more likely to support the conceptual design which is to be delivered at the end. Finally, can these parties give a contribution to the final flood defense system by means of collecting data.

2.3.4 Conclusion

From the stakeholder analysis, it is evident that the shear amount of parties has lead to overlapping responsibilities. This has also creates unfulfilled responsibilities and causes a confusing environment. There are several organizations responsible for managing the coast and rivers, and also several institutions which provide licenses. Also municipal organizations such as the DATT and Secretary and planning have partially overlapping functions. This environment discourages taking responsibility, as no single party can be held accountable. This makes it very difficult to execute plans.

An important conclusion is that the influence of regional and national government should not be forgotten. The lack of action shows that the local political climate is very difficult to navigate due to corruption, a lack of continuity in policy and insufficient funds. Therefore, it remains a viable option to approach the departmental or national government for getting approval and financing for the solution. This is also how the Bocana project was ultimately executed, as 55% of the 30 million USD was paid by the national government. The remaining 45% was payed by the Dutch government (Moor et al., 2002). The inner city drainage is seen as a local problem. If drainage could be incorporated in an integrated and marco-scale solution, funding might also be possible through the departmental or national government.

2.4 Understanding Flood Impact

It is predicted that 12% of all residences in Cartagena will be regularly affected by floods due to sea level rise or inundation by 2019. In 2040, this number will rise to 27.1% of the population (Invemar et al., 2014). In this chapter, the impact of these regular floods will be explained on the basis of four different categories: safety, economic, social and environmental issues.

2.4.1 Safety

Casualties

Over the years, people have died from the direct consequences of a flooding coming either from sea or due to rainfall. In Figure 2.22, the number of deaths due the floods over the years can be found. According to Vides (2008) the list is incomplete, but does provide some insight. Compared to other natural hazards, floods (inundacion) contribute the most to the number of deaths (blue bars) in Cartagena (see Figure 2.23).

> *"People are scared. When the water comes we have little time. Many cannot leave, they get infections. Some flee to their family "*
>
> — Olaya (neighborhood besides Ciénega de la Virgen, see Appendix A) community representative

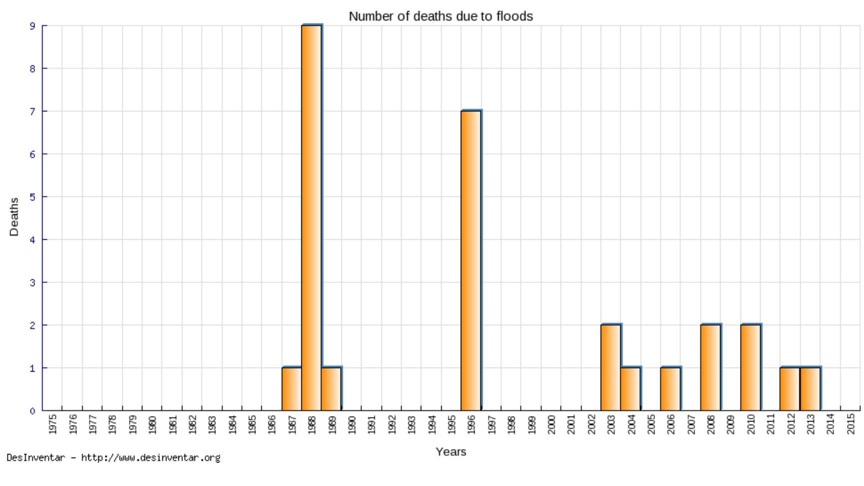


Figure 2.22: Number of deaths due to floods (DesInventar, 2015)

"We are worried about our kids. Sometimes we lose them in the floods."
— Olaya community representative

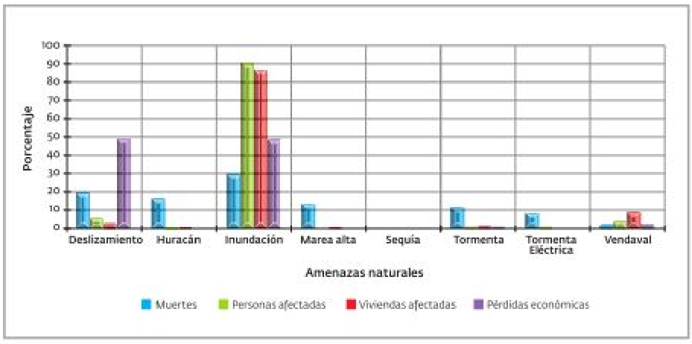


Figure 2.23: Consequences due to floods with respect to other natural disasters from 1932 till 2011 (Invemar et al., 2014)

Diseases

The District Department of Health (DADIS) stated Cartagena a warning concerning health risk due to diseases spread by rats and mosquitoes after floods (DADIS, 2014). Stagnant water acts as a breeding site for mosquitoes and therefore increases the spread of vector-borne diseases like dengue, zika and chikungunya (WHO, 2015). The DADIS explained that the pluvial floods increase the amount of stagnant water bodies, in which mosquitoes can easily breed. This rapidly increases the mosquito population and therefore the chance of vector-borne diseases (see Appendix B.4). The confirmed cases of the most important vector-borne diseases in Cartagena in 2016 (up to week 45) can be found in Figure 2.24. These cases can be found in all the neighborhoods of the city. Although people generally do not die from these diseases, the diseases are undesirable. Also, the treatment of the diseases costs money and people might be unable to work. This has a negative effect on the economy of the city.

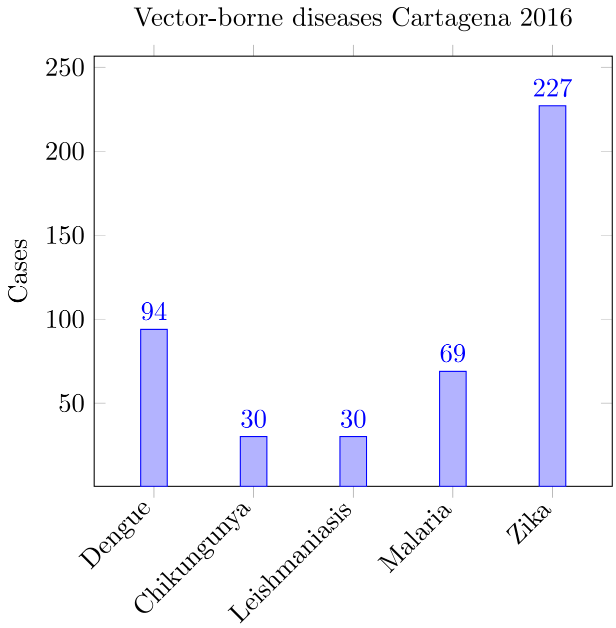


Figure 2.24: Confirmed cases of vector-borne diseases in 2016 up to week 45

In the neighborhood Torices, North-East of the historic center, the mosquitoes cause a serious health risk, as skin diseases and respiratory problems have increased. Because the rainwater remains in the streets and the sewers overflow, an increase of the mosquitoes population is inevitable. The local government has recognized the problem and granted 50 billion COP (17 million USD) to solve this problem (Álvarez Beleño, 2016).

The flooding causes an increase in the rat and mice population, which leads to additional health risks. Rats and mice can transmit leptospirosis and rat-bite fever by urine in stagnant water. Eight cases of leptospirosis were confirmed in Cartagena by week 48 of 2016. Other diseases, like salmonella are also spread by rats (Flórez Dechamps, 2016)(WHO, 2015).

> *"Flood reduction would be the most effective way to reduce the spread of diseases"*
> — DADIS Employee

Compared to other regions in Colombia the numbers of vector-borne diseases are significantly higher (Instituto Nacional de Salud, 2016). However, the spread of diseases are highly undesirable and according to the DADIS, the floods do indeed increase the spread of vector-borne diseases and leptospirosis in Cartagena (Appendix B.4). So protecting the citizens from flooding will increase the health of the Cartageneros.

Future situation

Most casualties occur during extreme weather events; with the increased possibility for extreme weather events, more people are at risk should no measures be taken. According to Plan 4C (see Section 2.5.2), it is expected that by 2040 the number of vector-borne diseases, like dengue and leptospirosis, is doubled compared to 2014 (CDKN et al., 2014)). In the Proyecto Desarrollo Ahora Si, it is also stated that the climate change will cause an increase of tropical diseases (Vélez-Trujillo, 2013).

> *"Hurricanes and floods are becoming more frequent. The government should warn and help us. "*
> — Bocagrande community representative

2.4.2 Economics

In addition to the safety hazard, the floods also have an economic impact. This can be subdivided into two components: the direct damages and the indirect damages.

Direct

The direct damages are damages that are caused directly by the presence of the water. These include damage to infrastructure and public property, damage to private property, damage to natural resources, lives lost and costs of evacuation.

Table 2.2: Direct annual flooding costs due to rainfall only in USD according to Plan Maestro (Consultores et al., 2007)

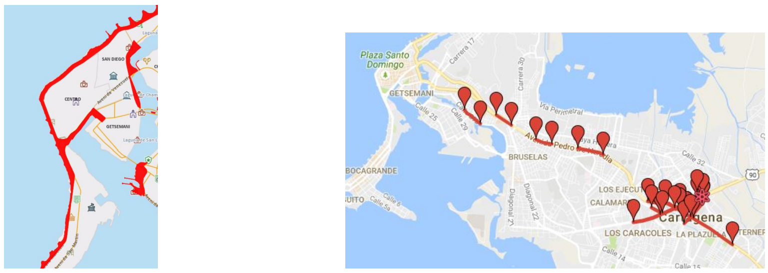
Type of damage	Value [USD]	Percentage [%]
Houses	6.800.000	53
Transport	2.800.000	22
Economic entities	2.400.000	19
Institutions	380.000	3
Expenses of the district of Cartagena	314.000	2
Public services	123.000	1
Total	**12.800.000**	**100**

It must be kept in mind that the above listed damages occur mainly in the Cienage de la Virgen adjacent neighborhoods. The area around Canal Ricaurte (Comuneras 5-6-7) suffers around 2.9 million USD in damages each year. Since these neighborhoods are among the city´s poorest, the relative impact of these 2.9 million USD is much higher than in richer areas.

As of yet, no data is available regarding the direct cost due to seawater induced floods.

Indirect

Indirect damages include a reduction in revenue or lost profits. One of the major impacts of the floods in the city is the congestion of roads. According to El Universal, floods cause local bottlenecks which cause a domino effect throughout the city, resulting in the collapse of the traffic system. Figure 2.25 gives the bottleneck locations. Already in 2019, the road connecting the peninsula to the city forms a bottleneck, because it will be flooded (in the data it is unspecified how severe or frequent the road will be flooded). Other local bottlenecks caused by flood can be found in 2.25b (BUELVAS, 2013). This has been confirmed by the DATT (see Appendix B.3).



(a) Flooded roads around the naval base and historic center (Alcaldia Mayor de Cartagena, 2016)

(b) Bottlenecks on the cities main roads Avenida Pedro de Heredia and Transversal 53-54 causing system wide congestion

Figure 2.25: Bottlenecks caused by floods

The congestion causes employees to miss working hours. It prevents supplies from reaching shops and factories and prevents costumers from reaching stores. Floods also prevent businesses from using their workplace. Stores may be flooded and, in Mamonal, workers are often forced to evacuate the premises. This causes loss of revenue (Jose Molina, 2010).

Tourism is also negatively impacted by floods. The floods cause backflow of sewage causing a unpleasant smell. Together with a ankle-deep water on the streets, this discourages tourists to leave their hotels. Planes are sometimes forced to land in Baranquilla due to flooding of the airport and convention guest are sometimes unable to reach their destination. This makes Cartagena less attractive as a place to do business (Gonzales, 2016).

> *"Rich people are leaving Cartagena. The water causes discomfort and they no longer want to live here. They take their business elsewhere."*
> — DATT employee

By interviewing the DATT, it became clear that frequent flooding by seawater has causes a reduction in property value in the city's wealthier seaside areas. Many wealthy residents have left Cartagena because of discomfort which is caused by frequent floods and congestion. When these residents take their business and tax money elsewhere, it hurts the city's development and economy (see full interview in appendix B.3).

Total damages

Considering the available time, it is outside the scope of this project to attempt to quantify the direct and indirect damages. However, according to Plan 4C, the 2011 flood (La Niña year) caused losses of about 5% of Bolívar's GDP, 90% of which is created in Cartagena. Thus, it is estimated that in 2011 Cartagena suffered 540 million USD in losses due to flooding. It is assumed this includes indirect and direct damages as this is not specifically mentioned(CDKN et al., 2014). No data exists on average annual direct and indirect costs for both sea and pluvial floods.

(a) (b)

Figure 2.26: Evacuation of Mamonal workers and a flooded bar in the Historic Centre (Jose Molina, 2010)

Future situation

Plan 4C (CDKN et al., 2014) stated that the economic development is under threat due to climate change. If nothing is done against the coastal erosion and heavy rainfall, the following scenarios are predicted for 2040:

- 28% of the industry under threat
- 35% of the road infrastructure at risk
- 100% of the historic center will be flooded (Figure 2.27, The degree or frequency of flooding is not quantified in the source.)
- 100% of the beaches at risk due to erosion

As the industry sector contributes to almost all of the GDP of the entire department Bolívar, it would be a huge economic set back if almost 30% of the industry will be lost. Also, the effect on the road infrastructure will create an economic loss as congestion will increase and more money has to be invested in new infrastructure. Especially because 54% of the roads in Cartagena already are in bad condition (CDKN et al., 2014). To improve and maintain this system, it must be understood that roadways must be able to resist the effects of climate, both present and future, and must be in line with the projected conditions of a potential higher sea level (CDKN et al., 2014). Lastly, the loss of the historic heritage and beaches will have a negative effect on tourism and cause risk for the economic development of Cartagena.
Concluding, it can be said that the economic losses due to inundations are already substantial. So it is clear that investments to reduce flood risk are a necessity. It is expected that climate change will lead to more severe inundations in the future. If the lack of action trend continues, the costs of the lack of action will be much higher than those assumed so far (CDKN et al., 2014).

2.4.3 Social

Inequality

In 2016, the WorldBank published an investigation on the income distribution of countries in the world. Colombia finds itself on the 10^{th} place of countries with the highest income inequality (Worldbank, 2016). This corresponds with a report published by the United Nations stating that the richest 10% of the country has an income 60 times higher than the income of the lowest 10% (United Nations Development Programme (UNDP), 2009). For reference: in the Netherlands this number is only 6.6 (OECD, 2015). Cartagena, as one of the biggest cities in Colombia, is no exception and has its fair share of poverty and inequality. Lack of development in flood-prone areas may increase the social inequality, creating distrust in the municipality and even social unrest which can be a threat to peace and stability in the region (APFM, 2013). Interviews with several local community associations stated that the inequality increases due to the floods. The people in the poor neighborhoods do not

Figure 2.27: The complete historic center will be flooded, flooding all but two touristic highlights in Cartagena by 2040 (DIMAR, 2016)

have the resources and political representation to make their needs public.

> *"We are alone. We have no money and no voice. The government doesn't help us"*
> — Olaya resident

For example, concessions for factories are given to companies by the local government. The companies then construct dikes to keep their factories dry and make existing natural channels smaller to create more space. As a result the water is pushed towards poor neighborhoods, like Policarpa. In that area they mostly live on lowlands resulting in frequent flooding. The people in these neighborhoods are thus forced to endure floods more frequently, or relocate. Because the overflowing drainage channels flow towards them, even small rain event can cause major problems in these vulnerable areas. According to pastor Caraballo, the inhabitants of these areas lack political or social power to defend their needs (see appendix B.5).

> *"The most vulnerable people suffer most. "*
> – Local Pastor

Desperation arises when the rain starts: there is very little time to pick up some small stuff, take the kids and then flee to a safe and dry place. The flooding then leaves them with nothing but what they could take in that very short time. Local citizens say that they do not want help in terms of material compensation, but a definitive solution (Darío Álvarez, 2016). Around 50% of the homes in Cartagena present some unsatisfied basic needs. Inundations make it difficult to satisfy these basic needs, as the water takes away many belongings frequently. In newspaper articles it is found that citizens on the lower income areas feel like local authorities are not doing enough to prevent this (Benítez, 2012).

Due to insufficient city planning and the lack of high quality building ground, the population groups with the lowest income have to resort to building in the more flood prone areas. Communities have expanded by building on top of waste and deposited sediment into the Ciénaga. Living in these low lying isolated areas increases the inequality even further as the chances to climb the social-economic ladder out of these places are small due to the poor living conditions. During and after floods people cannot return to work for several days as leaving their houses unoccupied makes them vulnerable to looting. These findings were confirmed by a visit to the Rafael Nuñez section of Olaya (see appendix B.6.1).

> *"We continue living here because we must. We continue our daily lives in the flood waters because we have no choice."*
> – Olaya community representative

A study by Rowlingson (2011) has shown that there is a direct link between the health problems and life expectancy of a group and their social-economic status. Even more it is shown that lower social-economic groups in countries with high inequality are worse of than the same group in a less unequal society. This leads to the conclusion that solving the problem of inequality is of high importance.

Figure 2.28: Family with their belongings after having fled to a dry place (Acosta, 2011)

Political Distrust

According to an interview with CARINSA (see B.1), inhabitants of Cartagena do not feel like the local government prioritizes public interests, but image and personal winnings instead. This results in lower public support for additional taxes for coastal protection. Residents are afraid it will end up in the politician's pockets. Interviews with communal associations (see B.6.1 and B.6.2) supported the statement that the residents have the feeling that the government offers no support, neither in the peninsula nor in the poor neighborhoods, neither before nor after a flood event. The people receive no reimbursement for lost property and very little is being done to reduce the flooding.

> *"The municipality thinks we have enough money to fix the problem ourselves. They try small, cheap solutions which fail."*
> – Bocagrande community representative

There are however campaigns being organized to change the people's mindset towards the long term. To educate them for example on financial planning and garbage disposal. The community representatives stated in the interviews (see B.6.1 and B.6.2) that small solutions and studies to solve the water management problems exist. However, the local government does not have the support and resources to implement a complete solution for the city. Separate solutions have been implemented, but appear to be ineffective.

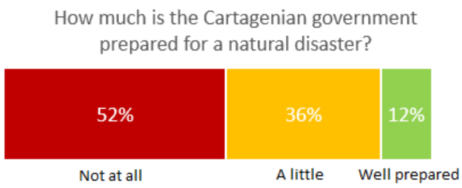


Figure 2.29: Amount of trust the Cartagenian citizens have in the ability of the government to respond to a natural disaster, based on (Cómovamos, 2015)

Well-being

At several locations the water levels can reach knee-high-levels in just several hours of rain. The water causes the electrical grid to fail due to short circuiting of detachment cables. This results in the inability to use electric equipment in most of the houses and causes public lighting to fail. Also electrical equipment gets damaged. Inundated areas become inaccessible, which results in a limitation of (social) activities of the residents. The water flowing through the streets creates dangerous situations, so people are unable to commute (Espectador, 2015). Inundations also result in the losses of recreational and social gathering areas like beaches or outdoor sports facilities and hereby reduces the citizens living comfort. In the lowlands (both Ciénaga de la Virgen and the peninsula), the inundations occur almost on a daily basis in the rain season. This causes several months of permanent chaos in the affected neighborhoods. People are afraid to leave their house and emergency services are blocked. Figure 2.30 shows that flooding is by far the highest feared disaster under the Cartagenian population.

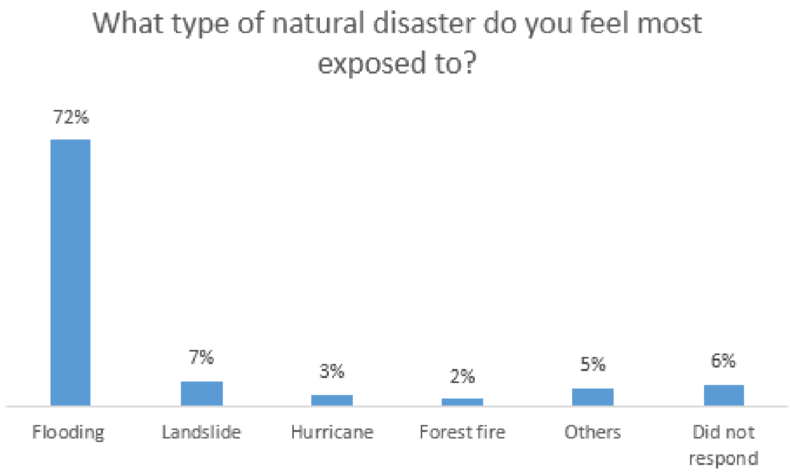


Figure 2.30: List of highest feared disasters, as voted by the local citizens. Based on (Cómovamos, 2015)

In addition, the stagnant water causes permanent bad smells and infections in various neighborhoods. The water brings sediment and contamination to the neighborhoods, as shown in Figure 2.31. Also, mosquitoes flourish in the numerous small water pools left throughout the city after the floods. These unacceptable living qualities are caused by overflowing or non-functioning sewer systems. Sediment and rubbish narrows the system and decreases the evacuation of the water (Álvarez Beleño, 2016).

"In the winter the rainwater remains in the streets for weeks. The low houses have no floors and the people live on wet ground."
– Olaya community representative

Residents of Cartagena answered in surveys from Cartagena Cómovamos (Cómovamos, 2015) that inundations are the most exposed disasters in their city. However, in the same survey the residents indicated that inundations themselves are not among the most problematic environmental issues in the city. The indirect nuisances of inundations are considered more serious problems. For example bad odors due to poor water and sewage management and the contamination of water sources are among the top five causes of irritation due to environmental issues. This top five is completed with traffic congestion, noise disturbance and poor waste management. This suggests that citizens are not well informed about the effects of flooding.

Future situation

Plan 4C states that in 2040 one fifth of all the Cartegenans will be affected by high tides if no measures are taken. Also, 27.5% of the population and 26.2% of the houses will be flooded. As the poorer neighborhoods like La Boquilla and Cienega de la Virgen are less resilient to flooding in comparison to the richer neighborhoods as Bocagranda, Historic Centre and the Industrial Zone, they will be more affected. The low income families are the most vulnerable. Thus, the inequality will increase if no measures are taken against the effects of climate change (CDKN et al., 2014).

Figure 2.31: Children play in contaminated area (Otero Brito, 2012)
1

2.4.4 Environmental issues

Due to the regular flooding, changing environmental conditions and the explosive grow of the city, the environment is suffering. The suffering of the environment in return causes problems to the city and its inhabitants.

Coastal erosion

The coastal erosion causes many problems. Due to coastal erosion, the beaches become very small. The smaller the beaches, the less attractive they become for tourists, resulting in a loss of income. Besides the beaches also function as a wave buffer zone. Wave energy is dissipated at the beach instead of at the revetments or roads. As an effect of less wave energy being dissipated, the impact on the sea defense is increased. This results into higher amounts of damage to be expected at the sea defense. On top of that, smaller beaches will increase the volume of wave overtopping. All the beaches in Cartagena are affected by coastal erosion (CDKN et al., 2014).

Water Quality

Only 6% of the residents stated that they are satisfied with the water quality in the Cartagena bay, the Ciénaga, the pipes, the lagoons and the beaches. 55% is unsatisfied and 39% has a neutral opinion (Cómovamos, 2015). The municipality states the water is of sufficient quality, though the citizens complain of bad odors. Especially at El Laguito the water quality has been deteriorating fast since it has been completely cut of from the bay in 2007. The water quality of the Ciénega de la Virgen has been greatly improved since the completion of the Bocana project. High amounts of waste are dumped into the Ciénega but with the Bocana project, an artificial circulation is created which transports the contaminated water out to sea. This leads to high amounts of plastic and contamination flowing to sea but keeps the Ciénega more or less clean (Arenas & Serje, 2015).

Wave overtopping

At this moment large volumes of water are blocking roads and flooding neighborhoods due to wave overtopping. The blockage of the roads causes many problems, like traffic jams, delay of emergency services and increase of transportation costs. The floods due to wave over topping cause damage to infrastructure and buildings. The salt water also causes corrosion to cables, pipes and cars. The area most effected by this is Carrera 1 (the boulevand) in Bocagrande.

Mangroves

The mangroves near Ciénega de la Virgen are threatened by urbanization and human activities (Devisscher & Tellam, 2016). These mangroves fulfill a essential function in coastal protection.

Figure 2.32: Garbage at the La Bocana water gate

Destroying the mangroves result in increased flood risk in the future. Healthy mangrove swamp can have more advantages such as an increasing fish population and attracting tourists.

Sewage overflow

During precipitation events the sewage system cannot cope with the volume of water. This causes the sewage system to back-flow and overflow onto the streets. This results in a dirty odor and contaminated water. People walk through this same water, which can cause infections and the spread of diseases. It is also not desirable that the content of the sewage systems ends up on the roads or even inside buildings.

Figure 2.33: Sewage water leaking into the street after mild rainfall (Rafael Nuñez sector of Olaya)

El Laguito lake

The neighborhood El Laguito, situated on the peninsula is built at a former sand spit. Between El Laguito and Bocagrande there was water. But due to human interventions and morphological changes the connection with the Bay of Cartagena was cut off. Nowadays, the water in the lake is stagnant. According to local residents the water is highly contaminated. (Torres Vergel, 2012)

Future situation

Ecosystems, like the beaches, coral reefs and mangroves are very vulnerable to climate change and must be protected accordingly. The threat of destroying mangroves becomes even bigger with the predicted sea level rise. 70% of the mangrove areas would be affected by the sea level rise. Also, as earlier stated, 100% of the beaches will suffer by coastal erosion and 18% of the islands will be affected by the sea level rise (CDKN et al., 2014).

2.5 Understanding Planned Solutions

To solve the flooding, there are already three major plans. In this section is analyzed if the flood risk is reduced sufficiently and discussed whether this is an effective way to do so.

2.5.1 Pluvial drainage master plan

On behalf of the municipality, the Office of Valorization contracted Consorcio Consultores Cartageneros to come up with a solution for the rainwater floods. This resulted in a report published in December 2007: Plan Maestro de Drenajes Pluviales de Distrito de Cartagena de Indias.

In the report of this master plan, an extensive analysis is done on the location, state and hydraulic capacity of existing infrastructure. Rainfall intensities and corresponding return periods are extrapolated for various weather stations in and around Cartagena. Based on this rainfall data, discharges are calculated for various return periods for basins and channels. The discharge values and hydraulic capacity of existing channels are combined to test whether or not there is sufficient capacity.

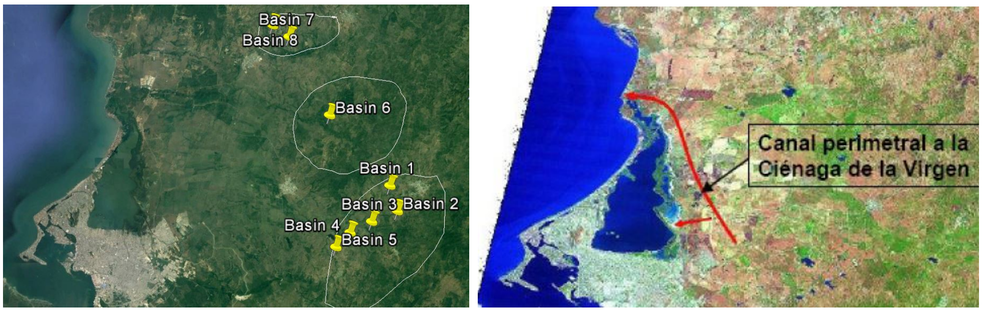
Short term

The consortium concludes that capacity is generally not sufficient and has thus proposed to upgrade the system of drainage channels in the city. This serves as the short and medium term solution. Some existing channels are expanded and new ones are to be build. Around La Popa hill some sediment traps will be installed in the main channels. In addition, soft measures such as garbage and as discussed from channels must be enforced as 92% of channels contain garbage accumulation and 94% have accumulated sediments (Consultores et al., 2007).

Figure 2.34: Short and medium term solutions: Expansion and addition of a total of 70 channels (Consultores et al., 2007)

Long term

In the long, term the consortium recommends a large bypass channel reduce the rural discharge entering the Ciénaga. The bypass will divert water northwards, directly to the sea. Retaining basins are recommended to reduce the peak discharges in the bypass channel which should reduce the required dimensions and thus cost of this channel. Furthermore, reforestation of the upper basin is recommended. An overview map of the locations which were recommended for retention basins are shown in 2.35a and the location for the bypass channel in 2.35b (Consultores et al., 2008).



(a) (b)

Figure 2.35: Proposed location of bypass channel and retention basins (Consultores et al., 2008)

Judgement

As of this moment in time, none of the infrastructure suggested in this plan has been realized. This statement is confirmed by the UTB. CARDIQUE is responsible for cleaning the channels, i.e. removing garbage and sediments. According to interviews with the Secretaría de Planeación and CARINSA, the main reason for the lack of action is a poorly organized institutional framework and a lack of funds.

It is also quite evident that the plan has a heavy focus of short and medium term solutions. The long term solutions are only elaborated in an order of magnitude calculation.

Only implementing these solutions is not enough. In general, the use of structural measures is costly, inflexible, may displace flood risk to another location and may be over topped if design event capacity is exceeded (World Bank, 2011). They must therefore be combined with soft measures such as reforestation or awareness to achieve optimum performance. Only using drainage channels will probably be a rather expensive and inflexible approach which is also a short term solution as no climate change effects are included. Sea level rise will reduce hydraulic gradients in the channels and reduce their capacity once again. Additional urbanization of the upper basins is likely to further increase discharge peaks. The bypass channel is ineffective in preventing the Ciénaga from rising due to sea level rise.

Some general shortcomings of the pluvial drainage master plan are:

- No problem analysis, discharge or flow pattern overviews are provided. Neither are calculations provided, and thus there is no proof that the design calculations are correct or based on correct input.
- It is not clear which methodology or theory is used to make calculations. It is impossible to reproduce or verify the calculations.
- The used theories and stochastics appear as basic order of magnitude calculations.
- No climate change factors appear included in the rainfall data. If rainfall increases the channels' capacity will not suffice.
- There is no integration between rainwater drainage, seawater inundation and coastal protection. This leaves the city's flood risk management disjointed and cost ineffective.

- The solution lacks integral and regional solutions, which make it unattractive for regional or national funding.
- There is no integration in terms of urban planning. This increases the chance of the channels becoming ineffective in the long term due to a changing city landscape.
- The plan does not include mitigation measures, such as evacuation and early warning. Also flood risk reduction by means of urban planning is not considered.
- Opportunities to improve urban planning, mobility and drinking water management are missed.
- No other alternatives are considered; no proof that this plan is the best solution.
- Flood risk might increase in the Ciénaga de la Virgen area. More drainage channels means an increased peak discharge and a quicker rise of the Ciénaga´s water level. This endangers the most vulnerable areas; the areas which the plan strives to protect. A retention basin and bypass channel is suggested to reduce the peak discharge. However, if these are not build soon, the channels might worsen the situation along the Ciénaga zone.
- When sea level rise is combined with subsidence, the available hydraulic gradient in the channels becomes smaller reducing the channels' capacity.
- It is not clear what water level is chosen at the canal mouths. Drainage capacity may be reduced during high tide or storm surges.
- Backwater curves of the Ciénaga and channels do not appear to be understood
- As indicated in Figure 2.36, none of the planned retention basins retain water which flows into the city. The Limon and Matute basins, and those located in Mamonal, are very problematic. No basins are planned here. The proposed basins serve to reduce the peak discharges in the bypass channel.

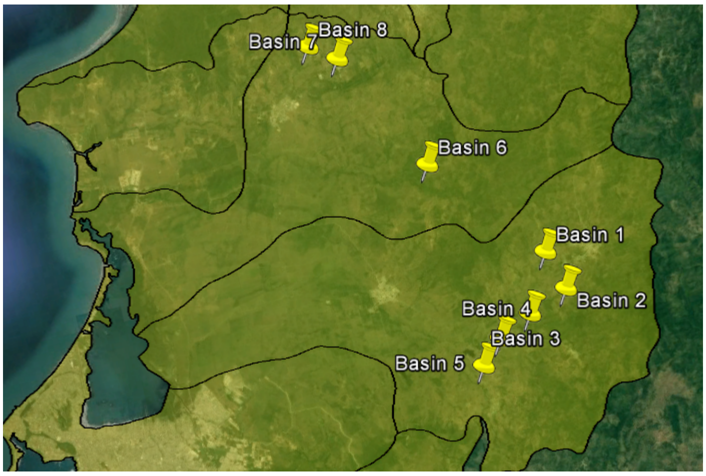


Figure 2.36: Location of proposed retention basins within drainage basins

Over the last few months, the municipality is also seriously considering implementing and financing the first steps of the plan: enlargement of existing channels and perhaps construction of a few new ones. It seems that the municipality wants to supply funds to implement 27 channels and design 113 more channels. The costs would be 300,000 million pesos (roughly 100 million USD). A far better cost-benefit ratio and long-term performance can be achieved if multiple integral alternatives are evaluated in a structured manner. Especially since in this plan none of this money will go to the components of the plan which could reduce the peak discharges in the city using upper basin management.

Many of the interviewed people say that they do not think this plan is the solution for the whole problem. CARINSA says it is too local and short term. The head of the action board of Bocagranda says that the plan should include Bocagrande, before it is called a master plan. The DATT, too, believes a more integral solution would be more effective.

2.5.2 Plan 4C

By 2040, Cartagena de Indias wants to be recognized as a city with urban and coastal planning based on climate compatible development by adaptation and mitigation measures (CDKN et al., 2014). A project team consisting of the MADS, INVEMAR, the Climate & Development Knowledge Network (CDKN), the Chamber of Commerce and the office of the mayor of Cartagena was created and in 2014, the project team developed a plan to achieve this goal: Plan 4C (CDKN et al., 2014).

Plan 4C mainly focuses on climate change. The focus is on five sectors in the city: the port and neighboring industry, tourism, ecology, protection of the historic center and adapting neighborhoods in Cartagena. General awareness about the consequences of climate change is generated. It shows points of interest for different studies to reduce the impacts and measures are promoted that will reduce the city's vulnerability to climate change, improve the efficiency of public investment and better the living quality of inhabitants. A view on how to fund the projects is also given. The mentioned resources are both public financing from local, regional or national governments and private funds invested by private enterprises.

Plan 4C is a first step in the right direction. A change of mindset is necessary together with a more long-term planning for the city of Cartagena to protect the city against climate change. But at this moment, it is not sufficient to tackle the problems. It sounds like a vision which should be complemented with specific proposals. Those specific proposals are missing and there are no signs that action is taken.

2.5.3 Coastal master plan

In 2011, a master plan for the coastal areas of Cartagena was developed. Although this is not certain, it seems the project is a private initiative. The involved companies are: Movicon S.A., MegaConstrucciones, Codifa S.A.S. and Atlante. Currently, there are no funds available to finance the project. The initiators plan to fund the project with income produced from the new land. The plan focuses on to urbanizing and exploiting the coastline to make it more profitable. To do this, it is proposed to the widen the coast from Marbella (before Crespo) to the tip Bocagrande. The goal is to come up with an integral design that solves problems mobility and urban infrastructure. It offers possibilities for the development of touristic, industrial and commercial activities. To our knowledge coastal defense is not prioritized and not explicitly mentioned as a goal or result of the plan. There are no official reports available; this information is based on a video presentation of the project.

For the stretch of coast from Marbella to the historic center, an artificial reef and a beach of 80 m wide are proposed. Also, Avenida Santander is rehabilitated and in the new situation is made space for touristic and commercial activities along the coast. An impression can be found in Figure 2.37.

Figure 2.37: Coastal master plan: Impression of stretch Marbella - Centro Historico

For the coastal strip in front of Bocagrande, a different design is proposed. Two dikes, each 800 m long, are built perpendicular to the coast. In between a 60 m wide beach will be created with possibilities for tourists, sport activities, a cultural center, parking lots and parks. Carrera 1 is transformed into a 6 lane toll road with cycle paths. At the tip of both dikes, a marina is planned. An impression of this part of the coastal master plan is presented in Figure 2.38.

Figure 2.38: Coastal master plan: Impression of Bocagrande

It is hard to say whether this plan is effective in reducing the flood risk because of the missing of a detailed report. The following questions should be considered before the plan will be implemented.

- If and how is the coast protected against, for example, sea level rise or tropical storms? In the presentation, no elevated areas or sea walls can be recognized.
- Is a rising water level in the Bay of Cartagena taken into account? And what about its effect on the peninsula and the historic center?
- For the beach between Crespo and the historic center: how will the beach be maintained? The artificial reef will make beach nourishments very difficult and it is likely that intensive maintenance is necessary after storms.
- For the same beach, no groyne or dike is included to block longshore transport. The Northern Bocagrande dike lays parallel to the beach. It is therefore likely that this beach will erode quickly.
- For the beach of Bocagrande: how is the beach maintained? It appears likely that the sand will be flushed out between the dikes during storms, or that it is transported from the center towards the dikes.
- Most probably, the dikes will (partly) block longshore transport of sand. This will cause erosion at the coast of Tierra Bomba. Is this taken into account?
- Is urban pluvial drainage taken into account in this plan?
- Has a cost benefit analysis been performed? This plan appears more costly than necessary.

2.6 Understanding Global Water Management

The flooding issues in Cartagena are expected to increase due to climate change effects (Vides, 2008). Other cities around the world, which are prone to flooding by rising sea level and/or precipitation, are also facing increased problems. It is important to understand how other cities react to similar challenges and what vision they have for future urban flood risk management. The goal compare Cartagena's approach to dealing with flood risk with global practice. And, by doing so, show the urgency for a new approach. In order to achieve this, a benchmark will be conducted for Cartagena in two steps. Firstly, in Section 2.6.1, a benchmark is done on annual investments for flood prevention. Secondly, in Section 2.6.2, an urban water management transition approach will be introduced. Cartagena will be ranked and evaluated in accordance to this ideology. Conclusions are given in in Section 2.6.3.

2.6.1 Investment costs

The investments in flood protection of Cartagena are compared to other cities prone to flooding. First, the investment costs of a wealthy city with a good flood protection, Rotterdam, will be compared. Secondly, Jakarta, which has recently started implementing a new master plan, will be investigated as it is a city with a gross domestic product per capita (GDPPC) similar to Cartagena. And finally, two cities with a lower GDPPC will be compared to Cartagena.

The GDPPC of Cartagena is 13,000 USD. This is higher than the Bolívar average (CDKN et al., 2014). According to local engineering firm CARINSA, Cartagena invests about two million USD each year to protect the city against inundations (Appendix B.1). These investments are mainly used for reparations of the existing infrastructure. The main infrastructure consists of coastal barriers to keep out seawater and channels that lead the water from higher basins to Ciénaga de la Virgen and the sea. As shown in Sections 2.2 and 2.4, repairing existing infrastructure will not be sufficient to adapt for future flooding problems. Compared to the damage of 540 million USD in 2011, 0.37% of this total damage is spent each year. It is clear that investments and damage are not in balance.

Rotterdam, The Netherlands (600,000 citizens)
The Dutch government is very aware of the flooding dangers, because a quarter of the Netherlands is below sea level. The flood protection of the Netherlands is designed for a design load with a return period of 10,000 years (in a new law in 2017 this will even change to almost 30,000 years). This is the highest in the world, resulting in on of the best flood protection systems. Following a huge flood in 1953, which caused 1,800 deaths, many investments have been made to reach the level of security the Netherlands has today. This water safety level is enforced through a law, the Water Act. Even now, money is being invested to sustain and improve such a high level of protection. According to the budgets of the Dutch Waterschappen, in 2015, the harbor city Rotterdam spent 129 million USD for maintaining dikes, creating underground storage facilities, drainage channels and building green roofs. This is more than 200 USD per citizen per year. The government realizes that although this is a high amount, not investing in a flood protection system will lead to significantly higher costs, especially because Rotterdam is a densely populated and economic important city. Even though Rotterdam's GDP per capita of 45,500 USD (Knoema, 2013) is three times higher than that of Cartagena, it is clear that even with a good-working flood defense system, money continuously needs to be invested to maintain and improve flood defense systems.

Jakarta, Indonesia (9.6 million citizens)
Jakarta has a GDPPC of 14,727 USD (Badan Pasat Statistik, 2016), which is similar to Cartagena´s. Jakarta rapidly subsides with an average of 7.5 cm and a maximum of 17.5 cm per year due to drinking water extraction. This makes it prone to floods. This accelerated the development and implementation of their master plan, costing around 27 billion USD. Up to 2022, the project will cost 1.7 billion USD per year. However, the implementation of the full master plan is far from certain. The plan is good example of an integral solution for fighting inundations in Jakarta. The master plan consists of a colossal offshore dike to protect the city against rising sea level until 2100. Besides protection against water, the dike creates opportunities for urban growth, creation of new land, improvement of transportation and economic growth for Jakarta. It is estimated that the project will have a revenue of 30 billion USD, mostly because of the land reclamation, resulting in an expected profit of 3 billion USD (The Coordinating Ministry for Economic Affairs, 2014).

For both Rotterdam and Jakarta it has to be noted that their economic assets are much higher than Cartagena´s. Floods in these cities will cause higher economic losses than in Cartagena. because of this, investment costs for Cartagena need not be as high. This is merely given as a comparison to show how other cities are coping with flooding threats.

Guayaquil, Ecuador (2.3 million citizens) & Abidjan, Côte d´Ivore (1.9 million citizens)
Guayaquil has a lower GDPPC than Cartagena (8,741 USD (El Telégrafo, 2014)), but invested one billion USD in flood protection over the last five years. Six hydraulic mega-structures were built to protect Guayaquil against floods and it is expected that it will save 10.2% of the GDP of Ecuador (El Telégrafo, 2016). Abidjan´s GDPPC of 4,050 USD (estimated by dividing Abidjan's contribution

to the GDP of Ivory Coast by the Abidjan's population (IDB, 2016; Zézé, 2015)) is lower than Cartagena´s. Abidjan started raising funds in 2016 for an integral flood defense system worth 564 million USD. The project will solve the drainage and the traffic problem and will be combined with creating recreational area. The project will be implemented over thirty months (Africa Infomarket, 2016).

2.6.2 Water sensitive cities

Brown et al. (2009) has conducted research into urban water management transitions and accordingly has created a framework. Figure 2.39 shows the framework which identifies six distinct developmental states that cities move through on their path toward increased water sensitivity. Water sensitive cities are characterized by proper water management. On this framework cities can be benchmarked on how far they are on the urban transition towards a water sensitive city. This ideal city manages the integrated water cycle to protect and increase health, reduce flood risk, creates public space that harvests, cleans, and recycles water. The opportunities of water must be seen and the city must be protected against its risks.

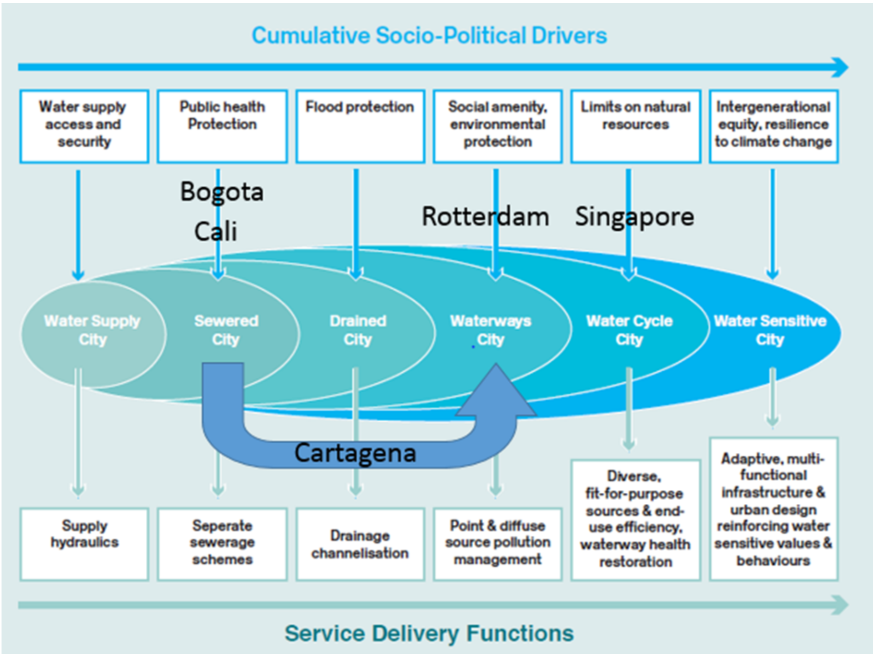


Figure 2.39: Water Sensitive City Transition Framework (Brown et al., 2008)

At the moment Cartagena finds itself at the beginning of the Urban Water Management Transition Framework, at an equal level as Bogota and Cali (Jefferies & Duffy, 2011). According to Acuacar (2016) there is a separate sewage scheme throughout the city. However, professors at the UTB state that this is not working properly in some parts due to leaks and bad connections (see Appendix B.7). Also is rainwater able to flow into the system, causing over-flow (see Section 2.2.1 Urban Sewage System). Drainage systems do exist, but definitely do not protect the citizens as intended. Ideally, Cartagena needs a strong flood protection and urban water needs to be managed in an integral manner. For Cartagena it is preferable to make a shift from a Sewered City to a Waterways City. By climbing up the ladder, Cartagena will be more adaptable to future situations. If investments are made, it is advisable to make use of no regret and integral solutions, making the investments profitable for a long term. Besides, it gives Cartagena the ability to solve other problems like congestion and urban planning and increasing the profit of the investments.

Examples of cities which are making a transition towards a Water Sensitive City are Rotterdam and Singapore. These cities have built integral solutions defending their citizens against floods, creating water security, stimulating urban growth and increasing the well-being of the city (Wong & Yuen, 2011). The cities have managed to live with water in a sustainable manner, rather than fighting it. Another example is the master plan of Jakarta. As stated in the previous chapter, the solution will improve infrastructure, create land and bring many more benefits, than just coastal protection.

2.6.3 Conclusion

It is clear that Cartagena has not reached a high level on the framework and also falls behind on the investments for flood protection. Jakarta, clearly, started a transition towards being a sustainable city by choosing for an expensive, but integral solution for the water problems. Although the initial investments are high, it is predicted that in the end the project will be profitable. The integral approach creates opportunities for direct profit through land reclamation and toll roads. The implementation could strongly benefit the economy of the city as, among others, it is easier for citizens to go to work and Jakarta will be more attractive to start a business. Even cities with a lower GDPPC have started investing in an integral flood defense system, while Cartagena is lacking in investments and vision. The current 2007 pluvial drainage master plan is not integral as it does not protect the complete city (see Section 2.5.1 Judgement). Also an integrated solution combined with improvement of the urban planning, mobility and drinking water management is absent. Rotterdam shows that, even if flood defenses are build, investments are needed for maintenance and improvement to uphold the high level of protection guaranteed to their citizens. Without proper maintenance the structures will deteriorate and lose their protective function. It is necessary to keep monitoring and improving the defense to keep up with the changing conditions. The government of Rotterdam realizes that investments can reduce risk of floods, and thus economic damage, and stimulate growth of income.

Investments are needed to improve the water management system of Cartagena. These investments are necessary to create a safe and prosperous city as Cartagena cannot thrive if constant flooding continues. Although investments must be made, in the long term Cartagena could profit greatly. Economic losses from floods, due to, among others, damaged infrastructures and congestion, will be reduced and these investments can create job opportunities. Also the economy will profit from these investments as an improved and flood free city will attract more investors and create new business opportunities. With the expected sea level rise and increased precipitation intensity, the city is in the future even greater risk taking into account citizen safety as well economical, social and environmental factors. The heritage of Cartagena is at risk and a fifth of the population will be affected by 2040 (CDKN et al., 2014). Most likely, economic damage will be higher than the costs of an integrated flood prevention system. Other cities are starting the transition to becoming a sustainable city and Cartagena also needs to start thinking about an integral solution for the water problem, defending their citizens and stimulating economic growth.

2.7 Boundary Conditions

In order to come up with a proper design, the physical boundary conditions are analyzed in this section. This is used in the next chapter to create a program of requirements. They also form the input of simulation models. In order for the project to be successful, the final design requires to withstand the boundary conditions.

2.7.1 Climate and precipitation

Cartagena features a tropical climate with a dry and wet season. The dry season is from December to April with average rainfall lower than 50 mm/month. The wet season is from May to November. The multi-annual average temperature in Cartagena is 27.9°C (CDKN et al., 2014). The daily average temperatures per month and the monthly average precipitation can be found in Figure 2.40.

For the design, the intensity and duration of an extreme rainfall event is most important. In Figure 2.41, an extreme value analysis for precipitation can be found (in millimeters of rainfall per day). The used meteorological station is Aeropuerto Rafael Nuñez.

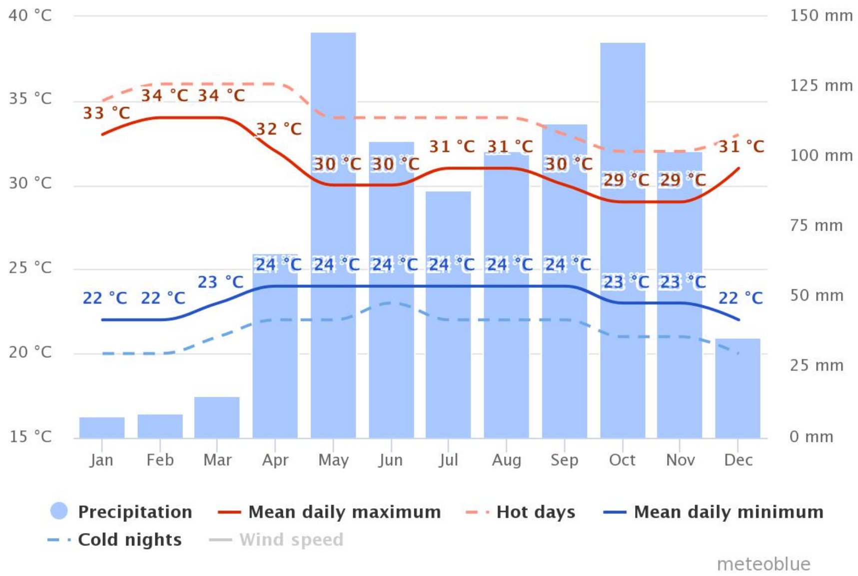
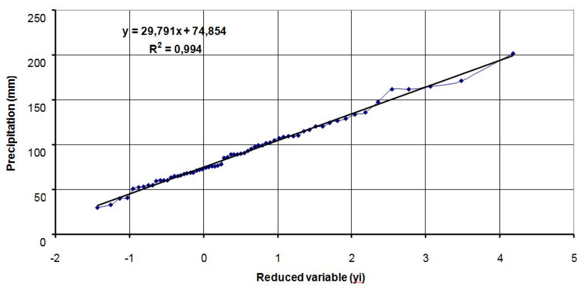


Figure 2.40: Average temperatures and precipitation (Meteoblue, 2016)



(a) Gumbel analysis of precipitation

Return period (years)	P(X≥Xi)	Precipitation (mm/day)
2	0.5	85.77
5	0.8	119.54
10	0.9	141.80
15	0.933	154.51
20	0.95	163.34
25	0.96	170.14
50	0.98	191.10
100	0.99	211.90

(b) Return period precipitation

Figure 2.41: Analysis of return period extreme rainfall events (Consultores et al., 2007)

Statistics about the intensity in millimeters per hour and about the duration of an extreme event were not available during this project. It is very likely that global climate change increases the probability and intensity of heavy rain events, but the yearly amount of precipitation could decrease (IPCC, 2013).

2.7.2 Water level variations

The water bodies surrounding Cartagena have fluctuating water levels due to tides, seasonal variations and sea level rise.

Tides

The coastal area of Cartagena is influenced by a semi-diurnal tide regime (Vides, 2008), see Figure 2.42. Every 24 hours Cartagena experiences two high tides and two low tides. The maximum tidal range is about 60 cm (see Table 2.3). It be notid that the measurement location is inside the Bay of Cartagena, due to the confined connection to the sea the maximum measured tidal range might be slightly lower here then at the sea side.

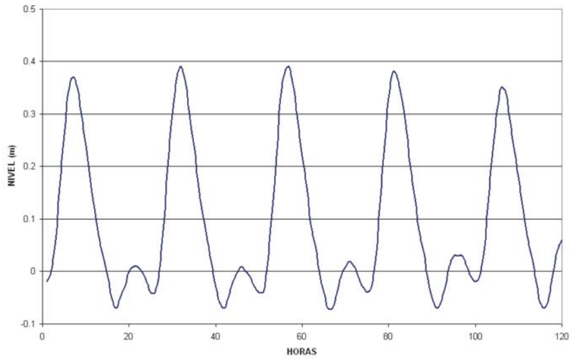


Figure 2.42: The semi-diurnal tidal signal near Cartagena (Vides, 2008)

Table 2.3: Tide at Bay of Cartagena

Component	Water level (m, relative to MSL)	Water level (m.s.n.m.)
HAT	+0.37	0.72
MHWS	+0.25	0.60
MHHW	+0.18	0.53
MHW	+0.09	0.44
MSL	0.00	0.35
MLW	-0.11	0.24
MLLW	-0.13	0.22
MLWS	-0.15	0.20
LAT	-0.24	0.11

Seasonal variations

In addition to the tide, the sea level varies with the seasons due to fluctuations in temperature, salinity and ocean currents. In October, the seasonal variation is maximum with +8.4 cm. In January it is minimum with -5.1 cm (NOAA, 2013).

Sea level rise

Near Cartagena the relative sea level currently rises with 5.31 ± 0.37 mm/year (Torres, 2013). This is caused by the absolute sea level rise due to global warming and by subsidence (see next paragraph).

Year	Lower bound	Mean	Upper bound
2016	0	0	0
2026	5	5,3	5,6
2040	15	17,5	20
2070	40	45	51
2100	80	90	100

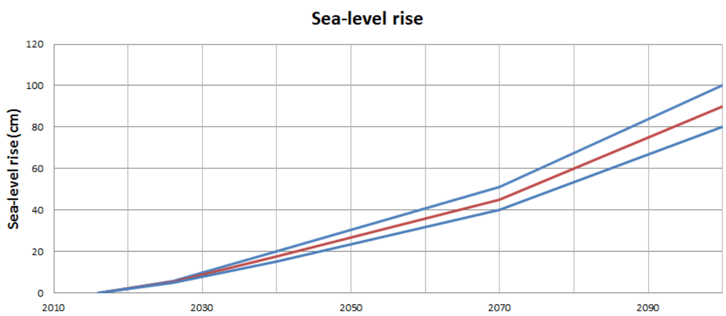


Figure 2.43: Predicted sea level rise (cm)

If a constant relative sea level rise is assumed, this will cause an increase of 5.3 cm in the coming 10 years. As the rate of sea level rise is increasing, it is reasonable to assume this extrapolation is underestimating the actual sea level rise in the future. A lot is unknown about the growth of the sea level rise per year, but according to the plan 4C, a total sea level rise of 15-20 cm in 2040 and of

80-100 cm can be expected in 2100 (CDKN et al., 2014). For the design phase, the rates for sea level rise until 2040 and 2100 determined and averaged to come up with a estimation of the sea level rise in 50 years (2070),

2.7.3 Subsidence

The effects of sea level rise are increased due to the effects of subsidence. Figure 2.44 shows the vertical land movement based on data from Sirgas (2016). Based on these data can be concluded that the city is sinking with an average of 2 mm per year. The sinking is most probably related to compression of the soil underneath the city, porosity and to the winning of natural gas underneath the city (Rodríguez, 2016).

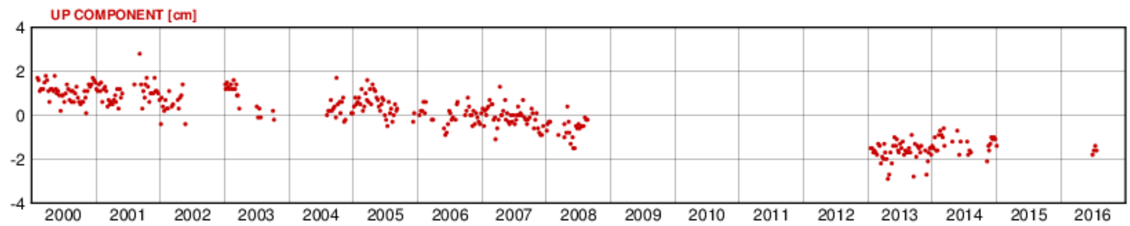


Figure 2.44: Vertical displacement as measured by Sirgas (2016)

2.7.4 Wind and wave conditions

Wind

The wind speed and direction are dependent on the season. Three seasons can be distinguished regarding the wind. During the dry season from December to April the trade winds coming from the North-East are dominant. There is a transition season between April and June, the trade winds are less predominant. During the rainy season from August to November the winds are weak and irregular.

Because the winds are either weak and irregular or coming from the North-East (see Figure 2.45), it is unlikely that water level rises due to wind set-up near the coast of Cartagena.

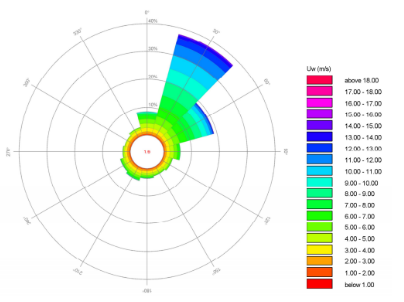


Figure 2.45: Windrose based on data from NOAA at 11°00'N, 76°15'W.

Waves

The used wave data is ARGOSS data as shown in Cornelissen et al. (2015). Based on this data the wave height offshore is calculated for different return periods, see Table 2.4. The full calculation and used data can be found in Appendix D. The main offshore wave direction is North-East and East. The wave periods vary between 4 and 12 seconds. During storm conditions waves have a period of 8 seconds (Moreno-Egel, Agámez, Castro, & Voulgaris, 2006).

Table 2.4: Extreme wave heights and return periods (using Weibull fit)

Return period (1/x years)	Prob. of exceedance	Wave height (m)
1	0.001369863	5.0
10	0.000136986	5.7
20	6.84932E-05	5.9
50	2.73973E-05	6.2
100	1.36986E-05	6.3

To come up with an estimate for the nearshore wave height, a very simplified simulation is done using SwanOne. The details can be found in Appendix D. This resulted in a significant wave height of 2.0 m for a 100 year return period at a water depth of 5 m.

2.7.5 Extreme events

El Niño-Southern Oscillation

The El Niño-Southern Oscillation (ENSO) is a worldwide perturbation of the oceanic-atmospheric system that occurs every 3-7 years. El Niño and La Niña are the extreme phases of this oscillation. During El Niño the trade winds which blow from east to west over the Pacific ocean, reduce in intensity. During La Niña the opposite happens, the trade winds are strengthened. This oscillation has consequences for the ocean temperature distribution and global weather patterns (Pietrzak, 2016).

El Niño and La Niña can also have significant influence on the conditions near Cartagena. Sea levels can rise significantly due to the ENSO. The El Niño of 1982 and 1995 caused a sea level rise of 15 and 25 cm, respectively (Restropo & López, 2008). Also the precipitation is affected by the ENSO. El Niño causes a drier and longer dry season, while La Niña produces an increase of precipitation during the wet season (Poveda, Jaramillo, Gil, Quiceno, & Mantilla, 2001). In 2011, La Niña caused long periods of heavy rain which caused severe floods throughout the North of Colombia. Data about the exact changes in water levels and precipitation due to ENSO was not available.

Hurricanes and tropical storms

Near Cartagena tropical storms and hurricanes are rare. Since 1842 only 10 hurricanes passed Cartagena within a range of 200 km. The strongest one was hurricane Joan in 1988 of category 1. Topical storm Brett in 1993 was the one which passed closest. Storm surges can raise the sea level more than a meter (Moreno-Egel et al., 2006). No return periods are given.

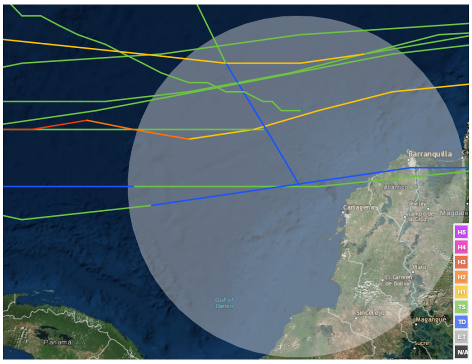


Figure 2.46: Tracks of hurricanes that passed Cartagena in a range of 200 km since 1842 (NOAA, 2016)

2.7.6 Additional coastal boundary conditions

Bathymetry

The bathymetry of the coast of the peninsula and the inner bay of Cartagena is shown in Figure 2.47.

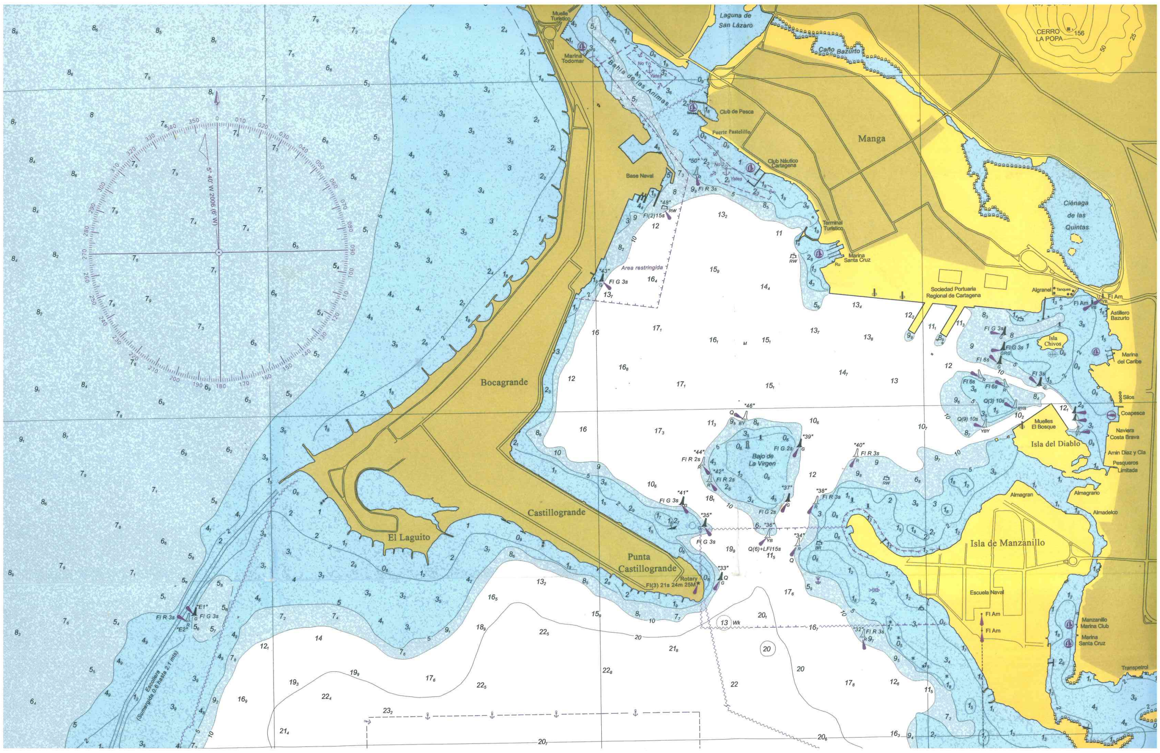


Figure 2.47: Bathymetry Bay of Cartagena (relative to MLWS) (Actualizaciones AN, 2006)

Currents

Currents near Cartagena are about 0.05 m/s going from NE to SW parallel to the coast. In the sector of Bocagrande the currents are stronger, up to 0.10 m/s (Vides, 2008).

Sediment transport

The net sediment transport direction along the coast of Cartagena is southwards. But in the case of a storm the sediment transport direction can change towards the North (Moreno-Egel et al., 2006). The main source of sediment is the Magdalena river further up North. The main source of sediment for Cartagena Bay is Canal del Dique, currently supplying the bay with $4.8x10^6$ t/yr of sediment (de Lacerda, Santelli, Duursma, & Abrao, 2013). At the moment, there are plans to build a sluice in Canal del Dique. This will reduce the sediment supply in The Bay of Cartagena.

The active zone reaches 2000 m out of the coast between the historic center and Marbella. In the sector of Bocagrande it is 500 m. The closure depth is -5.5 m (Moreno-Egel et al., 2006).

2.7.7 Geotechnical information

According to the director of CARINSA (Appendix B.1) the area of Ciénega de la Virgen mainly consists of different types of silty clay. Whereas, Bocagrande is build on sand.

Little information about the phreatic levels in Cartagena is known. From the very low water level clearance of the peninsula, the old city area and the Ciénega de la Virgen area it is assumed that the groundwater levels are high. During the wet season, rainwater is unable to penetrate the ground up to several days after a precipitation event, which supports this assumption.

2.7.8 Return periods

The design of a solution is based on a certain lifetime. For example, a breakwater has a lifetime of 50 years, but this does not cover the probability that the structure fails during this 50 years. The probability of failure to the structure is Poisson distributed. The probability that the breakwater fails one or more times during its lifetime can be computed with equation 2.1 (S. Jonkman, Vrijling, Steenbergen, & Vrouwenvelder, 2015).

$$p = 1 - exp(-1/f * T) \tag{2.1}$$

For example, if the breakwater has to withstand a storm with a return period of 50 years (f), the probability (p) that the structure fails one or more times during the 50 years of lifetime (T) is about 63%. Depending on the acceptable probability of failure, a certain return period of the design event has to be determined. Which probability of failure is acceptable depends on one hand on the direct economic losses in case of failure of the design. On the other hand the cultural heritage and the amount of lives at risk, with their environmental consequences have to be taken into account.

Table 2.5: Return period of design event

Prob. of failure (-)	*Lifetime (years)* 10	20	30	50	100
0,05	**195**	**390**	**585**	**975**	**1950**
0,1	**95**	**190**	**285**	**475**	**949**
0,15	**62**	**123**	**185**	**308**	**615**
0,2	**45**	**90**	**134**	**224**	**448**
0,25	**35**	**70**	**104**	**174**	**348**
0,3	**28**	**56**	**84**	**140**	**280**
0,5	**14**	**29**	**43**	**72**	**144**

2.8 Discussion

As could be read before, the city of Cartagena is vulnerable for floods coming from sea and rain-induced floods. However, while attempting to investigate the sources of the flooding problems, little information was available. This indicates that no one understands the problem which is likely one of the reasons for why it remains unsolved.

This lack of understanding may be caused by the lack of responsibility. The stakeholder analysis revealed that no one party is explicitly responsible for coastal protection. Within Cartagena, there is no party responsible for preventing floods. This is believed to be a large factor contributing to the fact that nothing has been done and why mild environmental conditions cause significant floods. The lack of responsibility is just one example of how poor management contributes to the problem. Poor urban planning, lack of maintenance and use of cheap, inefficient and local short-term solutions are all phenomena which contribute to the problem. Corruption, also a form of poor management, has reduced city budgets. It has been the reason that contracts are awarded to the wrong people and has caused plans to be poorly executed.

Recently, promises have been made to make significant investments to improve the situation. However, these plans are considered inadequate. The 2007 pluvial drainage master plans is by its very nature shortsighted because it focused only on rainwater. In addition to the earlier mentioned technical shortcomings, it does not address any of the managerial issues discussed earlier in this section. It is still a local, inefficient, short-term solution which lacks robustness, sound justification and is founded on shaky engineering. This is not worth the 100 million USD investment necessary for the first phase alone.

Plan 4C is supposed to provide an approach to prepare the city for climate change. However, it only recommends more studies. The analysis which is performed is vague as no methodology is provided. Inundation risks are presented in a qualitative, instead of quantitative, manner. When suggesting future work, no clear responsibility division or collaboration between parties is assigned and thus it is fair to assume follow up will be inefficient at best. The recommended studies are not connected in an integral manner. Therefore, it is expected that an integrated solution will not be found when the proposed research is conducted.

It is evident that these plans will continue the current trend of poorly coordinated and ineffective solutions. As the damages to investment ratio is completely out of balance. The city will definitely benefit if investments are made to effective treat the flooding issue in an integral way.

Chapter 3

Program of Requirements

The program of requirements is a result of the analysis phase. The design and solution generation phase will be based on the requirements and wishes as stated in this chapter. The solution has to adhere to all requirements and ideally fulfills all wishes. If more wishes are fulfilled, the solution is more successful at helping the city. It allows more people to benefit from the solution and not only the people who are directly affected by floods.

3.1 Requirements

3.1.1 Technical

- **Minimum structural lifetime of 50 years**
- **Withstand a 1 in 100 year design event (see Table 3.1) during its lifetime of 50 years (ULS):** As recommended by the USACE building codes. The USACE codes form the basis of many of the Colombian design codes and are therefore most easily understood by local engineers.
- **Ensure a reasonable return period is taken regarding operational use (SLS):** This depends on the function of every component of the design.
- **Integral approach:** The resulting approach is a solution for both rainwater and seawater related flooding throughout the entire city.
- **Robust design:** Considering the lack of available and reliable data, the design should be robust to take the uncertainties, including those related to climate change, in consideration. Until detailed studies reducing these uncertainties are performed, the solution must be able to account for them.
- **Low maintenance design:** History proved that Cartagena has difficulties with maintaining flood defense structures. Not maintaining structural flood defenses results in a false sense of security and may cause them to fail at the moments when they are most needed, resulting in more damage than in the lack of their presence.

3.1.2 Non-technical

- **Risk reduction must exceed the cost:** The risks reduction provided by this solution, expressed in monetary value, should be greater than the cost of implementing and maintaining this solution.
- **Fundable:** The solution should be such that it is likely to receive the required funds from private and or public investors.
- **Respect UNESCO status:** All interventions made in the old city center of Cartagena should comply with UNESCO regulations.
- **No regret measure:** The solution should maintain its function in the face of future alterations to the city´s urban landscape, environmental conditions (climate change) and future projects to reduce flood risk.

Table 3.1: Conditions of design event

Return period	100 years
Precipitation	211.9 mm/day
Offshore wave height	6.9 m
Nearshore wave height (5 m water depth)	2.0 m
Maximum water level	+2.47 m.s.n.m.
- *HAT*	*+0.72 m.s.n.m.*
- *50 years of sea level rise*	*+0.45m*
- *El Niño*	*+0.20 m*
- *Storm surge*	*+1.00 m*
- *50 years of subsidence*	*+.1 m*
Tidal current	0.05-0.10 m/s

3.2 Wishes

While solving the flooding problem, the opportunity presents itself to positively influence other aspects of the city as well. The wishes are defined as positive side effects which could result from a proper flood risk management solution. The wishes are based on factors related to the flood impact as described in the analysis phase. These are divided in technical and non-technical wishes. The non-technical part affects the social, economic and environmental interests of the city.

3.2.1 Technical

- **Environmental friendly design:** Sustainable material and construction methods will be used as much as possible, ensuring the environment is harmed as little as possible during the entire life cycle of the solution.

3.2.2 Non-technical

- **Encourage organized city growth:** Ensuring the solution stimulates an organized, planned and sustainable city growth.
- **Improve city image:** By focusing on a solution that is not only functional but also blends in with the city and ensures the beauty of the old city center remains intact.
- **Increase citizens´ well-being:** Not only by increasing the safety to flooding but also ensuring increased standards of living through increased health, recreation and mobility for all Cartageneros equally.
- **Stimulate city economics:** Stimulate the local economy by increasing opportunities for local business, ensuring sustainable conditions for industry and increasing tourist appeal for the city.
- **Improve living environment:** The solution works towards higher quality water in and around Cartagena, more green zones throughout the city are desirable to meet international eco-agreement demands.
- **Strengthen local resources:** High local content rates to ensure knowledge is collected and contained in the area. This way the local economy can profit from the realization of the solution.

Chapter 4

Flood Risk Reduction Strategies

The floods in Cartagena are caused by a complex combination of coastal, hydrological and social factors. To come up with the best possible solutions, a well-balanced mixture of pluvial flood risk management and Integrated Coastal Zone Management (ICZM) has to be formulated. Both management approaches can be divided into three main strategies, which will be explained in this chapter. The final solution will be a combination of multiple strategies. However, to clarify the thought process while ensuring that no possibilities of solving the problem are missed, this distinction between strategies is made.

Subsequently, the way in which these management strategies must be implemented is explained. The difference between structural and non-structural measures and the necessity of combining them will be explained. A distinction will be made on which scale the measures must be implemented. Integrally combining the measures used to achieve the management strategies, yields an elegant and cost-effective solution.

4.1 Pluvial Flood Risk Management

To solve the flood problems regarding excessive rainfall, there are three generally accepted strategies (Unie van Waterschappen, 2008). These are:

1. Lower the discharge peaks
2. Increase capacity
3. Increase storage in the city

In Figure 4.1 the approaches to lower the probability of flooding in the city are summarized. In this section, the strategies will be discussed more into detail.

4.1.1 Lower discharge peaks

There are two ways to lower the discharge peaks that enter the city. One way is by flattening the discharge peaks that enters the urban part of the catchment area by upper basin management. The goal of upper basin management is to retain water upstream in the catchment area. Examples are forestation, limited urbanization, green roof tops and water tanks on top of roofs in upstream located villages, retaining lakes or the use of weirs. The volume of water that flows through the city is equal, but is spread over a longer period (Winden, Oerman, Braakhekke, & Deursen, 2014). Another effective way to lower the volume of water that flows through the city is by using a bypass. A bypass splits off before the river enters the city and flows around the city towards another water body like a lake or sea or it connects again with the river downstream of the city.

4.1.2 Increase capacity

The second strategy to solve pluvial flood problems is increasing the capacity of the channels inside the city. The higher the capacity of the channels is, the lower the probability of flooding will be.

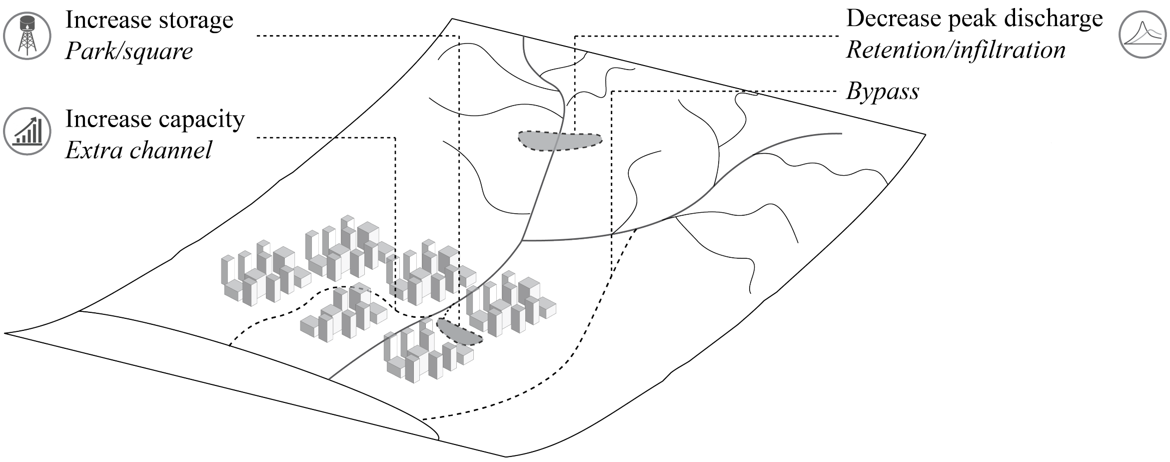


Figure 4.1: The three water strategies

The capacity can be increased by widening and deepening the channels. Also the number of channels and connections could be increased. However, inside a city the available space is usually limited by buildings and infrastructure.

4.1.3 Increase storage

Increasing the storage capacity inside the city is the third possible strategy used to decrease the probability of flooding. In case that the capacity of the channels is not sufficient and they are about to overflow, the water can be stored in designated areas. Examples are parks, squares, low-lying sports fields, underground parkings, basements or lakes. When the discharge in the channels are lower again, the storage areas can be emptied.

4.2 Integrated Coastal Zone Management

Integrated Coastal Zone Management (ICZM) is a process to address current and long-term coastal management issues such as dealing with coastal erosion, changing hydrological cycles and adapting to sea level rise (World Coast Conference, 1993). To improve the coastal safety the following strategies are identified (Bosboom & Stive, 2015). These are summarized in Figure 4.2.

1. Retreat
2. Accommodate
3. Protect

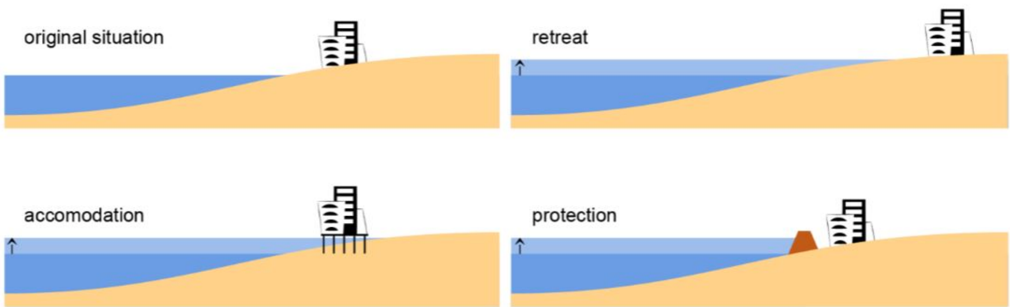


Figure 4.2: Coastal protection strategies (Bosboom & Stive, 2015)

4.2.1 Retreat

This strategy implies to 'do nothing'. Basically, the increased probability of flooding is accepted and everything gets the space and time to migrate landwards (Bosboom & Stive, 2015). Applying this to Cartagena would mean that all neighborhoods that are at risk of flooding due to coastal processes, should be relocated. This strategy is not commonly applied in cities.

4.2.2 Accommodate

'Accommodate' means adapting the coastal infrastructure in such a way that it is able to withstand the increased probability of flooding. The coastal retreat, erosion and increased risk of flooding is accepted (Bosboom & Stive, 2015). Applying the strategy 'Accommodate' could be done by regulating building development, switching to a different type of land use or adapting life style and ways of transport to the new situation.

4.2.3 Protect

If coastal erosion and increased probability of flooding are not acceptable, 'Protect' is the strategy that should be applied. Protective measures are taken to counteract coastal erosion and prevent flooding (Bosboom & Stive, 2015). There are two categories of possible measures: soft and hard measures.

Soft measures

The principle of soft measures is counteracting erosion by compensating the eroded sand. The process of erosion continues, but the eroded material is replaced with material from elsewhere. This is done by offshore or onshore nourishments. Another example of a soft measure is protecting the retreating shoreline by restoring marshes or mangroves (Bosboom & Stive, 2015).

Hard measures

Using hard measures means building structures to influence the coastal processes. Examples are groynes, onshore and offshore breakwaters, seawalls and revetments (Bosboom & Stive, 2015).

4.3 Strategy Implementation

4.3.1 Flood risk reduction measures

Each of the aforementioned strategies can be realized with a range of measures. Flood risk reduction measures can be divided into structural measures and non-structural measures. Structural measures range from heavily engineered structures such as revetments to natural solutions such as reforestation. Non-structural measures refer to solutions such as early warning systems and natural disaster insurance. Structural measures are highly effective at controlling water levels and discharges, but are inherently less flexible or robust to uncertainty. Often the most effective flood risk reduction is achieved by a mix of structural and non-structural measures, so a balance of active water management and robustness is achieved (World Bank, 2011). In Figure 4.3, frequently used flood risk reduction measures are ordered according to their robustness and cost benefit performance.

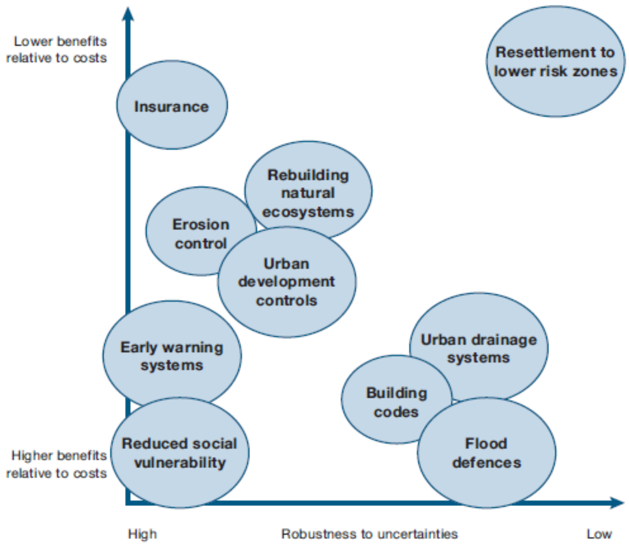


Figure 4.3: Flood risk reduction measures ordered on robustness and cost benefit performance (World Bank, 2011)

4.3.2 Implementation scales

The above mentioned measures may be applied at various scales. Flood risk reduction measures may be implemented at the regional scale down to the individual building scale. A solution is most effective, both in terms of flood risk reduction and cost benefit performance if measures are applied at various scales.

It is therefore decided to follow a top-down flood risk reduction approach. Large-scale regional plans are made to control the source of flood risk. These regional solutions are complemented by small-scale measures. These local measures can significantly reduce residual flood risk. Also, the sum of risk reduction achieved by many small measures may reduce flood risk for large areas.

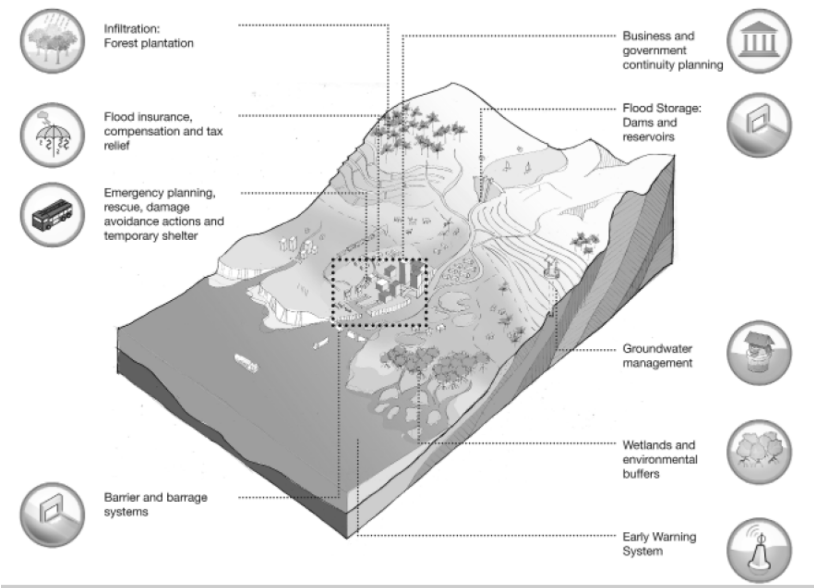


Figure 4.4: Example of regional risk management measures (World Bank, 2011)

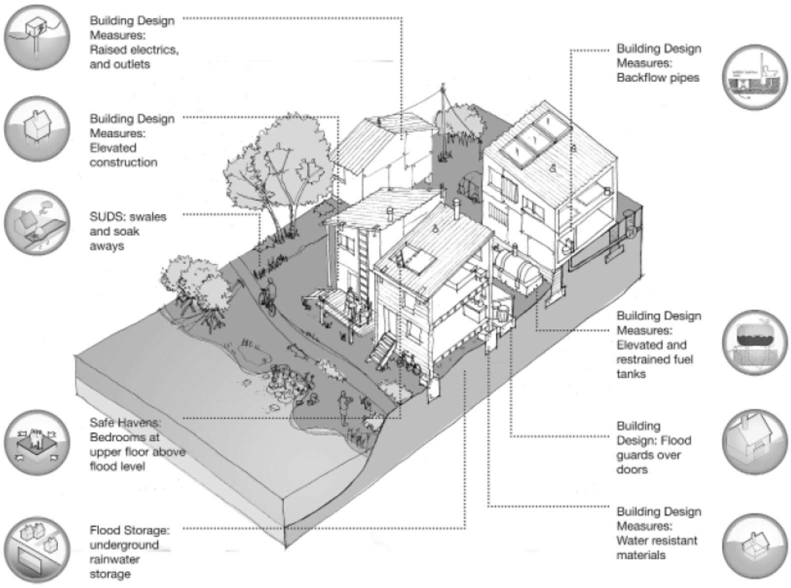


Figure 4.5: Examples of risk reduction measures for individual buildings (World Bank, 2011)

Chapter 5

Synthesis

Based on the strategies discussed in the previous chapter, several brainstorming sessions were conducted. During these sessions hundreds of possible solutions, both realistic and unrealistic, were conceived. The most promising ideas were selected and combined to create several sound alternatives.

The discussed alternatives focus on the large-scale integral flood risk reduction measures. As stated in Chapter 4, each alternative should however be complemented with local and non-structural measures. The alternatives contain elements of all three strategies to reduce the pluvial flood risk, because all of them are applicable to Cartagena. Not all the strategies regarding ICZM are suitable in this situation. 'Retreat' is not a realistic option, because the loss of economic, cultural and social value would be extremely high. All the infrastructure and much of the urban area, including the World Heritage Site of the historic center, would be lost. Furthermore, all the citizens of the peninsula, Marbella and the neighborhoods bordering the Ciénaga have to be relocated. This strategy therefore would result in a highly undesirable scenario. ´Accommodate´ would result in raising all the buildings and roads in the aforementioned areas, which would again be very costly. Besides, raising the historic center is impossible as it is a protected area. Concluding, the only realistic option regarding the rising water levels, is using the strategy 'Protect'. This strategy will be clearly visible in description of the alternatives.

This chapter describes the various alternatives. In order to structure them, the alternatives for Ciénaga de la Virgen, the bay, the coast and Mamonal are presented separately. Some of the alternatives require integration of the bay and Ciénaga alternatives. However, protection of the Caribbean coast and Mamonal are treated as separate issues.

5.1 Ciénaga de la Virgen

The Ciénaga alternatives include measures which directly affect the water level in the Ciénaga and discharges entering the Ciénaga. The analysis and brainstorm resulted in the realization that the only manner to protect the Ciénaga shores from sea level rise is to close the connection with the sea, or using compartments to regulate the water levels in critical zones. To prevent water quality deterioration, closing the Ciénaga should not be done without guaranteeing that circulation and refreshing continues. In addition, it is considered impossible to create water bodies large enough for retention within the city. Frequently discussed water bodies are identified in the map in Figure 5.1.

5.1.1 Alternative 1 - Keep water out of the city

This solution mainly focuses on decreasing the discharge peak that enters the city by retaining and bypassing. The upper basin is managed in such a way that the water volume entering the city is regulated. In the upper basin of Matute and Chapundun, a retention lake will be designed just outside the city.

The large rural catchment areas to the East of the Ciénaga influence the floods in the city. Large discharge peaks causes the water level in the Ciénaga to rise, reducing channel capacity and flood-

Figure 5.1: Important inner city water bodies.

ing the banks. If this water is diverted from the Ciénaga and discharged into the sea North of the Ciénaga, it is unable to cause flooding. By designing a bypass channel along the Ciénaga, the water from the rural areas will not flow into the Ciénaga. The bypass is assisted by several upper basin retention lakes, which reduce the peak discharge in the channel and thus reduce the required capacity.

The biggest catchment area in the city is the area of Canal Ricaurte. The channel is flooded regularly, because the capacity of Ricaurte is not sufficient. These floods are reduced by the construction of a bypass from Ricaurte to the bay. The altitudes in the city make it is impossible to design a channel for this bypass. Therefore, it is necessary to make use of an underground tunnel to discharge the water into the bay.

Lastly, a dam is placed in the Ciénaga to create a separate compartment. This will protect the neighborhoods from both sea level rise and pluvial floods. The water level can be regulated and lowered beforehand if an event with high precipitation is expected. This increases the hydraulic gradient of all the channels, which results in an increase of the discharge capacity of the channels. Also, extra water storage is available in the lowered compartment. Level control works are used to pump water from the compartment into the Ciénaga in the rainy season. An inlet is included to let the water flow from the Ciénaga into the compartment during the dry season, after which it is pumped back into the Ciénaga again. This ensures continuous circulation and refreshing of the water. A desired balance between sweet and salt water can be achieved and high water quality can be assured.

The dam is extended overland to serve as a dike which is connected to the Vía Perimetral. This dike serves as a boundary, blocking urbanization into the new compartment. Roads may be build on the dam and dike to improve accessibility of neighborhoods around Marbella.

Alternative advantages:

- Retention and bypassing lowers stress on existing infrastructure.
- Retention lakes are relatively cheap and flexible measures.
- Circulation of water in the Ciénaga is ensured.
- The capacity of current channels and storage of urban drainage water is increased.
- It gives opportunities for improved accessibility if a road is build on the dam.

Alternative disadvantages:

- The isolated Southern compartment requires constant pumping.
- Retention basins fill up and can overflow if rainfall lasts for long periods.
- The bypass channel and retention infrastructure are outside of the city. Out of sight, out of mind, mentality makes ensuring sufficient maintenance difficult.

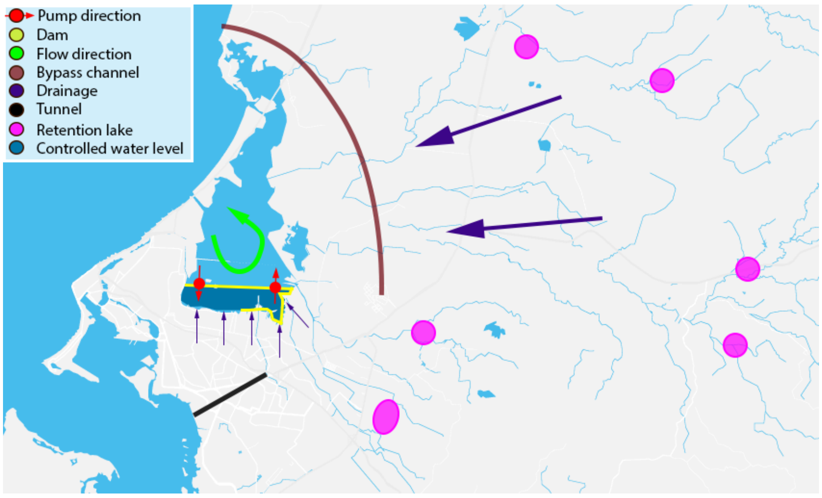


Figure 5.2: Ciénaga alternative 1 - Keep water out of the city

5.1.2 Alternative 2 - Controlling the urban shore

When considering the Southern shoreline of the Ciénaga, it is clear that the water levels must be separated from the sea. This is the only way to protect these areas from sea level rise and storm surges. However, closing the Ciénaga completely is not advised as it is very likely to return to a state of extremely poor water quality, as was the case before La Bocana was build.

The following solution is proposed: a Southern section of the Ciénaga is separated from the rest by a dam. The Northern part functions as it currently does; circulation is maintained by La Bocana. The water level in the new compartment is artificially controlled by pumps. Caño Juan Angola is used to connect the compartment to the bay, which is closed off as well (see Section 5.2). The water levels in the bay and the Southern compartment of the Ciénaga are lowered. These water bodies can be used for storage of rainwater and as a buffer against flooding. Lowering these water levels improves drainage in the urban channels as the hydraulic gradient in the channels is increased. To reduce required pump capacity, the large rural discharges (a total of 1400 m^3/s for 100 year return period) drain into the Ciénaga, which will drain by gravity into sea through La Bocana (Consultores et al., 2007). The smaller urban discharges enter the compartment (total 280 m^3/s for 100 year return period) and need to be pumped away. During the wet season, rainwater is used to circulate and refresh the water in the new compartment in order to maintain desired water quality. During the dry season, water is allowed to flow in the compartment from the higher Northern compartment to maintain circulation. By either draining water in the bay and/or in the Ciénaga, desired salinity and water quality is maintained. If desired, a (partial) tidal system may be created as well. In anticipation of an extreme event, water levels may be lowered further to create extra storage.

Transportaton may improve if roads are build on top of the dam. The road on top of the dam could be extended Northwards behind the airport to connect it directly to the national highway. To the East the dam continues as a dike, later it turns clockwise until it connects to the Vía Perimetral (see Figure 5.3). This dike serves as a barrier against urbanization in the South and the Vía Perimetral could be extended on top of this dike.

Alternative advantages:

- The water level is controlled along the urban shore.
- It improves urban drainage and increases storage of rain water.
- The water level is controlled in Caño Juan Angola and Laguna Cabrerro.
- Ciénaga water is circulated.
- Urban and rural discharge are separated.
- It provides opportunities for improved accessibility if a road is build on the dam.

Alternative disadvantages:

- Caño Juan Angola is a bottleneck for discharge.
- Vía Perimetral must be extended towards El Pozón or another artificial border is required to prevent urbanization of the Ciénaga after water levels are lowered.

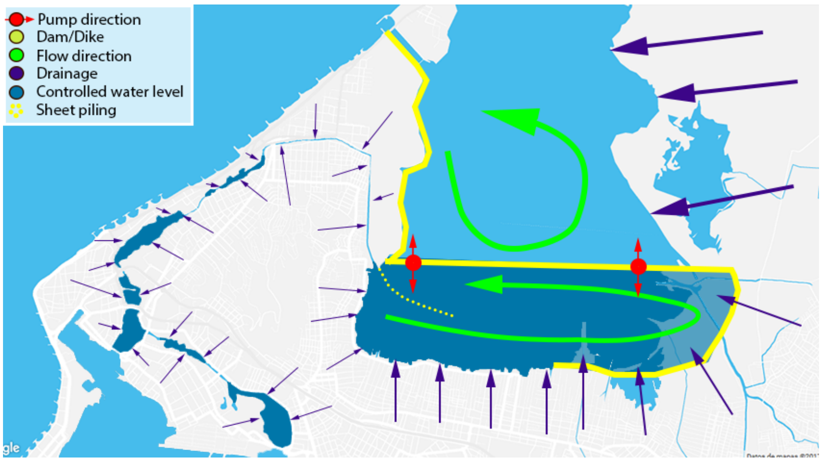


Figure 5.3: Ciénaga alternative 2 - Controlling the urban shore

5.1.3 Alternative 3 - Isolating and dividing the Ciénaga

For this alternative it is also desired to isolate and regulate water levels along the urban shore. A similar dam is constructed as in the previous alternatives. However, this dike extends only far enough to include canal Ricaurte. The dam then extends overland and serves as a dike to protect the remaining shore from high water levels. The canals Matute and Chapundun drain through this dike into the Ciénaga by mechanic means. It is assumed that upper basin retention lowers the peak discharges sufficiently to allow the pumps to discharge the incoming water from Matute and Chapundun. The obtained advantage is that the large water quantities from Matute and Chapundun will not have to pass through the Caño Juan Angola bottleneck. Controlling the water level in the compartment increases storage capacity for rain water and increase the capacity of existing channels. Water levels may be lowered further in anticipation of an extreme event to create extra storage.

In addition, La Bocana is upgraded in such a way that it is possible to close off the Ciénaga and pump water out of it. This will make the entire Ciénaga more resilient against sea level rise. However, until sea level rise demands it, La Bocana will remain open and continue ensuring circulation of the Ciénaga. In addition, the water level could be lowered in the compartment and the Ciénaga, in anticipation of a storm, to increase storage and minimize the required pump capacity at Matute and Chapundun.

East of Ricaurte, the dam continues overland and also functions as a barrier against urbanization. A road may be build on top to connect the airport to the Vía Perimetral and to the national highway North of the airport if desired.

Alternative advantages:

- Less discharge needs to be pumped through Caño Juan Angola compared with alternative 2.
- Most urban waste flows towards Caño Juan Angola, allowing it to be collected.

Alternative disadvantages:

- Drainage in areas around Matute and Chapundun requires large pumps.
- Many pumps and regulatory works make it vulnerable to lack of maintenance.
- It is unclear if water quality can be maintained while the Ciénaga is closed off.

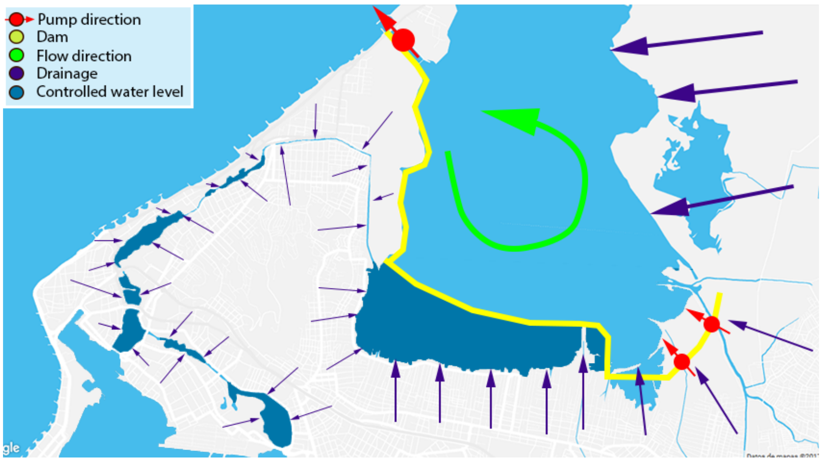


Figure 5.4: Ciénaga alternative 1 - divided Southern shore.

5.2 Inner Bay of Cartagena

The parts of the city neighboring the inner bay must be protected against sea level rise. This is a coastal protection issue. A retreat strategy means abandoning the city. Accommodation entails reconstructing the whole city landscape. Both are considered impossible and too expensive. Protection is the only remaining option.

Apart from constructing a new seawall all along the bay, an effective solution is (partially) closing the inner Bay of Cartagena. This shortens the coastline required to be protected. If the water level in the bay is artificially controlled, pluvial drainage in the city is improved. The best possibilities for closing the inner bay are the following: by connecting Bocagrande with Manga, by connecting Castillogrande with Manga or by connecting Castillogrande with Isla Manzanillo. This solution allows the following opportunities to reduce flood risk:

- It protects the areas behind the closure against sea level rise.
- Lower water levels within the closed part of the bay of Cartagena improve drainage of surrounding areas.
- Lower water levels in anticipation to heavy rainfall create additional storage.

Additionally, the barriers present several opportunities for the city of Cartagena. Sheltered new land or beaches can be created within the closure. The dams may be build such that they can accommodate roads. Constructing roads over the barriers can provide much needed relief on the roads around the historic center as traffic towards and from the peninsula may use a different route.

5.2.1 Alternative 1 - Barrier between Bocagrande and Manga

A dam between Bocagrande and Manga is constructed from the point North of the marine of the naval base, directly Eastwards to Fuerte Pastelillo, as shown in Figure 5.5. To regulate the water level in Las Quintas, the water body North of Manga, a second closure must be constructed. A potential place to do this is under the Barzuto bridge.

A road on the Bocagrande-Manga dam would provide a second point of entry for the peninsula. In addition, lowering the water level within the closure improves drainage in the historic center, Manga and the North of Bocagrande.

Alternative advantages:

- The historic center and Las Quintas are protected from sea level rise and pluvial drainage is facilitated.
- Major harbors and industries are not influenced.

- Active water quality control may be implemented to achieve a desired mix of sweet and saline water of good quality. Partial tidal oscillations of the water level can be maintained if desired.
- The naval base keeps its direct connection to the bay.

Alternative disadvantages:

- Small locks are necessary to serve the marinas and boats to Bazurto market on the inside of the barrier.
- Seawalls must be constructed over long distances.
- There is no space for land creation.

Figure 5.5: Dam Bocagrande - Manga

5.2.2 Alternative 2 - Barrier between Manga and Castillogrande

A more radical solution is building a dam between Castillogrande and Manga as shown in Figure 5.6. This solution protects a larger area. The barrier at Barzuto is the same as in alternative 1.

Once again, a road may be incorporated into the dam's design. In addition to improved access to the peninsula, this alternative provides the opportunity for land reclamation. Behind the dams, the calm water allows land to be reclaimed cheaply. This prime real estate can be sold to cover some of the expenses. Flexible water management allows the city to control the salinity, quality and movement of the water within the bay, the Ciénaga and the intertidal lagoons.

Alternative advantages:

- Bocagrande, Castillogrande and most of Manga are protected against sea level rise and pluvial drainage is facilitated.
- Major harbors and industries are not influenced.
- Pressure is increased on the urgency of the plans of the naval base to relocate to Isla Tierra Bomba.

- Opportunities arise for land reclamation.

Alternative disadvantages:

- Small locks are necessary to serve the marinas and boats to the inside of the barrier.
- The naval base either needs to move or needs to get its own private lock to ensure a fast exit to the sea.

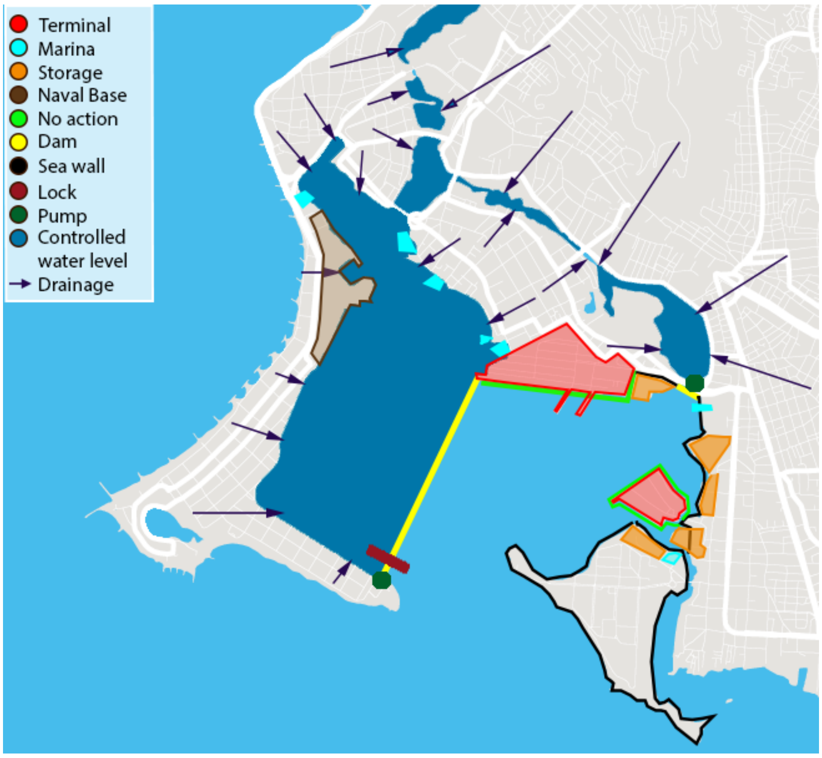


Figure 5.6: Dam Manga - Castillogrande

5.2.3 Alternative 3 - Barrier between Castillogrande and Isla Manzanillo

The third option for closing the bay is most effective in terms of coastal defense, but consequently carries many implications. This option consists of a dam between Castillogrande and Isla Manzanillo, as shown in Figure 5.7. To complete the closure, a dam between Isla Manzanillo and Zapatero is built. The repercussion of this alternative is that the container terminal (SPRC), cruise terminals and harbors at El Bosque are no longer accessible. Huge navigation locks are required to maintain access to the harbors, which would need to be bigger than 300 m in length. This is extremely costly, is considered to be unrealistic and is therefore not taken into account in this alternative. Alternatively, the terminals must be relocated; considering local politics this move is extremely difficult if not impossible. However, relocation is calculated to be financially profitable. Refer to Appendix E for the calculations. Finally, smaller locks are installed to serve the marinas.

A road between these two neighborhoods could meet much resistance, since it connects a safe and rich area to a poor area. A guarded toll road could be a solution to this problem. However, including a road on the dam is not a requirement. The alternative allows the water level to be managed in the bay, lagoons and Ciénaga as a whole. Detailed modeling and ecological studies are required to determine how to optimally balance salinity, tidal movements, drainage and circulation. If the container terminal is moved to Mamonal, the mobility of the Cartageneros will increase. Currently, most of the containers arriving in Manga are distributed inland by trucks. These large and slow trucks must first drive through the city, resulting in congestion on the road infrastructure.

Alternative advantages:

- The complete coastline of the inner Bay of Cartagena is protected and pluvial drainage is improved.
- Living conditions and travel times around Manga and El Bosque will improve if the terminals are relocated.
- The available land from the terminals can be sold for residential purposes.
- Pressure is increased on the urgency of the plans of the naval base to relocate to Isla Tierra Bomba.
- Opportunities arise for land reclamation.

Alternative disadvantages:

- Small locks are necessary to serve the marinas and boats on the inside of the barrier.
- A major transformation and investment is necessary to relocate the terminals.
- The naval base either needs to move or it needs to get its own private lock to ensure a fast exit to the sea.

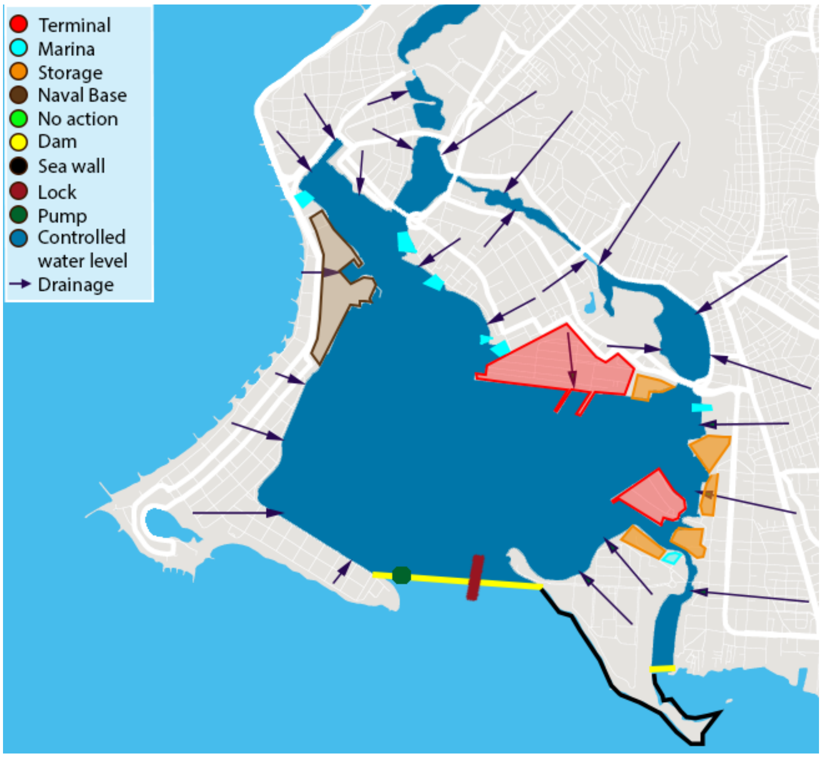


Figure 5.7: Dam Castillogrande - Isla Manzanillo

5.2.4 Alternative 4 - Raising seawalls around the bay, no barrier

The bay stays open, which results in a higher water levels along the inner shores due to sea level rise. The current sea and quay walls at Castillogrande, parts of Bocagrande, parts of Manga and Isla Manzanillo are not sufficient to cope with the expected sea level rise. The heights of these walls need to be increased accordingly. The other parts of the bay are either already sufficiently high or their state is unknown. Due to sea level rise, high tide and storm surges will cause the water level in the bay to be too high to discharge pluvial water by gravity, pumps must be installed all along the bay to be able to drain the rainwater in the bay. The combination of the great length of coastal protection and many pumping stations makes this alternative expensive and extremely vulnerable to poor maintenance.

Alternative advantages:

- It provides open access to sea for all boats.
- There is local experience with construction of this infrastructure.

Alternative disadvantages:

- Many pumps are needed to discharge rain water.
- Many pumps make the system vulnerable due to lack of maintenance.

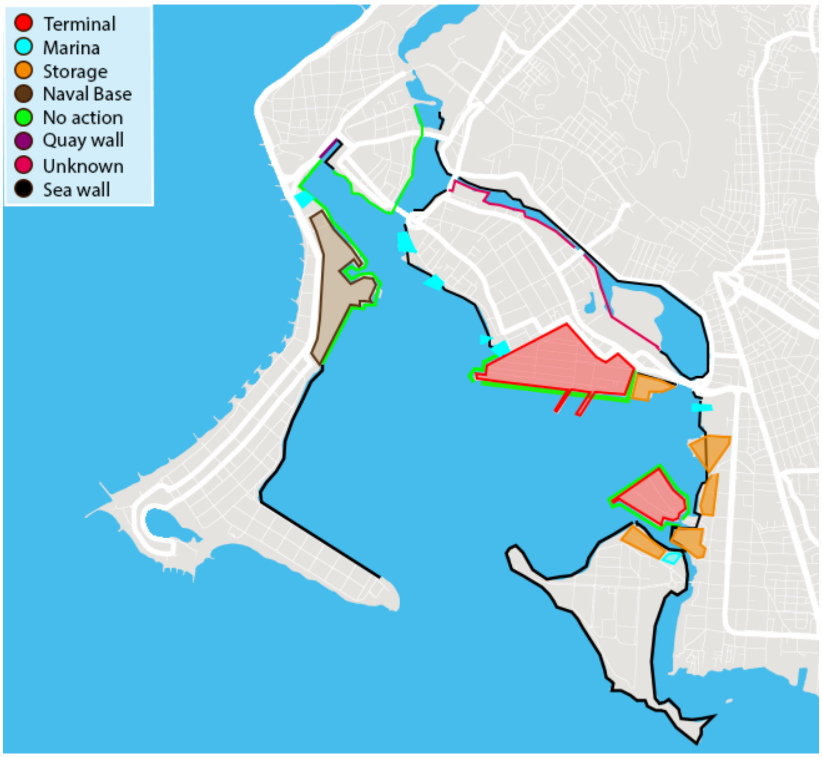


Figure 5.8: Rise coastal protection

5.3 Coast

In this section, three different options for protecting the coast are discussed. It is evident from the analysis that only storm-induced erosion occurs. Structural erosion is not encountered along the coast of Cartagena. Multiple groynes and breakwaters are thus unnecessary, as these do not protect the coast against storm-induced erosion and sea level rise (Bosboom & Stive, 2015). Therefore, the solutions for coastal protection consist of seawalls, revetments and beach nourishment.

If the coast is protected and the holes in the seawalls are closed, rainwater is unable to freely flow into the sea and is thus trapped in the city. This section will only focus on coastal protection, excluding pluvial drainage. The final integral design will cope with the pluvial drainage.

5.3.1 Alternative 1 - Two groynes

This alternative consists of creating wide and high beaches in front of Bocagrande and in front of the historic center up to Marbella. This protects the outer shoreline of the city against sea level rise and sea-induced floods. This alternative has many possibilities to solve transportation problems and to create an attractive area for tourists, local entrepreneurs and residents.

Marbella – historic center

At this moment, the seawall along the coast is very low and the breakwaters are in bad shape. One groyne, which can partly be built with the material of the current breakwaters, is constructed at the end of this stretch. This groyne will hold the sediment of the newly created beach. To protect the coast against storm surges and wave action during storms, a new seawall is constructed.

The opportunities presented by this alternative are numerous. The tip of the groyne may serve as a place to build a café or a restaurant. The coastal avenue can be expanded and incorporated into the design of the new seawall if desired. A cheaper alternative would be to build a boulevard only for pedestrians and cyclists. The widening of the beach provides extra space for restaurants and recreation.

Maintenance of this stretch by means of nourishment is required at yet to be determined intervals. Modeling is required to determine sediment movement and beach behavior.

Historic center – Bocagrande

Along the West coast of the historic center, there has never been a beach. In this alternative this remains the same; only the revetment and seawall are upgraded. The groynes along the coast are removed. To solve the traffic jams where the coastal avenue crosses the main road coming from the city, the upgraded seawall and revetment can be extended seawards such that space is available for redesigning the intersection. It is possible to add extra lanes to the existing road by building on top of the seawall, behind the seawall or behind the revetment.

Bocagrande

Along the coast of Bocagrande a new beach is constructed. At the Southern tip a new and longer groyne is constructed to retain the sand. This groyne could have multiple functions, like a marina or a hotel at the tip of the groyne. To protect the peninsula against storms a seawall is constructed at the end of the beach. Again, this can be done in combination with an expansion of the coastal avenue or a boulevard for pedestrians and cyclists can be created.

Maintenance of this stretch by means of nourishment at intervals will be required. Modeling is required to determine sediment movement and beach behavior.

El Laguito and Castillogrande

The beach near Castillogrande is sheltered by El Laguito and Isla Tierra Bomba. The beach should be maintained and raised according to sea level rise. Therefore, a seawall might not be necessary to protect the adjacent neighborhoods against storm conditions. However, this should be modeled in more detail. The tip of Castillogrande and the southern site of El Laguito are protected with a revetment. This solution for El Laguito and Castillogrande applies for all the alternatives.

Alternative advantages:

- It creates long stretches of beach.
- There is space for a multi-functional seawall.
- It is attractive for tourists.
- It is relatively cheap compared to the coastal master plan, but offers many of the same possibilities.

Alternative disadvantages:

- Maintenance by nourishments is necessary.
- Longshore sediment transport will be blocked partly by the groyne, which might have a negative effect on the coast of Isla Tierra Bomba.

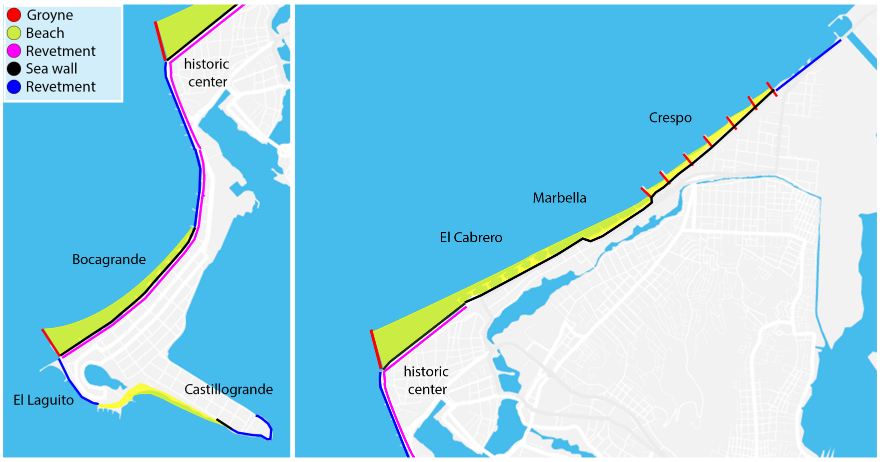


Figure 5.9: Overview of alternative 'Two groynes'

5.3.2 Alternative 2 - Green coast

Marbella – historic center

Mangroves are widely acknowledged as protection against natural hazards, storms and coastal erosion (Spalding, McIvor, Tonneijck, Tol, & van Eijk, 2014). In this solution mangroves are planted to defend the coast at Marbella using a 'Building with Nature' approach. As beaches are preferred for tourism and recreation, the mangroves are planted alternately with the existing beaches. Nourishment are necessary to create sufficient beaches. Two 900 meter long stretches of 100 meter wide mangrove forests are planted along the beach. However, mangroves need to be combined with hard barriers, as mangrove forests as stand-alone solutions do not always work. The height of the seawalls is thus increased to withstand storms. Small stretches of mangrove forest dissipate wave energy, decreasing the maintenance costs of the seawalls behind them (Spalding et al., 2014). The effect of the mangroves on the longshore sediment transport must be modeled.

Historic center – Bocagrande

The beach at Bocagrande is widened and heightened by offshore nourishment North-West of the beach. In time, this causes accretion of the beaches at Bocagrande. The size and location of the nourishment, the frequency, the sediment flow and resulting sediment distribution must be determined by morphological models. The current groyne at the tip of Bocagrande is sufficient to counter erosion. The revetment in front of the historic center and the Northern part of Bocagrande is heightened and widened.

Alternative advantages:

- Mangroves dissipate wave energy, decrease damage to the seawalls and thus maintenance costs.
- Mangroves maintain the coastline, as erosion is prevented and soil build-up is encouraged.
- Mangroves are a rich ecosystem with vast quantities of carbon dioxide storage, which can benefit fishery.
- Offshore nourishment is cheaper than onshore nourishment.

Alternative disadvantages:

- It is unclear how the beaches in between the mangrove forests transform and what happens with the longshore sediment transport.
- A seawall remains necessary.
- It takes years to form the beach at Bocagrande.
- It is unclear if mangrove forests between the beaches are desired by the citizens.
- The mangroves require intensive monitoring and maintenance.

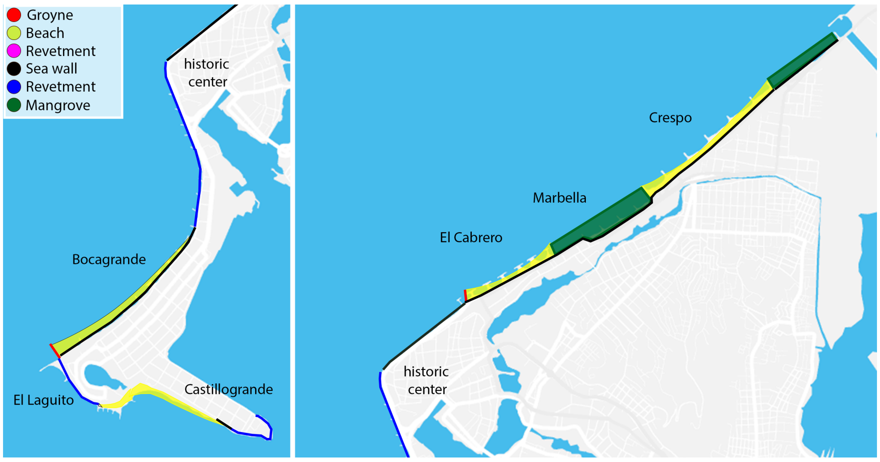


Figure 5.10: Alternative using mangrove swamp

5.3.3 Alternative 3 - Improve current design

This alternative is based on the current coastal defenses of Cartagena. Figure 2.17 shows the current situation of the coastal protection of the peninsula. The coastal defense currently consists of defenses like revetments, groynes, breakwaters and beaches. At the moment the only section which appears to be in good shape is the coast in front of the Crespo tunnel. This alternative is in essence a large maintenance project.

Marbella – historic center

The current seawalls are very low, often damaged and perforated to allow for pluvial drainage, which make them unsuited for protection against current and future sea conditions. The existing seawalls are raised, repaired and the rainwater outlets are closed. New seawalls are built if necessary. The revetment is also raised and widened to withstand current and future conditions. The beaches in front of the seawalls are restored and maintained, which will protect the seawalls against scouring. Lastly, the groynes and breakwaters are repaired and maintained properly.

Historic center – Bocagrande

The groynes and breakwater in front of the historic center and the North side of Bocagrande are removed as they have not been successful in creating a beach in the past. Expected is that a natural flow of sediment does not reach these locations, which makes them unsuited for constructing beaches. The beaches at South side of Bocagrande are currently in good shape. The only measure applied is nourishment against storm-induced erosion. The height of the seawalls is raised accordingly to the sea level rise and the holes in the seawall are closed. Figure 5.11 shows the improved coastal design.

Alternative advantages:

- It is a relative easy and cheap solution.
- There is local experience with construction of this infrastructure.

Alternative disadvantages:

- No extra beach is created.
- There is no space for infrastructural improvements.
- The peninsula becomes very vulnerable during storm conditions as it becomes a bowl with high water near the buildings on all sides.

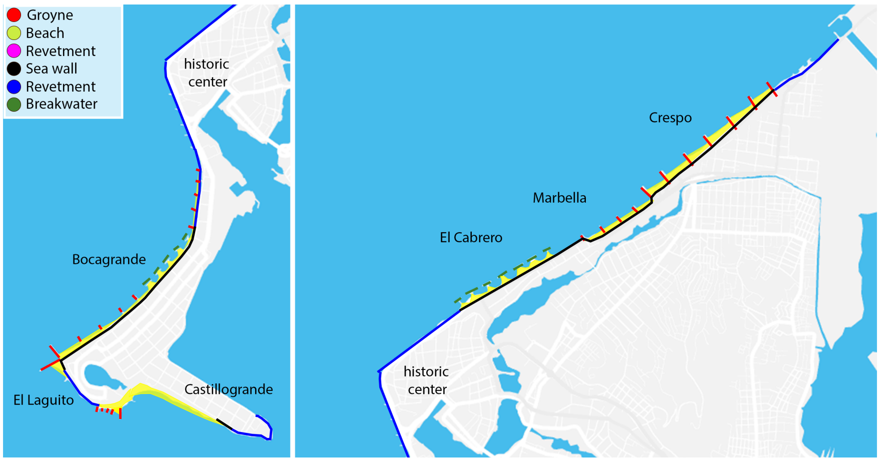


Figure 5.11: Alternative: Raise current coastal protection

5.4 Mamonal

The industrial zone of Mamonal is located in a catchment area, which is separated from the city. The problem in this area is that companies build their own dikes, narrow existing channels and creeks to expand their operations. As a result, the channels and creeks are forced to make harsh turns. This shifts the floods to vulnerable residential areas as Policarpa. This can be seen in Figure 5.12. The coast of this zone is managed by the companies themselves and most industrial complexes are located on slightly elevated positions and are connected with jetties to deeper water. Sea level rise should thus not be a significant risk.

Figure 5.12: Retention area in catchment area of Mamonal (indicated with blue)

Basically, there are three possible solutions:

1. Retention upstream or in the industrial zone
2. Bypass around the industrial zone
3. Straighten and improve functionality of existing creeks and channels

Upstream in the basin, areas are available for retention (see Figure 5.13). Another possible location for retention is within the industrial zone. This water can be used for drinking water, cooling or other production processes. Due to the fact that this retained water is already fresh instead of salt, it will reduce the costs for the industry.

A different possible solution is creating a bypass to divert the water from the vulnerable areas to the Bay of Cartagena. However, a large bypass channel seems to be unfeasible as Manonal consists of many small basins with several elevation ridges. These ridges are impossible to cross with a bypass

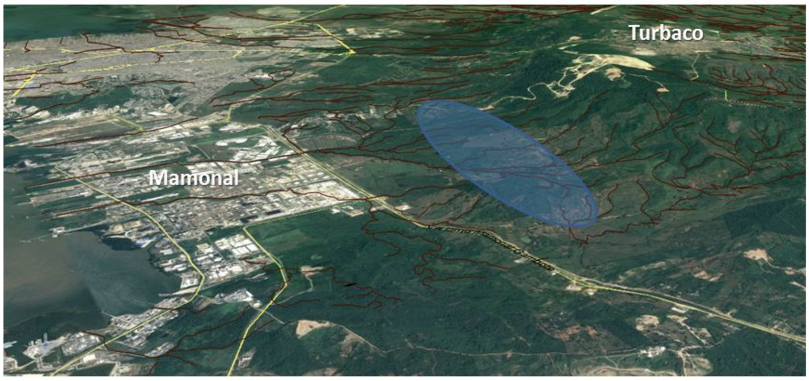


Figure 5.13: Retention area in catchment area of Mamonal (indicated with blue)

unless expensive tunnels are used.

Lastly, the existing channels can be improved to tackle the flood problem. Their capacity must be restored and many of them must be smoothened to increase the capacity and prevent flooding. For this step considerable cooperation and communication between all Mamonal companies is required.

The most successful solution for the Mamonal area would be a comprehensive combination of retention and channel rehabilitation. The areas for these retention lake must still be determined. For future developments of the area, more effective communication and perhaps guidance by a central organization such as the ANDI is desired to prevent the situation from deteriorating.

5.5 Non-Structural and Small-Scale Measures

The aforementioned large-scale alternatives must be complemented by a range of small and non-structural measures. Below follows a description of the measures that can make a positive contribution to the reduction of the flood risk in Cartagena.

The effect of non-structural and especially small-scale measures is hard to quantify and a subject for further research. The strength of small-scale measures lies in implementing them on a large scale; one storage tank of 1 m^3 will not make a difference, but the effect will be very noticeable if every house has one.

5.5.1 Non-structural measures

Early warning system

Early warning systems are a relatively cheap and very flexible method to reduce flood risk. The underlying principle is that precautions can be made in a timely manner to reduce flood risk if extreme events are predicted. Precautions include actions such as evacuating critical areas and increasing storage capacity by lowering the water level in retention areas. For Cartagena, the occurrence of hurricanes and tropical storms could be predicted several days in advance. By means of radio or SMS notifications, the local government could inform people in critical areas.

Evacuation plans and safe havens

In case of an extreme design event, evacuation of critical areas could reduce flood risk by removing citizens from harm's way. Critical areas in Cartagena are coastal areas prone to high waves and storm surges and areas along channels which are likely to overflow.

Evacuating poor areas is difficult as people are afraid their belongings will be stolen. To prevent looting, evacuation must be mandatory for everyone and should be accompanied by police or military patrols. Transportation for evacuation of poor areas must be provided by the government.

Citizens may be evacuated to safe rural areas outside of the city boundaries or to safe havens within the city. Public spaces such as sports stadiums or shopping malls could be used to temporarily shelter evacuated people.

Proper waste management

According to the UTB (see Appendix B.7) the waste management of Cartagena is currently causing problems regarding drainage. Solid waste management is done inadequately, partly because of the lack of awareness of municipal authorities about the extent of their responsibility and partly because the omission of the companies in charge is in compliance with the rules. The government must put effort into defining and controlling the responsibilities for the cleaning consortia and generate awareness among citizens about the problems that come with dumping waste. Systems to improve the urban waste management are currently being developed (El Universal, 2016a).

Water intensive crops

Cultivation of water intensive crops in the upper rural basins reduces the (peak) discharges reaching the city. The slopes between Turbaco and the city and between Turbaco and Mamonal are suitable locations to grow crops. Rice patties, for example, can serve as many small-scale retention basins and can increase infiltration.

Reforestation

Reforestation of the upper basin slows down surface runoff and increases infiltration. It is however expected to be rather difficult to implement and protect large-scale forests in the upper basins of Cartagena. Reforesting the creeks and rivers in the basin is still worth considering as this reduces flow velocity in the creeks and thus lowers discharges peaks.

Designated flood areas

Within the city there is no space available to construct retention basins. Some areas may be identified as emergency flood planes. Public spaces such as parks, squares and sports fields may be flooded on purpose to create additional storage in case of excessive rain. Flooding these open areas would result in less damage than flooding a populated area.

Regulated urbanization

One of the most effective ways to improve flood risk is to incorporate city planning with water management. Uncontrolled urbanization of the Ciénaga shores has been a major source of flood risk in Cartagena. Laws which prohibit building in areas that are prone to flooding can be used to prevent the situation from further deteriorating.

5.5.2 Small-scale measures

Green roofs

Green roofs are known to slow down the discharge of rain water. Vegetation on roofs holds water and thus lowers the discharge peak.

Green zones

Increasing the amount of green zones is closely tied to regulated urbanization and requires proper planning in new urban development. Green areas may be gardens, parks, grass along sidewalks, etc. These areas slow down surface runoff, which lowers discharge peaks. Infiltration is also increased, resulting in the same effects.

Green areas could also be implemented in territory which has already been urbanized. Encouraging people to have gardens instead of concrete patios or planting grass, trees and other plants along sidewalks are ways to increase the green surface area.

Storage tanks

Tanks to (temporarily) store water can be placed at many locations. They can be placed on roofs with the potential to be heated and used as warm water supply in the household. Other places are next to houses or underground. With help of filters, the water gets more suitable for domestic use. Storage tanks can be placed at many locations in the city and provide easy re-use of rainwater.

Drainage in roads

Many parts of the city do not have any rainwater drainage infrastructure. This should be built to connect the entire city to the large channels. Drainage incorporated into the roads is possible with the use of very porous asphalt or grids. Porous asphalt reduces the discharge speed. Grids are of help when drainage channels are constructed below the roads or on the roadsides.

Chapter 6

Evaluation of Alternatives

A multiple-criteria decision analysis (MCA) is done to evaluate the proposed alternatives. This is a scientific evaluation method to rate and compare technical, social, ecological, economical and political performance for different alternatives in a transparent way. For all the alternatives in the three different areas, an evaluation can be found in this chapter.

6.1 Evaluation of Alternatives for Ciénaga de la Virgen

For the area around the Ciénaga, the following alternatives were proposed:

- Keep water out of the city
- Controlling the urban shore
- Isolating and dividing the Ciénaga

To complete the analysis the pluvial drainage master plan (Consultores et al., 2007) is evaluated alongside the others. The complete analysis and results can be found in Figure 6.1. The criteria are based on the functional requirements and wishes as stated in Chapter 3. The criteria in which the alternatives score highest and lowest will be briefly discussed to facilitate discussion. A detailed explanation of the criteria and their weightings can be found in Appendix F.

6.1.1 Keeping water out of the city

This alternative successfully diverts water out of the city and uses retention lakes to store significant quantities. However, this solution is expensive, not flexible and inefficient as very large civil works such as the bypass channel are needed. No work is done to improve the inner city so local economics are not stimulated. The remote location of the civil works could hinder maintenance

6.1.2 Controlling the urban shore

This alternatively very efficiently increases inner city discharge capacities by increasing the hydraulic gradient, this improves living conditions in the city. The barrier in the Cienaga effectively ensures sea level rise protection while creating significant storage capacity. This alternative has no major downsides.

6.1.3 Dividing the Cienaga

Once again the storage and water level control achieved in the Cienaga is where this alternative performs well. However, the required number and capacity of the pumps make the solution inflexible, sensitive to poor maintenance and not environmentally friendly. Changing the layout or operation of La Bocana will prove politically difficult as the city is very pleased with its performance

6.1.4 Conclusion

The alternative 'Controlling the urban shore' scores best on the MCA (see Figure 6.1. It scores above average on every criteria, which indicates that there are no significant disadvantages compared to other alternatives. It can be used for the final concept without many adjustments.
It is striking how poorly the pluvial drainage master plan performs. The MCA clearly highlights how the master plan disproportionately focuses on capacity and how inflexible this solution is.

#	Criterium	Importance/ weight	Keep water out of the city	Controlling the urban shore	Isolating and dividing the Ciénega	Plan Maestro de Drenaje
1	Reduction discharge peaks	5	5	4	4	3
2	Efficiency discharge reduction	4	2	3	3	2
3	Capacity increase	5	4	4	4	4
4	Efficiency capacity increase	4	4	5	3	2
5	Storage	5	5	5	5	1
6	Protection sea-level rise	4	3	4	4	1
7	Flexibility	4	2	3	2	2
8	Water quality	3	4	4	4	3
9	Economic feasibility	4	2	3	2	2
10	Political feasibility	4	4	3	2	5
11	Technical feasibility	4	3	4	4	4
12	No regret measure	5	3	4	4	2
13	Environment friendly design	3	3	3	2	3
14	Improve living quality	2	4	5	5	3
15	Improved accessibility	2	4	4	4	1
16	Stimulate economics	2	1	3	3	1
17	Strengthen local resources	1	3	3	3	3
18	Improve urban planning	2	4	4	4	1
19	Maintenance	4	3	3	2	4
		Result	3,39	3,78	3,37	2,55

Figure 6.1: MCA for Ciénaga alternatives

6.2 Evaluation of Alternatives for the Bay of Cartagena

Four alternatives are evaluated according to criteria based on functional requirements and wishes as stated in Chapter 3. These include raising the walls in the inner bay and compartmentalizing the bay in three different ways. The alternatives highest and lowest scoring criteria are briefly discussed to allow for discussion. Again, a detailed explanation of the criteria and the weightings can be found in Appendix F.

6.2.1 Raising the sea wall

This solution is politically and technically the most feasible as it is the simplest solution and most in-line with current practice. Yet, this alternative is very inflexible, inefficient, expensive and does not explore any integral opportunities to improve other aspects within Cartagena.

6.2.2 Closure Bocagrande-Manga

This alternative is politically and technically relatively simple to achieve as disturbance to recreational and commercial activities in the bay are kept to a minimum. Consequently, as impact is minimized, so is the area which is protected and improved by this alternative. It therefore scores average across the board. The closure presents the opportunity to improve access to Bocagrande.

6.2.3 Closure Manga-Castillogrande

This alternative presents the opportunity to connect two wealthy parts of Cartagena. Besides improved accessibility, this allows Cartagena's peoples become more connected accross social classes as the physical travel distance between the rich of Castillogrande and the less well-off in the city center is shortened. However, more pump capacity is needed as the seepage and drainage discharges into the compartment increase.

6.2.4 Closure Castillogrande-Isla Manzanillo

As a flood risk reduction measure (criteria 1,3 and 5) this alternative performs very well. However large discharges much be pumped and considering local politics it is deemed nearly impossible to relocate both the Naval Base and the SPRC terminal.

6.2.5 Conclusion

The alternative 'Closure Manga - Castillogrande' scores best. It has to be noted that the required pump capacity is not very favorable. Intelligent design and operational decisions should account for this weakness. Calculations are required to obtain the order of magnitude of the pump discharges.

Readers will notice that the Castillogrande-Isla Manzanillo closure performs nearly was well as the Manga-Castillogrande closure. However, based on the understanding of local politics it would be extremely difficult to realize this alternative as relocation of the SPRC terminals will prove to be a very lengthy process at best. Shambolic politics and bureaucracy hinder such large scale reorganization of the city landscape. The MCA does not properly reflect how much of a drawback this aspect is and therefore the Manga-Castillogrande closure is a more achievable and thus better alternative.

#	Criterium	Importance/ weight	Raising sea walls	Closure Bocagrande - Manga	Closure Manga - Castillogrande	Closure Castillogrande - Isla Manzanillo
1	Efficiency protection	4	1	3	4	5
2	Water quality	3	3	3	3	3
3	Storage	5	1	3	4	5
4	Improved urban drainage	5	1	3	4	5
5	Pump capacity	4	5	3	2	1
6	Flexibility	4	3	3	3	3
7	Economic feasibility	4	2	3	3	4
8	Political feasibility	4	5	4	3	1
9	Technical feasibility	4	5	4	4	4
10	Social benefits	4	3	4	5	4
11	No regret measure	4	2	4	4	3
12	Environment friendly design	3	3	3	3	3
13	Improve living quality	3	1	3	4	5
14	Improve accessibility	3	1	5	5	4
15	Stimulate economics	2	1	2	3	3
16	Strengthen local resources	1	3	3	3	3
17	Maintenance	4	2	4	4	4
		Result	**2,48**	**3,39**	**3,64**	**3,61**

Figure 6.2: MCA for Bay alternatives

6.3 Evaluation of Alternatives for Coast

Four alternatives are evaluated. Besides the three earlier defined coastal alternatives, also the locally conceived coastal master plan is evaluated. The following alternatives are evaluated:

- Two groynes
- Green coast
- Improve current design
- Coastal master plan

The complete MCA can be found in Figure 6.3. For a detailed explanation of the criteria and their weightings, see Appendix F. The best and worst scoring aspects of each alternative are briefly elaborated to allow for discussion.

6.3.1 Two groynes

The two groynes concept is rather effective against sea level rise as widen beaches as sea wall provide buffer against incoming waves and high water levels. This concept is, in its current form, not very environmentally friendly as it does little to simulate the environmentally and the large quantities of sand which are to be dredged will disturb ecosystems off the coast to some degree.

6.3.2 Green Coast

The Green Coast alternative will prove rather difficult to maintain as the mangrove forests will require careful management. Preventing deforestation or preventing uncontrolled growth of the green, forested, sections will be difficult. Improved mobility also scores very low as no plans to expand the coastal avenue are included. As expected this design scores well in environmental friendliness as mangroves are added the coastal stretch and as longshore sediment transport is not greatly hindered erosion of Isla Tierra Bomba is not expected.

6.3.3 Improve current design

Improving the current coastal protection infrastructure is an inflexible approach and opportunities to improve accessibility or local economics are missed. However, if executed properly it is effective against sea level rise and since the system is basically in place it is the most feasible both politically and technically.

6.3.4 Coastal master plan

The coastal master plan requires immense quantities of sand to create the planned beaches and the dikes completely blocks longshore sediment transport which is expected to increase erosion of Isla Tierra Bomba. The advantage of this alternative is the exploitation of many new opportunities to improve local resources, stimulate economics and improve living conditions.

6.3.5 Conclusion

From the MCA follows that the alternative 'Two groynes' is the most suitable one. This alternative offers a lot of flexibility, which can be used to increase the environmental friendliness of the design.

The local coastal master plan does perform quite well. Its main downfall is the high costs needed to build this solution.

#	Criterium	Importance/ weight	Two groynes	Green coast	Improve current design	Coastal master plan
1	Protection sea-level rise	5	5	5	5	3
2	Maintenance	5	3	1	4	2
3	Beach width + length	4	4	3	2	5
4	Improved urban drainage	5	3	3	3	3
5	Volumes of sand	3	3	3	4	1
6	Flexibility	4	4	3	1	4
7	Economic feasibility	4	4	3	3	2
8	Political feasibility	4	4	2	5	3
9	Technical feasibility	4	5	4	5	4
10	Coastal erosion Tierra Bomba	3	3	5	4	1
11	No regret measure	5	4	4	3	3
12	Environment friendly design	3	2	4	2	2
13	Improve living quality	2	4	3	2	5
14	Improve accessibility	3	4	1	1	5
15	Stimulate economics	2	3	2	1	5
16	Strengthen local resources	1	3	3	3	3
		Result	3,72	3,11	3,18	3,11

Figure 6.3: MCA for Coastal alternatives

6.4 Conclusion of the Evaluation

For Ciénaga de la Virgen the alternative 'Controlling the urban shore' performs best. For the bay, the Manga-Castillogrande closure is the best solution and to protect the coast 'two groynes' is the best solution. These three alternatives must now be combined and sewed together to form one elegant integral solution for the city of Cartagena. It should be kept in mind that the alternatives which are presented to be the best ones are the best among the select few alternatives presented when tested by this specific set of criteria. Better alternative may be possible and especially local opinions should be used to guarantee the most appropriate concept is chosen in consequent steps.

The selected alternatives may be improved with some simple measures. The Ciénaga area would benefit from retention basins in the Matute and Chapundun basins as described in alternative 1: ´Keep water out of the city´ (section 5.1.1). The opportunities for the tunnel proposed in this alternative to alleviate the pressure on Canal Ricaurte should be explored. Extra attention should be paid to reducing the required pump capacity in the bay. Intelligent design may reduce this capacity or efficient operational strategies may be proposed. The coastal solution scores rather poorly on environmental friendly design. Some measures should be taken to improve its performance on this important criterion. The chosen solution will be worked out and modified in the following chapter.

Chapter 7

Final Conceptual Design

The best alternative for each area has been selected. These are combined to create a comprehensive solution for Cartagena. In this chapter, the final design is presented at a conceptual level. Subsequently, the functional and operational aspects are described. Technical detailing and some order of magnitude calculations follow to verify feasibility and determine basic dimensions of the most important components. This technical review is followed by social and political considerations. Some opportunities related to the integral design are discussed and a rough cost estimate is presented.

7.1 Conceptual Design

7.1.1 Description of the system

Ciénaga de la Virgen and the Bay of Cartagena

The most important components of the proposed solutions are the two dams that compartmentalize the Bay of Cartagena and the Ciénaga de la Virgen. Within this compartment the water levels are regulated. The dam in the Ciénaga extends Northward as a dike to protect the airport and some neighborhoods against high water levels in the Ciénaga. Towards the South it is also extended as a dike that additionally prevents urbanization into the compartment. It is proposed to build one single pumping station besides the airport. A weir is placed in Caño Juan Angola, just South of the airport. This weir will regulate if and how much water flows through the channel. A strip of sheet piling is placed at the mouth of Juan Angola to ensure circulation in the Ciénaga compartment. The dam in the bay connects Castillogrande with Manga. A navigation lock is built in this dam to maintain access to the marinas within the compartment. Next to the lock a water inlet is constructed. A small dam between Manga and El Bosque completes the closure of the intertidal lagoon system. Here a small lock is built for small fishing boats to access Bazurto market. Another water inlet work is built at this location. In the upper Matute and Chapundun catchment areas, two retention basins are planned just outside the city. Figure 7.1 shows an overview of the works.

Caribbean coast

The Caribbean coast is protected by a combination of widened beaches, seawalls and revetments. The current Crespo shore is maintained, but a seawall is added. From Marbella to the historic center, the beach is widened and elevated by nourishment. A large groyne at the end will limit erosion of the beach. A seawall is added to protect against extreme water levels and storm waves. Between the historic center and the beginning of Bocagrande, a revetment is constructed and the coastal avenue is widened on this stretch as extra lanes are added onto the revetment. The beach is widened and heightened in front of Bocagrande and a seawall is constructed behind it, again with a coastal avenue on top of it. El Laquito is protected by a revetment and Castillogrande by its beach. This beach should be nourished to ensure it grows in height in accordance to sea level rise. A wall is built behind this beach to prevent it from spilling onto the road. See Figure 7.1 for an overview of the works.

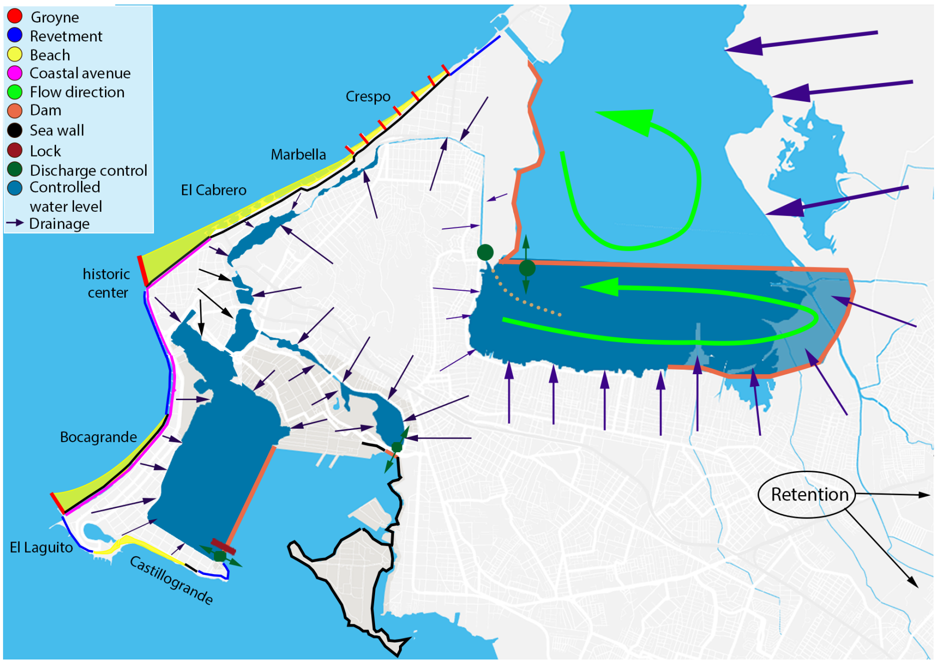


Figure 7.1: Integral solution for Cartagena

7.1.2 Operation of the system

Ciénaga de la Virgen and the Bay of Cartagena

Operating this system revolves around achieving desired water levels and water quality in the compartments. This should be done in an efficient manner so that installed pump capacity is optimized and operational cost are minimized. Smart design should allow pump capacity to be added in the future so investment costs are spread out. In anticipation of a rainfall event the water levels in the compartments should be lowered. This will provide a storage buffer for rain water and increase urban drainage as the hydraulic gradients of the drainage channel are increased. The discharge control work in Caño Juan Angola provides some additional flexibility to the system as the water level in the Ciénaga can be lowered further than that in the bay. This is done since the Ciénaga compartment requires more storage. Separating the compartments is more economical than lowering to the level required for the Ciénaga.

Currently, the following operation of the system is proposed for circulation: during the wet season, water from both compartments is pumped out of the Ciénaga. Frequent rainfall will ensure that the water in both compartments is refreshed. During the dry season, sea water will be allowed to enter the bay compartment through two inlets. This water is then pumped out of the Ciénaga compartment. In this manner circulation is maintained as is water quality. Sheet piling at the mouth of Juan Angola directs the water towards the shore to circulate throughout the entire compartment. Ciénaga de la Virgen is circulated with La Bocana as is currently the case.

Much more detailed research is needed to determine an optimal design. The desired balance of saline and freshwater should be determined for the two compartments. Placing a second pump in the bay allows circulation to change direction, creating a more flexible system which can control the water quality and levels more accurately in the compartments. The design allows (partial) tidal movement within the compartments if desired. In addition, detailed rainfall, discharge and storage calculations are required to properly determine the required capacity and location of the pump station(s).

Caribbean coast

Coastal protection is not a dynamic system and thus does not require an operation description. Yet maintenance is very important. Beaches must be kept in good condition by regular nourishment. In addition, the seawalls and revetments must be inspected and maintained, especially after storms.

Complete system integration

The strength of this solution is that the coastal protection and pluvial systems strengthen each other. The compartments' dams protect the city from sea level rise, while improving drainage and providing storage. Pluvial drainage during high sea levels will no longer be an issue.

7.2 Technical Details of Drainage System

In this section, the cross sections of the closure dams are determined using rough calculations. Some order of magnitude computations are also done to verify whether the concept of drainage is realistic and the storage volumes are sufficient.

7.2.1 Closure dams

To create a compartment in which water level can be controlled, two closure dams are built. For both dams an indication for the height is given based on the ULS.[1] The dams are designed for a lifetime of 100 years (which implies a sea level rise of 1 m and a higher maximum water level of the design event). Because a closure dam is such a massive construction which cannot be replaced easily, the design lifetime is extended. It is possible to construct a road on top of both dams to improve the accessibility.

There are many different ways to construct a closure dam. The dam could be a concrete, earth or rockfill structure or could be made out of caissons. The method of closure is not determined either, it could be horizontal or vertical (CIRIA, CUR, & CETMEF, 2007a). To give a indication of the height, it is assumed that the slope of both closure dams is 1:3 (vertical:horizontal). This is a regularly applied slope for sea dikes in the Netherlands (Rijcke, 2013). The necessary crest height is taken as the sum of *HAT + Rise due to El Niño + Storm surge + Sea level rise (100 years) + Subsidence (100 years) + Wave overtopping.*

Design closure dam Castillogrande - Manga

The crest height is 3.12 m according to the used design conditions (see Table 7.1).

In the bay, only waves smaller than 0.5 m occur. The used overtopping criterion is limited to $q = 200l/s/m$ (no damage to well-protected crest and embankment). This criterion is set to reduce investment costs. The road on the dam will be closed during design events. Calculations (based on a sloped dam) show that no additional crest height is needed to reduce wave overtopping (see Appendix G.3).

Table 7.1: Design height dam Castillogrande - Manga

Component	Additional water level
HAT	0.72 m.s.n.m.
El Niño	+ 0.2 m
Storm surge	+ 1.0 m
Sea-level rise (100yrs)	+ 1.0 m
Subsidence (100yrs)	+ 0.20 m
Total	3.12 m.s.n.m.

If a 4-lane road in combination with a bike lane is desired to connect Castillogrande and Manga, the width at the crest should be 20 m. An impression of the water levels and crest height can be found in Figure 7.2.

[1] insufficient time to define and check for SLS.

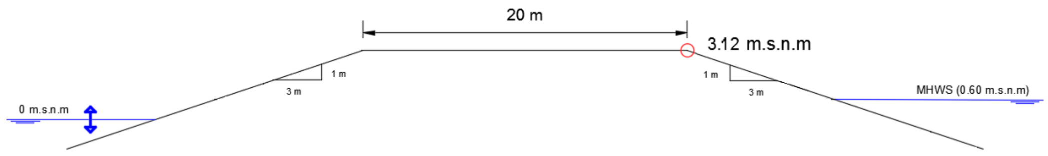


Figure 7.2: Cross section of closure dam Castillogrande - Manga

Design closure dam Ciénaga

It is assumed that there are no significant waves in Ciénaga de la Virgen. So no additional crest height to limit wave overtopping is needed. The crest height is 3.12 m according to the used design conditions (see Table 7.2).

Table 7.2: Design height dam Ciénaga

Component	Additional water level
HAT	0.72 m.s.n.m.
El Niño	+ 0.2 m
Storm surge (100yrs)	+ 1.0 m
Sea-level rise (100yrs)	+ 1.0 m
Subsidence	+ 0.20 m
Total	3.12 m.s.n.m.

An impression of heights and water levels is given in the cross section in Figure 7.3.

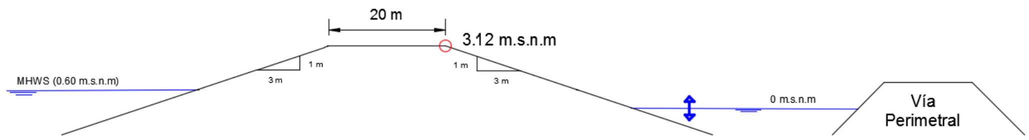


Figure 7.3: Cross section of closure dam Ciénaga

7.2.2 Groundwater flow

Bay

Lowering the water level in the inner bay after realizing the Manga-Castillogrande closure will cause a gradient in the groundwater levels. Since the peninsula consists of sand, which is a highly permeable soil, water may flow from the sea, underneath the peninsula into the closed compartment. If the dam is impermeable but resting on sand, water will also flow under the dam. The soil types at the bottom of the bay are unknown, but sand will be considered as a worst-case scenario. It might not be economical or feasible to lower its water level if the discharge entering the compartment is too large. Figure 7.4 gives a conceptual illustration of how the seepage mechanism works.

Using Darcy's law, a rough estimate is made in the order of magnitude of the volume of water which flows into the closure (using (Fitts, 2002)). If the water level within the closure is on average 0.5 m below the water level at sea and in the open part of the inner bay, normal groundwater seepage into the closure will on average be 3600 m^3/day which translates to 0.41 m^3/s.

About 300 of the 400 l/s flows underneath the dam. Measures such as sheet piling (down to an impermeable layer) or use of geo-textile may be used to reduce this discharge, which would make

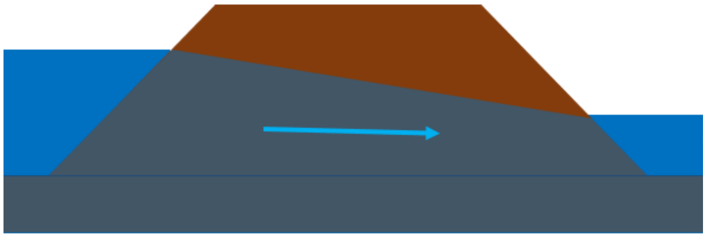


Figure 7.4: Seepage mechanism

the pumping complex cheaper and save on long term energy costs. A cost-benefit analysis should be performed here.

It should be noted that these values will change during a design event. Water level at sea may rise due to a storm surge and high tide, while the level within the closure is lowered for additional storage. With climate change, La Niña, high tide and storm surge, the water level may rise 2 m. The water level within the closure may be lower than is currently the case, creating a head difference of 3 m. This results in groundwater seepage into the closure of roughly 213,000 m^3/day during a design event which translates to 2.5 m^3/s. Once again, the majority of the discharge flows underneath the dam. Stability of the dam and possible piping should be considered during these conditions.

See Appendix G.1 for the full calculation.

Ciénaga

The soil underneath the Ciénaga is clay according to CARINSA (see Appendix B.1). Since clay is very impermeable, groundwater flow will not be an issue

7.2.3 Storage and pump capacity

During design events significant amounts of rainwater will drain into the compartment in the Ciénaga and into the compartment in the bay. Some basic inflow-outflow, associated storage and buffer calculations are required to test the feasibility of the design and to give an indication of required pump discharges. The buffer calculation will give an indication to what extent the water level must be lowered in order for the bay and Ciénaga to be able to store the water that is drained during a design event.

In the storage calculations of both water bodies it is assumed that the pump which removes water from the system is located in the other water body, i.e. the water is drained from the considered body through Caño Juan Angola. This is because this channel will be the drainage bottleneck. The capacity of this channel during a 100 year return rainfall event is 38 m^3/s according to Perez and Ramirez (2004).

Ciénaga de la Virgen

By combining the direct rainfall onto the Ciénaga with the discharge from urban drainage channels, the total inflow into the Ciénaga during a design event is determined per fifteen minute intervals. Since the area of the Ciénaga is known, the changes in water levels are calculated. The results are presented below. For a full explanation of the design event, input discharges and assumptions please refer to Appendix G.

From this rough estimate, it is concluded that the water level of the compartment must be lowered by approximately one meter prior to this rain event to create a buffer large enough to store the discharges in the Ciénaga. It must be kept in mind that this only holds the used design event. Installing a pumping station on the Ciénaga side would reduce the required storage.

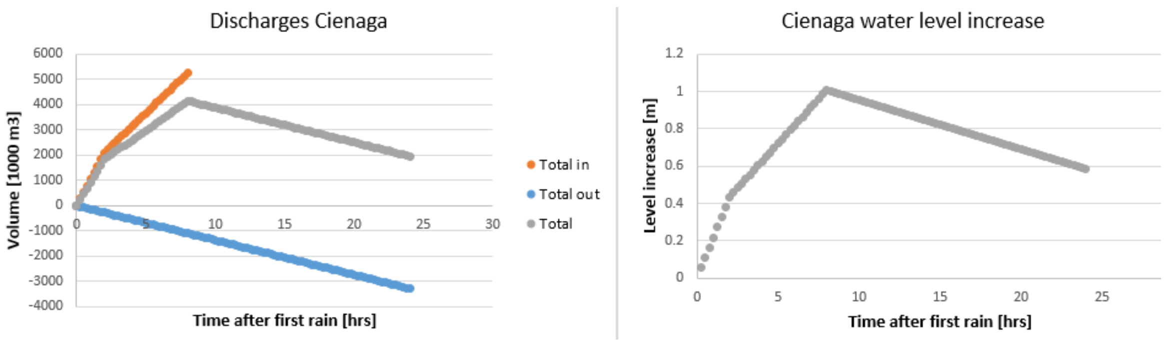


Figure 7.5: Discharges in the Ciénaga and water level movement.

Additional modeling should be done to describe the interaction between the bay and the Ciénaga compartment. The required storage and associated pump capacity should also be considered for prolonged rain events of a lower intensity.

Inner bay

The same rain event is used to calculate the storage capacity of the compartment in the bay. Both the direct rainfall onto the bay as the rainfall in the part of the city that drains to the bay closure are taken into account. The outflow consists of the discharge of the Caño Juan Angola to the Ciénaga. Using this data, an estimate is given regarding the water level rise of the bay during the rain event. The result can be found in Figure 7.6 and the full explanation of the calculations in Appendix G

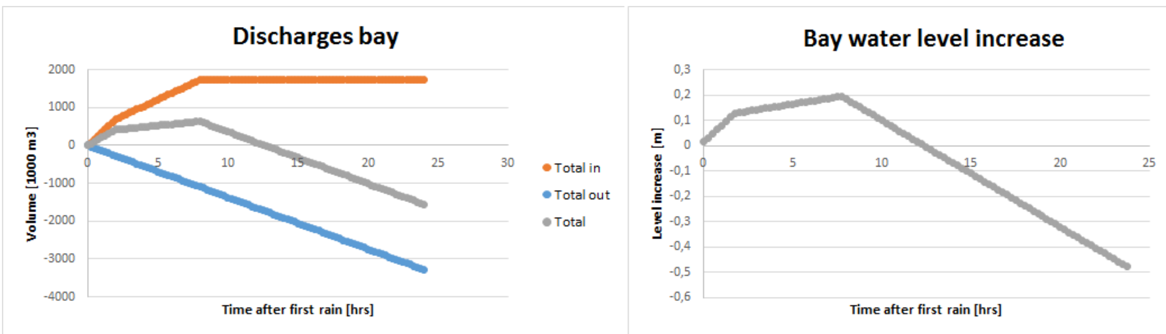


Figure 7.6: Discharges in the bay and water level movement

From the results can be concluded that the increase of the water level in the bay is small. It is smaller than the current tide difference. No pumps are necessary to increase the storage capacity of the bay.

Conclusion

The results from these rough calculations indicate that the best location for the pump station is in the Ciénaga. If this pump has a capacity of 75 m^3/s, a storage buffer of 0.80 m is required.

Operation of this system in the face of a design event is as follows: the bay and the Ciénaga compartments are lowered by 0.5 m. The control work in Juan Angola is closed and the water level in the Ciénaga compartment is lowered by an additional 0.30 m. During the event water is pumped from the Ciénaga compartment at 75 m^3/s. At the end of the event the water levels in the bay and Ciénaga compartments will be roughly equal. Juan Angola is opened again and both bay and Ciénaga compartment water levels are brought to the desired level. Figure 7.7 shows how water levels vary during the event.

Much more additional work is needed in this area. Proper hydrological models should be used to determine the peak discharges in drainage channels, as well as rainfall hydrograms. The interaction of

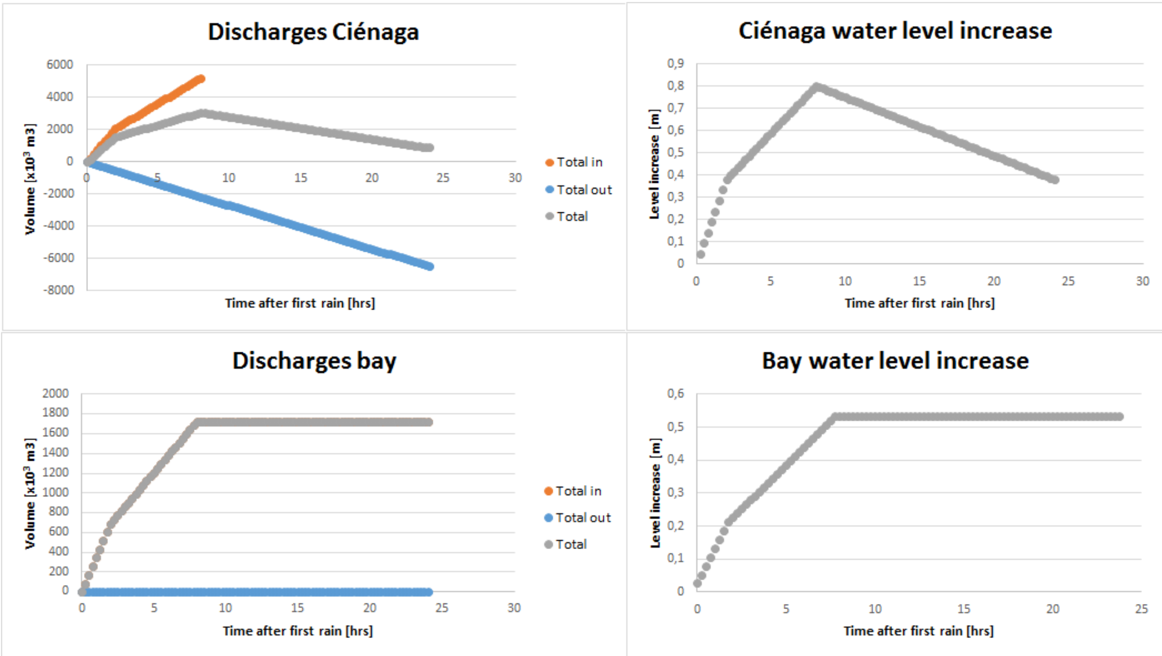


Figure 7.7: Water level movement of the Ciénaga and bay compartments during design event with operations as described above.

the two compartments through Juan Angola must be considered in more detail too. The same holds for the storage calculations: bathymetry and seepage should be considered. Overtopping volumes from the sea side will drain into the bay closure and should also be considered. The storage calculation should be done for a less intense, but much longer rainfall event as well. Positioning of pumps, inlet locations and control works should be determined considering water quality management. However, it has been proven that the design is feasible.

7.3 Technical Details of Coastal Defenses

For the coastal defenses, the height of the seawall behind both stretches of beach is determined by means of some rough calculations. The same is done for the revetment between the historic center and Bocagrande. The grain size and stability of layers are not considered. This should be done during later stages of the design. Also the revetments near El Laguito and the coastal defenses of Castillogrande are not yet considered. Some order of magnitude calculations are done to determine the necessary volumes of sand. The length of the groynes and the complete widening of the beaches should be investigated by morphological modeling to make sure the concept is working.

The coastal structures are designed for a lifetime of 50 years. The height of the seawall and the revetment is determined by the sum of *Maximum water level design event + Wave overtopping*. The calculations for the additional height due to wave overtopping can be found in Appendix G.3.

Design seawall

The level of the crest of the seawall is 3.07 m.s.n.m., see Table 7.3. For wave overtopping, the criterion is that it should be less than 10 l/s/m. This should be safe for people on top of the wall (van der Meer et al., 2016).

The cross section in Figure 7.8 shows more details regarding levels and slopes.

Table 7.3: Design height seawall

Component	Additional water level
HAT	0.72 m.s.n.m.
El Niño	+ 0.2 m
Storm surge	+ 1.0 m
Sea-level rise (50yrs)	+ 0.45 m
Subsidence (50yrs)	+ 0.10 m
Wave overtopping	+ 0.6 m
Total	3.07 m.s.n.m.

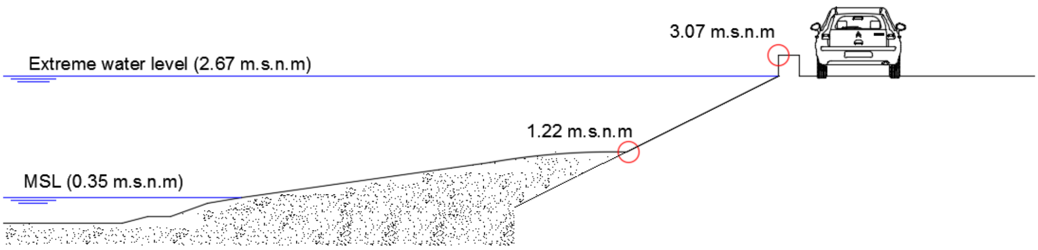


Figure 7.8: Cross section of seawall design

Design revetment historic center - Bocagrande

For the revetment, the design height is 4.72 m.s.n.m. (see Table 7.4). Wave overtopping causes a significant heightening of the seawall. During later stages of the design, the wave conditions should be modeled to make sure this height is necessary. Because of the favorable orientation of this part of the coast, the wave height might be lower, which leads to less wave overtopping.

Table 7.4: Design height revetment

Component	Additional water level
Maximum water level	2.47 m.s.n.m.
Wave overtopping	2.25 m
Total	4.72 m.s.n.m.

More details are given regarding levels and slopes in the cross section in Figure 7.9.[2]

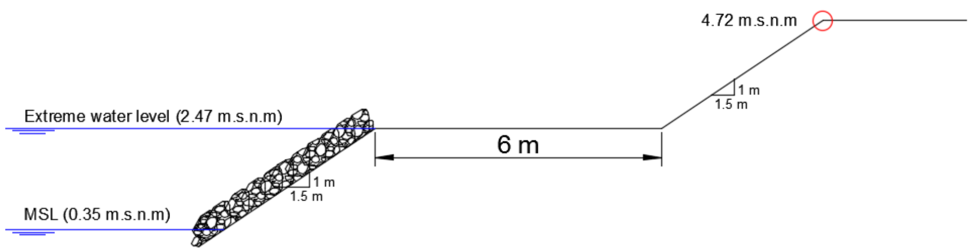


Figure 7.9: Cross section of revetment design

[2]A mistake has been made during wave overtopping calculations (see note in Appendix G.3.3 for explanation).

Beach nourishments and groynes

To design a nourishment, the following aspects need to be taken into account (Bosboom & Stive, 2015):

- Origin of sand: source of sand (land-based or marine)
- Use of material with a similar grain size
- Location of nourishment

To nourish the coast, large quantities of sand are required. According to professor Mauro Maza, sand used for previous nourishments is dredged just offshore the coast of Cartagena. Quality and origin of sand should thus not be a problem.

Also the location of nourishing is very important. For this project, two possible locations are identified, at the beach or at the shoreface (see Figure 7.10). Nourishing directly on the beach could be very difficult because dredging equipment has to cross the breaker zone. However, this is the most effective way to widen a beach. But if the beach is widened, the whole profile needs to be elevated. Therefore, a large amount of sand will move to the lower shoreface. This is not considered as coastal erosion, but it will reduce the width of the beach. If a shoreface nourishment is carried out, only 20-30% will reach the beach zone after 5 years. Usually this is done to maintain a coastline. So for the coast of Cartagena a combination of onshore and offshore nourishment is proposed. This will directly widen the beach and the long-term decrease of beach width will be limited. After the construction is finished, a shoreface nourishment is frequently done to let the beach rise together with the sea level rise. The volume and frequency of those maintenance nourishment depends on the rate of sea level rise (Bosboom & Stive, 2015).

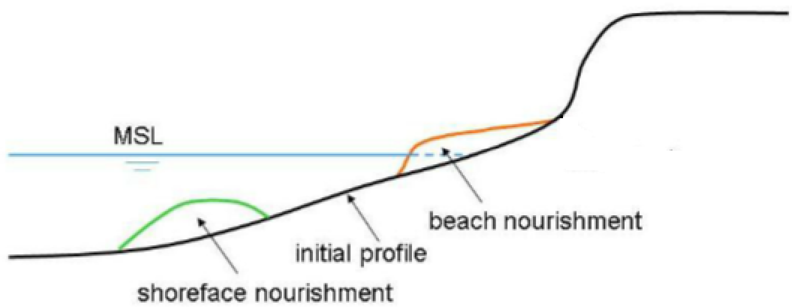


Figure 7.10: Nourishment locations

Using morphological models, the exact locations, volumes and frequency of the nourishments should be determined during later stages of the design. No data is available for the beach near Castillogrande, so this should be further investigated.

As proposed before, the beach of Bocagrande and the beach at the historic center - Marbella will be heightened to a level of 1.22 m.s.n.m. (MSL +0.87 m). The theoretical volume of sand that is needed to elevate the whole active profile is $V = Filldistance * Height * Width$. This results in $1,000,000m^3$ ($500m * 2000m * 1m$) for the stretch of beach at Bocagrande. For the stretch at historic center - Marbella $6,000,000m^3$ ($2000m * 3000m * 1m$) is needed.

In the 2011 coastal master plan, two dikes are constructed to maintain the beaches. Therefore it is assumed that two groynes, but not as massive as in the coastal master plan, are sufficient to retain the beaches. Their effectiveness and size should be determined by morphological modeling. To reduce the volume of sand a submerged breakwater may be used. The impact and efficiency should be analyzed using a morphological model as well.

7.4 Possible Sources of Resistance

Implementing all the works in the city can be experienced as very radical and disruptive by local people. Identifying possible sources of resistance early in the design process can prevent a lot of complications later.

Connectivity bay

Especially marine transport for tourism will be hindered with the construction of a dam in the bay. The small boats destined to the Rosario islands or Barú represent a large proportion of the water transportation. In the new situation, these boats either have to pass the lock, which increases the travel times significantly, or relocate their berth places out of the closed bay.

Many wealthy citizens have their private yachts moored alongside the peninsula or in the marinas in Manga. These boats will have to pass through the locks as well.

Political complications

It is anticipated that political resistance to the proposed solution will occur due to three reasons: lack of funds, fear of change and disturbance of existing plans.

According to the Secretaria de Planeacíon nothing is done to reduce flood risk yet, partly because of a lack of funding. Coastal protection is the responsibility of the national government (according to CARINSA). They should partly fund this project, but it is a stakeholder of which is not known if any budget is available (according to CARINSA). Therefore, it can be expected that the funding of this project will be an issue.

According to the DATT, the Cartageneros do not like and resist change. It is likely that local officials will consider the project impossible or consider reconstruction of the coastal avenue as a great inconvenience.

The final and perhaps greatest source of resistance will be due to conflicting interests. Powerful people are involved with the 2011 coastal master plan, and thus might not agree with the plan proposed in this research. The UTB expects that these people do not want to lose the opportunity to realize theirs. The first stage of the pluvial drainage master plan is being executed and the possibility exists that this is considered sufficient. There is already a plan for the space which will be available after the naval base departs. Along with hotels and shopping malls a cruise terminal is proposed here. This cruise terminal will not be possible at this location after the bay is closed.

Social complications

The effect of new infrastructure on a neighborhood must not be neglected. People are generally resistant to change and therefore citizens might worry about their neighborhoods future. Expected is that for the area South of the Ciénaga this will not cause many social complications, since their living conditions are being improved without significant downsides. Construction might cause some nuisances, but this is only temporary. Their neighborhoods are untouched.

The neighborhoods of Manga and Castillogrande are expected to show more public resistance because of changes in their skyline and increased traffic noise by higher traffic flows, if the road will be constructed. All residents and local businesses should be kept informed throughout the entire project and the design should be aesthetically pleasing to fulfill the public wishes. Resistance is generally lower when people understand the cause and aim of change in their neighborhood. Since most works are built into the bay and the Ciénaga, the adaptations in the neighborhoods themselves are minimal and this will limit social resistance. However, construction of the seawall in front of Marbella and Bocagrande could produce a lot of resistance as this obstructs ocean views.

Environmental complications

When closing the inner bay of Cartagena, questions will be asked about the preservation of the ecosystem in the water. The same counts for the division of the Ciénaga de la Virgen. Currently, tourist activity and industrial discharge have wiped out much of the biodiversity in the inner part of the bay (Banco de Occidente, 2009) and oxygen is mainly dissolved. A closure of the bay will take away the tidal interaction and fresh water from Canal del Dique. It however increases the circulation of the water and reduce contamination because of the connection with the Ciénaga. Also may it increase the level of oxygen in the water. The exact environmental effects should be investigated in cooperation with parties such as the CIOH and INVEMAR. The effects can then be assessed by parties as EPA Cartagena, ANLA and CARDIQUE, who provide permits for such projects, if it meets their environmental requirements.

Maintenance

The pumps in the solution require intensive maintenance. Garbage has to be collected to prevent the drainage and inner water bodies of becoming clogged. Clear responsibilities have to be defined and controlled to guarantee the functioning of the pumps. In the past, it proved to be difficult to maintain hydraulic interventions. Also the static interventions should be maintained regularly: the dams, walls and groynes have to be checked on leakages and damage and the beaches should be assured of continuous sediment delivery.

7.5 Opportunities

Besides the possible complications, the solution creates also a lot of opportunities. It offers ways to fund the project and improve the accessibility and city image.

7.5.1 Land reclamation

When the water level is controllable, it is safer and cheaper to extend the coastlines within the closure. Land reclamation is a profitable opportunity. It is undesirable to urbanize the Ciénaga compartment as this compartment is needed for storage. In addition, the land would not be very valuable.

The inner bay of Cartagena is more suitable for land reclamation. The possibilities of doing so are described below. The costs for land reclamation are considered to be 200 USD per square meter, according to a dredging rule of thumb. This includes revetment and quay wall costs.

Island Bajo de la Virgen

When connecting Manga with Castillogrande by means of a dam, the opportunity arises to create new land on the shallow part, 'Bajo de la Virgen' in the middle of the bay. This shallow part has an area of around 60.000 square meters with a depth of less than two meters, which can easily be used for land reclamation. The reclamation of this area will thus cost 12 million USD. When considering the price per square meter of Castillogrande, 2,400 USD/m^2 (Paul Juan Realty, 2017), the new island is worth approximately 144 million USD. Apartment buildings or hospitality establishments in the same style as on the peninsula are probably the best selling options.

The dam connects to the island on the East, so the island is fully located on the inside of the barrier. The East of the dam is not used for land reclamation. This will remain the dredged opening to the terminals at Manga and El Bosque. The creation of island Bajo de la Virgen means a road on top of the dam is necessary to provide the transport to Manga and Castillogrande.

Widening the peninsula

Controlling the water levels makes widening the current peninsula more economical. The shallow part (with a depth between 0 and 4 m) suitable for reclamation is on average 40 m wide for a length of 900 m at Bocagrande and 130 m wide for a length of 1000 m at Castillogrande. In total this is a surface of 166 thousand m^2, which will costs 32 million USD to reclaim, if desired. At Castillogrande,

this surface allows for adding a complete new block over the length of the inner-coast. This new block (with a width of 100 meter) is worth around 240 million USD, considering the real estate price of 2400 USD/m^2 at Castillogrande (Paul Juan Realty, 2017).
The area of the naval base is considered as a restricted area. If they decide to relocate, the possibilities to gain land increase. The stretch along Bocagrande is currently considered to be too narrow to use for residential purposes.

7.5.2 Improved accessibility

The option of building roads on top of the dams is kept in mind to improve (future) accessibility. A direct link between Castillogrande and Manga will reduce traffic loads on Bocagrande and handles traffic flows to the rest of the city, while avoiding the historic center. A road on the dam in the Ciénaga will improve the safety and the travel times in the West-East and reversely directed traffic. It reduces the traffic loads going through the city of Cartagena over Avenida Pedro De Heredia. If this new road is connected to highway 90 close to El Pozón, the problematic traffic flow at the main highway entrance of Cartagena (Bomba El Amparo) will decrease. Also the traffic to and from the North part of Cartagena will have a shorter travel time as they get the possibility to avoid the urban and densely loaded transport network in the city. This will avoid the most problematic junctions in the city, shown in Figure 7.11 and direct highway traffic over an alternative route, instead of over Avenida Pedro De Heredia. An increase in capacity is needed on the links in orange in the figure as this connects the new roads with the current main infrastructure. However, more elaborate traffic data should be gained to predict an accurate change in traffic loads with the implementation of these new roads.

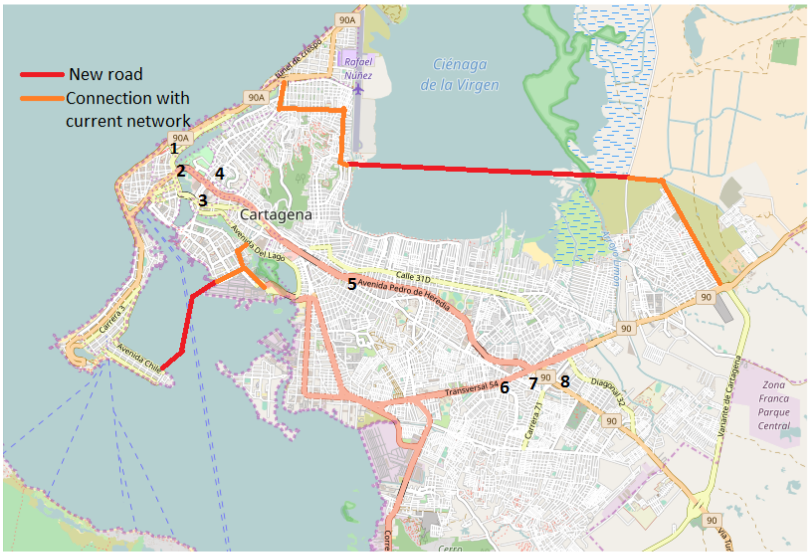


Figure 7.11: Main transportation network of Cartagena with new connections and most critical road intersections: (1) Las Tenazas, (2) India Catalina, (3) Reloj Solar, (4) Castillo San Felipe, (5) María Auxiliadora, (6) Blas de Lezo, (7) Bomba El Amparo, and (8) La Plazuela as indicated by (Quiñones-bolaños & Bustillo-lecompte, 2016)

7.5.3 Improved image of the city

When the city is able to handle sea-level rise and pluvial floods in an integral way, it will be an example for other cities in the region or even worldwide. Cartagena will conserve its historical heritage, remain an attractive city for tourists and have a compatible port and industrial zone. Inequality will be partly counteracted and prosperity in the whole city will grow.

7.6 Costs

A rough cost calculation is given as an indication of the economic feasibility of the solution. Several reference projects are used to give an estimation of the costs. The reference costs are modified to the conditions and requirements that apply in this research. Some of the costs are unknown, so for several aspects of the solution no estimation can be given. Table 7.5 gives a rough cost range for the most cost-intensive parts of the solution. A more elaborate explanation of the unit costs are broken down in Appendix G.4.

Table 7.5: Cost calculation

Type	Range (M USD)	Average (M USD)
Seawall	61 - 69	65
Revetment	4 - 10	7
Groynes		1
Nourishment	17 - 50	33
Ciénaga dike	10 - 15	13
Ciénaga dam	90	90
Bay dam	63 - 74	68
Pumping station		40
Navigation locks	26 - 64	45
Urban drainage	Unknown	Unknown
Retention basin	Unknown	Unknown
Sub total		362
Contingency		*30%*
Total		**471**

In Table 7.5, it is noted that the costs for urban drainage and urban storage are not taken into account. Further research should give insight in the values that need to be considered when designing the total system. Educated guesses can give a total cost estimation for the complete system.

The costs for maintenance will be approximately 0.1 million USD per km flood defense per year (Hillen et al., 2010). For a stretch of 21 km, which is the case for Cartagena, this means 2.1 million USD per year.

7.7 Monitoring & Maintenance

In order to ensure the system performs as it should be during its entire lifetime, monitoring and maintenance are two essential aspects.

Monitoring the drainage system consists mainly of two parts, checking the condition and performance and predicting the weather conditions. The condition of the dams should be monitored such that indications of probable failure are detected early and can be repaired. Also the pumps should be maintained to guarantee the necessary capacity. Besides, it is essential to keep the drainage channels clean and free of obstacles to maximize the capacity.

In addition, the weather forecasts should be watched carefully. In order to create additional storage prior to an extreme event, time is needed to lower the water level in the inner bay and Ciénaga compartment. An early warning is needed for optimized performance.

The coastal defense system is designed for a minimum of 50 years. It is essential that every component works as designed when an extreme event does happen. Monitoring the condition of the seawalls and revetments can indicate shortcomings in early stages. Maintenance should be applied to fix the problems and to ensure the system works as designed. Also the beach profile in combination with water levels needs to be monitored. The profile must be measured multiple times a year and right before and after a storm to obtain information on seasonal variations (Brampton & Institution of

Civil Engineers (Great Britain), 2002). When the data indicates the beaches are eroding and getting too small or low, maintenance nourishments should be done.

7.8 Funding

Funding is an important aspect of the solution. Several parties need to be convinced of the importance of the solution and the profitability of the proposal before they will supply the necessary funds. The government of Cartagena is responsible for the well-being of its citizens. As this solution improves this, they should provide part of the funding of the project. Funds could be extracted from the relevant municipal secretaries and departments In addition, the mayor of Cartagena should be convinced that the water problems of the city will be solved to gain his support.

If the solution proves to improve the socio-economics of the region of Bolívar, the regional government can provide funds from the budget of regional development. The Ministerio de Hacienda may decide to fund on behalf of the national government if local politics prove to be too difficult to navigate, a potential client is Fondo Adaption. Also coastal protection and historic heritage are to be maintained by the national government. To strengthen this, the Ley del Sitio states that the national government is responsible for financing projects in Cartagena concerning coastal protection, rainwater drainage, and local channels and lagoons. Thus to obtain regional and national funds the problem should be considered not just as an improvement for the city of Cartagena, but as a regional or a national improvement.

Besides the government, parties able to supply funds are listed below.

- Acuacar has the responsibility of the drainage services in their newly signed contract. Part of the urban drainage solution should thus be financed by them.
- Chamber of Commerce Cartagena, serves as the organ of general interests of commerce and promotes regional development.
- FINDETER may finance the project as it funds sustainable infrastructure projects.
- Inter-American Development Bank can provide loans to government and state corporations if the project contributes to economic and social development.
- World Bank lends money to support development and change initiatives, if this project proves to decrease the inequality in Cartagena.

Chapter 8

Conclusion

The research and alternative development which has been presented has revolved around 3 central questions as discussed in Chapter 1. This conclusion will concisely answer these questions.

Question 1: What are the causes of the floods in Cartagena and is the associated current or future flood risk urgent enough to demand action?

Cartagena de Indias has to deal with several floods per year. These floods are caused by excessive precipitation and high water levels in the Caribbean Sea, Bay of Cartagena and Ciénaga de la Virgen. Especially the areas of the peninsula, South of Ciénaga de la Virgen and the industrial zone of Mamonal suffer from the consequences.

The water level in the Ciénaga rises very fast during rainfall as the urbanization and deforestation of the upper basin increases discharge peaks. This causes the low-lying neighborhoods to flood and decreases the hydraulic gradient in urban drainage channels. This decreases the capacity of the channels, which are already insufficient; flooding occurs in upstream areas. Combined with unplanned urbanization into the Ciénaga this part of the city is frequently flooded.

The sea walls in the coastal areas and inner bay are deteriorated and are not designed for current nor future conditions. During high tide water flows onto the streets. Due to storm-induced erosion of beaches, coastal protection is reduced. Furthermore, the drainage is limited during high tide as there is small height difference between land and sea. Lastly, rainwater outlets function as seawater inlets during high tide.

In the industrial zone, companies build their own dikes pushing the water back into residential areas. The channel capacity is reduced by having harsh turns and therefore increasing the flooding problems.

The floods have impact the city in different ways. The living quality of entire neighborhoods is affected. The water is a direct danger to inhabitants causing casualties. Afterwards, stagnant water increases the spread of vector-borne diseases. Also the economy is affected. The direct damage due to pluvial floods alone is 12.8 million USD annually. Besides, there is indirect economic damage due to congestion, inaccessible workplaces, loss of real estate and reduced tourism. In the La Niña year of 2011 total damages in Cartagena are estimated at 540 million USD. The environment also suffers damage due to waste and sewage overflow that flows into the surrounding water bodies.

In the future, the situation will worsen. Flooding due to high water levels will become more frequent and more intense, because of the sea level rise and subsidence. Due to the the rising water levels in the surrounding water bodies, the drainage of rainwater in the city will become complicated. In 2040, 26.2% of the houses are flooded, 100% of the historic center is flooded, 28% of the industry is at risk, 100% increase of vector-borne diseases is expected and all beaches will erode.

It can be concluded that the flood risk in Cartagena is very high and one of the, if not the, most significant threat in the future. If no action is undertaken, the city will suffer from much greater damages than currently occur.

Question 2: Will the current plans work and solve the problem?

Currently, there are plans to tackle the floods. The most important ones are:

- Pluvial drainage master plan (2007) - A design to solve flooding due to excessive rainfall.
- Coastal master plan (2011) - A master plan to create an attractive zone along the coast with opportunities for economy, tourism and improved infrastructure.
- Plan 4C (2014) - A vision about how to transform Cartagena in a climate compatible and competitive city.

The main issue regarding those plans is that every time only a single cause of the floods is taken into account. The Pluvial drainage master plan only focuses on increasing the capacity of drainage channels, plan 4C only thinks about climate change and the coastal master plan does not take pluvial drainage into account. The floods in Cartagena are caused by a complex combination of high water levels and insufficient drainage. An effective solution should be an integral and no-regret measure. Every cause of the floods has to be considered. Otherwise, the cities flood risk management will remain disjointed and vulnerable. To conclude: these plans will not sufficiently nor cost-effectively reduce the flood risk.

Question 3: What is the best integral solution to reduce flood risk in Cartagena?

To come up with an integral solution without precluding future interventions, all strategies to tackle both causes of the floods are considered. The pluvial flood risk should be reduced by a combination of reducing discharge peaks, increasing capacity and increasing storage is used. The only realistic option for Integrated Coastal Zone Management is to protect.

Many alternatives are evaluated and the best one among these is selected and elaborated upon in the final conceptual design. It is a combination of all three strategies regarding the drainage problems and it offers protection against rising high water levels. The core of the solution are two closure dams: one in Ciénaga de la Virgen and one in the Bay of Cartagena. Together they create a closed water body of which the water level can be regulated. In this way, large pars of the city are protected against high water levels. Besides providing extra storage, it also increases the drainage capacity as the hydraulic gradient is increased. The increased storage capacity is sufficient to deal with extreme rainfall events. The design also guarantees water refreshment in the water bodies of Cartagena. The Caribbean coast is protected by a combination of sea walls and revetments, which protect the city against high sea levels. Furthermore, two groynes trap sand to form more beaches. These beaches must be maintained by regular nourishments. In combination with small-scale measures and upper basin management, this creates an integral solution solving all the urgent water problems and simultaneously gives Cartagena many possibilities to increase its value.

Chapter 9

Recommendations

The broad research and resulting proposal which is presented in this document are a good first step. However, far more studies are required to determine which flood risk reduction solutions is the most desirable for Cartagena. Various issues were encountered, but not considered in this study. Yet, these are essential to finalize the design successfully, secure a smooth implementation and guarantee operations as designed. Below follows a review of these issues and follow up steps are recommended. First general recommendations are done on how to approach solving the problems. What should be done to make from the current conceptual a sound final design is explained next. Afterwards it is advised how the implementation and operation should be handled. The recommendations below are based on the final conceptual design presented in this document. Further analysis of the problem may very well result in a different and more appropriate alternative.

9.1 General Problem Approach.

The most important consideration for solving flooding in Cartagena is producing a solution which focuses on all causes of the problem. Tackling only one cause will lead to disjointed and potentially conflicting solutions which will require additional future interventions. Due to the size of investments and to optimize the benefits, it is recommended to solve the problems in an integral way. Points of attention in future designs are climate change (and the corresponding uncertainties), the problems with funding large-scale projects in Cartagena and maintenance which is often performed poorly.

9.2 Final Design

To make a proper final design out of the conceptual design presented in this report, additional data and modeling is needed to understand the complex processes that the solution is subjected to. Also, some additional data is needed to optimize the benefits of the integral solution. During this study data is sometimes found to be incorrect or outdated. This data should be improved and updated.

Missing data

- Influence of climate change on precipitation
- Influence of climate change on ENSO
- Soil conditions
- A comprehensive overview of the direct and indirect damages due to coastal and pluvial floods

Specific modeling

- Rainfall-runoff model of urban area and complete catchment area
- Waves
- Coastal morphology

- Traffic models, to determine whether or not roads on the dams will improve the congestion problems in the city and if so the necessary capacity. This should be complemented by a cost-benefit analysis
- Water quality modeling within the inter-tidal lagoons and compartments.

The information obtained by analyzing missing data and the results of modeling should be used to update the boundary conditions. Also, a look must be taken at the design criteria and the structures should be checked according to the SLS. The current design event still brings a significant probability of failure (39%). It has to be decided whether this is acceptable.

From conceptual to final design

More detailed consideration of all aspects which have been briefly touched upon in this conceptual design is necessary. Some aspects have not been considered yet. The following components should be worked out:

- Settlement and stability due to lowering of the water level
- Design of navigation locks
- Quantification of the effects of small-scale measures
- Design of the retention basins and quantify their effects
- Determine whether a underground drainage tunnel is needed and feasible to increase the capacity in channel Ricaurte.
- Comprehensive cost benefit analysis for the location of the bay closure and whether or not roads will be constructed
- Quantification of the effect of small and non-structural measures.

Political complications

One of the most important aspects of creating a solution for Cartagena is navigating the local politics. This is perhaps the most challenging aspect of future work.

- Pressure should be applied to local and national governments to relocate the naval base out of the inner bay. It is hindering expansion of the local road network and located on very valuable ground. In the interest for the navy: they have a poor connection to the Caribbean Sea and no room for expansion at their current location at Bocagrande. Most importantly, it is the biggest complication in creating the Manga-Castillogrande closure.
- Any party which aims to continue this study and develop solutions for Cartagena must maintain a close relationship with local government. Communication between departments is already poor and an integral solution requires coordination of different local departments.

9.3 Implementation

The construction of the solution should be tendered internationally. To ensure smooth management, one single party should be appointed as project manager who centralizes the regulation of tasks of the contractors. No subdivision in management of separate aspects in the project will ensure simple communication between executive parties.

9.4 Operation

Some critical problems must be overcome to ensure that the flood protection system operates as designed. In the past maintenance has proven to be difficult to carry out and manage. Maintenance, which is linked to a proper monitoring system, is essential to ensure the necessary performance.

It must be clear whom is responsible for monitoring and maintaining the flood defense system. It is strongly recommended to make the same department responsible for both monitoring and maintenance. The responsibility for the coastal protection and the drainage system should be placed under one single department. Centralization will enhance communication and efficient use of funds. Sufficient budget needs to be available for the responsible departments to make sure they can do what is necessary. The following responsibilities must be clearly communicated and assigned.

- Monitoring system for the drainage system: to identify water levels, check pump capacity, etc.
- Maintain drainage channels (keep them clean and free of obstacles)
- Inspect seawalls, revetments, dams and dikes regularly and repair when necessary
- Maintain beaches to prevent gradual storm induced erosion and retreat due to sea level rise

A weather forecasting system needs to be coupled to the operating system. This allows predictions to be used to optimize the storage capacity in the compartments and maximize the drainage capacity of channels when a storm approaches the city. The water level can be lowered further than the normal operation mode in advance to accommodate the additional expected discharges.

At this moment, waste water is discharged into Ciénaga de la Virgen. Compartmentalizing the Ciénaga will cause the water quality in the smaller body to deteriorate quickly if waste disposal is not handled correctly. Sewage and waste management should become a main priority of a governmental department.

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Appendices

Appendix A

Overview Map

Figure A.1: Overview of Cartagena

Appendix B

Interviews

B.1 CARINSA - Santiago Rizo

CARINSA is a local engineering firm, conducting several big engineering projects in and around Cartagena. Examples are the tunneling of highway 90A at Crespo, coastal protection at Crespo, La Bocana and the Vía Perimetral along the south side of the Ciénaga. Below follows a chronological account of the topics discussed and the most important conclusions.

- Social aspect is always the hardest. Engineering is easy.
- Ciénaga de la Virgen, lack of urban planning, no drainage, dirty water.
- Via Perimetral build to combine urban planning and flood defense. Fixed line to enhance planning, because this road also functions as an artificial border to stop the uncontrolled urban expansion towards the Ciénaga. Now, it is clearly visible if people build new houses on the lake-side of the road, so expected is that the urban growth in this direction will decrease, or at least will become more controllable.
- Soil is very bad.
- Solutions must be robust, work without maintenance. La Bocana is a good example.
- Local government has no money due to lack of tax income.
- National government only does coastal protection and highway systems. That is how CARINSA found finances the tunnel, La Bocana and Vía Perimitral.
- There is no maintenance.
- No single party is responsible.
- Solution should include urban planning, social aspects, financing plans and enhance development.

B.2 Secretaria de Planeación - Sara Luna Alvis

- She is a lawyer, working on stipulating where exactly the public area ends with respect to the cities drainage channels. i.e. up to what point are houses permitted.
- In 2001 a set of norms was written which specified what has to be done for various parts of the District of Cartagena. This included actions such as exectution of a drainage plan, water transport plan, plan for the city's caño's and lagunas and basin management. The 2007 pluvial master plan is the result of this document.
- Mrs. Alvis thinks water management is one of the most important issues for the city. She too, is often effected by it and could not leave her office the day before the interview due to flooding.
- The Secretaria de Valorizacion Distrital de Cartagena is important for the 2007 pluvial master plan, especially regarding local funding.
- An interview with Javier Muton will be arranged by her. He is a former secretary of Planning employee and currently a professor at the University of Cartagena.

- When asked about the lack of initiative and action she replied nothing is being done primarily due to lack of funding and poor organization. Many parties share responsibilities for water management but since it is so expensive no-one takes the first step in responsibility and all wait for other actors to make this step instead.
- When asked about plan 4C she said it lacks an integral approach for the city. It only comprises of small scale policy changes or plans which solve many small problems locally.
- She believed our ranking of the city's most pressing issues was quite accurate.
- Our solution must be integral and a macro-scale project. It must in one plan contain rain water drainage, coastal defense, urban planning and mobility. If we manage to combine this it has a change of succeeding. She heavily agreed with a document containing a philosophy for the city and water.
- We should check out Ley del Sitio - Ley 1784 del 17 de junio del 2016.

B.3 DATT - Jose Padilla and Carlos Vergara Aguilar

We first spoke to Mr. Jose Padilla who then refered us to Carlos Vergara, a statistician and transport engineer.

Jose Padilla:

- The inundations in Cartagena have two main causes: rainfall and sea water. Rainwater may accumulate locally or may flow from other parts of the city or basin to cause floods. Sea water may enter the city by means of wave over topping or high tide can cause water to flow into the streets through rain water drainage holes cut into the sea walls.
- Floods cause drivers to drive slowly to protect their cars from water damage and to avoid damage from hitting speed bumps or potholes hidden by the water. The salt water is especially harmful for cars as it causes severe erosion. Drivers also slow down so that pedestrians are not covered in water. Speeding and splashing pedestrians is considered very rude, not surprising since the flood water often contain sewage water and waste.
- Driving slower creates many traffic jams in the rainy winter as only a little rain in required to cause significant flooding.
- The city is working on plans to make use of the water to improve mobility by means of public transport ferries.

Carlos Vergara:

- From a transport perspective, Cartagena can be seen as a collection of islands: the peninsula, the historic center, Manga, Marbella/Crespo, the Popa area and the rest of the city south of the Ciénaga. Within these islands the roads network is generally sufficient. However the connections between these islands are bottlenecks. Often 4 lanes converge to 1 to cross a bridge or narrow passage.
- When it rains however the traffic shuts down completely. 10-15 minutes of rain is enough to flood some streets. This forces drivers to slow down which causes a collapse of the entire road network. Mild to heavy rains can easily cause a delay of 3 hrs. Which is impressive considering the city is only about 10km x 10km.
- It is very difficult to implement plans. People in Cartagena do not like change. This was very evident in the Transcaribe project which was the first form of ordered and centralized public transport in the city which uses elongated buses to transport people. People saw investing in the project as a game or did not see how it would be profitable. In addition it was difficult to get all administrative organizations of the municipality working together. However, it is now considered a very successful project which many people are proud of.
- In the long run the use of cars must be discouraged to improve mobility with in Cartagena. Use of bicycles and public transport must be encouraged as these transport methods use fewer m^2 road per person.

- Bocagrande and Castillogrande are very low. About 50cm, so sea water often enters the streets and rainwater is harder to drain. Many basements or car parks also flood. For this reason areas become less attractive, as well in Bocagrande as in some parts of Manga.
- Corrosion to cars from salt water is a severe consequence of sea water floods. Many people by cars in other cities so that their license plate is not from Cartagena. Cars from Cartagena are infamous across the nation for being heavily corroded and are thus harder to re-sell.
- The historic center is also very low. Bocagrande and the historic center are the two rich areas of the city and thus a lot of inconvenience and discomfort is experienced by the cities wealthy residents. Many of them chose to leave Cartagena and take their business else where. Successful businesses leaving the city is harming its development.
- It is dificult but important to convince the people that there are problems within the city that need large investments to be resolved. Especially convincing the people that the benefits of resolving the problem are larger than the costs is difficult.

B.4 DADIS - Jorge Luis Morelo Muñoz

- There are two causes of floods in the city: poor drainage of rain and high tides which enter the city streets
- In respect to deaths resulting from flooding, these have only been caused by pluvial floods. Drownings have occurred as well as death due to the collapse of houses.
- The main health risk related to flooding from sea is sewer backflow. High sea level water causes the sewage system to flood into the areas which are below sea level.
- The pluvial floods do reduce the health of the population. Chikungunya, denque and zika are all spread by mosquitoes. Floods which lead to stagnant water bodies, allows mosquito's to multiply faster resulting in more mosquitoes and thus a high infection rate. Mosquitoes larva do not survive in salt or brackish water so sea water is not contributing to the problem.
- Leptospirosis is caused by a bacteria found in the urine of several mammals. When eaten it is harmless as stomach acids kill the bacteria. However during floods the bacteria may be present in the floodwater allowing them to enter the body through open cuts infecting people.
- The city is actively trying to reduce the amount of mosquitoes by educating its citizens about stagnant water, killing unhatched eggs and fumigation of areas in extreme cases. However, reducing stagnant water resulting from pluvial floods would be more effective.

B.5 Pastor Luis A. Caraballo

Mr. Caraballo is a pastor who has his own charity organization which strives to help the youth in the most disadvantaged and vulnerable communities. He strives to supply very cheap meals, provide education about job opportunities, and help kids who are trapped in a life of crime and gangs. He enters and speaks to these communities daily.

- Socially Cartagena can be seen in three parts: Old Cartagena (historic center and parts of Manga), New Cartagena (Bocagrande, Castillo Grande and Manga), and the Third Cartagena (the rest, i.e. the places tourist and business travelers do not see or know about.
- Save some homeless people, all of the poor and extremely poor people live in these neighborhoods. Many of them are victims and refugees of the countries armed conflict and others have come from the countryside seeking a better life in the city. These people settle on the outskirts of the city and are thus responsible for most of the urban expansion.
- Many of the poor people are what Mr. Caraballo called 'True Carribeans.' People who loved to have fun and thought in the short term. It is not uncommon for people to have a speaker system which is worth more than their house. Part of what Mr. Caraballo is trying to achieve is to shift the mindset of these people towards the long term. To educate them for example on financial planning and garbage disposal.

- Because they settle on the outskirts (next to the Ciénaga, to the East and to the South besides Mamonal), these are the people who are responsible for the majority of the urban growth.
- The people in the poorest area are the most vulnerable since they live in low areas with little to no infrastructure
- These people do not have the resources and political representation to make their needs public. As an example: in the industrial area concessions for factories are given to companies by the local government. The companies then construct dikes to keep their factories dry and make existing natural channels smaller to create more space. As a result the water is pushed towards poor neighborhoods in the area. These people are then forced to endure frequent floods or to move away.
- There is currently very little being done by the government to reduce flooding. In some areas, garbage is removed from the drainage area. However, many places are not lucky enough to have drainage channels.
- If a flood does strike, the government offers no support. The people receive no reimbursement for lost property.
- Poor urban planning by the government is not only a problem in the poor areas but also in Bocagrande. Here huge apartment buildings are build and connected to an old sewage system which was not designed for the capacity it is currently forced to deal with. When it rains the system is often overloaded and sewage waste flows into the streets. There are no regulations for this. It is also not mandatory to include parking lots in high rise buildings so residents park their cars on the streets which reduce the amount of traffic lanes increase congestion

B.6 Interviews with Leaders of Communal Associations

The goal of the interviews with the communal associations that represent the citizens is to get a broad understanding of the scope of the water problems, how often do they occur, how intense are they and especially how much hinder and damage is experienced. Interviews are held with representatives of 'Juntas de Accíon Communal' (JAC) (Community Board of Action). This board is a non-profit, social organization and represents a community, sector or a group of neighborhoods. All citizens interested in voluntarily representing the neighborhood and who carry out some kind of professional work or activity in the respective community can join the local neighborhood association. Then from every local group, representatives are elected to join the communal group. They form a so called mechanism of citizen participation and have the status to be valid in the sector that elected them. Functions of the JAC are organizing programs to improve the conditions of a sector and to promote the sense of individual belonging in the community. They seek greater coverage and quality of the public services of the sector and access to social security for their residents by entering into contracts with public and private companies. A JAC member can be seen as a community leader (Diario El Meridiano de Córdoba, 2011). As seen in Figure B.1, the communities in the problematic areas are 1 for the peninsula and 4, 5 and 6 for the Ciénega de la Virgen.

B.6.1 Juntas de Acción Comunal - Marco Tulio Herrera Díaz

Mr. Herrera Díaz is the president of the Communal Board of Action for the neighborhood Olaya Herrera sector Rafael Nuñez (part of no. 5). He represents the interest and the voice of the residents in political discussions about their neighborhood. During the interview the following questions and answers were given.

- **Did a flooding ever influence your business activities? How?**
  Yes, because, when there is rain, the streets are completely flooded, so people can´t go out. Water enters the houses and people have to stop to work because they have to take care of their children and help them to get away from the water. This happens a lot in the winter season, specially between October and December, almost every day.
- **What precautions are taken by yourself/family/friends to prevent negative impact from water?**
  They evacuate people, send them to a communal house or a school to stay safe while others

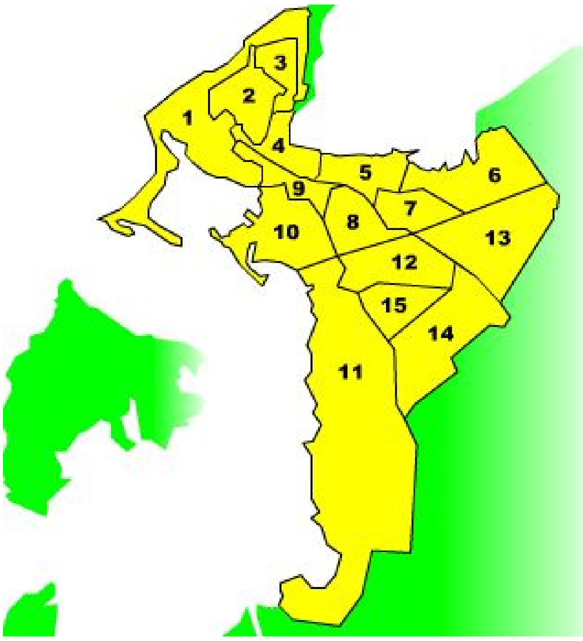

Figure B.1: Unidades Comuneras de Gobierno Urbano (URBANAS, 2016)

work to restore the houses. In some cases, people don´t want to leave their house, because they think that others can steal their things. They prefer to stay in the water rather than to lose the few things that they have.

- **Does the government compensate to pay for the reparation of the water damage or do you have to pay for it yourself?**
Because the state doesn´t help in time and ignores the community, residents have to fix everything for their own counts. There are people that work in the administration to achieve money.
- **Did the water cause unsafe situations?**
Yes, because when it rains so hard, they have to leave everything and when the house is empty, others rob everything. Furthermore, bad odors are a problem here and people get inflammations caused by the dirty water.
- **Do you get information from authorities to prepare for inundations?**
No, all of these events are always a surprise to the community. Some people can afford to raise their houses and can be prepared for floods, but others can´t do anything. On the other hand, children and elderly are sent to other places before the rain and wait in these places until the water level goes down or disappears.
- **Do you think the municipality does enough to prevent floods and water damage, and provide support and aid after the flood?**
No, they don´t do anything for these neighborhoods, they forget this community. They don´t have support neither before nor after the floods
- **What solutions to decrease the water problems do you know exist? Do they work?**
Currently, relocation is the best solution that exist, together with the home improvement. But the real problem is that they receive water from a pipe that comes from Ceballos and ends in the neighborhood, and together with the bad water service, affects this sector a lot.
- **Do you trust the government/mayor in making the right decisions regarding to water management?**
They have hope that government is going to help them, that they are going to carry out their promise to help this sector.
- **If the municipality provides you 1 million pesos, what would you do to improve your neighborhood?**
Distribute food to the others, because not everyone can count on something to eat. Try to

help the ones in need. Once a cellphone company donated approximately 9.000.000, and the JAC bought 30 bags of asphalt (200.000 each one) to fix the road, the other part of money was invested in food.

- **Do you think the inundation increase the inequality in Cartagena?**
Yes, because each time it rains, it causes violence, costs of reparation and poverty. You can see that even in the same neighborhood people with a better economic position bought houses, cars and improved their situation. While they are comfortable, others suffer a bad situation during floods. Compared to other neighborhoods the inequality increases because the government pays more attention to neighborhoods like Bocagrande, Centro, and others than to communities like Olaya.

B.6.2 Juntas de Acción Comunal - Gina Olmo de Trucco

Mrs. De Trucco is the president of the JAC for the neighborhood Bocagrande (part of no. 1). She represents the interest and the voice of the residents in political discussions about their neighborhood. During the interview the following questions and answers were given.

- **Did a flooding ever influence your business activities? How?**
Yes, because sometimes she has to use many alternatives to arrive to her job. For example on Tuesday 15/11/2016 she had to get to her job in a wheelbarrow, because she lost few days of work. Also she had to stop working because she can't enter Bocagrande, and the water doesn´t disappear quickly. These events happen every time it rains, even if is just for a short time. And now the weather is unpredictable.
- **What precautions are taken by yourself/family/friends to prevent negative impact from water?**
She changed things in her house like her windows, to prevent accidents from the strong winds, and in the buildings they reinforced their parking lot. When Bocagrande is flooded, she and her family don´t get out in their cars.
- **Does the government compensate to pay for the reparation of water damage or do you have to pay for it yourself?**
The government thinks that residents of Bocagrande have enough money to fix the damage, and they say that they (government) don´t have enough money to invest so the government does not compensate for reparation costs. The residents have to make costs themselves when they have to fix their cars, windows and other things that they have lost.
- **Did the water cause unsafe situations?**
They are scared for the water to keep on entering their houses, they lost the ability to go out. When something happens the ambulance can´t reach them because the floods block them.
- **Do you get information to prepare for inundations?**
The government says nothing, so people of JAC try to look for information on the internet (Intellicast) and then try to communicate with e-mails or social networks to the other residents.
- **Do you think the municipality does enough to prevent floods and water damage, and provide support and aid after the flood?**
The only things that exist are studies. A small scale solution using duck valves as been implemented. However, this measure has failed to be effective. After a flood just try to clean and remove the stones and sands that the sea left behind. Only when the citizens call to ask for help, the government comes and repairs the sewer system to prevent it from overflowing, they don't do this before potential inundations as prevention.
- **What solutions to decrease the water problems do you know exist? Do they work?**
There is a process where La Andi, Camacol, and the other labor groups of Bolívar ask for support by the government. These entities want to take action, because it´s not a local problem and they need support and resources.
- **Do you trust the government/mayor in making the right decisions regarding to water management?**
No, because they don´t know how to manage this problem and don´t have enough money. They prefer to invest in works like the duck valves (it cost much money but it wasn´t effective) than do improve the situation as a whole.

- **If you had the authority, what would you do to solve the water problem?**
  Discuss with the people who really know about this problem, to find the best solution and make it a governmental project. All of this to avoid that they spend the money (that they don´t have) on separate solutions, but invest in a complete solution.

B.7 UTB - Professor Mauro Maza

Professor Mauro Maza is an engineering professor at the Universidad Tecnologica de Bolívar (UTB). He specializes in coastal engineering and is our supervisor from the UTB.

- **Sewage system**
  Acuacar claims to have a separated sewage system where rain and waste water are treated separately. However this is not the case everywhere. Rain water often finds its way into the waste water system. This can happen due to infiltration through cracks in the pipes or due to direct inflow from a poorly built connection.
- **Drainage system**
  The rainwater drainage system in the city is very limited. The water is supposed to be discharged though drains and channels, driven by gravity. Often, especially during high tide, the gradient is not sufficient for the water do run off by gravity. In addition not all areas of the city are attached to this drainage system. Here pools of water form and remain for a long time after the rain has stopped.
- **Political climate**
  Although few people are willing to say it, corruption is a very big problem in Cartagena. It causes a lot of money to disappear and makes the decision making process inefficient and often wrong decisions are made.
- **Current developments**
  Currently the topic of pluvial drainage is picking up momentum. The office of the mayor apparently wants to execute the 2007 pluvial master plan. Because of this development many people are talking about it and it is mentioned in the press more often. At the end of December 2016, an engineer from Cartagena, working for a Canadian engineering firm, strongly criticized the current plan. It is especially important for the mayor to perform well in the coming months as people have been discussing starting the impeachment process.
- **Extreme events**
  It has been many years since Cartagena suffered from an extreme weather event. La Niña of 2011 caused a lot of severe rains over a long period of time. This caused lot of damage but hurricanes form a much greater threat. In 1988, hurricane Joan passed North of the city. It completely flooded the peninsula and separated it from the rest of the city for several days. If such an event was to occur today, it would be a complete disaster for the city. Due to erosion, damaged coastal protection, clogged channels and drains and a lot of uncontrolled urbanization the city less prepared now for such an event than it was in 1988. High sea levels and waves would flood the city and prevent high intensity rain from draining the city, worsening the situation.
- **Communication**
  There is little to no communication between the Secretary of Planning and the people in charge of the master plans for both the coast and the pluvial drainage. This is concerning as it this will make it impossible to have the two master plans reinforce each other or to let them become a water management system within the city.

  In addition, it has become clear that several contractors will work on the pluvial drainage master plan. Different channels will be build by different contractors. This is concerning since these contractors are not communicating. There is therefore a large possibility that the quality of the work will vary and connections between channels will be poor. The use of different contractors is also suspicious as it implies that no tender was send out by the municipality but that contracts were handed out based on different criteria.
- **Matute**
  The drainage basin of canal Matute is an excellent example of why elevated areas of the city

flood in addition to the low areas. Because the main channel of Matute does not have sufficient capacity it fills up with moderate to high rain intensity. Once the main channel is full, secondary channels and streets can no longer drain into the main channel. This causes the water to accumulate in elevated areas as it cannot drain into the main channel.

- **Ricaurte**
  Canal Ricaurte is the largest urban channel of Cartagena and it drains the largest urban basin. The capacity of this channel is insufficient. Because the area is so densely urbanized it is difficult to make significant changes to the basin layout.
- **Waste Management** The waste management in Cartagena is extremely poor and inconsistent. Garbage is therefore thrown onto the streets and channels, resulting in waste accumulation in the channels. This decreases the capacity of channels drastically.

Appendix C

Stakeholders

C.1 Stakeholder Description

Acuacar

Acuacar provides the drinking water and sewage services in the city. As heavy rainfall overloads the current sewage system, it is in Acuacar's best interest to solve the problem so they can improve their services. As a company which is held in high regard locally, it might be able to influence local government. Outside of the city limits it seems that Aguas de Bolívar is the company which provides public water services.

ANDI - La Asociación Nacional de Empresarios de Colombia

The ANDI is an organization which represents the needs and wishes of the industrial sector within the country. In Cartagena this means that the ANDI defends the interests of the industrial area of Mamonal. ANDI has considerable influence on local politicians and the mayor as they represent significant economic power within the city. Their stance regarding flood risk reduction will depend on the nature of a solution. A solution with will reduce risk in Mamonal will be endorsed. However, a solution which impedes operations or forces companies to change land use or relocate will most likely be met with resistance.

ANLA - Autoridad Nacional de Licencias Ambientales

The ANLA is responsible for monitoring, controlling and approving projects and ensuring a balance between development and protection of the environment. They hand out construction licenses and thus any proposed solution must be in accordance with their rules and regulations.

Cámara de Comercio de Cartagena

"The Chamber of Commerce of Cartagena is a private non-profit association whose primary purpose is to serve as the organ of the general interests of commerce before the government and the merchants themselves, promoting regional development" (cited from http://www.cccartagena.org.co/).
The Chamber of Commerce has already been involved in projects such as Plan 4C which aim to prepare Cartagena for the consequences of climate change including flooding issues. It is an influential party which can exert pressure on local officials and might be able to supply data or funds.

CARDIQUE - "Corporacion Auonoma Regional del Canal del Dique

The Regional Autonomous Corporation of the Canal del Dique (Canal Dique), in its area of jurisdiction as the highest environmental authority in charge of managing the environment and natural resources, favors sustainable development with an ecosystem approach in its three ecoregions: Dique Canal , Marino Costera - Cuenca, Ciénaga de la Virgen and Montes de María, through the planning, management and execution of environmental plans, programs and projects, using its technical, technological, human and investigative capacity" (cited from http://www.cardique.gov.co/corporacion/detalle/2).

Although CARDIQUE has no authority within the city of Cartagena it is an important stakeholder. Any solution that is build outside of the city limit or which has an influence beyond the city limits must be approved by CARDIQUE.

CCO - Comision Colombiana del Oceano

"The Colombian Ocean Commission is an inter-sectoral advisory, consultation, planning and coordination body of the national government on the national policy of the ocean and coastal areas and its related, strategic, scientific, technological, economic and environmental issues related to the sustainable development of the Colombian seas and their resources (cited from http://www.cco.gov.co/cco/nosotros/la-comision.html)." This stakeholder may prove to be of use when the problem needs recognition and a solution needs promotion.

CDKN - Alianza Clima y Desarollo

"The Climate Development Knowledge Network (CDKN) is managed by an alliance of organisations led by PricewaterhouseCoopers LLP (PwC), and including Fundación Futuro Latinoamericano, LEAD International, LEAD Pakistan, the Overseas Development Institute, and SouthSouthNorth. It supports decision-makers in designing and delivering climate compatible development. They do this by combining research, advisory services and knowledge management in support of locally owned and managed policy processes. They work in partnership with decision-makers in the public, private and non-governmental sectors nationally, regionally and globally. They hold strongly to the ideals of human development and environmental sustainability" (cited from http://cdkn.org).

The CDKN has already been involved in research regarding the cities problems regarding floods and climate change. Its data could be of use and it could also be a potential endorser of the solution.

CIOH - Centro de Investigaciones Oceanográficas e Hidrográficas

"The Center of Oceanographic and Hydrographic Research provides technical and scientific advice to other national entities with the purpose of contributing to the knowledge and use of our seas, as well as the safety of human life at sea." (cited from http://www.cioh.org.co/). This stakeholder may prove to be of use when the problem needs recognition and a solution needs promotion.

Corperación turismo

"Leading the consolidation of Cartagena as a sustainable tourist society, through the planning of tourism development of the city, within a framework of trust and coordination with the different stakeholders; managing routing, promotion and competitiveness of tourism in the city" (cited from http://www.cartagenadeindias.travel/). This institution strives to improve the cities image and by doing so make it more tourist-friendly. They connect several large institutions within the city and would be interested solving the flooding problems as this would make the city a more pleasant destination.

DATT - Departemento Administrativo de Transito y Transporte

The DATT's mission is to provide good mobility to the citizens of the city. This is done by maintaining road safety and setting traffic rules (DATT, 2010). Frequent flooding is one of the biggest causes of delays and accidents on the road in Cartagena. Therefore, the DATT should be very interested in measures which reduce flooding.

Departmento/Gobernacion de Bolívar

The Department of Bolívar forms the regional government. It strives to increase the well-being of its citizens by attempting to improve their socio-economic position. Development of the region is desirable to this stakeholder. The department may exert pressure on the municipal government and the mayor. It may also appeal to the National government or award projects its self. It is therefore an important stakeholder and should be considered as a possible financier.

DIMAR

"Manage public areas, maritime, rivers and coastal activities and take care of integral safety to enhance the future development of maritime interests" (cited from http://www.dimar.mil.co/).
This stakeholder carries out the government policy when it comes to implementing projects along the coast. They should be convinced of the severity of the problem and influenced to endorse the proposed solution.

El Universal

El Universal is the most popular and therefore influential newspaper in the region. The importance of the media in creating public support should not be underestimated. El Universal frequently reports about the floods and their consequences and will also gives process updates on any work being done on solving the issue. El Universal is the key in raising attention to the problem.

Engineers (local and foreign)

The solution to the problem will be developed by engineers. The local engineers suffer from water problems on a daily basis during the wet season. It is likely that they understand the problem better than anyone else. Their knowledge is thus of great importance. However, in the past Colombia has struggled to provide innovative and integral solutions. This is where foreign experience will be of great value and it is this quality that our solutions must exhibit.

EPA - Establecimiento Público Ambiental

To be a public entity of the district order in charge of managing and orienting the environment and the renewable natural resources that propitiates actions that aim for the conservation, restoration and sustainable development, aiming for a better quality of life and the assurance of the sustainable development guaranteeing the participation of the community and the criteria of equity and citizen participation (cited from http://www.epacartagena.gov.co/). As the flooding causes sewage water to mix with surface water and causes large amount of rubbish and debris to flow through the city streets. Sustainable development and improved hygiene will be a direct consequence of reduced flooding. Thus EPA will be interested in the results. It is however unclear how much influence this party has on the decision-making of such projects.

FENALCO

FENALCO is a trade union which strives to protect commercial interest of private and civil institutions alike. They strive to improve the socio-economic situation in department by supporting sustainable development (FENALCO, 2016). As less flooding will lead to better mobility, it should stimulate economic growth and facilitate local businesses to prosper. FENALCO will thus be interested in the result but it is unlikely that it will be able to exert considerable influence to realize the project.

FINDETER

"We are the development bank for the sustainable infrastructure of Colombia. We grant rediscount loans through financial intermediaries to finance public and private infrastructure projects throughout the country, and we provide technical assistance in the execution of infrastructure programs. In addition, we issue guarantees, manage public funds, and provide project-structuring services" (cited from http://www.findeter.gov.co). FINDETER may prove to be a very useful party once a solution is found as it can provide the funds if the city is not capable or willing to finance the project. It is desirable to engage this stakeholder early in the process to convince them of the necessity of the project.

Hotels and restaurants

Hotels and restaurants are dependent on tourists and are primarily focused on generating and maintaining income. Flooding hinders business as the mobility of the clients, employees and supplies is hindered. In just the first week we have also seen some restaurants and bars which were flooded to the point that they could not open to receive customers. The owners of these places are probably part of the upper or upper-middle class and thus might have some influence in local politics.

Inter-American Development Bank

The Inter-American Development Bank (IDB) is the largest provider of development financing for Latin America and the Caribbean. It aims to stimulate economic and social development. It does this by providing loans to governments, governmental agencies and state corporations.

A project must fulfill several requirements before being eligible for IDB loans. The project must effectively contribute to economic and social development, be confident with the principles of Agreement Establishing. It must be technically, economically, environmentally, financially and legally sound. The IDB will then keep an eye on the project throughout its preparation, approval, implementation and completion (IDB, 2016).

IDEAM

"IDEAM is a public institution providing technical and scientific support to the National Environmental System, which generates knowledge, produces reliable, consistent and timely information on the state and dynamics of natural resources and the environment, which facilitates the definition and adjustment of Environmental policies and decision-making by the public and private sectors and citizens in general" (cited from http://www.ideam.gov.co/). This stakeholder may prove to be of use when the problem needs recognition and a solution needs promotion.

INVEMAR - Instituto de Investigaciones Marinas y Costeras

"To carry out basic and applied scientific research based on natural renewable resources and marine and coastal ecosystems, which is of national interest. The purpose is to gather necessary scientific knowledge to formulate policies, make decisions and to elaborate plans and projects that will help us in the development of the management of sustainable resources, the recovery of marine and coastal ecosystems, and to improve the quality of life of Colombians through the rational implementation of the scientific capacity of the institute and its articulation with other public and private entities" (cited from http://www.invemar.org.co/). This stakeholder may prove to be of use as a source of information and when the problem needs recognition and a solution needs promotion.

Local businesses

Although it is nearly impossible to quantify, it is certain that local businesses are losing revenue due to the flooding. While in conversation with people we have been told multiple times that supplying local stores and markets as well as factories and garages is nearly impossible to the high water levels in the streets and the congestion which follows. Some areas of the city are completely cut off following even mild rain. This prevents employees from reaching their workplace, reducing productive working time. Customers are also restricted in their mobility by high water further reducing income.
Businesses would profit and development would be facilitated when floods are reduced. As many citizens are local business owners they can collectively exert pressure on the mayor and local government. However, it is difficult to communicate with this large group.

MADS - Ministerio de Ambiente y Desarrollo Sostenible

"Being the public body responsible for defining the national environmental policy and promote the recovery, conservation, protection, planning, management, use and exploitation of renewable natural resources to ensure sustainable development and guarantee the right of all citizens to enjoy and inherit a healthy environment" (cited from http://www.minambiente.gov.co/). The problems faced by the Cartageneros are exactly the problems that the MADS is trying to solve. The MADS has the influence to pressure either the mayor of the city or the department of Bolívar to take action. It also has the power to authorize projects itself. It can therefore prove to be a vital stakeholder. Complex and corrupt local government may be circumnavigated by tendering directly to the MADS. MADS however only has a small budget to carry out researches or studies. They do not have budget for implementation, nor wants to be responsible for drainage problems.

Mayor of Cartagena

The mayor is the most influential figure in this project. He has the power to approve a project and also to cancel it, regardless of public opinion. The mayor may also cancel any maintenance funding to existing project or cancel project which are already in the construction phase. As a anti-corruption measure, the mayor may only serve a 4 year term. In addition, he may not tender projects in the last year of his term.

The municipal mission is "Built collectively with equality for everyone, including girls, children, adolescents and youth. Cartagena should be a city to dream, to enhance its geographic, ecological, cultural, historical, tourist and port wealth, and projected into the future with an inclusive urban development that favors urban infrastructure to strengthen the natural vocation of the city, facilitating mobility based on multimodal public transport and environmentally sustainable means such as bike paths, malls and walkways. A city with provision of parks and public spaces reserved for the meeting, enjoyment and collective ownership. A city in which citizens and citizens coexist peacefully, are quiet and calm, respect the rules, protect their environment, recognize and respect diversity, comply with the agreements and self-regulate their behavior to ensure the full exercise of freedoms and rights of everyone."

The mayor is head of the municipality and thus he should pursue these core values. Which in theory means that the mayor should be actively be searching for ways to solve the water problems in the entire city. However, the reality reveals that the local government and thus the mayor are not earnest when it comes to resolving inundation issues. Many plans are being proposed, almost no serious action is taken. It will be of vital importance to gain the mayor's support and to keep him informed and enthusiastic about the project.

Ministerio de Hacienda

The Ministry of Agriculture is also capable of awarding and realizing large scale infrastructure. It aims to improve the macro-economics of the country, it aims to create peace and promote equality among Colombian citizens. The flooding Cartageneros face, obstruct the Ministerio de Hacienda's goals and effect a large number of people. The ministry may exercise pressure on local officials or decide to fund a project themselves. If local politics prove to be too difficult to navigate, the national ministries can be of great aid. However, like the MADS, this ministry is likely to only provide aid in solving the coastal problems.

Politicians

The local politicians should be closely involved in the project. If they are supportive the project is much likelier to be executed. All infrastructure will eventually become their responsibility as well. As for the mayor, it seems they must first be convinced of the magnitude and consequences of the problem.

Residents

Residents of the city are the victims of the flooding and thus have a great interest in resolving the issues. They want to live in a safe and comfortable environment. Their mobility and supply of the goods they desire should not be hindered by water. They can exert pressure on the local government.

Secretaria de Planeación

The Secretary of Planning is in charge of urban planning and strives to improve the social and economic position of its citizens. As urban planning is a vital component of this project, especially when considering the neighborhoods south of the Ciénaga de la Virgen. Involving this party should be fruitful as effective integral flood defense and urban planning should be orchestrated hand in hand (de Planeaccion, 2016).

Secretaria de Salud

"The Secretary of Health contributes to the continuous increase in the level of health and quality of life of the population of the Bolívar department through the planning, direction, coordination, monitoring and control of the competencies of law, using processes according to the levels of complexity of the provision of health services, promoting community participation, assurance, health promotion, disease prevention, treatment and rehabilitation of the sequels with efficiency and quality." (cited from http://secsaludbolivar.gov.co/). Spread of diseases is facilitated by stagnant water and sewage water overflow onto the streets. In addition, floods spread debris and contaminates through the city. Flooding may also directly injure citizens. It is therefore in the secretary's best interest to solve this issue. It may pressure the mayor or the Department of Bolívar to take action.

SIAB - Sociedad de Ingenieros Y Arquitectos de Bolívar

The Bolívar society of Engineers and Architects consult the local government. Its advice is held in high regard and thus it is vital that the SIAB endorses the solution.

SPRC - Sociedad Portuaria Regional de Cartagena

The port is one of the main drivers behind the local economy and employs a large amount to people. It may be able to exert some influence on the local government if the flooding frequently limits operations.

Transport companies (both of people and goods)

The public transport in the city consist of a few privately head companies. These companies are currently fighting to maintain their private status. Water is the main cause of delays and thus customer satisfaction and profits will increase with reduced flooding. Logistical companies also struggle with the floods as high water levels and the resulting traffic congestion reduce mobility and efficiency which in turn cuts profits.

UNESCO

UNESCO sets very strict regulations in place in order to protect world heritage sites. It is therefore important that the effect the solutions will have on the historic center is well-known and that it complies to the UNESCO rules. UNESCO may also pressure the mayor and local government to take action if it becomes evident that the lack of action and persist flooding significantly damages the historic center.

Universities

The local universities are a great source of local knowledge. The opinions and advice they provide are generally trusted by local officials. The universities can even influence the national government as they verify the extend of the problem and endorse proposed solutions.

World Bank

The World Bank (WB) is an international financial institution that provides loans to developing countries for capital programs. It comprises two institutions: the International Bank for Reconstruction and Development (IBRD), and the International Development Association (IDA). The World Bank is a component of the World Bank Group, which is part of the United Nations system. The World Bank's stated official goal is the reduction of poverty. However, according to its Articles of Agreement, all its decisions must be guided by a commitment to the promotion of foreign investment and international trade and to the facilitation of capital investment. The World Bank lends money to middle- and low-income countries to support development and change initiatives. Development projects are implemented by borrowing countries. The World Bank can be of great help when shown that such a project decreases the inequality in the city of Cartagena.

C.2 Ranking of Municipal Priorities

Based on the two most recent 4 year city plans (Plan de Desarollo - Ahorra si Cartagena 2013-2015 and Plan de Desarollo - Primero la Gente 2016-2019) and a poll conducted by Cartagena Como Vamos, the main priorities of the city are ranked. This gives us an indication of how urgent the city considers the water issues.

C.2.1 Plan de Desarollo - Ahorra si Cartagena 2013-2015

In this four year plan the main priorities and their sub-components can be ordered as follows:

1. Social inclusion
    - Education
    - Health
    - Security
    - Sports and recreation
    - Inclusion and prosperity (focus of women's rights)
    - Culture
2. Economic development
    - Local development
    - Competition
3. The city
    - Habitat (Specific mentioning of the 2007 Master plan)
    - Infrastructure for development (coastal defense)
4. Citizens and government
    - Institutional strengthening and development
    - Decentralization and local strengthening

C.2.2 Plan de Desarollo - Primero la Gente 2016-2019

In this four year plan the main priorities and their sub-components can be ordered as follows:

1. Fight inequality
    - Education
    - Equality (racial, social class and gender equality)
    - Arts and Culture
    - Sports
    - Fight extreme poverty
    - Opportunities for the youth
2. Adapt the territory for the people
    - Cartagena, a city to invest in
    - Environmental education and control
    - Sound risk management (Specific mentioning of the 2007 Master plan and coastal defense)
    - Animal rights
    - Strong city planning
    - Urban development making Cartagena competitive
    - Public space and mobility
    - Roads for mobility and and development

  - Housing and public services

3. Create citizenship and fortify institutionality
   - Cartagena without fear
   - Peace
   - Transparent government and management
   - Healthy municipal finances

C.2.3 Poll of citizens

In a presentation by Cartagena Como Vamos (2015) the results of a poll are presented. 1139 citizens of both genders, of all ages above 18 and from all neighborhoods and socio-economic classes were interviewed. These people were asked for the three greatest sources of annoyance in the city. The top 5 are:

1. Traffic congestion
2. Bad smells due to stagnant water and sewage backflow
3. Excessive noise
4. Waste management
5. Pollution of water sources

Lack of rain water drainage causing floods and floods caused by high tides are number 11 and 14 respectively.

Appendix D

Wave Calculations

D.1 Extreme Wave Analysis

From Cornelissen et al. (2015), the ARGOSS data for the coast of Cartagena is extracted and shown in Figure D.1. This data is taken from the 11°00'N, 76°15'W (Cornelissen et al., 2015). The water depth at this location is about 2800 m (Navionics S.p.A., 2017).

	lower	337.5	22.5	67.5	112.5	157.5	202.5	247.5	292.5	
lower	upper	22.5	67.5	112.5	157.5	202.5	247.5	292.5	337.5	total
0.0	0.5	0.1	0.4	0.1	0.0	0.0	0.1	0.0	0.0	0.7
0.5	1.0	0.5	8.1	1.7	0.6	0.8	0.9	0.3	0.2	13.3
1.0	1.5	0.4	15.0	1.0	0.2	0.4	0.7	0.2	0.2	18.1
1.5	2.0	0.2	18.2	0.2	0.0	0.1	0.2	0.0	0.0	19.0
2.0	2.5	0.1	17.4	0.0	0	0.0	0.1	0.0	0.0	17.7
2.5	3.0	0.1	14.3	0.0	0	0	0.0	0.0	0.0	14.4
3.0	3.5	0.0	9.6	0	0	0	0.0	0.0	0.0	9.7
3.5	4.0	0.0	4.9	0	0	0	0.0	0	0	4.9
4.0	4.5	0	1.8	0	0	0	0	0	0	1.8
4.5	5.0	0	0.4	0	0	0	0	0	0	0.4
5.0	5.5	0	0.1	0	0	0	0	0	0	0.1
5.5	6.0	0	0.0	0	0	0	0	0	0	0.0
6.0	6.5	0	0	0	0	0	0	0	0	0.0
total		1.5	90.1	3.0	0.8	1.3	2.0	0.6	0.6	100.0

Figure D.1: Wave scatter plot based on data from ARGOSS, as found in Cornelissen et al. (2015).

This data is used to determine the wave height for certain return periods. The two widely used distributions for long term statistics are the log-normal distribution and the Weibull distribution (Holthuijsen, 2007). For lower probabilities, the wave heights form a straight line which, according to the TU Delft Offshore Hydromechanics handbook, can be used to extrapolate the wave heights for extreme values (Journee & Massie, 2001). Both distributions are used to compute the extreme wave heights, to determine which one gives the best fit.

First, the log-normal distribution is used. The daily conditions in Figure D.1 are transformed into a probability of exceedance, see table D.1.

To use this data to predict a extreme wave height, the data must be transformed into the return period of a single storm. This can be done using equation D.1.

$$RP_{\underline{H_s}>H_s} = \frac{D_{storm}}{Pr(\underline{H_s} > H_s) * 365 * 24} \tag{D.1}$$

With:
D_{storm} = The duration of the design storm [hours]
$RP_{\underline{H_s}>H_s}$ = The return period [years]
$Pr(\underline{H_s} > H_s)$ = The probability of exceedance [-]

Table D.1: Probability of exceedance for certain wave heights

Upper bound	Occurance (%)	Cum. Occurance (%)	Pr(H<H_s)	Pr(H>H_s)
0,5	0,7	0,7	0,006993007	0,993006993
1	13,3	14	0,13986014	0,86013986
1,5	18,1	32,1	0,320679321	0,679320679
2	19	51,1	0,51048951	0,48951049
2,5	17,7	68,8	0,687312687	0,312687313
3	14,4	83,2	0,831168831	0,168831169
3,5	9,7	92,9	0,928071928	0,071928072
4	4,9	97,8	0,977022977	0,022977023
4,5	1,8	99,6	0,995004995	0,004995005
5	0,4	100	0,999000999	0,000999001
5,5	0,1	100,1	1	0

According to Moreno-Egel et al. (2006), the duration of a design storm near Cartagena is 12 hours.

A plot of the return period versus the wave height with an extrapolated fit can be found in Figure D.2 .

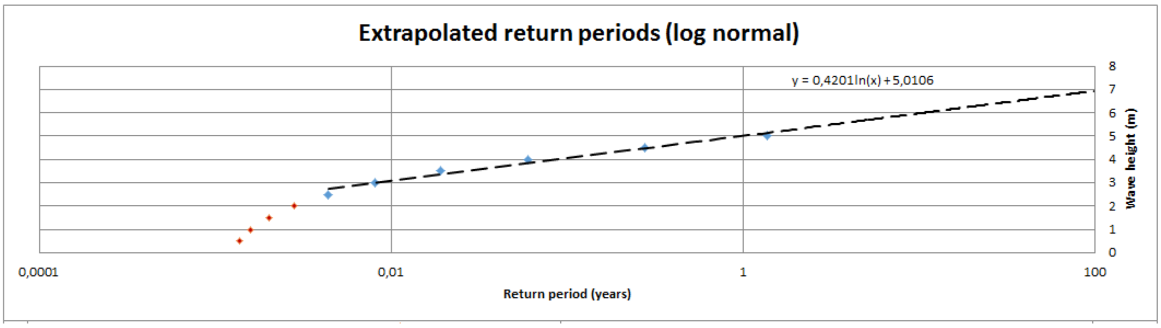

Figure D.2: Return period versus the wave height using log-normal distribution

This results in the following wave heights for certain return periods, if the log-normal distribution is used.

Table D.2: The extreme wave height for certain return periods

Return period (year)	Wave height (m)
1	5,0106
5	5,68672487
10	5,977916
20	6,26910713
50	6,65404086
100	6,945232

Now, the Weibull distribution is used to determine the extreme wave heights. First, the probability of exceedance for certain wave heights is needed. These can be found in Table D.1. Subsequently, with this probability the Weibull variable is computed using equation D.2.

$$y = ln(-ln(1 - Pr(\underline{H_s} < H_s)) = ln(-ln(Pr(\underline{H_s} > H_s)) \quad (D.2)$$

With:
y = The return period [years]
$Pr(\underline{H_s} > H_s)$ = The probability of exceedance [-]

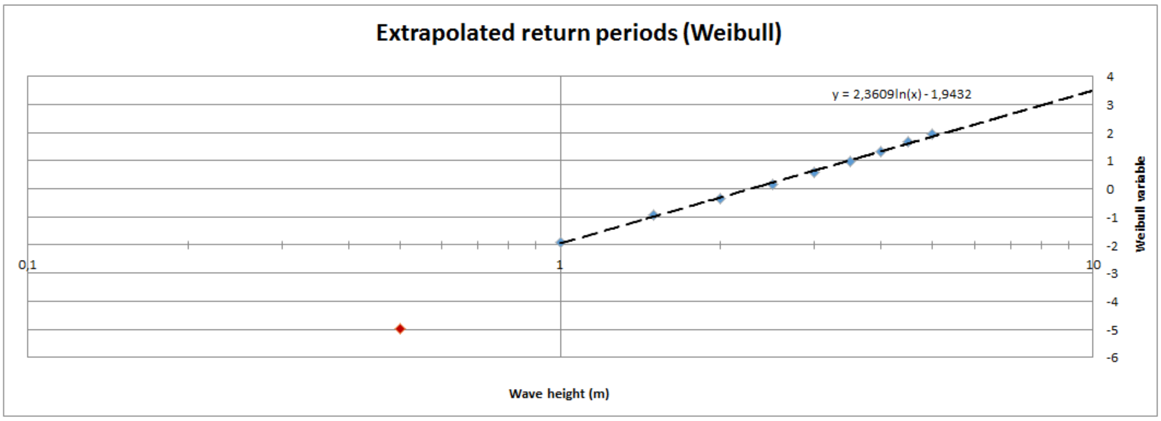

Figure D.3: Return period versus the wave height using Weibull distribution

The next step is plotting the wave height versus the Weibull variable and fitting the distribution. Now, for different return periods, the probability of exceedance is calculated using equation D.1. This probability of exceedance is transformed into a Weibull variable using equation D.2. The fit in Figure D.3 is extrapolated to come from the determined Weibull variables to the extreme wave heights. This can be found in Table D.3.

Table D.3: Determination of Weibull variable and resulting wave heights

Return period (year)	Pr (H>Hs)	Weibull variable	Wave height
1	0,001369863	1,886015235	5,062853695
5	0,000273973	2,104436846	5,553600988
10	0,000136986	2,185560103	5,747745562
20	6,84932E-05	2,260593332	5,933352048
50	2,73973E-05	2,351857764	6,167206315
100	1,36986E-05	2,415754366	6,33639795

If you look at Figures D.2 and D.3, you see that the Weibull fit is better. So, the Weibull fit is used to determine extreme wave heights.

D.2 SwanOne Computations

To give an estimate of the nearshore wave height, the model SwanOne is used. This is a one-dimensional model to simulate nearshore wave heights. (Delft University of Technology, 2016)

For this phase of design, only a rough estimate of the wave height is needed. Therefore, the situation is simplified. Below, the main simplifications are explained.

- The depth contours are parallel along the coast. (Restriction that comes with using SwanOne)
- The normal of the coast is oriented 132.5°. In reality, it is about 120°. (Restriction that comes with using SwanOne, otherwise angle between waves and normal of the coast becomes too large.)
- No complete wave spectrum is used as input. The only input regarding waves are those of 6,34 m high (100 year return period).
- There is no current.
- The waves have a period of 8 s (Moreno-Egel et al., 2006).

The bathymetry is obtained using a nautical chart of Navionics (Navionics S.p.A., 2017).

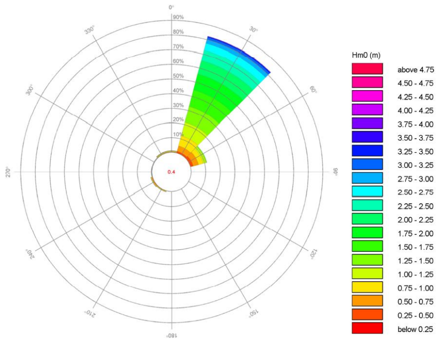

Figure D.4: Offshore wave climate (Consorcio Dique, 2015)

Most of the time the waves come from NNE-direction, see Figure D.4.
2 runs are done with SwanOne, one run with wind of 18 m/s coming from NE-direction and one run without wind. This is done, because during the rainy season, when most floods occur, the winds are weak and irregular. The strong winds occur during the dry season.

The simplified situation with input looks like Figure D.5.

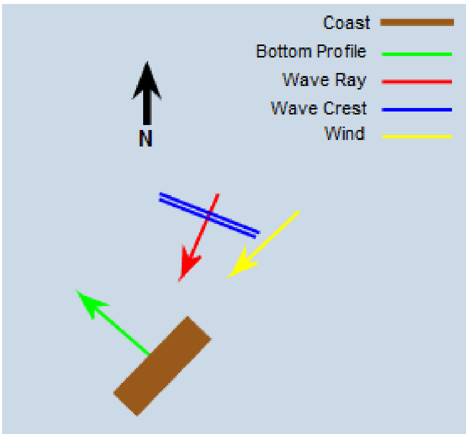

Figure D.5: Simplified situation in SwanOne

This results, using a offshore wave height of 6.3 m with a return period of 100 years, in a significant wave height of 2,0 m for the situation without winds. If the strong winds are taken into account, the significant wave height would be 2,1 m. Because the strong winds do not occur during the rainy season, it is decided that the significant wave height of 2,0 m is used. Also, the difference between the significant wave heights is only 0,1 m, implying that the wind from this direction is not a significant factor in the development of the waves towards the shore in this situation.

Appendix E

Implications of Moving the Terminal

A major container terminal, cruise terminal and a palm oil storage are located on the island of Manga. Furthermore, there is a small terminal at El Bosque. There are two possibilities to take care of the terminals. The first one is to create a big lock in the barrier that makes it possible to serve the capacity of the incoming ships to the terminals. The second option is to relocate the terminals and use the land for residential or recreational purposes. This second option will increase the quality of living around the inner bay and in the city, as no industry is present anymore and heavy traffic in the city will be reduced, a more elaborate calculation is explained below. The land that comes available only when removing the terminal at Manga is around 390,000 square meters. The selling of this land will result in approximately 620,000,000 USD when using the current ground price at Manga of 1,592 USD per square meter (Paul Juan Realty, 2016). The size of the land of the terminals that have to be removed is 625,000 square meter, plus 4830 meters of quay (World Port Source, 2017). The costs for creating the land that is suitable for new terminals of the same size is approximately 260,000,000 USD. This takes into account the costs of the ground for a new terminal, the costs for adapting the ground to build the quay and the dredging costs, the underlying equation can be found in Table E.1. In this calculation it is assumed that the equipment on the terminals can be reused, the exploitation costs will remain the same and logistical costs of the transfer are not taken into account. The calculation of the units is done with Google Earth and (World Port Source, 2017).

Table E.1: Costs of preparing a terminal

Type	Price [USD]	Unit	Total [million USD]	Note
Ground	290	625,000	181.25	290 USD/mˆ2*
Quay	6,000	4,830	28.98	Assumed 6,000 USD/m**
Dredging	4	12,075,000***	48.30	Assumed 4 USD/mˆ3
Total			**258.53**	

* (Paul Juan Realty, 2017)
** Based on price of similar sized terminals in the Netherlands
*** 250 m out of shore, 10 m deeper than current depth and a length of 4830m

Appendix F

Multi-Criteria Analysis

F.1 Method

A MCA is widely used to evaluate different alternatives. The MCA is used to evaluate three sets of alternatives in this report. First, a set of criteria is defined for each set. Those criteria are based on the program of requirements and wishes, that followed from the general problem analysis. The explanation of all used criteria can be found in the sections below. Subsequently, the importance of every criterion is determined. This importance, also based on the program of requirements and wishes, is expressed in a weight in the range 1 (not important) - 5 (very important). The third step is to rate every alternatives for all criteria. Again, the score ranges between 1 - 5 (very poor, poor, neutral, good, excellent). The final score is computed using the equation below.

$$Finalscore = \frac{\sum Weight(i) * Score(i)}{\sum Score(i)} \tag{F.1}$$

F.2 Criteria Ciénaga de la Virgen

Reduction discharge peaks	What is the absolute reduction of the discharge peaks?
Efficiency discharge reduction	How efficient are the discharge peaks reduced?
Capacity increase	What is the absolute increase of the capacity of channels in and around Cartagena?
Efficiency capacity increase	How efficient is the capacity increased?
Storage	What is the absolute increase of storage volume in and close to the city?
Protection sea-level rise	Is protection against sea-level rise present?
Flexibility	Is the alternative designed such that it can be adjusted to additional wishes from stakeholders?
Water quality	Is the water quality in the Ciénaga de la Virgen improved or worsened?
Economic feasibility	Do the benefits balance the costs?
Political feasibility	Is the implementation of the plan feasible or will there be a lot of resistance from government, companies or residents?
Technical feasibility	Is the project executable?
No regret measure	The solution should maintain its function in the face of climate change, changing city landscape and future water-related project?
Environment friendly design	Does the design stimulate a better environment?
Improve living quality	Does the design improve living conditions for local residents (improved recreational possibilites, less odor because of sewage overflow, etc.)?
Improved accessibility	Does the design improve the accessiblity of the city?
Stimulate economics	Will the design stimulate economic growth in the future (more jobs, more tourists, etc.)?
Strengthen local resources	Will local engineers and contractors be able to participate in the project, such that knowledge is collected and contained in the area?
Improve urban planning	Does the design stimulate improved urban planning (and limit unplanned city growth)?
Maintenance	Is a lot of maintenance needed? (The less, the better)

F.3 Criteria Bay of Cartagena

Efficiency protection	How efficient is the inner bay protected against high water levels?
Water quality	Is the water quality in the Ciénaga de la Virgen improved or worsened?
Storage	What is the absolute increase of storage volume in and close to the city?
Improved urban drainage	Is the urban drainage improved by the solution?
Pump capacity	The less pump capacity, the better
Flexibility	Is the alternative designed such that it can be adjusted to additional wishes from stakeholders?
Economic feasibility	Do the benefits balance the costs?
Political feasibility	Is the implementation of the plan feasible or will there be a lot of resistance from government, companies or residents?
Technical feasibility	Is the project executable?
Social benefits	Does the solution stimulate integration between different neighborhoods without local resistance?
No regret measure	The solution should maintain its function in the face of climate change, changing city landscape and future water-related project?
Environment friendly design	Does the design stimulate a better environment?
Improve living quality	Does the design improve living conditions for local residents (improved recreational possibilites, less odor because of sewage overflow, etc.)?
Improve accessibility	Does the design improve the accessiblity of the city?
Stimulate economics	Will the design stimulate economic growth in the future (more jobs, increased tourism, etc.)?
Strengthen local resources	Will local engineers and contractors be able to participate in the project, such that knowledge is collected and contained in the area?
Maintenance	Is a lot of maintenance needed? (The less, the better)

F.4 Criteria Coast

Protection sea-level rise	Is protection against sea-level rise included in the design?
Maintenance	Is a lot of maintenance needed?
Beach width + length	What is the total area of beach? (The more, the better)
Improved urban drainage	Is urban drainage improved by this alternative?
Volumes of sand	How much sand is needed? (The less, the better)
Flexibility	Is the alternative designed such that it can be adjusted to additional wishes from stakeholders?
Economic feasibility	Do the benefits balance the costs?
Political feasibility	Is the implementation of the plan feasible or will there be a lot of resistance from government, companies or residents?
Technical feasibility	Is the project executable?
Coastal erosion Tierra Bomba	Does the solution enhance or reduce coastal erosion at Tierra Bomba?
No regret measure	The solution should maintain its function in the face of climate change, changing city landscape and future water-related project?
Environment friendly design	Does the design stimulate a better environment?
Improve living quality	Does the design improve living conditions for local residents (improved recreational possibilites, less odor because of sewage overflow, etc.)?
Improve accessibility	Does the design improve the accessiblity of the city?
Stimulate economics	Will the design stimulate economic growth in the future (more jobs, more tourists, etc.)?
Strengthen local resources	Will local engineers and contractors be able to participate in the project, such that knowledge is collected and contained in the area?

Appendix G

Design Calculations

G.1 Peninsula Groundwater Flow

Theory

Estimations of groundwater flow may be made using Darcy's law. This law states the following relation:

$$Q_s = -K_s \frac{dh}{ds} A \tag{G.1}$$

in which:
Q_s = Discharge
K_s = Hydraulic conductivity
$\frac{dh}{ds}$ = Groundwater gradient
A = Area perpendicular to flow

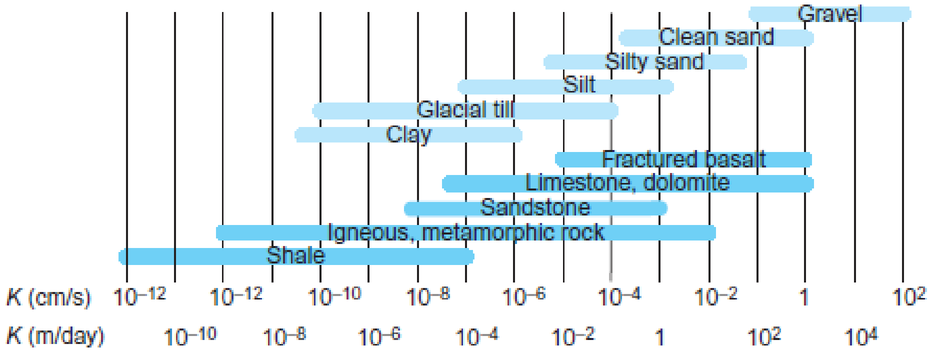

Figure G.1: Typical hydraulic conductivity (Fitts, 2002)

Method

The total volume flowing underneath the peninsula into the closure is calculated by dividing the peninsula into sections. Water will also flow underneath the dam used to close the bay. It is assumed that the sand layer is equally thick everywhere and has the same hydraulic conductivity. Thus the only factor influencing the flow is the hydraulic gradient which depends on the width of the sections ($\frac{dh}{ds} = \frac{difference\ in\ waterlevel}{width\ of\ peninsula}$).

Input

K_s = 100 m/day (see Figure G.1)
dh = Difference in water level between sea and closure. Chosen to be 0.5m for normal conditions 3.0 for extreme conditions
$\frac{dh}{ds}$ = Hydraulic gradient, = $\frac{difference\ in\ water\ level}{width\ of\ peninsula}$ d = sand layer depth, chosen to be 15m, roughly equal to depth of the bay.
A= Area = Section length * aquifer depth

Calculation and result

Table G.1: Normal operational conditions calculation summary

	Bocagrande begin	Bocagrande middle	Bocagrande end	Castillo-grande	Dam	**Total**
Width [m]	160	300	400	270	50	-
Lenght [m]	300	700	1600	1400	1 700	-
Area [m2]	4500	10500	24000	21000	25500	-
dh/ds [[m/m]	0.00312	0.00167	0.00125	0.0019	0.01	-
Discharge [m3/day]	1406	1750	3000	3888	25500	**35545**

This rough estimate shows that about 35545 m^3/day which is 0.41 m^3/s of groundwater seepage occurs during normal conditions

Table G.2: Extreme operational conditions calculation summary

	Bocagrande begin	Bocagrande middle	Bocagrande end	Castillo-grande	Dam	**Total**
Width [m]	160	300	400	270	50	-
Lenght [m]	300	700	1600	1400	1 700	-
Area [m2]	4500	10500	24000	21000	25500	-
dh/ds [[m/m]	0.01875	0.01	0.0075	0.0111	0.06	-
Discharge [m3/day]	8473	10500	18000	23333	153000	**213270**

This rough estimate shows that approximately 213000 m^3/day which is 2.5 m^3/s of groundwater seepage occurs during extreme conditions

G.2 Storage Capacity

It should be checked whether or not the water level can be sufficiently lowered in the Ciénaga and in the bay in order to store sufficient water during a design event.

G.2.1 Ciénaga de la Virgen

The calculation is build up as follows:

- As stated in Chapter 3 the 100-year rainfall event is 211.9 mm/day. This is used for direct rainfall, but this rainfall is concentrated into an 8 hour long event.
- Inflow into the Ciénaga consists of: direct rainfall and urban drainage canal discharges.
- The urban channel discharges used are those presented in the 2007 pluvial drainage master plan, see Table G.3.
- In this plan a peak discharge and peak time (average 2hrs) are provided along with a base time (average 6hrs) for 100-year event, base discharge is not provided.
- It is assumed that base discharge is half of the peak discharge.
- It is assumed peak canal discharge and peak rainfall occur simultaneously. This is not entirely physically correct as one would expect some delay.
- It is assumed that the rainfall intensities have the same shape as the discharges, i.e. the peak rainfall lasts for 2 hours and has double the intensity of the remain rainfall which lasts for 6 hours.
- It is assumed that the peak discharge occurs at the start of the rain event and is followed by base discharge, see Figure G.2.
- The total discharges of all small channels is estimated to be slightly larger than Ricaurte's. The sum of the areas of the remaining urban basin is roughly equal.
- The calculation is performed at 15 minute intervals up to 24hrs after the start of the rainfall.
- To estimate the increase in Ciénaga water level due to channel discharges the total discharge is divided by the compartment's surface area (5.2 million km2).

Table G.3: Urban channel discharge (Consultores et al., 2007)

	Peak discharge [m3/s]	Peak time [hr]	Base discharge	Base time [hr]
Ricaurte	88	2	44	6
Matute	103	2	51.5	6
Rest	100	2	50	6
Caño Juan Angola Outflow	-38	24		

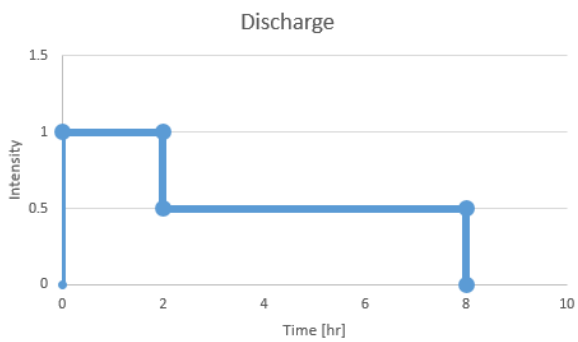

Figure G.2: Discharge in time schematic, y-axis values represent peak discharge(1.0) and base discharge (0.5)

The estimate of using a base discharge of half the peak discharge has been deemed a reasonable estimate with the following check:

- Ricaurte area is 7,330,000 m2 * 212mm /day = 1,553,960 m3
- This is roughly equal to 88m3/s * 2hrs + 44m3/s*6 hrs = 1,584,000 m3

The resulting discharges entering and exiting the Ciénaga are depicted below. The resulting water level movement is included. Based on this rough calculation it can be concluded that the compartment water level should be lowered by roughly 1 meter, relative to its current level, in anticipation of an extreme event. In this manner the water level in the Ciénaga will not exceed its current level during a design event. This is the case if water only exits the Ciénaga through Caño Juan Angola and no pumps are used.

The Ciénaga is rather shallow, 1-2m, thus this could be an issue. Regardless more work is needed to determine the exact compartments behavior. Its capacity should be checked not just for a design event as modeled above but also for less intense but prolonged rainfall.

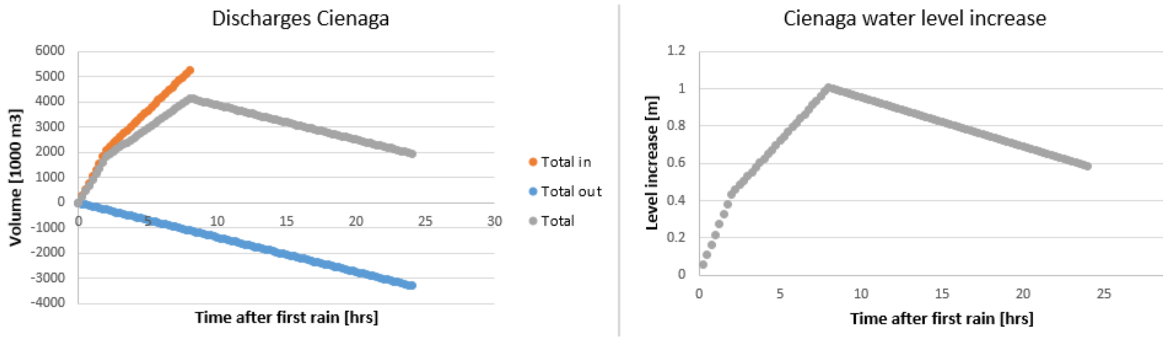

Figure G.3: Cienaga discharge balance and resulting water levels

G.2.2 Inner Bay

The storage capacity for the inner bay is also calculated. The following is assumed:

- The same rain event is used as for the Ciénaga.
- Inflow into the bay consists of direct rainfall and discharge of the rainfall in the city.
- The delay of the discharge of the rainfall in the city, which will occur, is not accounted for.
- The catchment area consists of the bay itself, the peninsula, a part of the historic center, Manga and the area North of Ciénaga Las Quintas.
- Extra water due to wave overtopping at the Caribbean coast of the peninsula is not accounted for.
- To estimate the increase in the water level of the bay due to the precipitation the total incoming water volume is divided by the surface of the bay (3.2 million km^2).
- The outflow consist of the discharge of Caño Juan Angola (no pumps are used).

During the assumed precipitation event the bay must be lowered 20 cm to remain equal to its designed level. This will not cause any problems as this is even smaller than the current tide. After 12 hours, the water level is already back at its initial level. To really determine the storage capacity more accurate calculations with the correct data need to be made as many assumptions are made.

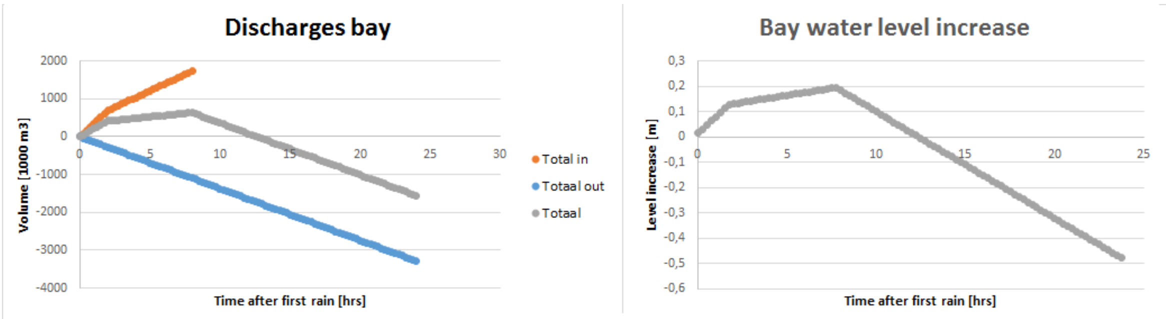

Figure G.4: Bay discharge balance and resulting water levels

G.3 Wave Overtopping

During the final conceptual design the height of 4 different components is determined. Only for the closure dam in Ciénaga de la Virgen wave overtopping could not play a role because of the lacking of waves. For the closure dam in the bay, the seawall and the revetment, wave overtopping could require a higher crest height. In this appendix is for all components determined what the additional crest height due to wave overtopping should be.

Wave overtopping can lead to damage to property behind the seawall, revetment or dam or dangerous situations for traffic or people. Therefore, the overtopping volumes should be limited.

According to the EurOtop manual for wave overtopping, the following formula should be used for design assessments. It gives the maximum overtopping discharge (van der Meer et al., 2016).

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.1035 * exp(-(1.35\frac{R_c}{H_{m0} * \gamma_f * \gamma_\beta * \gamma^*})^{1.3}) \tag{G.2}$$

Where:
q = Overtopping discharge $[m^3/s/m]$
g = Gravity constant $[m/s^2]$
H_{m0} = Significant wave height $[m]$
R_c = Crest freeboard $[m]$
γ_f = Influence factor for roughness [-]
γ_β = Influence factor for oblique incident waves [-]
γ^* = Influence factor for storm wall on a slope ($\gamma^* = exp(h_{wall}/R_c)$)

G.3.1 Closure dam bay

On top of the dam, a road could be constructed. But it is assumed that it is no problem to close this road during extreme conditions. The wave overtopping should be limited such that no damage to the crest occurs (ULS). According to Pullen et al. (2007), it should not exceed 200 l/s/m.

In the bay there are only waves smaller than 0.5 m. All influence factor are taken equal to 1. This is very conservative, because it is not likely the waves are normal incident looking at the orientation of the dam and by choosing a rough material at the slope of the dam the wave overtopping could be limited. There is also no storm wall present. Taking 1.0 for the influence factors gives the results presented in Figure G.5.
Figure G.5 shows that no additional crest height for the closure dam in the bay is needed, even if the very conservative approximation is used.

G.3.2 seawall

The seawall is schematized as a sloped wall with on top a storm wall. Due to the shallow foreshore due to the beach, it is assumed that the wave height at the toe of the structure equals 0.7 m (Rule of

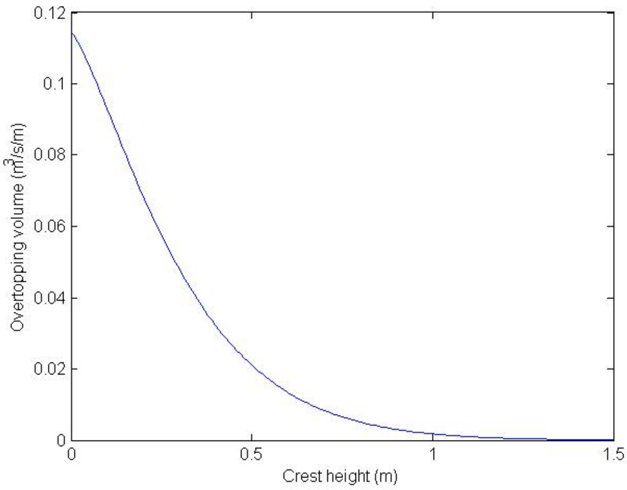

Figure G.5: Wave overtopping at closure dam bay for non-breaking waves

thumb: $Significantwaveheight = 0.5 * waterdepth$ (Molenaar & Voorendt, 2016)). On top of and just behind the seawall are people walking and at the other ends of the roads buildings are located. Therefore, the overtopping volume should be limited to 10 l/s/m van der Meer et al. (2016). This is considered to be ULS.

All factors are assumed to be one, except the one for the storm wall. During extreme water levels the crest freeboard is equal to the height of the storm wall. So, the influence factor becomes 0.57. The result is plotted in Figure G.6.

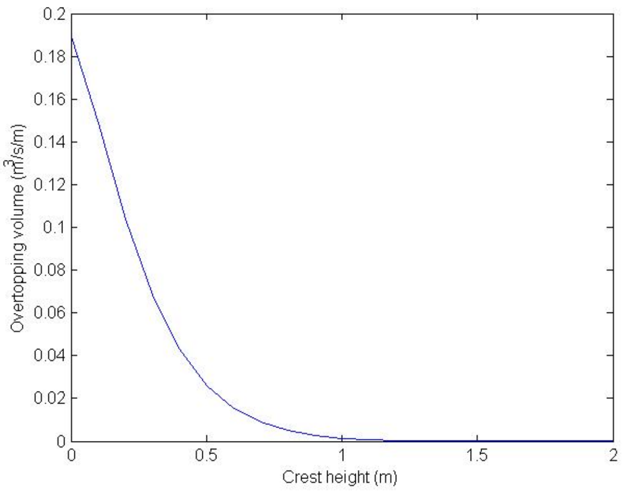

Figure G.6: Maximum wave overtopping at seawall

From the figure is read that the crest height should be 0.6 m in addition to the extreme water level.

G.3.3 Revetment

The revetment is designed as a sloped dike. On top of the dike, there is could be road. According to van der Meer et al. (2016), the wave overtopping should be limited to 20 l/s/m. For this volumes, it is still safe for traffic.

Assumed is that at the toe of the structure wave heights of 2.0 m occur. Looking at the orientation of this stretch of coastline, it is very likely that the wave height is smaller. But because of lacking data, this wave height is taken for the calculation. To limit the additional height due to wave overtopping, a berm is designed. Most probably, it will be a rubble mound revetment. Therefore, a influence factor of 0.9 for the roughness is taken. The slope of the revetment is 1:1.5. This is a regularly applied slope for revetments (CIRIA, CUR, & CETMEF, 2007b). All this gives the result presented in Figure G.7.

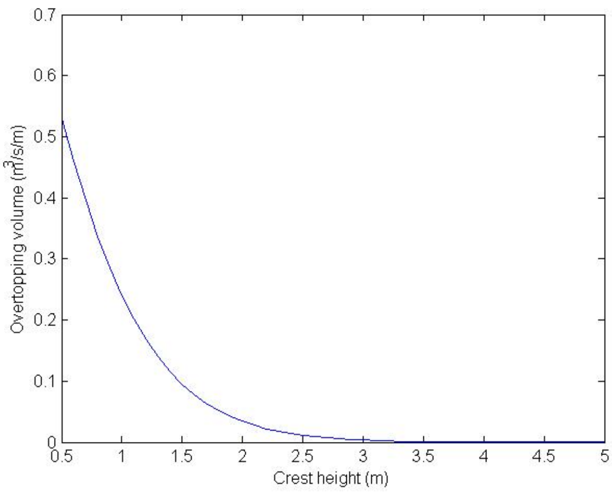

Figure G.7: Maximum wave overtopping at revetment

As can be seen, the additional crest height due to wave overtopping is 2.25 m.

NOTE: A mistake has been made during the design of the height. ULS is used for the design, but the used criterion for overtopping volumes is incorrect. For the ULS, this should have been 200 l/s/m. This would have resulted in a additional crest height of 1.1 m due to wave overtopping. Due to a lack of time this could not be corrected anymore in the report.

G.4 Cost Calculation

In this appendix are the costs of every component of the design of the flood defense system estimated.

- **Permits:** Before the start of the construction, the necessary construction licenses have to be obtained. The costs for these permits depend on the involved parties. They are considered to be significantly low and can be invoiced with the construction costs.
- **Seawall:** Based on reference projects, the costs for a concrete seawall with a height of 3.07m above m.s.n.m are between 12.2 and 13.8 million USD per km (Bos, 2008). For the length of 5 km in this solution, the costs thus range between 61 and 69 million USD.
- **Revetment:** The costs of impermeable revetments range between 2.5 and 6.3 million USD per km (Hudson, Keating, & Pettit, 2015). 1600 meters of revetment is necessary, this will thus cost between 4.0 and 10.1 million USD.
- **Groynes:** The price of rubble rocks is 40-60 USD per m^3. This is based on reference projects (Hudson et al., 2015). Assumed is a length of 200m for each of the two groynes, with an average assumed height of 3m (average depth of 1.5m + sea level rise + high tide) from the bottom of the sea. The slope of the groyne is 1:2, so a 3m high groyne is 12m wide. The volume of the two groynes is 2*200*0.5*12*3 = 7200m^3. The costs thus range between 288 and 432 thousand USD.
- **Nourishment:** The costs of nourishments depend highly on the origin of the material. 7 million m^3 is needed. The unit price of nourishments range between 2.5 to 7.2 USD per m^3 (S. N. Jonkman, Kok, & Geldenhuys, 2010), depending on the location of the nourishment. The estimated costs range between 17.5 and 50.4 million USD. Considering that the material can be gained from deeper water close to the shore, the costs of nourishment can be assumed on the lower side of this range.
- **Dike:** Around the Ciénaga, a dike with a crest height of 3.12 m and a length of 3.2 km on the West and and 3.8 km on the East part. Many cost ranges are given depending on various construction techniques. According to (Hillen et al., 2010), a range of costs that can be used for the dikes around the Ciénaga is 1.4 to 2.1 million USD per km stretch. This means a total costs between 9.8 and 14.7 million USD.
- **Dam:** Based on reference projects a closure dam in the Ciénaga costs approximately 4 million USD per m height per km length. (Dijkman, 2007). In the Ciénaga a length of 5.25km is necessary, with an average depth of 1.15m (average of 1.5m B.1 - 0.35m m.s.n.m) and a designed crest height of 3.12m. In total the height of the dam is thus 4.27m which comes to a total costs of 89.7 million USD. In the bay 2.1km of dam is necessary with a designed crest height of 3.12m and an average depth of 13m (Bajo de la Virgen decreases the average depth significantly). According to experts of Royal HaskoningDHV, the costs range is 30-35 million USD per km for the considered dam. This gives an estimated cost range of 63 and 73.5 million USD for the dam in the bay. The total dams will thus cost between 152.7 and 163.2 million USD. If the decision is made to use the dam to construct a road, the above assumption cannot be made and further research should be carried out to determine the dimensions.
- **Pumping station:** A pumping station that can handle the required capacity of 75m$^3/s$ will cost approximately 40 million USD, based on the prices of pumping stations in the Netherlands with similar properties (Hoogheemraadschap Rijnland, 2014).
- **Navigation locks:** For the calculation of the costs of the locks, the navigation locks in the Afsluitdijk at Kornwerderzand are used as a reference project. The major difference of this design is the type of road crossing the lock. In the design of the lock in the Netherlands an important highway is considered, while in Cartagena a much smaller urban road is the case. This requires modifications in the cost calculation. The dimensions of the lock can be considered likewise. This allows the boats of the naval base to pass the lock. If the naval base relocates, the lock does not need to satisfy the needs of the big marine ships. This reduces the required length and thus reduces the total costs of the lock. A sash lock will cost around 25.6 million USD. The costs for additional measures as embankments, breakwaters and a small outer port are 38.4 million USD. If the decision is made to construct a road on the dam, a movable bridge is necessary to maintain the traffic flows. The costs of this bridge are considered in the calculation

of the road over the dam. An elaborate calculation of the costs can be found in (Witteveen + Bos, 2013). The costs above are given in order to give an estimate for the locks. However, it cannot be considered to be the actual costs. More research has to be conducted to determine the final design of the lock.

- **Urban drainage system:** To improve the urban drainage system, green roofs, green zones and improved drainage in roads can be implemented in the current system. The scale of these improvements has not yet been determined so a cost calculation cannot be made.
- **Additional storage:** Storage tanks on the roof, next to houses, in basements or other places underground can be placed to improve the capacity of the urban storage. Upper basin storage is necessary as well to decrease the discharge peaks. Likewise as for the urban drainage system, the scale has not yet been determined, so costs cannot be given.
- **Maintenance:** The maintenance costs can be calculated as a percentage of the total investment costs. Assumed here is a cost estimation of 0.1 million USD per km coastal protection per year (Hillen et al., 2010). For Cartagena this means 2.1 million USD per year.
- **(Optional) Reclamation:** According to a dredging rule of thumb, the costs for reclamation are considered 200 USD per square meter, this includes the costs for revetment and quay wall as well. Depending on the chosen option for land reclamation, the costs can be calculated.
- **(Optional) Roads (+bridge):** The length of the roads will be 2100m for the connection Manga-Castillogrande and 5250m for the dam over the Ciénaga. 2 lane roads are considered on both dams, however a higher design speed on the Ciénaga is required as this road will serve major through traffic between East and West of Cartagena. The construction costs of the roads can be calculated when the desired capacity of the roads is known. Further research is necessary to estimate the costs of the roads.
  The costs of a bridge vary widely depending on the requirements. Based on the average costs of movable bridges in the Netherlands, (H.E. Klatter; J.M. van Noortwijk, 2003), the bridge considering the requirements in this case can assumed to be the same as a medium sized movable bridge in the Netherlands with a cost-range of 25-30 million USD.