Faculty of Civil Engineering and Geosciences, TU Delft

Report Project Cartagena

A flood free city

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October 2015

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Preface

This report is the result of a multidisciplinary study focussed on the problems with flooding in Cartagena de Indias, Colombia. This study is performed for the course CIE4061 ”Multidisciplinary Project”, as part of our master programmes in Hydraulic Engineering. For a period of two months , the Universidad de Cartagena provided facilities for us to work on the project.

During the project we worked at two locations: Centro and Piedra de Bolivar. Most of our time was spend at the latter location, since there was more interaction with Colombian engineering students and researchers possible at this location. About halfway the project, some students decided to go on strike for 4 weeks and did not allow any teachers and professors to enter the buildings. Fortunately, students were still able to enter, so we could continue our project.

We would like to thank our supervisors Dalia Morena from Universidad de Cartagena, Henk-Jan Verhagen and Jan van Overeem from TU Delft for making the project possible and their feedback during our study, as well as Javier Mouthon for providing a lot of information. Special thanks go to Juan Serrano for all his help and arranging the beautiful apartment. Finally, we would like to thank our sponsors Van Oord, TVR Loopbaanconsult and BT Geoconsult for financing the project and of course our new friends Jesus, Javier, Leydy, Dayana, Melissa, Gina and Margareth for being such great company in and outside the office by showing us around in Cartagena. Without you, the project would not have been the same!

Cartagena de Indias, October 16th 2015

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Abstract

Cartagena is a city located at the Caribbean coast of Colombia, founded in 1533 by the Spanish. Its population consists over one million inhabitants, making it the fifth largest city in Colombia. Due to its strategic location, the port of Cartagena has grown into the largest port of the Caribbean coast, making it very important for the Colombian economy. The city is famous for its colonial centre 'Centro Historico', that is a UNESCO world heritage site since 1984. Together with Centro, the peninsula of Bocagrande, Castillogrande and El Laguito, attract a lot of tourists thanks to its wide stretching beaches. The areas are however prone to flooding.

The focus of this project is to provide a well-structured analysis of the flood problems in the neighbourhoods Centro, Bocagrande, Castillogrande and El Laguito, because of their major importance to the touristic, economic and cultural values of Cartagena. From this analysis an integrated conceptual solution is performed to improve the drainage and coastal protection system to ensure the future development of the city in a political and social desirable way.

In the current situation the studied areas suffer from frequent flooding. The coastal protection and drainage system are insufficient. The surface level gradient is too small and the outlet drains are constructed as holes through the coastal protection, allowing the seawater to intrude during high water levels at sea. Flooding already occurs at mild conditions, such as spring tide or a single heavy rainfall event. These floods cause a lot of damage to properties and the infrastructure. The salt water intrusion causes damage to cars and buildings. Also hinder to all kind of commercial activities due to significant congestion, or even inaccessibility, results in a huge loss of revenue. Prognosis is that the frequency and intensity of these problems will increase in the future, due to the expected sea level rise and land subsidence.

In recent years, various studies have already been performed on these problems, but the municipality has never given priority to implement these proposals. The decision makers do not see the urgency of the problem. Since most political functions have a maximum term of four years, this hampers decision making with a long-term vision. Also there is only a very small budget available for disaster prevention, leading to a limited investment budget. Another issue is the large amount of public and private organizations that operate without good collaboration, causing a haziness of their responsibilities.

A program of requirements was established after analysing the problem, to which the design levels were equipped. For feasibility of the design, it is necessary to obtain additional investors next to the municipality. Therefore an extensive stakeholder analysis was performed to indicate all potential public and private interested parties. The studied areas were divided in smaller areas and global solutions were developed on element level, where the coastal protection and drainage were distinguished. A multi criteria analysis (MCA) was performed on these global solutions to indicate the best elements for the final solution.

In order to let the solution succeed, the stakeholders that have authority to start a project

should sense the urgency of the problem. These stakeholders are the mayor of Cartagena, the Bolívar department and the Ministry of ADS. Since the water levels at sea are expected to increase considerably in the upcoming years, the future development of Cartagena is at stake. In order to let all parties collaborate to implement a solution, the final design is constructable within four years and will be performed in phases, where the most flood prone areas have gotten the highest priority.

From the MCA, the best elements were combined to create a final solution. The final solution includes elements that bring additional value to the peninsula by constructing a marina and a promenade to attract private investors. The safety is guaranteed by upgrading the current coastal protection system and will be implemented by a strongly revised drainage system. The surface gradient will be increased by heightening two roads, the outlet drains will be equipped with check valves and a comprehensive pumping system will be installed.

Chapter 1

Introduction

1.1 Background

Colombia is a country with a rich and turbulent history. After Colombia became independent under the leadership of Simon Bolívar in 1819 there has been a continuous tendency of civil wars and rebellion. However, since the appointment of president Uribe in 2002 a lot of progress has been booked and the political situation has become more and more stable. For example Colombia now is the number three largest economy of South America. Thanks to these positive developments Colombia is able to focus on other major problems that are threatening the countries development.

(a) Colombia (b) Cartagena de Indias

Figure 1.1: Location of Colombia and Cartagena de Indias

One of the problems that the country is coping with are the continuous threat of coastline erosion, sea level rise and heavy rainfall. Combined with storm conditions this frequently results in floods and the expectation is that the frequency will only increase more in the coming years. This offers a lot of interesting opportunities for engineering experts from all over the world. Cartagena de Indias is one of the cities that experiences the consequences of these floods.

The city of Cartagena de Indias (in this report also simply referred to as 'Cartagena') is located at the Caribbean coast (figure 1.1) and has a total population of over one million people, making it the fifth largest city in Colombia. The old city center of Cartagena was founded by the Spanish in 1533 this had a large influence on the architecture as can be seen by the colonial fortresses and monuments the city possesses. Therefore the 'Centro Historico' was added to the UNESCO world heritage list in 1984 [1]. Due to the strategic geographic location that the Spanish conquistadors also recognized, the port has grown into the largest port of the Caribbean coast. Together with the historic center, the wide stretching beaches of Bocagrande and Castillogrande provide an environment that attracts a lot of tourist every year.

1.2 Problem description

High water levels at sea generated by storms and the tide in combination with heavy rainfall, an insufficient drainage system and insufficient coastal protection are the cause of the floods in Cartagena. With the upcoming climatic sea level rise the city is expected to suffer more frequently from floods in the coming years.

In consultation with the Universidad de Cartagena it has been decided to focus the research on the specific areas of Bocagrande, Castillogrande, El Laguito and the historic center (Centro Historico). These areas already experience floods during mild conditions [2] such as high tide or a single rainfall event. The decision to focus the research on these areas is substantiated by their major contribution to the touristic, economical and cultural values of Cartagena de Indias (see also appendix A).

Besides the continuous threat of flooding, the country is coping with its cultural boundary conditions as well. Due to its anti-corruption policy many political functions have a maximum term of four years. As a result it is hard to invest in long-term solutions that require regular maintenance.

1.2.1 Damages

Intrusion of salt water results in a lot of damage to property and infrastructure. Coastal protection works and roads deteriorate due to the salt water and a bad design. Moreover, cars, taxis and buses suffer from corrosion by the salt water.

Congestion that is caused by the floods prevents traffic from reaching its destination. This hinders all kind of economic activities such as construction works, employees traveling to their jobs and the supply of restaurants and shops. Special attention is given to the tourism sector which generates a lot of income for the city.

Also the residents encounter a decrease of the liveability. Their cars experience a lot of corrosion, in some cases their apartments do as well. During high tide a large part of their environment is neither accessible by foot nor by car. In addition the stagnant water is a source for inconvenient smells and a breeding place for insects such as mosquitoes.

1.2.2 Future situation

The frequency and intensity of the floods in Cartagena are expected to increase in the future if no measures are taken. Due to the expected effects of accelerated sea level rise, the frequency of tidal intrusion will increase and the effects will be higher. Due to land subsidence the gravity runoff capacity of the drainage system is expected to worsen and the continuous construction of hard structures will further decrease the infiltration capacity to the subsoil. Therefore the damages are also expected to increase proportionally with the occurrence of the floods. An impression of the current and future situation is shown in figure 1.2 to illustrate the extend of the problem.

Figure 1.2: Current and future situation with increased sea level rise and storm surge level

1.3 Research approach

The focus of the project is to provide a well structured analysis of the flood problems in Centro, Bocagrande, Castillogrande and El Laguito and from this analysis form a well integrated conceptual solution that can be used as a recommendation for the municipality to clearly explain the effects of the flooding and improve the future economic development of the city.

1.3.1 Research question

”In what way can the flood problems in Cartagena de Indias be mitigated by improving the drainage and coastal protection system in such a way that it is a desirable political and social expansion of the city enhancing the economic and social development?”

In order to reach this goal the following questions are of importance for the research.

- What are the main causes leading to flooding due to tidal intrusion and wave overtopping in the focus areas?
- What are the main causes leading to flooding due to precipitation in the focus areas?
- Who are the main influential stakeholders and what is their motive to support or oppose a flood protection design?
- What possibilities are there for an integrated protection system in the focus areas?
- Is there a combined and integrated flood protection system that could convince the local government and stakeholders to support the project?

Chapter 2

Analysis

To get to a solution that covers the entire problem it is an important step to identify all the related key factors. The area analysis reveals the current level of protection, consequences of flooding and causes of flooding. A more detailed description per areas is given in appendix B.

2.1 Area analysis

As stated in the introduction the research focuses on the specific areas of Bocagrande, Castillogrande, El Laguito and Centro Historico. Besides their susceptibility to flooding, these areas have a major contribution to the touristic, economical and cultural values of Cartagena. The areas are shown in figure 2.1a.

(a) Research focus areas

(b) Critical areas

2.1.1 Current problems

Currently in Cartagena there is a lot of flooding related to two major aspects. The first being tidal intrusion due to the low altitude of the land mass. The second being the lack of drainage when either high precipitation or tidal intrusion occurs. Both result in flooding causing several problems as described in chapter 1. In figure 2.1b a sketch of the most critical areas relating to precipitation and tidal intrusion is given. The entire peninsula however suffers from the effect of floodings.

2.1.2 Current system

At most locations in the focus areas the current protection is very limited. For example the seawall at Bocagrande that was originally meant to keep the sea water out, has been partially removed to drain rainwater. It now serves both as a drain for rainwater as a tidal inlet. This section gives an overview of the coastal protection level and the deficiencies within the current situation.

Coastal protection

Over the years a lot of coastal works have been constructed, either to protect or extend the coastline. Figure 2.2 gives an overview of the current coastal protection sytem, without giving a verdict on its functionality.

Figure 2.2: Current coastal protection

At the moment of research a sea wall is under construction that stretches the bay along Bocangrande and Castillogrande. See appendix C for all the current (coastal) construction works.

Naval base

The naval base located between Bocagrande and Centro at the bay side is not taken into account. For the upcoming years it is not sure whether the naval base will move to another spot or the base remains at its current position. So in the additional research this is not taken into account. A short recommendation will be made later for what a possible completion could be for the new owners if it were sold, otherwise the naval base would take precautions themselves.

Drainage system

Urban water management focuses on the surface water and groundwater in urban areas including rainwater runoff, drinking water supply, the wastewater system and their relation with the catchments in the area. The city of Cartagena is equipped with a separated sewer system, meaning that the stormwater and wastewater are discharged through separated systems. The current stormwater drainage system is predominantly designed for runoff by gravitation. The current drainage system proves to be insufficient, as can be noticed by the frequent floods in these areas, since the water is not able to runoff during high water levels at sea and the insufficient capacity induced by the small surface level gradient.

The stormwater runs off over the pavements towards the surface waters via drainage outlets, of which the locations are shown in figure 2.3a. Part of the rainwater on the peninsula flows into the sea and El Laguito lake, however the largest part is directed towards the bay. The division is shown in figure 2.3b.

(a) Outlets on the peninsula

(b) Drainage directions

Figure 2.3: Current drain system

The area has very little area available for infiltration or retention. Therefore most stormwater will runoff over the paved surfaces and the drainage system. During excessive rainfall events the streets are flooded in few minutes. Due to the lack of infiltration, even minor rainfall events cause a lot of discomfort.

Another cause of flooding is the direct connection to the surface water bodies during high tides. This causes tidal intrusion. The drainage outlets then become tidal inlets at the lower elevated areas. At some locations the outlets do include valves, but due to bad maintenance their functionality has decreased.

Sewer system

Currently there is a separated sewer system in Cartagena. A combined sewer system is assumed to be too expensive. The wastewater is pumped towards Punta de Canoa, north of the city, where it flows into the ocean. The stormwater is directly drained to closer water bodies. With this system special attention should be given to stagnant water to avoid a hatchery for mosquitoes and stench. Also maintenance is important during dry periods, to prepare the system for sudden runoff peaks. Furthermore, it is important to prevent mixing with the wastewater system. See also appendix B.

2.2 Flood risk

In order to quantify the effects of flooding in terms of damage, an assessment has been made. This has been done with the use of elevation maps and damage functions, these can be found together with a more extensive elaboration on flood risk in appendix D. From this flood risk analysis it has become clear what the damages due to different levels of flooding are. With both the direct damages, e.g. damage to buildings and loss of life, as the indirect damages, e.g. loss of business, being quantified a well structured argument in favour of a solution can be made.

The total damages can be found in table D.5. As is seen the damage that can be prevented is considerable. Things that need to be considered are that these values are rough estimates as specific values are not known at this time for the expected loss of business and are estimated on the current GDP. As said before the situation without waves can be assumed to occur with high certainty, where the situation with waves represents the extreme condition.

Table 2.1: Total flood damage caused by direct and indirect sources in USD

Part of the city	Without waves (USD)		With waves (USD)	
Bocagrande	$	438,436,263	$	963,777,174
Castillogrande	$	49,264,674	$	160,008,846
El Laguito	$	10,920,555	$	59,837,345
Centro	$	225,268,498	$	408,524,195
Total	$	**723,889,989**	$	**1,592,147,560**

Chapter 3

Stakeholders and Political system

A design for the existing problem can not be made without knowing for who it will be made and what their wishes and desires are. Especially in a country such as Colombia it is important to have political and social support to get a project of the ground. For this reason this stakeholder analyse is made.

The first part of this chapter identifies the characteristics of stakeholders that are involved with the problem and a possible solution. The second part of this will zoom in on the current political situation and organizations in Cartagena and Colombia.

3.1 Stakeholder analysis

The stakeholder analysis process is based on documents that were provided by Erik Waumans (Van Oord, project sponsor). Going through four basic steps results in a good insight of how each stakeholder has to be managed: identification, understanding, prioritizing and definition of specific actions.

In total a number of 30 stakeholders have been identified. This chapter only gives a summary of the prioritizing and specific actions to influence stakeholders. The full process of the stakeholder analysis is given in appendix E.

3.1.1 Prioritize stakeholders

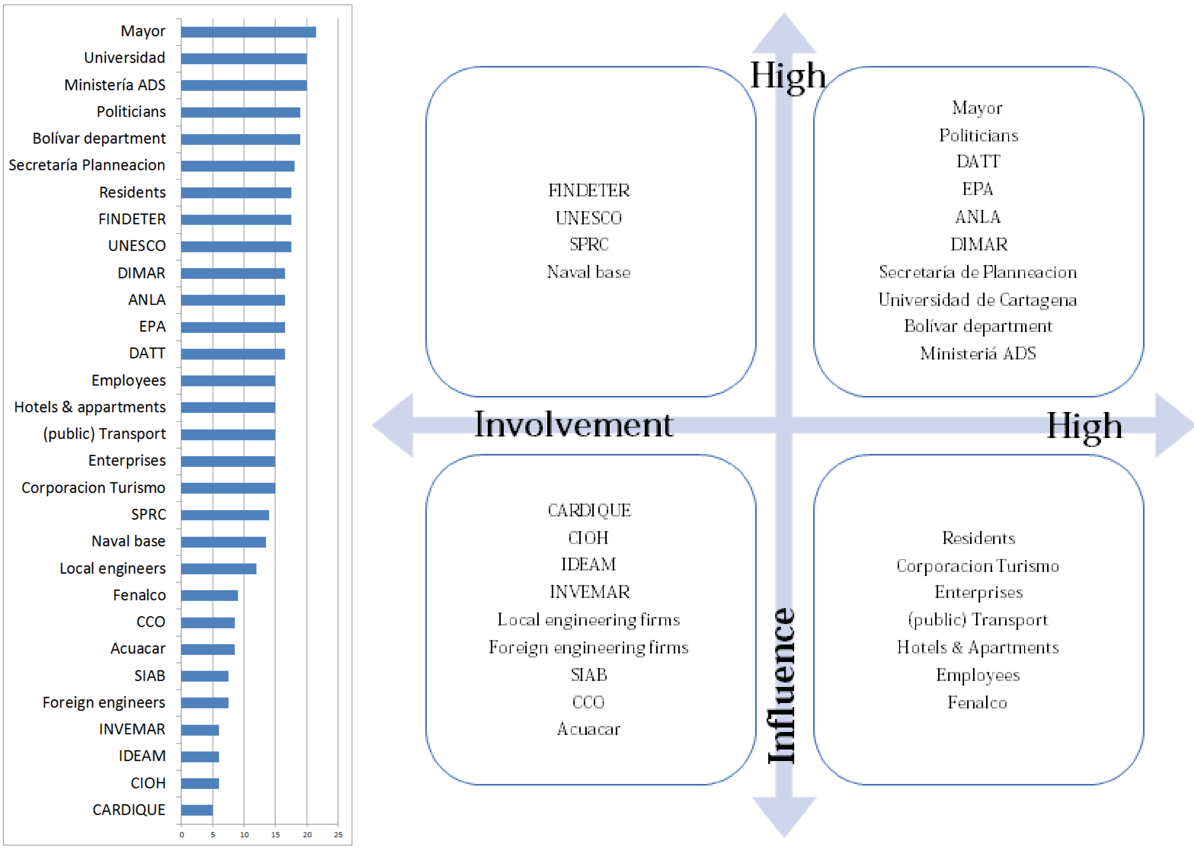
Stakeholders are ranked on three criteria to quantify their level of importance: 'influence', 'opinion' and 'involvement'. This section only briefly describes the criteria. In appendix E the quantification scales and outcomes are given as well.

Influence is an indication of the position that the stakeholder has within the network of all stakeholders. How many other stakeholders does it influence and in what way? Here it is also important to note whether the stakeholder is influenced by other stakeholders.

Opinion is a reflection of the stakeholder's point of view on the problem, not its opinion on possible solutions. Stakeholders that experience the problem as significant get a high rating, stakeholders that do not acknowledge the problem score low.

The involvement of stakeholders is partly intertwined with their opinion. However, there are some differences. The involvement is focused on the stakeholder's responsibilities and the positive and/or negative effects that the problem and/or the solution can have on the stakeholders. Things like status, benefit, etc. play an important role.

The quantitative values for all three criteria are combined in one value that reflects the level of importance of the stakeholder. From interviews and the analysis of the political system it has become clear that especially 'influence' is a key criteria for projects within Colombia. In comparison to 'opinion', the 'involvement' of stakeholders will also have more impact on a positive result. Based on this information the following weights are given to the criteria: influence (2.5), opinion (1.0) and involvement (1.5). This results in a hierarchy of stakeholders as presented in figure 3.1.



(a) Importance of stakeholders

(b) Influence vs. involvement

Figure 3.1: Hierarchy of stakeholders

3.1.2 Conclusions

From the stakeholder analysis and additional interviews it has become clear that there are three parties that have the authority to start a project: the Ministry of ADS (National Environmental Policy), the Bolivar department and the mayor of Cartagena. At this moment in time they do acknowledge that the flooding of the peninsula and the historic center is a problem. However, the authorities do not see the urgency of the problem. This results in continuous postponement of a durable solution.

The shortest route to increase the sense of urgency is through the local government, since this is the area where the (future) problem has the largest impact. Therefore the mayor of Cartagena is the most important stakeholder within this project. This is also confirmed by what was heard in several interviews: ”if the mayor does not acknowledge the problem, then there is no problem”.

There are several stakeholders that have influence on the mayor such as the Bolivar department and the Ministry of ADS. Other parties that can put some significant pressure on the mayor are the secretaries of the municipality, UNESCO and the University. Also FINDETER could be of great value once it is convinced about a solution.

Colombia no longer is a development country. High investment costs are possible as long as they can be substantiated and the benefits and/or revenues are made clear.

Another thing which cannot be concluded clearly from the stakeholder analysis is the influence of the press (newspapers, radio stations, etc). This is a powerful medium to explain the problem, the urgency and the benefits of a solution. Especially for stakeholders in the category 'Users' this might be a good tool to create some support.

It should be kept in mind that the network of stakeholders is a dynamic network. The importance of stakeholders might change over time, or new stakeholders might arise. This makes it a very complex task to accurately manage and satisfy all stakeholders. Also the concept and technical details of a design influence the opinion of stakeholders.

A general strategy of stakeholder management is deducted from the documents provided by Erik Waumans. This is shown in figure 3.2.

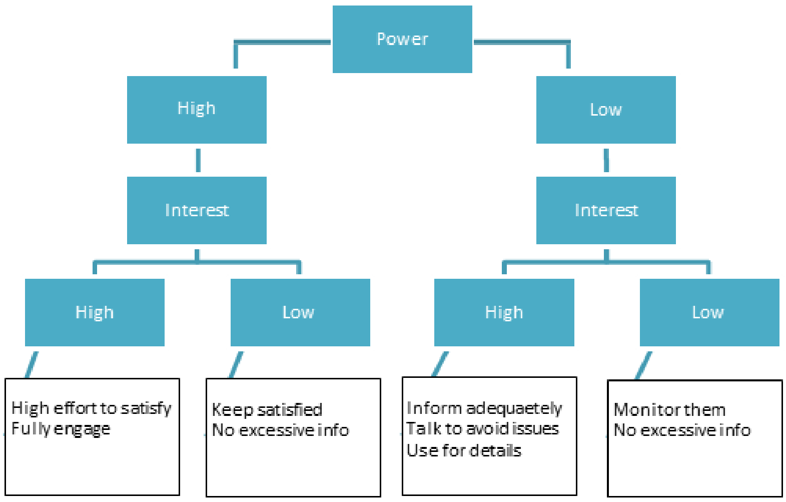


Figure 3.2: General stakeholder management strategy

Especially the contact with the local government and university should be intensified for the preliminary state of the design. Once there is a conceptual design, also other parties such as FINDETER, Ministery of ADS and the Bolivar department have to be involved in process in order to create wide support for a solution. Another important medium to create additional support is the use of the press.

3.2 Political system

In order to make a design that takes the important stakeholders into account also the current political system and its weak points is assessed in this section.

3.2.1 Introduction

Colombia is a presidential republic and one of the oldest democracies of South America. The democracy is separated into three powers, respectively the Executive, Legislative and Judiciary power.[3]

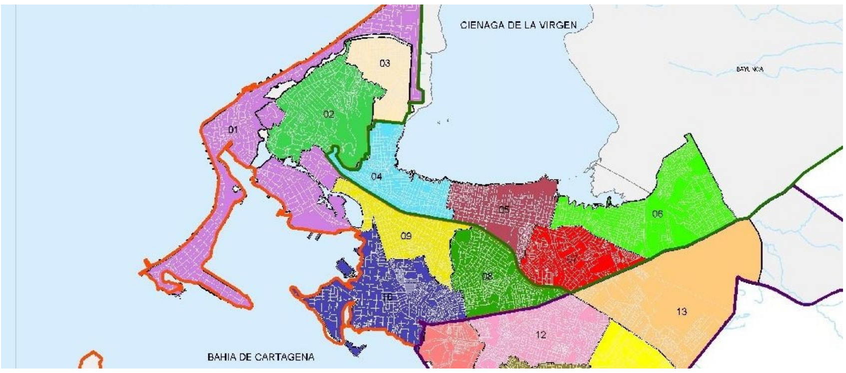


Figure 3.3: Map of the UCGs (see appendix F for a larger version [4])

The 1.142 million km^2 area that Colombia covers is divided into 32 departments plus the capital district Bogotá. The departments on their turn, are subdivided into municipalities. The municipality of Cartagena de Indias is located in the department of Bolívar. The departments are run by their Governor and a Department Assembly, the municipalities are run by the mayor and a Municipal Council. All these representatives are elected for a maximum period of four years.

In 2011 the National Statistical Administrative Department counted 995.709 inhabitants in Cartagena[5]. From all the inhabitants, about 90 % lived in the urban area and the rest in rural areas in 2003 [6]. The department Bolivar is one of the poorest departments of Colombia. In 2010 the GDP per capita in Bolivar was US$ 6,176.70. In 2003, 54% of the people were classified as living under great poverty in Cartagena[6].

The municipality of Cartagena is divided into 15 Unidades Comuneras Gobierno (UCGs, [6]. Bocagranda, El laguito, Manga and Centro are all part of the the first 'comuneras' (UCG 1). The borders of the different UCGs can be found in figure 3.3.

For each UCG the public investment has a different distribution as is shown in the overview of table 3.4 ([6]). The main investments are in education, infrastructure and sports & recreation. Only 0.40 % of the total budget is spent on disaster prevention. For the focus area it is striking that only 0.03% is spent on disaster prevention, while the UCG is completely surrounded by water. Other, more central areas as UCG 2 and UCG 9 invest significantly more with 3.1% of their budget.

Comuna	Total Investment	Participation	Sectors									
			Health	Education	Infraestruc .	Sports and recreation	Basic equipment	Social development	Housing	Security	Disaster prevention	Capacity building	Other
Comuna 1	3.726	7,70%	-	179	1.650	773	44	15	-	17	1	100	948
Comuna 2	3.708	7,60%	-	1.724	1.790	79	-	-	-	-	115	-	-
Comuna 3	2.529	5,20%	65	2.027	304	94	12	28	-	-	-	-	-
Comuna 4	1.819	3,80%	-	629	1.128	55	8	-	-	-	-	-	-
Comuna 5	1.232	2,50%	-	504	540	177	-	-	-	-	-	10	-
Comuna 6	895	1,80%	-	442	247	190	-	16	-	-	0	-	-
Comuna 7	1.523	3,10%	-	723	433	362	5	-	-	-	-	-	-
Comuna 8	7.900	16,30%	-	545	1.376	5.955	24	-	-	-	-	-	-
Comuna 9	2.046	4,20%	-	692	828	66	18	-	381	-	61	-	-
Comuna 10	1.892	3,90%	-	447	269	89	997	-	-	89	-	-	-
Comuna 11	425	0,90%	-	60	217	73	74	-	-	-	-	-	-
Comuna 12	3.785	7,80%	30	311	984	2.441	18	-	-	-	-	-	-
Comuna 13	7.269	15,00%	-	1.633	5.521	70	36	-	-	8	-	-	-
Comuna 14	1.352	2,80%	-	340	855	71	86	-	-	-	-	-	-
Comuna 15	1.733	3,60%	-	68	874	39	741	10	-	-	-	-	-
Corregimientos	6.661	13,70%	23	921	2.695	201	2.645	119	23	20	13	-	2
Total	*48.495*	*100%*	*118*	*11.246*	*19.712*	*10.735*	*4.707*	*187*	*404*	*135*	*190*	*110*	*949*
Sectored	100%		0,20%	23,20%	40,60%	22,10%	9,70%	0,40%	0,80%	0,30%	0,40%	0,20%	2,00%

Figure 3.4: Investment per sector within Comunas in 2003 [6]

3.2.2 Coastal management

According to Rangel-Buitrago et al. [7] there are 3 governmental institutes that are working on the coastal erosion. These are: The Ministry of Enivironment and Sustainable Development (MADS), General Maritime Directorate (DIMAR) and Colombian Oceanic Commision advise (CCO). Nonetheless, none of these institutes has legal responsibility for its implementation. The three governmental institutes are working with different organizations. An overview of the organizations is given in figure 3.5. Their responsibilities are described in appendix F.

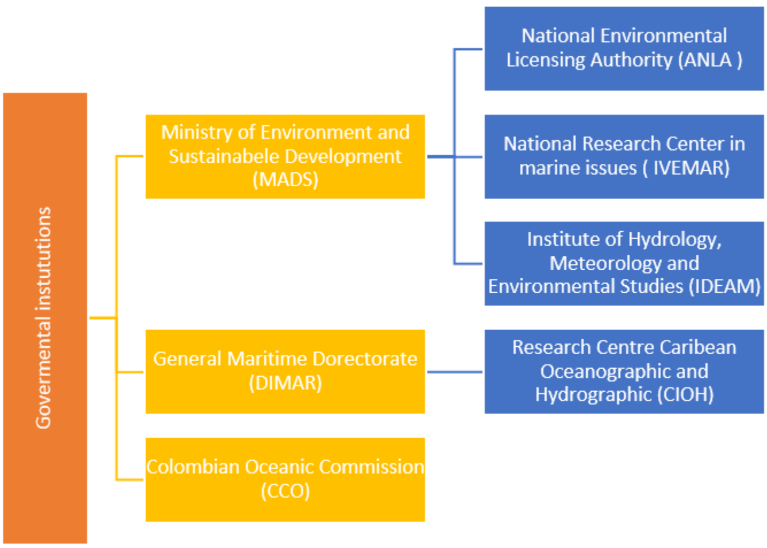


Figure 3.5: Coastal institutes

In general it can be stated that the National Government is responsible for protection level of the coastline. The Bolívar department and the municipality of Cartagena are mostly interested in the economical and social development of their territory. However, in same cases the municipality and department also give order for protection works. This has been the case for the seawall currently under construction at Bocagrande and Castillogrande. Nonetheless, the project is rather described as an 'architectural' project than a 'coastal' project.

3.2.3 Urban drainage management

According to the report Informe de Diagnostico [8], four institutes are related to the drainage system in Cartagena. Below the institutes and a short explanation about there work is given.

Secretaria de Infrastuctura: Its main function is to take care of the civil works that need to be done in the city like roads, public buildings and bridges.

Corporacion Autonoma Regional del Canal del Dique (CARDIQUE): In charge of the environmental and natural resources in the Canal del Dique area. It designed a regional management plan (Plan de Gestión Regional Cardique) to generate and recover public space, conserve and recover the mangrove and environmental education. The institute has a total budget of $ 60.489.833.397 COP.

Aguas de Cartagena: This is the water company of Cartagena. The goals of the company are the extension of the water network in the city, improve the knowledge about correct use of the system and training about the maintenance of the infrastructure of the water.

Establecimiento Publico Ambiental (EPA): EPA is responsible for managing the urban environment of the District of Cartagena. Together with the urban environmental authority it controls the environmental changes in order to ensure the preservation of the environment. The EPA made a plan with clear objectives about the drainage. However, still nothing has been changed to the drainage system since it is not clear who is responsible for the execution. The budget of the EPA is $ 3.630.000.000 COP.

Similarly to the coastal management, it is not clear who is responsible for the drainage systems. Also the different organizations are not working together in a optimal way. For example, if the Department Of Public Works and the Environmental Department would work together to keep the channels free from garbage, the flooding problems could be reduced.

3.2.4 Political instability

The maximum election period is four years. This system was introduced as a part of the anti-corruption policy. The mayor of the municipality has the authority to cancel or rearrange all construction works and budgets. During election campaigns this fact plays an important role in the support for strong candidates, since the mayor can decide which companies will get the new contracts. It also happens regularly that a mayor quits before the official end of his term. These factors make it hard to implement programs for longer periods.

3.2.5 Maintenance

Maintenance in Cartagena is often interpreted as "fix it when it is broken" (restoration). Normally for institutes in Cartagena, investments are more important than maintenance and budgets are not enough to cover both of them. As a result there is no maintenance. This differs from the typical Dutch interpretation that considers maintenance in order to guarantee a minimum level of protection. Figure 3.6 graphically displays the difference between maintenance and restoration.

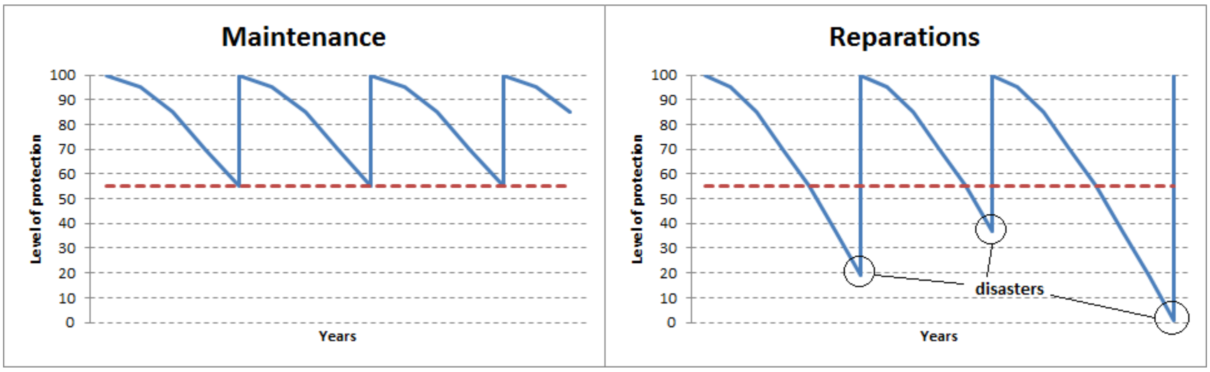


Figure 3.6: Maintenance versus reparations

The restoration way of thinking is partly motivated by the political instability. Solutions are often designed for direct improvement, the effect on the longer time scale and future development are not taken in account. The short term mindset is supported by the low maintenance costs. Nonetheless it also results in a high level of disaster acceptance and unforeseen expenses.

3.2.6 Conclusion

The conclusion includes three levels as derived from the interview with Klaas de Groot (ARCADIS, appendix K). The levels are defined as following:

- **Relational** level describes the interaction with stakeholders.
- **Institutional** level describes how responsibilities are divided and managed.
- **Knowledge** level describes the quality and quantity of knowledge that is available.

On a relational level it seems that in Colombia all stakeholders are involved equally in the process. Nonetheless in most situations there is no stakeholder and/or communication strategy which results in the stakeholders being equally important. It is recommended to determine in advance what stakeholders are consulted on what subjects on at what time during the project.

The institutional level is very complicated in Colombia. It is not always clear which institute has the final responsibility. This also implicates that there is no one to blame which enhances a 'wait-and-see' attitude.

Colombia has more than sufficient universities, companies and well-educated engineers. The quantity and quality of knowledge, in most cases, is not a bottleneck. However, due to the branched structure of institutes and organizations there is not a lot of exchange of information on different specialties. This lack of interaction between specialists makes it difficult to reach an integral approach.

Chapter 4

Boundary conditions

Another important aspect for making a proper designing is knowing what are the boundary conditions of the area that the design is made for. In this chapter a short description of the climatic and coastal boundary conditions is made. The full substantiation of the analysis is given in appendix G.

4.1 Climate

The Colombian Caribbean knows a wet and a dry season. The average minimum and maximum temperatures are 19°C and 37°C. The amount of sun hours per month is 250 h. In January the sun intensity is the most with an average of 280 sun hours per month. The humidity varies between 78 % and 82 % [9].

4.2 Precipitation

Cartagena has a dry season from December until April and a wet season from May until October. From May the precipitation rate increases until the highest precipitation rate is reached in October. In December the precipitation rate suddenly drops to 25 mm and in January until March there is almost no rainfall [10].

Table 4.1: Peak and total amount of precipitation

Duration [h]	**Peak precipitation discharge** [mm/h]	**Rainfall during event** mm / m^2
1.00	130	130
2.00	92	184
3.00	74	223

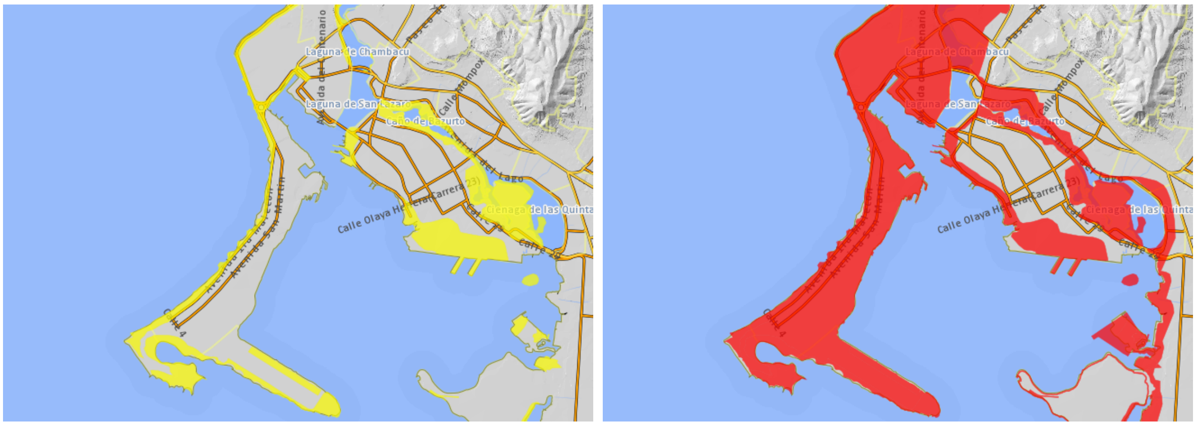
The normative rainfall that will be taken into account is for a return period of 1/100. Depending on the duration different volumes of precipitation must be drained. A list of volumes is given in table 4.1. In this calculation only the peak precipitation discharge is known therefore the assumption is made that the rainfall has a constant distribution. This leads to an over estimation of the total amount of rainfall that will occur. For a fully functioning design this value is however not unreasonable as the design of the drainage system will have to function when a 1/100 event occurs. A possible gamma or lognormal distribution could be applied, however the amount of data is too limited to give an accurate distribution.

4.3 Tidal range

For the Cartagena coast, a tidal analysis has been performed by Torres and Tsimpli [12]. They used hourly measurements gathered over a time span of 49 years. Based on these measurements they made a calculation of the tidal constituents. The coastal area of Cartagena seems to be influenced by a predominantly semi-diurnal tide. The tide presents two low waters and two high waters within a day. The maximum range between these two level is no more than 60 cm, therefore the tide can be categorized as micro-tidal [6]. Taking into account the astronomical tide the maximum tidal range can go up to 68 cm.

4.4 Sea level rise

According to the first NCAP project, Cartagena is one of the cities in Colombia that is highly vulnerable to the sea level rise[13]. The NOAA, National Oceanic and Atmosphercic Administration, has made a long term expectation based on the monthly mean sea level based on data from 1949 to 1992 [14]. According to the graph the sea level will be 5.31 mm/yr +- 0.37 mm/yr with a 95 % confidence interval. According to the data of the UHSLC (University of Hawaii Sea Level Center [15]) the sea level rise will be 5.98 mm/yr a bit more that estimated with the NOAA. If we assume a sea level rise of 5.6 mm/yr, the sea level will rise 0.28 m in the coming 50 years. The municipality of Cartagena has made their own predictions of the flood prone areas for moderate en strong see level rise [16], see figure 4.1.



(a) Moderate see level rise

(b) Strong see level rise

Figure 4.1: Effects due to see level rise [16]

4.5 Land elevation

There is no clear data of the land elevation in relation to mean sea level. For some reasons these values are not given free by the authorities. However from physical observations it has been concluded that land level is approximately equal to mean sea level at Punta Castillo, from this the other values have been estimated, see table 4.2. From the available data it can be concluded that the focus area is almost completely flat, which partly explains the observed low runoff capacity, see chapter 2.

Table 4.2: Surface elevations in reference to MSL

Area	Surface level
Centro	MSL + 1.25 m
Bocagrande	MSL + 0.50 m
El Laguito	MSL + 0.70 m
Castillogrande	MSL + 0.30 m
Punta Castillo	MSL + 0.00 m

4.6 Wind and wave conditions

Two periods can be distinguished: one from November-July, the other from August-October. Both the wind and waves conditions are characterized by these two periods.

4.6.1 Wind

The windspeed reaching the coast of Cartagena is depended on the season. The maximum daily windspeed around March can reach up to 11 m/s, where in the season around October the windspeed does not exceed 8 m/s. These values originate from observations of various weather stations.

The values calculated with the Argoss data are shown in table 4.3. These values are clearly higher than the observed values of the weather stations. This can be attributed to the fact that with a Weibull distribution an extreme value analysis is performed and the results are extrapolated. For further calculations in this report the extrapolated values will therefore be used, since these values give expected values, rather than values based on past observations. Hurricane circumstances are included in the Argoss data.

Table 4.3: Wind speeds found from the Weibull analysis

Return period (years)	Wind speed
5	13.78 m/s
10	13.83 m/s
25	14.11 m/s
50	14.56 m/s
100	15.76 m/s

The wind direction is also greatly dependent on the season. In the first period of November-July the wind is coming predominantly from the Northern/NorthEastern direction, where in the second period also wind is coming from the Western direction. However, for both wind directions the wind is largely blocked by land masses and there is a limited fetch for set-up to occur. The analysis shows no significant wind patterns that reach the coastline and therefore it is assumed that wind set-up does not play a role.

4.6.2 Storm surge

Storm surges can have an extensive effect on the elevation of the water. It should be considered in the design height of any structure that will be constructed. From [17] it can be found that storm surges in this area can increase the sea level up to **1m** above MSL.

4.6.3 Waves

During the period of November-July the wave climate is predominately dependent from swell waves coming from the NNE. The average height is 0.71 ± 0.4 m, where the highest waves exceed 2 m. In the period of August-October also waves from WSW direction are present. The highest waves in this period reach 1.5 m. Direction and magnitude are displayed in a wave rose in figure 4.2.

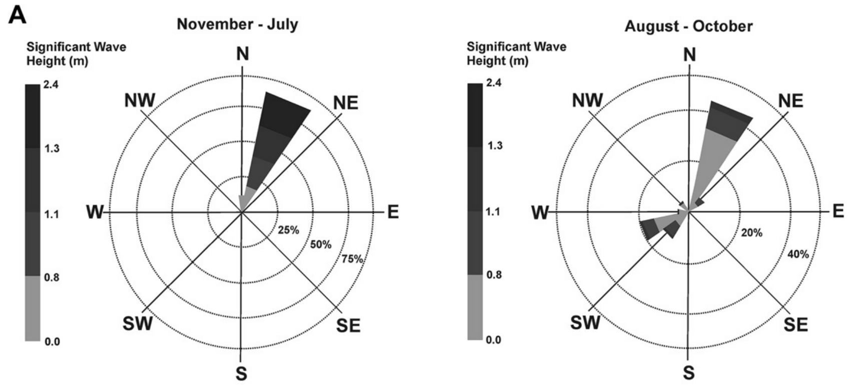


Figure 4.2: Waverose, indicating direction and height [2]

Another check has been made with the Argoss data. The same location as used to find the data for the winds speed was taken. The values found are transformed to wave heights in shallow water close to the coastline using SwanOne. They can be seen in table G.8.

Table 4.4: Shallow water wave heights calculated with SwanOne

Return period (years)	H_s **(shallow)**
5	1.59 m
10	1.60 m
25	1.62 m
50	1.63 m
100	1.67 m

The wave height acquired with SwanOne are a bit lower than the previously mentioned maximum wave heights observed. Still it is chosen to use the shallow wave heights calculated with SwanOne, as the represent expected significant wave heights. In Appendix G.5.3 a full derivation with SwanOne is made where the waves are transformed. For the 1/100 return period a shallow water wave height of **1.67m** is found.

4.7 Coastal evolution

With waves coming in predominantly from the northeast, the beaches of Cartagena are under constant thread of erosion. In the past several problems were caused due to this erosion and the inhabitants tried to prevent this by constructing several groynes along the beaches.

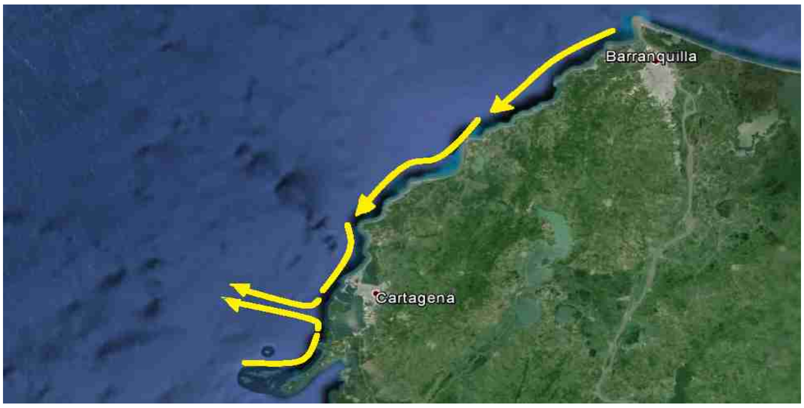
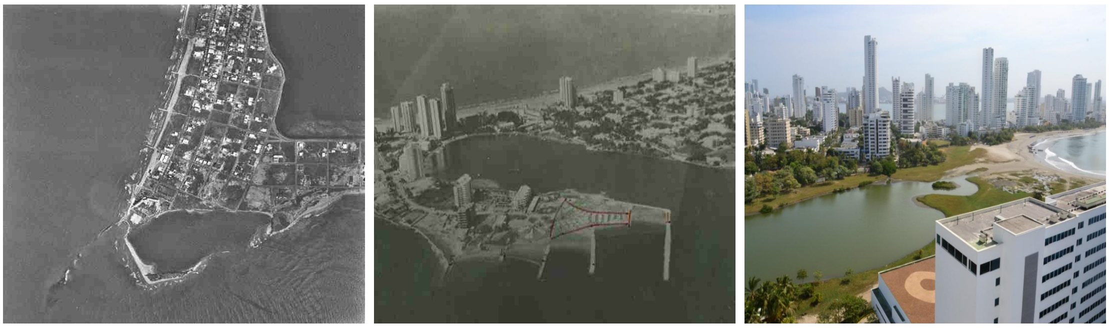


Figure 4.3: Main transport direction of sediment [54]

Most of the sediment transport towards Cartagena originates from up north. Sediment from the Magdalena river is an important source for the coastline of Cartagena. The Magdalena river flows into the Caribbean Sea at Barranquilla, where the sediment continues its travelling. However due to the construction of a massive groyne a large part of the sediment sinks into the ocean. This has caused a lot of erosion downstream. The other source of sediment is coming from the south, from the peninsula of Barú. See Figure 4.3 for an overview sketch.

At a more local scale, drawings and photographs of the Cartagena coastline do not show large changes over the past centuries. However there still are two eye-catching, human-induced changes. The first significant change to address is the construction of groynes along Bocagrande. The second human-induced change is the formation of El Laguito. This part of the peninsula has its origin as a natural sand spit at the tip of Bocagrande. Somewhere around 1960 the sand spit was further filled by human work. To protect this new land groynes were constructed. Due to natural accretion and the construction of additional groynes a lot of new land has been created from the mid-60's up to the late 70's. The development of El Laguito is shown below in figure 4.4. In the years after, the accretion continued which resulted in a complete closing of the El Laguito lake. Nowadays people are complaining about a bad water quality and stench of the lake, however local authorities claim that the water quality is still okay.



(a) Begin 60's (b) Late 70's (c) Nowadays

Figure 4.4: Impression of the El Laguito development (Retreived from [20])

4.8 La Niña

The ENSO effect (better known as El Niño Southern Oscillation) affects Cartagena as well. For Cartagena the cooling phase, La Niña should be considered instead of El Niño. On the Pacific coast of Colombia the sea level can rise 20-30 cm due to the effects La Niña [13]. The effect on the Cartagena coast is normally negligible. Only in 1982 and 1995 there was a bigger sea lever rise of 15 cm and 25 cm, respectively. Therefore, a possible sea level heightening during El Niño should be taken into account.

4.9 Soil conditions and phreatic level

Stated in the report, Plan de Manejo Ambiental, Description Del Proyecto [21], the soil conditions in the considered neighbourhoods consists primarily of silty sand granular material that is gray to reddish brown with the presence of limestone and chert. Underneath a layer of high plasticity clay is detected. There are no exact measurements available, but according to Santiago Rizo (appendix K) the soil consisting of primarily sand can be confirmed. The sand forms a good foundation for construction projects, but might induce problems with seepage over the years, due to the expected sea level rise. The same report states that the phreatic levels along the Avenida San Martin alignment varies between 0.3 m and 0.45 m below surface level. Due to the expected sea level rise, this is expected to increase in the future.

4.10 Seepage and Piping

Seepage is a flow of water that is able to pass the coastal defence system via gaps, cracks or connections between structural parts. When the floes goes through a pipe-like channel underneath the structure, eroding sediment particles, the process is called piping. This is potentially very dangerous, since once all sediment is flushed away, the water flow is able to carry the entire structure. The structure has to be designed to prevent these effects. The formulas of Bligh and Lane define a limit state that indicates a critical ratio between the differential head and the seepage distance [22]. The seepage distance consists of a horizontal and vertical part. The estimation of Bligh is that L = $\Sigma\ L_V + \Sigma\ L_H$. Lane estimates the seepage length as L = $\Sigma\ L_V + \Sigma\ (1/3) \cdot L_H$. The dimensions are illustrated in figure 4.5.

The structure should be able to meet a design sea level which is determined to be MSL + 2.03m and the phreatic level of 0.45m. Therefore the differential head is assumed to be 2.03 + 0.45 = 2.48 m. The sand is assumed to be dense and can be categorized as fine sand, so a C_b-value of 15 and C_l-value of 7.0 should be taken into account.

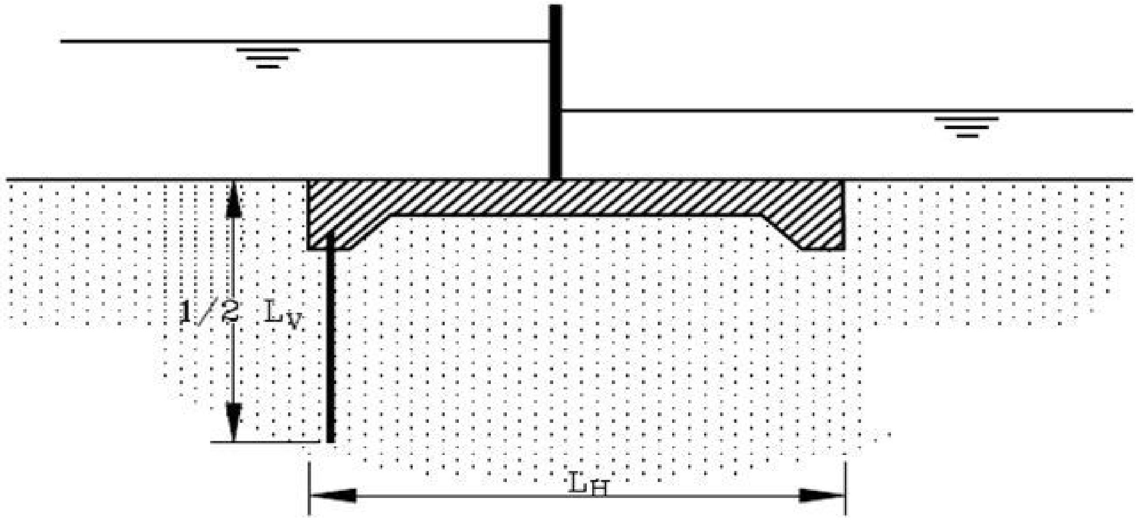


Figure 4.5: Seepage method of calculation

4.11 Subsidence

The last years SIGRAS is a reference system identical to the International Terrestrial Reference System (ITRS). Reference stations are positioned all over America to identify the tectonic plate moments and crustal deformation. From those data the subsidence is extracted from the station in Cartagena to the discrete station velocities in relation to the land subsidence. According to figure 4.6 it can be concluded that the relative subsidence is 2.2 mm/year. In figure 4.6 the vertical component from 2000 until 2014 is shown.

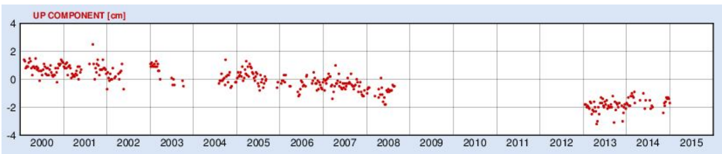


Figure 4.6: Subsidence from 2000 until 2014[55]

4.12 Resources

A quick scan of the economical situation and local resources shows that all types of construction materials are available. Most commonly used products are concrete and refractory clay.

4.13 Overtopping

However not really a boundary condition, it is wise to include allowable overtopping values. These are based on the "European Overtopping Manual" (2007), see table 4.5.

Table 4.5: Allowable overtopping discharge

Allowable damage	Discharge [l/s/m]
Embankment seawalls / sea dikes	
No damage if crest and rear slope are well protected	50-200
No damage to crest and rear face of grass covered embankment of clay	1-10
No damage to crest and rear face of embankment if not protected	0.1
Promenade or revetment seawalls	
Damage to paved or armoured promenade behind seawall	200
Damage to grassed or lightly protected promenade or reclamation cover	50

For the conditions that are present in Cartagena an overtopping discharge of **200 l/s/m** is implemented.

4.14 Stakeholders

From the stakeholder analysis a few things can be derived which should be taken into account in the design. For a project to be feasible it should provide enough political and social support to push it through the political process. This could be found in either an increase in status for important stakeholders or providing additional value.

It should be taken into account that a relatively short term vision is in place. With the mayor changing every four years, this vision implies that a project must be realizable within this period. Taking lobbying and the political process into account a project should be constructed within 2-3 years.

In addition to this in the current political environment it is difficult to realize an organization that is responsible for maintenance of the coastal system. Therefore it is important to try and minimise the amount of maintenance required for the project.

Chapter 5

Program of requirements

To make the design process more straight forward a program of requirements is prepared which clearly states the demands and requirements the design should fulfil. In this a section there are hard demands and more subjective demands which are clear stated below.

5.1 Summary of boundary conditions

All proposed solutions need to satisfy the boundary conditions that are discussed in chapters 2, 3 and 4. Most of the boundary conditions are hard values directly derived from climatological circumstances for a 1/100 condition. These are listed in table 5.1.

Table 5.1: Summary of boundary conditions

Boundary condition	**Value**
Maximum rainfall event duration	3 hours
Maximum rainfall event intensity	233 mm/m^2
Maximum discharge peak	50.000 m^3
Maximum wind speed	15.76 m/s
Maximum tidal range	0.68 meter
Maximum storm surge	1.00 meter
Maximum shallow water wave height	1.67 meter
Maximum effect of La Niña	0.30 meter
Maximum allowable overtopping discharge	200 l/s/m
Expected sea level rise over 50 years	0.28 meter
Expected land subsidence over 50 years	0.11 meter

5.2 Design level

Each area needs a minimum design level considering high tide, La Niña, sea level rise and land subsidence (see table 5.2).

Table 5.2: Minimum level of protection

Boundary condition	**Value**
High tide	MSL + 0.34 meter
La Niña	MSL + 0.30 meter
Sea level rise	MSL + 0.28 meter
Storm surge	MSL + 1.00 meter
Land subsidence	MSL + 0.11 meter
Total	MSL + 2.03 meter

Protection against local wave conditions should be added to the design level. For Centro, Centro Sea, Boca Beach and El Laguito the maximum wave conditions are assumed for a 1/100 event. For Castillo Beach and Punta Castillo 75% is taken into account. For Castillo Bay, Boca Bay and Centro Bay the wave conditions are assumed to be 50% of the maximum conditions. Due to the lack in variety of measuring points these reductions are rather based on common sense and physical observation than on hard data. Table 5.3 shows the design levels per area.

Table 5.3: Design levels per area

Centro, Centro Sea, Boca Beach & El Laguito (100%)	**Value**
Minimum level	MSL + 2.03 meter
Waves	MSL + 0.84 meter
Total	MSL + 2.87 meter
Castillo Beach & Punta Castillo (75%)	**Value**
Minimum level	MSL + 2.03 meter
Waves	MSL + 0.63 meter
Total	MSL + 2.66 meter
Castillo Bay, Boca Bay & Centro Bay (50%)	**Value**
Minimum level	MSL + 2.03 meter
Waves	MSL + 0.42 meter
Total	MSL + 2.47 meter

In addition to these values a freeboard must be added. This freeboard will differ per structure required and will be determined in a later stage. The values of the freeboard take into account the maximum allowable overtopping of 200 l/s/m. These values include the dampening of waves due to revetments, slopes or other structures. These values are too much dependent on the type of structure and its design and can only be taken into account in a later stadium of design.

5.3 Additional requirements

From the area analysis, flood risk assessment, stakeholder- and political analysis it has become clear that there are other requirements that will result in a solution that fulfills our goal.

Table 5.4: Design level Castillo Bay, Boca Bay and Centro Bay

Additional requirements
The design should have a service time of 50 years
The design should be low maintenance
The design should be constructed within 2-3 years
The design could allow an overtopping / overflow discharge
The design should have a drainage capacity to drain 233 mm/m^2 within 3 hours
The design should provide value leading to political and social support
The design should clearly state the investment costs
The design should clearly state the possible revenues
The design should give the municipality more status

Chapter 6

Elements of solutions

6.1 Introduction

In this chapter the solutions for the current problems are investigated at element level. First a distinction is made between solutions for the drainage and the coastal problems. For the coastal problems the solutions are clustered in three groups: 'Building with nature', 'Added value' and 'Hard structures'. Just like the coastal solutions also the drainage solutions are divided in three groups: 'Prevention', 'Retention' and 'Runoff', which is shown in figure 6.1. In sections 6.2 'Coastal solutions' and 6.3 'Drainage solutions' the possible new designs are given.

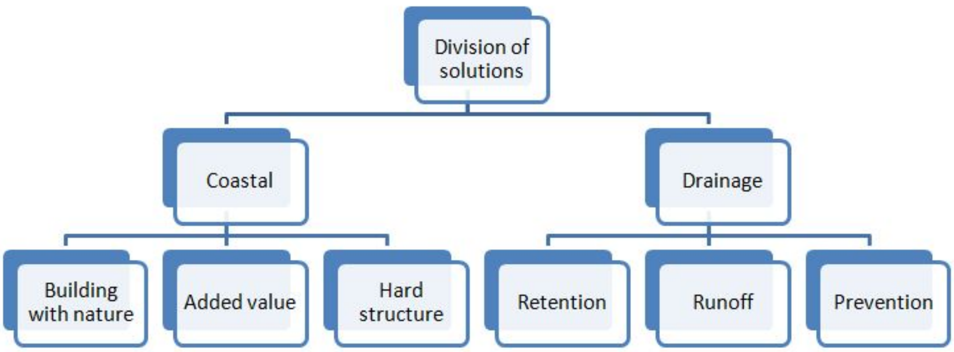


Figure 6.1: Overview of the solutions

For the design of solutions, the drainage and coastal system is further subdivided into smaller areas. This distinction is made based on the different characteristics of the area, i.e. a beach has different demands for a solution than a revetment. This is done separately for the coastal and drainage system and is shown in figure 6.2. The navy base will not be taken into consideration as its future development is uncertain.

Each element of the possible solutions will be described briefly. Then per area an evaluation will take place about which options could be suitable as some solutions can already be rejected based on the characteristics of the area. The options that could be suitable will be graded with a Multi Criteria Analyisis (MCA) in the next section.

To find out which design creates the most value, for each area a MCA is made, which can be found in chapter 6.4. The MCA shows the best solutions for each individual area. In chapter 7, the individual solutions will be merged into a combined system where drainage and coastal protection are integrated to form a total system.

(a) Coastal areas

(b) Drainage areas

Figure 6.2: Division of the areas

6.2 Coastal solutions

In this part the idea behind the main groups of coastal solutions, e.g., building with nature, added value and hard structure will be explained. Also a first selection will be made for which elements are suitable for further investigation.

6.2.1 Building with nature

This part of the report illustrates the solutions based on the 'building with nature' approach. The building with nature approach uses soft measures in a way that the properties of natural elements work together with the forces of nature rather than against them. The advantages of these measures are that they are sustainable, relatively cheap and work on a long term. On the other hand they are often less effective and the visible safety is low.

Possible solutions

Nourishment One of the most common practices in the building with nature approach is to ensure that the beach is extended. This is done by making sure that more sediment is deposited on (existing) beaches. A longer beach means that the slope of the beach becomes more gentle. This slope forces the waves to break further away from the coastline than in the present situation. The extension of the beaches can be achieved by nourishments at the beach or nourishments at the edge of the upper shoreface as a sandbar.

This solution on first investigation seems viable for areas that have beaches, such as Boca beach, El Laguito, Castillo beach and Punta Castillo, in front of them and either have coastal protection against erosion or are located in areas that do not suffer from erosion much.

GeoHooks Another way to trap more sediment is to use sand trapping elements like GeoHooks [24]. This does not create much extra value compared to the nourishments that create beaches, but it does trap sand to reduce waves.

This presents a bit of an eyesore and is only desirable for sections that do not offer recreational use and that do suffer from erosion. This leaves the Centro Historico and Centro sea areas.

Vegetation In addition to reducing the waves by trapping extra sediment, one could also protect the coastline by building natural defences in front of the shore. Where in building with hard constructions sometimes a breakwater or revetment is needed, in building with nature it is strived for to use the properties that some vegetation have to reduce the influence of waves.

Again this is something that is not applicable to areas with recreational use, but could prove useful for erosion sensitive areas. It could be implemented in the Centro Historico, Centro sea and El Laguito area.

Oyster or coral reefs Another solution for the reduction of tidal waves can be achieved by extending the foreshore. This can be done by building oyster or coral reefs on which the waves start to break.

Not applicable to areas where many boats such as fisheries are located with relation to anchors and nets. This rules out El Laguito.

Wetlands A solution that can trap sediment and reduces waves is the creation of more extensive intertidal areas. These more extensive areas are known as wetlands. Wetlands are naturally occurring areas, usually at the debouchment of (big) rivers. Wetlands also can serve as a wastewater treatment system and are nowadays mostly build for this purpose.

This will require a large amount of space that is only present at the Centro Historico area.

Sea grass Instead of just building with natural elements also a combination with other types of construction can be made to enhance the protection level or to generate additional values. Sand bars at the end of the upper shoreface can for instance be covered with seagrass. This will mean that the bar does not really has the function of a nourishment anymore, but more of an offshore breakwater, as the seagrass will retain the sediment in place.

This would make for a viable option for all areas that suffer from much erosion and also for recreational areas as the breakwater would be located offshore and out of sight. This would imply the entire sea side of the peninsula and Centro Historico. With the exception of Punta Castillo as it does not suffer from much erosion.

Rich revetment Another measure to combine building with nature with a structure is that of rich revetment. In this solution constructed revetments are covered with vegetation which will reduce the run up of waves, depending on the type of vegetation and the condition. A proven way of doing this is to use a reinforced mattress through which plants can grow that hold the sediment in place. The plants need time to grow, so at first a filter is needed to retain the sediment. This function can be fulfilled by a biodegradable geotextile.

This would not be implementable for recreational areas and only useful for areas that suffer from erosion. It would be very suitable for Centro Historico, Centro sea, El Laguito and Punta Castillo.

Overview of suitable solutions

	Nourishment	GeoHooks	Vegetation	Reefs	Wetlands	Sea grass	Rich revetment
Centro historico		√	√	√	√	√	√
Centro sea		√	√	√		√	√
Boca beach	√			√		√	
El Laguito	√		√			√	√
Castillo beach	√			√		√	
Punta Castillo	√	√		√			√
Castillo bay				√			
Boca bay				√			
Centro bay				√			

Table 6.1: Possible Building with nature solutions

6.2.2 Added value

The goal of this variant is to create a solution for the main coastal problem and solving smaller issues as well or creating new features. An advantage of the solution is that the solution does not just create coastal safety but also adds new values, e.g. recreation and aesthetics. However, the investment costs of the solutions will often be much higher.

Possible solutions

Promenade In this option the recreation possibilities are expanded. A pedestrian promenade is constructed which offers space to activities such as running, skating, street-food etc. Also the promenade could be home to street vendors, small-scale restaurants and live music, providing a true Caribbean atmosphere.

This could be implemented in all the areas that have a high touristic value such as Centro historico, Boca Beach, El Laguito and the entire bayside.

Marina The marina will exist of a quay wall to protect the area against flooding and a jetty structure with finger piers to create enough berths for yachts to moor. The quay wall can be integrated with the funcion of a promenade in above paragraph. This could lead to sharp increase of the land value (interview Prof. Mouthon Bello, appendix K).

It would only be applicable on the bay side where little wave conditions exist, like the Centro, Boca and Castillo Bay side.

Retention dike An interesting concept for a combination between coastal protection and a retention facility is the implementation of a retaining basin inside a dike that would be constructed along the coast as coastal protection. The idea is that during high tide the drainage capabilities are very limited or have to consist of large pumps that force the water out. If a large dike is constructed to keep out seawater, a retaining basin will be constructed inside the dike. The retention basin will catch the runoff water and store it temporarily, until low tide, when it is being discharged by gravitation.

This could prove to be a viable solution on the entire bay side and at Centro Historico as it would diminish the floodings substantially.

Step dike A step dike is an embankment designed in the shape of giant stairs. The 'steps' are created by a number of horizontal flat surfaces that can be used for several functions. On the crest of the step dike a promenade is constructed that allows different activities like strolling along the sea, relaxing, doing sports and creating a park like area. This could create additional value for both residents as tourists.

The step dike seems to only have two prime locations where it would coincide with the current activities. These locations would be Centro Historico and El Laguito.

Overview of suitable solutions

	Promenade	Marina	Retention dike	Stepdike
Centro historico	$\surd$		$\surd$	$\surd$
Centro sea			$\surd$	
Boca beach	$\surd$			
El Laguito	$\surd$			$\surd$
Castillo beach				
Punta Castillo			$\surd$	
Castillo bay	$\surd$	$\surd$	$\surd$	
Boca bay	$\surd$	$\surd$	$\surd$	
Centro bay		$\surd$		

Table 6.2: Possible Added value solutions

6.2.3 Hard structure

Hard structures are the old fashioned solutions. They are highly visible structures and help control the local issues. However, they could have a negative influence further on the coast, and score low on aesthetics.

Possible solutions

Sea wall A sea wall is a concrete or rocky wall that expands along the coastline and prevents the coast from eroding and flooding. It reflects the incoming waves which could lead to big problems with scour at the bottom of the sea wall. Also seepage could form an important issue.

It could be implemented at any area, except for Boca beach and Castillo beach, due to the presence of beaches. It could be implemented at the back of the beaches though.

Revetment Revetments are structures that are built alongshore to the coastline to protect the land behind it from erosion. They require maintenance every few decades, since the structure degrades after some time due to breaking waves.

The revetment would be useful to apply to the erosion prone areas of Centro Historico, Centro sea, El Laguito and Punto Castillo. At these points it would not hinder any current activities.

Groynes Groynes are rocky, concrete or wooden walls or barriers constructed perpendicular to the coast. Their main goal is to capture sand from the alongshore sediment transport, in order to let the beach increase between the groynes. However, on the down drift side there is shortage of sediment, which could lead to erosion problems.

Groynes are widely applicable as they do not hinder any activities, but are capable of reducing erosion. It would only need to be applied to the erosion prone areas at the sea side.

Breakwater An offshore breakwater consists of natural boulders or concrete blocks that are placed offshore. The structure breaks the incoming waves further offshore to reduce the energy closer to the shore.

A breakwater only seems desirable at locations with a lot of erosion. The erosion prone areas where this could enhance the coastal protection are Centro Historico, Centro sea, Boca beach and El Laguito.

Overview of suitable solutions

	Sea wall	Revetment	Groynes	Breakwater
Centro historico	√	√	√	√
Centro sea	√	√	√	√
Boca beach			√	√
El Laguito	√	√	√	√
Castillo beach			√	
Punta Castillo	√			
Castillo bay	√			
Boca bay	√			
Centro bay	√	√		

Table 6.3: Possible hard structure solutions

6.3 Drainage solutions

In this part the idea behind the main elements of drainage solutions: 'Retention', 'Prevention' and 'Runoff' will be explained. Similar to the section about coastal solutions, a selection of the possible and suitable solutions will be given.

6.3.1 Retention

The retention solutions are meant to collect the stormwater temporarily so that it can be released slowly and controlled into the sea during low tide. This way the peak discharge will be distributed over a longer period of time. Advantage of this system is that the water can be released into the sea by means of valves, which requires less pumping capacity. However, in case of an excessive rain event a lot of storage is needed. An other disadvantage lies in the danger of stagnant water which is the perfect habitat for mosquitoes.

Possible solutions

Multi purpose areas For this solution parts of existing buildings are investigated to implement a water retaining function besides its current function.

Most of the considered buildings consist of a basement. Often these are used for parking of cars. In the wet season these garages can be redesignated to serve as retention basins. It remains a question however how desirable this solution is, since the cars need to be parked somewhere else and after the water is pumped out also the garage needs to be cleaned.

Rooftop retention Instead of storing water underneath buildings, water can also be stored on top of buildings. Retention basins can be constructed on the rooftops of the buildings in the Bocagrande peninsula. The volume of the retention area is uncertain, since it is unclear how much extra load the current buildings can withstand. The water collected on top of the buildings can be used for purposes inside the building, such as flushing of toilets. This way the water won't end up on the street. In appendix H a rough estimate is made and a total amount of 540 m^3 can be stored.

Green roofs The concept of a green roof is that it holds the water with its vegetation and root system and delays the water runoff to the surface. The implementation of green roofs could partly decrease the peak in drainage volume that the flood prone areas must be able to drain. It also has a number of other advantages that can be found in appendix H.

Around 25% of Bocagrande consists of buildings with a roof suitable for green roofs. This is a total area of 0.27 km^2. With a possible retaining capacity of 10 mm per event this would reduce the drainage volume by 2660 m^3.

Underground retention There is an option for underground retention of water, by constructing storage basin underneath lowrise buildings. With a storage depth of 0.5 m a total estimated amount of 93450 m^3 can be stored in underground storages. For a more detailed elaboration see appendix H.

Absorbing vegetation A more natural solution can be found by the possibilities of planting vegetation that can absorb a certain part of the water during a rainfall event. These flora also have to be able to survive in the dry period.

Succulent plants can be considered, since these plans can store moisture within the body an can also retain it for a long period. The way they take in the water is via a extensive shallow root system. This implies that there is also need for infiltration. The infiltration capacity of the surface has to be limited though, as the succulent plants can take in the water from the shallow root system in a very short time span. Examples of succulent plants are cacti and aloe species. In appendix H an elaborated calculation can be found that result in the unit of one square meter of cacti to be able to absorb 0.14 m^3 of water.

Canals This element consists of several small canals that can hold the excess rain water during the peak periods. They will be constructed alongside the roads and will have to be dimensioned appropriately to the required volume. For a normative precipitation event of 223 mm the capacity of a canal would have to be relatively large. These canals could be interconnected which would give an even distribution to the amount of water each canal would hold. The canals would have to be dug in to ensure that the water would runoff into the canals from the streets. Crossings could be implemented by means of culverts.

A problem of this option could be the eventual runoff from the canal to the sea, a slope towards the sea could facilitate this. This could be done by a consort which would pump the water out. If the water would not be able to runoff properly problems can occur with water quality as well as attract mosquitoes.

Roads retention It was estimated that 70% of peninsula was covered with buildings. The other 30% can therefore be considered to be covered with roads, as almost the whole peninsula is fully built. Water retention possibilities can also be investigated here. Permeable pavement is an option an a rough estimate is that on average a square meter of permeable pavement can retain 0.084 m^3 a day.

A possible restraint of this solution is the high groundwater level of the flood areas. Currently the groundwater is low enough to let the water infiltrate, but with the increase in sea level and therefore groundwater this could pose a problem. However for short term it could pose a good addition and possibly also in the future if there are sheet pile walls.

Overview of suitable solutions

	Multi purpose areas	Rooftop retention	Green roofs	Underground retention	Absorbing flora	Canals	Roads retention
Centro				√	√		√
Sea side		√	√	√	√		√
Bay side	√	√	√	√	√		√

Table 6.4: Possible retention solutions

6.3.2 Prevention

The solutions in this section are based on the prevention of flooding due to stormwater of high valued areas, e.g. the roads, the hospital etc. A big disadvantage of these solutions is that it only solves the problems locally.

Possible solutions

Closure of Cartagena Bay Since at the studied areas there is not enough space available for the retention of water, another solution is seeked into using Cartagena Bay. In order to create space for water retention, a part of Cartagena Bay will be transformed into an enormous retention basin, by closing it off from the rest of the bay. Aim is to protect the bayside of Bocagrande, Castillogrande and Centro from tidal intrusion and be able to let the rainwater runoff. The concept will be elorated further in appendix H.

Elevation of roads Elevation of the road with an earth body could be used to prevent the traffic congestion during flooding. The earth body could also function as coastal defence at the roads located near the sea. Through the earth body beneath the roads, pipes with valves need to be constructed, in order to let the stormwater runoff to the sea. Furtermore, the roads need to be connected to the current parking lots and buildings. Disadvantages of this solutions is that it forms an obstruction getting to the beach and that it is only a solution to the traffic problems during flooding but not to the other flooding problems.

Polders A polder is an area of land surrounded by embankments in which the water levels are controlled artificially, meaning it has no direct connection with surrounding waters. The water can be managed by means of pumping or drainage by opening sluices at low tide. Often a system of ditches is applied, to drain water from low-lying areas, from which the water is drained or pumped out again.

Valves The current system is designed to discharge stormwater by gravity into the Caribbean Sea or Cartagena Bay during low water levels in the surrounding water. To prevent tidal intrusion during high water levels, a check valve is a suitable option.

A check valve is a valve that only allows flow through it in one direction. There are many different types of valves available to process the stormwater. The best available options are the duck valve and the inline check valve. These are extensively discussed in appendix H.

Overview of suitable solutions

	Closure of bay	Elevation of roads	Polder	Valves
Centro		√		√
Sea side		√		√
Bay side	√	√		√

Table 6.5: Possible prevention solutions

6.3.3 Runoff

The runoff solutions are designed to discharge the stormwater immediately into the sea. This can be done by the use of pumps or by creating higher elevation levels, allowing the water to be discharged into the sea by gravitation.

Possible solutions

Elevation In the middle of the peninsula the roads have the highest elevation level, and will decay gradually towards the sea and bay side. When the gradient of the roads on the peninsula increases, the runoff will improve. This gradient can be increased by heightening the roads with the highest elevation level even more. At Centro this is not possible, due to UNESCO World Heritage regulations.

Pumps With a small bed slope available, the runoff can be increased by installing pumps. These could remove the water from the streets even without a gradient or hydraulic head being present. There are two options for pumps available: mobile and fixed pumping systems.

Mobile versus fixed pumps The implementation of fixed pumps requires a good system of pipes and retention basins, this is not present in the current situation. An investment is needed in order to achieve this. The system has a continuous and predictable capacity, however it is not really flexible.

Mobile pumps can be deployed whenever and wherever required, this makes them a lot more flexible. They are basically similar to a vacuum cleaner, the streets serve as retention basin. Investment costs are lower since no additional infrastructure is needed, on the other hand it requires higher administrative costs like planning, coordination and service.

With the implementation of pumps it could still occur that for short periods of time a small layer of water is present on the streets. However the duration and level can be significantly reduced. Pumps are therefore considered a feasible (part of the) solution.

Overview of suitable solutions

	Elevation	Mobile pumps	Fixed pumping system
Centro		√	√
Sea side	√	√	√
Bay side	√	√	√

Table 6.6: Possible runoff solutions

6.4 Multi criteria analysis

To create a system that is not only technical feasible but also adapts to the social standards, stakeholders are included as an important criteria. A process is created whereby when a certain solution is implemented the 'involvement', 'interest' or 'opinion' can change. The stakeholders adapt to that as well [25]. Hereby the most desirable option is chosen and possible financiers and more influenced stakeholders can be engaged at the project.

Important in the multi criteria analysis (MCA) are the different criteria by which the solutions are measured. The criteria are chosen on based on the stakeholder analysis. This MCA indicates only a rough sketch of the criteria. In the following MCAs the criteria will be subdivided to create a more precise MCA.

1. **Social** Is there support in the community and does the solution benefit parts of the population?
2. **Technical** How feasible is the solution in short and long-term and does it have secondary impacts?

3. **Administrative** Is there already funding for this system and how easy is the system to maintain and operate?
4. **Political** Would there be political and public support?
5. **Legal** Are there legal challenges that need to be considered?
6. **Economic** Is the solution cost beneficial and should there be funding by private parties?
7. **Environmental** Does the solution contribute to the environmental goals of the community?

The weights reflect the preference of the different stakeholders in this project. The weights are determined by the interviews held, presented in appendix K

Table 6.7: Criteria with weights

Criteria	**Weight**
Social	0.09
Technical	0.15
Administrative	0.15
Political	0.18
Legal	0.11
Economic	0.19
Environmental	0.13
Total	1.00

The different elements of solutions are given a ranking of 1-5 where 1 is negative 3 is neutral and 5 positive according to the criteria. In appendix H the ranking of the different solutions can be found.

6.5 Results

In table 6.8 and 6.9 the results of the multi criteria analysis for the coastal solutions can be found. For a full derivation of the MCA for each section see appendix H.

Table 6.8: Results MCA Building with Nature and Added Value

	Geohooks	Vegetation	Reefs	Wetlands	Sea grass	Rich Revetment	Nourischment	Promenade	Marina	Retention dike	Step dike
Centro Historico	3.07	3.24	2.58	2.87	3.02	3.47		2.76		2.60	3.20
Centro sea	3.07	3.24	2.58			3.47				2.60	
Boca beach	1.80		1.98				3.11	3.33			
El Laguito		2.58			2.49	3.13	3.11	2.42			2.78
Castillo beach			2.13		2.69		3.11				
Punta Castillo			2.22			3.13	2.96			2.44	
Castillo bay			2.22					3.33	3.02	2.56	
Boca bay			2.22					3.33	3.02	2.56	
Centro bay									2.49		

Table 6.9: Results MCA Hard Structure

	Sea wall	Revetment	Groyns	Breakwater
Centro Historico	3.51	3.73	3.38	3.38
Centro sea	3.51	3.73	3.38	3.38
Boca beach			3.38	3.38
El Laguito	3.51	3.73	2.93	3.07
Castillo beach				
Punta Castillo	3.67			
Castillo bay	3.67			
Boca bay	3.67			
Centro bay	3.67			

In table 6.10 and 6.11 the results of the multi criteria analyses for the drainage system can be found. For a full derivation of the MCA for each section see appendix H.

Table 6.10: Results MCA drainage system

	Multi purpose area's	Rooftop	Green roofs	Underground	Absorbing flora	Channels	Road	Close of Bay	Elevation of road	Valves
Centro Historico				2.40	2.04		2.49		1.96	2.62
Sea Side		2.29	2.13	2.09	2.04	1.69	2.49		2.36	2.62
Bay side	2.24	2.29	2.13	2.09	2.04	1.69	2.49	2.62		

Table 6.11: Results MCA Drainage system Runoff

	Elevation gradient	Mobile pumps	Pumping system
Centro Historico	2.00	2.31	2.49
Sea side	2.13	2.31	2.49
Bay side	2.13	2.31	2.49

Chapter 7

Global solutions

Based on the results of the multi criteria analysis of the elements, three concepts have been developed. These concepts will be further evaluated on their feasibility and chances of success. The three concepts are based on different points of view:

The Green City: aims for an environment friendly solution and a sustainable image
The Safe City: aims for solid and simple solutions that easily merge with current structures
The Showpiece: aims for a solution with additional value and opportunities for investors

In this section each concept will be discussed separately. Per concept a qualitative description of the design and the financial and political opportunities is provided. Subsequently a more quantitative description is given of the drainage capacities, construction time, risk and initial cost. Finally the three concepts are evaluated with the use of a multi criteria analysis.

(a) Green City (b) Safe city (c) Showpiece

Figure 7.1: Overview of the 3 global solutions

7.1 System 1: Green City

The idea of this system is to give the city a green and sustainable image. The coastal protection however still has priority together with the stormwater system it should appear as a natural part of the city. An impression is shown in figure 7.2a.

(a) Impression (designrulz.com)

(b) Elements

Figure 7.2: Overview Green City

7.1.1 Design of the coastal protection

Figure 7.2b and table 7.1 show the characteristics of all the considered elements. Along Centro and Centro Sea a rich revetment is constructed including the building with nature approach. Boca Beach is further extended by means of a nourishment and additional groynes located at the small parts of the beach. El Laguito suffers high erosion rates so a rich revetment is constructed to dissipate wave energy.

Table 7.1: Characteristics of Green City concept elements

Element	**Length [m]**	**Width [m]**	**Volume [m3/m]**	**Volume [m3]**
Centro - Rich revetment	1.800	15,00	37,50	67.500
Centro sea - Rich revetment	1.200	15,00	37,50	45.000
Boca Beach - Nourishment	1.800	50,00	250,00	450.000
Boca Beach - 4 Groynes	320	4,00	20,00	25.600
El Laguito - Rich revetment	1.100	15,00	37,50	20.480
Castillo Beach - Nourishment	1.000	50,00	200,00	200.000
Castillo Beach - 4 Groynes	320	4,00	16,00	20.480
Punta Castillo - Rich revetment	640	12,00	24,00	15.360
Castillo Bay - Ext. foreshore	1.000	100,00	450,00	450.000
Boca Bay - Ext. foreshore	1.000	100,00	450,00	450.000
Centro Bay - Seawall (small)	1.300	1,50	6,00	15.600

Castillo Beach will also be protected through a widening of the beach with the use of groynes and a nourishment. At Punta Castillo again a rich revetment will be constructed. At the bayside (both Castillo- and Boca Bay) the foreshore will be extended with an intertidal area which reduces incoming waves. The last part of the concept is to construct a small seawall along Centro Bay.

7.1.2 Design of the drainage system

Because of the UNESCO world heritage status of Centro the drainage system is divided into two parts: Centro and 'Peninsula'. The peninsula covers the areas of Bocagrande, El Laguito and Castillogrande.

The limitations by UNESCO to make changes in the appearance result in a design at Centro that is hidden for the public eye. First part of the design is to reconstruct the roads (where necessary) to create a sufficient slope. Stormwater will runoff by gravity, from the street towards the sewer infrastructure. The sewer system will not be able to discharge the stormwater by gravity so pumps are installed to discharge it towards the sea. In order to prevent intrusion the outlets are equipped with valves. To reduce the required pumping capacity roads with a permeable pavement will be constructed. The increase in infiltration capacity will result in a lower peak discharge.

At the peninsula the same system will be implemented with some additions that also consider the Green City image. For example green roofs offer an extra retention capacity that lowers the peak discharge. Planting of vegetation with high absorption capacities further decreases the peak discharge. In order to guide the water into the right direction the land will be elevated at specific locations to create a sufficient slope. In the historic center this is not possible due to UNESCO restrictions.

7.1.3 Politics and finance

This option is likely to be supported by stakeholders that do take high care about sustainable value, such as the EPA. Other stakeholders that might be interested in this solution are parties that take some care about sustainability such as the Mayor, Bolívar department, MADS and FINDETER. However, these stakeholders are also interested in keeping the investment costs low.

It is unlikely that stakeholders will be strongly against this solution.

Summarized, all stakeholders care about sustainability in their own ways. The lack of strong opponents makes that it scores very high on politics. However the lacking opportunities for promising investments and the high investment costs make it score low on finances.

7.1.4 Cost and benefits

With rules of thumb for the cost per unit for the elements a rough estimation of the costs is made for the coastal protection for this system. An overview of these costs can be found in table 7.2. An overview of the drainage costs is given in table 7.3

Table 7.2: Costs coastal protection of the Green city

Element	**Cost [EUR]**
Centro - Rich revetment	5.400.000
Centro Sea - Rich revetment	3.600.000
Boca Beach - Nourishment	6.750.000
Boca Beach - 4 Groynes	176.000
El Laguito - Rich revetment	3.300.000
Castillo Beach - Nourishment	3.000.000
Castillo Beach - 4 Groynes	176.000
Punta Castillo - Rich revetment	1.920.000
Castillo Bay - Ext. foreshore	6.750.000
Boca Bay - Ext. foreshore	6.750.000
Centro Bay - Seawall (small)	2.600.000
Total	**40.422.000**

Table 7.3: Coast Drainage system in euro of the Green city

Elements	**Costs [EUR]**
Centro	10.034.083
Sea Side	12.950.585
Bay Side	11.335.849
Total	**34.320.518**

The newly formed beaches will increase tourist activity on Bocagrande and Castillogrande. The inclusion of the green solutions for the drainage will give the city a more natural look, it will increase the experience of the people living and visiting the city.

7.2 System 2: Safe City

The Safe City concept bundles solid engineering solutions with low investment costs and aims to keep hold to current structures as much as possible. Typical structures are revetments and seawalls (see figure 7.3a).

(a) Impression (staticflickr.com)

(b) Elements

Figure 7.3: Overview Safe City

7.2.1 Design of the coastal protection

Figure 7.3b and table 7.4 show the characteristics of all the considered elements. Centro and Centro are protected by a simple revetment. Boca Beach will be protected by a combination of nourishment, new groynes and a seawall. At El Laguito a seawall is constructed to diminish overtopping by waves.

Table 7.4: Characteristics of Safe City concept elements

Element	**Length [m]**	**Width [m]**	**Volume [m3/m]**	**Volume [m3]**
Centro - Revetment	1.800	15,00	37,50	67.500
Centro Sea - Revetment	1.200	15,00	37,50	45.000
Boca Beach - Nourishment	1.800	50,00	250,00	450.000
Boca Beach - 4 Groynes	320	4,00	20,00	25.600
Boca Beach - Seawall	1.800	1,50	7,50	13.500
El Laguito - Revetment	1.100	15,00	37,50	41.250
Castillo Beach - Nourishment	1.000	50,00	200,00	200.000
Castillo Beach - Seawall	1.000	1,50	6,00	6.000
Punta Castillo - Seawall	640	1,50	6,00	3.840
Castillo Bay - Seawall	1.000	1,50	6.75	6.750
Boca Bay - Seawall	1.000	1,50	6.75	6.750
Centro Bay - Seawall (small)	1.300	1,50	6,00	7.800

A widening of the beach by nourishment and the construction of a seawall are implemented at Castillo Beach. Punta Castillo will be protected by a seawall, as is the case for both Castillo Bay and Boca Bay. At these two locations a seawall is currently under construction, which will need an upgrade. Centro Bay will get protection from a small seawall.

7.2.2 Design of the drainage system

The Safe City drainage system focuses on reliable and proven solutions. More sustainable and innovative solutions such as retention by vegetation, green roofs and permeable pavements are not considered.

The stormwater of the whole area (Centro and the peninsula) is discharged with the use of pumps and sewer infrastructure. Valves are installed at the outlets in order to prevent intrusion. As is the case for the Green City, land elevations will be performed at specific location to guide the water into the right direction. An example of the possible division of the area is shown in figure 7.4.

(a) Centro

(b) Bocagrande

Figure 7.4: Example of drainage directions and pump locations

7.2.3 Politics and Finance

This option is likely to be supported by stakeholders that don't take high care about additional value, such as the DATT and ANLA. Other stakeholders that might be interested in this solution are the parties that will have to finance the project, such as the Mayor, Bolívar department and MADS. However, these stakeholders are also interested in additional value.

It is unlikely that parties such as FINDETER, Corporacion Turismo, hotels & apartments will participate in financing of this solution.

Summarized, there are no stakeholders strongly against this solution. However the stakeholders that are in favor do not have large influence. It therefore scores neutral on politics and finances.

7.2.4 Cost and benefits

With rules of thumb for the cost per unit for the elements a rough estimation of the costs is made for the coastal protection for this system. An overview of these costs can be found in table 7.5. An overview of the drainage costs is given in table 7.6

Table 7.5: Costs Coastal protection of the Safe city

Elements	**Costs [EUR]**
Centro - Revetment	4.500.000
Centro Sea - Revetment	3.000.000
Boca Beach - Nourishment	6.750.000
Boca Beach - 4 Groynes	176.000
Boca Beach - Seawall	7.200.000
El laguito - Revetment	2.750.000
Castillo Beach - Nourishment	3.000.000
Castillo Beach - Seawall	4.000.000
Punta Castillo - Seawall	2.560.000
Castillo Bay - Seawall	4.000.000
Boca Bay - Seawall	4.000.000
Centro Bay - Seawall (small)	2.600.000
Total	**44.536.000**

Table 7.6: Cost drainage system of the Safe city

Elements	**Costs [EUR]**
Centro	1.900.000
Sea Side	7.000.000
Bay Side	3.600.000
Total	**12.500.000**

Most important benefit is the prevention of damage and the improved accessibility by avoiding congestion. No real additional sources of additional income are created.

7.3 System 3: Showpiece

The showpiece solution will turn Cartagena into an even more attractive city for tourists and inhabitants. The main goal remains prevention of flooding, however this solution will focus on adding extra value where possible. The 'Cartageneros' will be even more proud of their city if this solution is executed. Besides this solution offers promising opportunities for investors.

7.3.1 Design of the coastal protection

Figure 7.5a shows an impression of a typical solution. The promenade at Bocagrande and the marina at Castillogrande are characteristic for the added value solution.

(a) Impression (marinas.com)

(b) Elements

Figure 7.5: Overview Showpiece

Figure 7.5b and table 7.7 show the characteristics of all the considered elements.

Table 7.7: Characteristics of Showpiece concept elements

Element	Length [m]	Width [m]	Volume [m3/m]	Volume [m3]
Centro - Revetment	1.800	15,00	37,50	67.500
Centro Sea - Revetment	1.200	15,00	37,50	45.000
Boca Beach - Nourishment	1.800	50,00	250,00	450.000
Boca Beach - 4 Groynes	320	4,0	20,00	25.600
Boca Beach - Promenade (big)	1.800	10,00	50,00	90.000
El Laguito - Seawall	700	6,00	30,00	21.000
Castillo Beach - Nourishment	1.400	50,00	200,00	280.000
Castillo Beach - Seawall	1.400	1,50	6,00	8.400
Punta Castillo - Seawall	640	1,50	6,00	3.840
Castillo Bay - Seawall (small)	1.000	1,50	6,75	6.750
Castillo Bay - Marina	-	-	-	-
Boca Bay - Promenade (small)	1.000	3,00	13,50	13.500
Centro Bay - Seawall (small)	1.300	1,50	6,00	7.800

Centro and Centro Sea will be protected by a revetment that keeps the historic look of the center in tact. Boca Beach will be equipped with a large promenade for tourist and recreational activity. To create enough construction space the beach is widened and additional groynes are constructed. At El Laguito the promenade turns into a wide seawall that runs op to the Hilton Hotel. It can be used as a walkway and for sidewalk cafés. From the Hilton Hotel up to Punta Castillo a nourishment is carried out and a seawall is constructed. The seawall continues along Punta Castillo and Castillo Bay. At Castillo Bay a marina is constructed in front of the seawall. The seawall turns into a small promenade at Boca Bay. Finally the Centro Bay is protected by a small seawall.

7.3.2 Design of the Drainage system

The drainage of this solution is similar to the drainage system of the 'Green City' solution (see 7.1).

7.3.3 Politics and finance

This option is likely to be supported by stakeholders that do take high care about additional value, such as Corporación Turismo, hotels, apartments and FINDETER. Other stakeholders that might be interested in this solution are the parties that will benefit from the additional value, such as the Mayor, Bolívar department, MADS, EPA and DATT. However, these stakeholders are also interested in keeping the investment costs low.

It is unlikely that parties such as ANLA will be in favor of this solution.

Summarized, there are a lot of stakeholders in favor or interested in this solution. It therefore scores high on politics. Interesting opportunities for investors result in a high score on finances as well.

7.3.4 Cost and benefits

With rules of thumb for the cost per unit for the elements a rough estimation of the costs is made for the coastal protection for this system. An overview of these costs can be found in table 7.8. An overview of the drainage costs is given in table 7.9

Table 7.8: Costs Coastal Protection of the Show piece

Elements	**Costs [EUR]**
Centro - Revetment	4.500.000
Centro Sea - Revetment	3.000.000
Boca Beach - Nourishment	6.750.000
Boca Beach - 4 Groynes	176.000
Boca Beach - Promenade (big)	12.600.000
El Laguito - Seawall	2.800.000
Castillo Beach - Nourishment	4.200.000
Castillo Beach - Seawall	5.600.000
Punta Castillo - Seawall	2.560.000
Castillo Bay - Seawall (small)	2.000.000
Castillo Bay - Marina	1.265.000
Boca Bay - Promenade (small)	5.500.000
Centro - Seawall (small)	2.600.000
Total	**53.551.000**

Table 7.9: Costs drainage of the Show piece

Elements	**Costs [EUR]**
Centro	10.034.083
Sea Side	12.950.585
Bay Side	16.735.849
Total	**39.720.518**

Based on a capacity for 230 boats, an annual occupancy of 70% and a price of €30.00 per day per boat the annual turnover will be approximately €1.700.000. In addition it is expected that the marina, in combination with the upgrade at Boca Beach, will attract additional visitors which benefits the local economy.

7.4 Drainage capacity analysis

A quick calculation is used to verify the capacity of the drainage systems. Values used for calculation are extracted from appendix H. For the different elements a separate approximation is made. The required drainage capacities are given per area in table 7.10. A more detailed description of the presented values in this section is given in appendix I.

Table 7.10: Required drainage capacity

	Sea side	**Bay side**	**Centro**
Required capacity [m^3/h]	29 733	89.200	49 567

From a quick calculation it is estimated that permeable roads are able to retain between 4,3 % and 8,4 % of the stormwater of a single rainfall event for the different areas. See 7.11.

Table 7.11: Volume retained by permeable road

	Sea side	**Bay side**	**Centro**
Road area [m^2]	84.893	138.102	148.518
Volume retained [m^3]	7.131	11.600	12.475
Stormwater [%]	8,0 %	4,3 %	8,4 %

Green roofs retention can only be applied at the peninsula due to restriction by UNESCO. The possible capacity is only 1,1 % of the stormwater of a single rainfall event, see table 7.12.

Table 7.12: Amount of green roof retention

	Sea side	**Bay side**
Green roof area [m^2]	100.000	300.000
Volume retained [m^3]	1.000	3.000
Stormwater [%]	1.1 %	1.1 %

Additional vegetation is split up in urban areas and road area. The road area considers space along the roads. Vegetation could reduce the discharge volume with 7,1 to 7,8 %.

Table 7.13: Overview of vegetation retaining capacities

	Sea side	Bay side
Accumulative street length [m]	12.127	19.730
Road vegetation area [m^2]	9.702	15.600
Road vegetation, capacity [m^3]	1.358	2.184

	Sea side	Bay side
Urban vegetation, current area [m^2]	20.000	60.000
Urban vegetation, possible area [m^2]	20.000	60.000
Urban vegetation, total area [m^2]	40.000	120.000
Urban vegetation, capacity [m^3]	5.600	16.800

	Sea side	Bay side
Total capacity [m^3]	6.958	18.984
Stormwater [%]	7,8 %	7,1 %

Land elevation could contribute to an improved drainage system. With the use of the Chézy formula it is possible to determine the required elevation level. The Manning-Strickler roughness coefficient for concrete and initial flow at 0,5 m/s are assumed for this calculation. This results in a minimum required slope of approximately 1:1600 for runoff by gravity.

7.5 Construction time

Construction time is an important criterion with respect to the political system of Cartagena. Appendix I gives a qualitative estimation of the construction time per concept. The results are shown in I.3

Table 7.14: Ranking drainage elements

Drainage solution	Green City	Safe city	Showpiece
Centro	5	5	5
Sea side	11	7	11
Bay side	11	7	11
Total	27	19	30

7.6 Overview cost and building time

To summarize some of the above, figure 7.6 shows a graphical view of the cost and construction time.

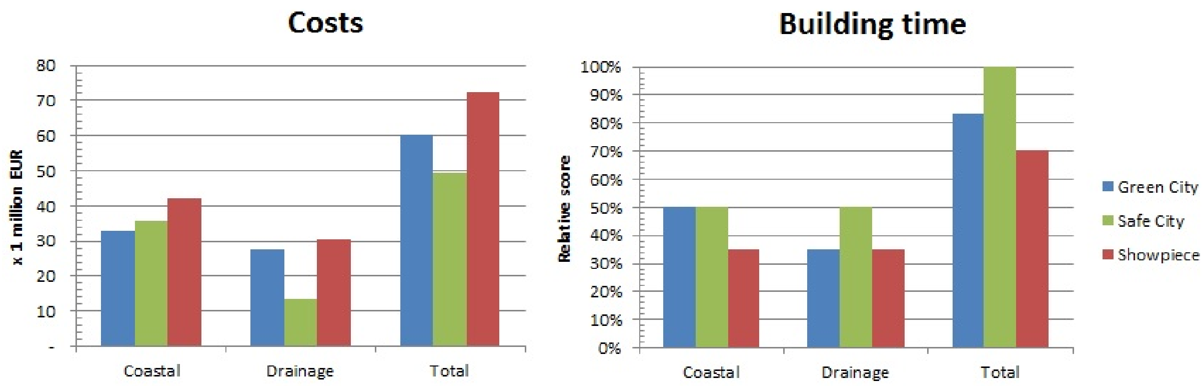


Figure 7.6: Overview initial cost and building time

7.7 MCA

In order to obtain the final design, each concept is given a value based on a multi-criteria analysis (MCA). The same criteria and weights apply as for the MCA performed for the elements (see Appendix H for a detailed description).

Understanding of the differences between the criteria as well as a clarification of the assigned scores is of main importance. This will help with the justification of specific choices in the design.

7.7.1 Outcome

In agreement with the foregoing division in coastal protection and drainage, the MCA is also performed separately for both parts. The total scores are shown in table 7.15 (coastal) and table 7.16 (drainage). The accumulate scores are given in 7.17.

Table 7.15: Weighted MCA scores Coastal Protection

Coastal protection	**Green City**	**Safe City**	**Showpiece**
Social	0,36	0,27	0,36
Technical	0,27	0,53	0,40
Administrative	0,47	0,62	0,62
Political	1,00	0,60	0,80
Legal	0,33	0,44	0,22
Economic	0,44	0,67	1,11
Environmetal	0,44	0,27	0,27
Total	**3,31**	**3,40**	**3,78**

Table 7.16: Weighted MCA scores Drainage system

Drainage system	**Green City**	**Safe City**	**Showpiece**
Social	0,27	0,27	0,27
Technical	0,27	0,53	0,27
Administrative	0,31	0,62	0,31
Political	0.80	0,60	0,80
Legal	0,33	0,44	0,33
Economic	0,67	1,11	0,67
Environmental	0,36	0,27	0,36
Total	**3,00**	**3,84**	**3,00**

Table 7.17: Total weighted MCA scores

	Green City	**Safe City**	**Showpiece**
Total	6,31	7.24	6.78

7.7.2 Conclusions

Resulting from the MCA the Safe City is considered the best out of the three concepts. Main factor in this result is the higher score on its drainage concept, which scores significantly better on economical, technical and administrative criteria.

Results of the coastal protection MCA are in favor of the Showpiece concept. The most eye-catching difference is caused by economical criteria. Showpiece offers a lot of promising opportunities to finance (parts of) the project with the help of private investors.

Although the Green City has the lowest scores in both analyses, it excels on political and environmental criteria. This fact should be taken into account for the final design. However the costs of the green roofs and permeable roads far outweigh the retentive benefits.

Based on these conclusions the three concepts will be merged into a final design which will be discussed in chapter 8.

Chapter 8

Final design

The final design uses elements of all the three global solutions. The multi criteria analysis clearly shows the strengths and weaknesses of each global solution. By combining the strengths of each solution the final solution becomes more attractive than each of the three global solutions. This chapter starts with a brief explanation of the main final design choices. Subsequently the coastal protection solution per area is presented including artist impressions, followed by the presentation of the drainage solution. An evaluation of the design is made by discussing the method of construction, maintenance, construction time, costs and benefits and the risks. Also some interesting opportunities for policy measures are discussed. In Appendix J an extensive elaboration of each choice and some calculations are made.

8.1 Brief description of the design choices

Politics are an essential factor for the success of the project. A combination of the Green City and the Showpiece solution provides a solid base for political support, where the Safe City solution scores quite low on this aspect. Additional presence of vegetation on the Bocagrande peninsula improves the quality of life and creates a more welcoming atmosphere. This additional value for residents and the additional attraction on tourists will have a positive effect on the opinion of politicians. Another important contribution to a solid political support comes from the Showpiece solution, mainly due to the generated additional value. The high score on economic value is especially caused by the promenade at Bocagrande Beach and the marina at Castillogrande Bay. The promenade will add more commercial and recreational possibilities. At the side of the bay the marina will generate income and will most likely result in an increase of land value. Other parts of the Showpiece solution are not included in the final design to limit the initial costs. The drainage solution is completely defined by the Safe City option. Although it does not score particularly high on politics, it is expected that the great score on economics will have a very positive effect on the opinion of politicians. Vegetation will also be part of the final solution, however the contribution to the drainage capacity is only marginal. Green roofs and permeable roads are not a part of the final solution due to their high initial costs and low contribution to the drainage capacity.

8.2 Coastal protection

8.2.1 Technical requirement

To design a coastal structure first the design height must be calculated. For each section a design height has been calculated based on the overtopping criteria for revetments and seawalls, which is $Q = 200l/s/m$ as is discussed in chapter 5. The height is in reference to the MSL, the level of the land in relation to the MSL is found in table 8.1.

Table 8.1: Surface elevations in reference to MSL

Area	**Surface level**
Centro	MSL + 1.25 m
Bocagrande	MSL + 0.50 m
El Laguito	MSL + 0.70 m
Castillogrande	MSL + 0.30 m
Punta Castillo	MSL + 0.00 m

The height of the structure is based on the following summation: $Requiredheight = MSL + tide + LaNina + sealevelrise + landsubsidence + stormsurge + freeboard$. In table 8.2 the required heights for the different structures can be found.

Table 8.2: Overview design levels incl. freeboard

Location	**Type**	**Design level**
Centro	Revetment	MSL + 2.30 m
Boca Beach	Step dike	MSL + 2.30 m
Boca Beach	Sea wall	MSL + 2.80 m
El Laguito	Revetment	MSL + 2.10 m
Castillo beach	Wall	MSL + 2.50 m
Puncta Castillo	Revetment	MSL + 2.10 m
Castillo Bay	Retaining wall	MSL + 2.10 m
Boca Bay	Retaining wall	MSL + 2.10 m
Centro bay	Q-wall	MSL + 2.10 m

8.2.2 Design Coastal system

With the required height per section designs are made. For the coastal defence a protection system with added value is preferred as this came forth as one of the key selling points of the Showpiece variant. This is the variant which had the highest MCA score on coastal protection. However not on every section the added value descirbed in the Showpiece is desired, so only the promenade and marina are constructed in an attempt to reduce costs. To fulfil the protection levels of the remaining parts revetments and seawalls are used. Nourishments are used to preserve and extent current beach states. The final solution is shown in figure 8.1.

Each design will be described shortly and gives an impression of the design as a finished product.

Figure 8.1: Overview of the coastal protection for the Final design

Promenade, Boca Beach

The coastal protection on Boca Beach is one of the parts of the coastal protection system containing an important aspect that generates added value as the structure build will be a promenade. The design consists of a wall able to retain the water during extreme conditions. On both sides of the wall a staircase is constructed to be able to access the beach. A nourishment in front of the promenade will ensure enough recreational space is maintained.

For the retaining wall structure two types are considered, the stepped face wall and the vertical wall. On these a promenade has been found to be the best fitting solution to create added value, chapter 7.

The design for the promenade will consist of a sand body on which a promenade will lie. A stepped face wall is constructed at both sides of the promenade to access the beach. The profile of the top will have a width of 3.5 m where there is space for a walkway, vegetation, lighting etc. [26]. Other considered designs can be found in the appendix.

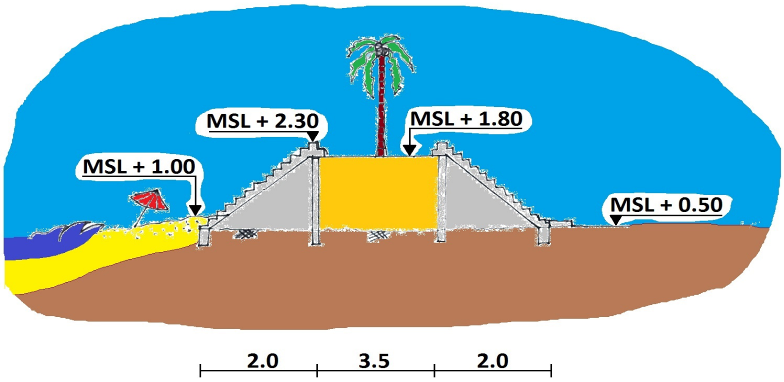


Figure 8.2: Design 2: stairs

The stairs design comes forth as the most promising variant as it is aesthetically appealing, fits well in the area and meets all the requirements and desires. The main advantages are that the beach will be easily accessible, the height of the structure is low so the view off the beach will be less limited and the width of the structure is only 2 meter more than for the vertical walled promenade. As the structure will consist of a lot of concrete with vegetation, lighting, stone pavement and the use of wood for the benches the aesthetics of the structure can be improved. An artist impression of the design can be found in figure 8.3

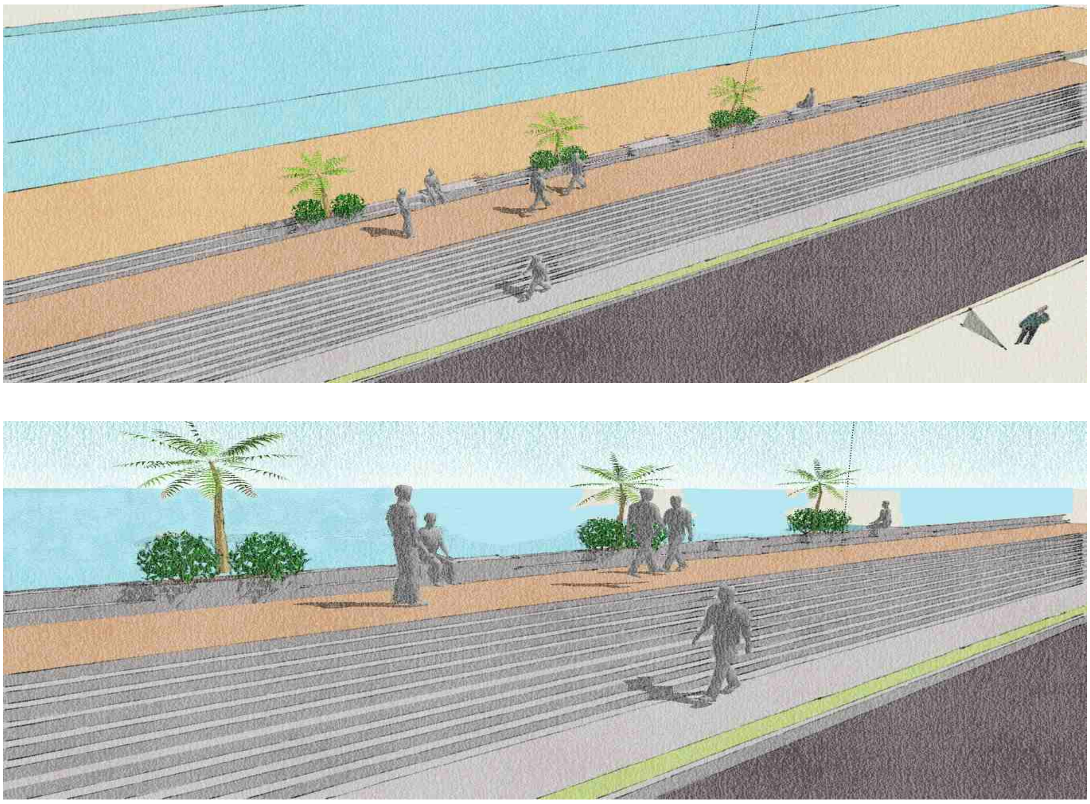


Figure 8.3: Impression of the promenade design

Revetment, Centro, El Laguito and Punta Castillo

The promenade will be attached to revetment at both sides. The entire stretch of Centro will be constructed with revetment as well as the south-western stretch of El Laguito in addition to Punta Castillo. The revetment will be constructed to stop wave impact on the shoreline and to retain the high water levels. It serves no further purpose than water retention so it does not require specific finishing.

The revetment will be constructed by means of a mild bottom slope of 1:3 and a steeper top slope of 1:2. An illustration of the revetment with its dimensions is shown in 8.4 for the revetment in Centro. The dimensions and volumes for each revetment can be found in the appendix.

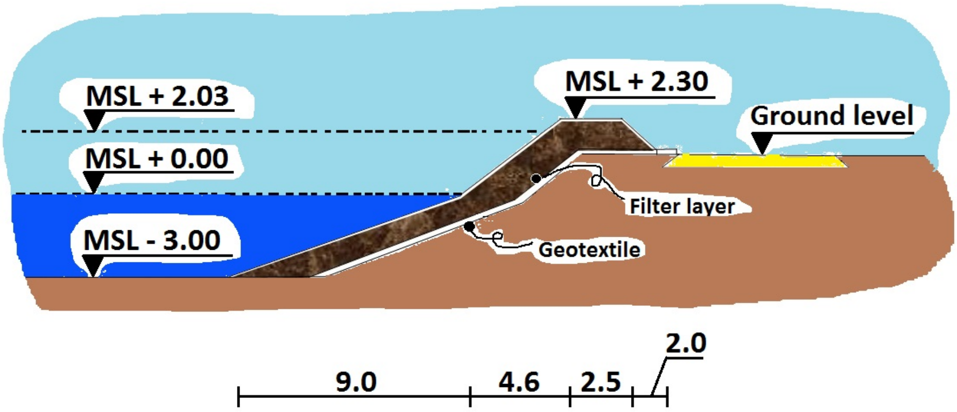


Figure 8.4: Overview revetment

The size of the armour stones has been determined in the appendix and is shown for the different areas in table 8.3.

Table 8.3: The armourstone size used in revetment

	D_{n50}	M_{50}
Centro	1.04 m	2,571 [kg/m^3]
El Laguito	0.77 m	1,087 [kg/m^3]
Punta Castillo	0.77 m	1,087 [kg/m^3]

An artists impression of how it will fit in the coastal view is given in figure 8.5.

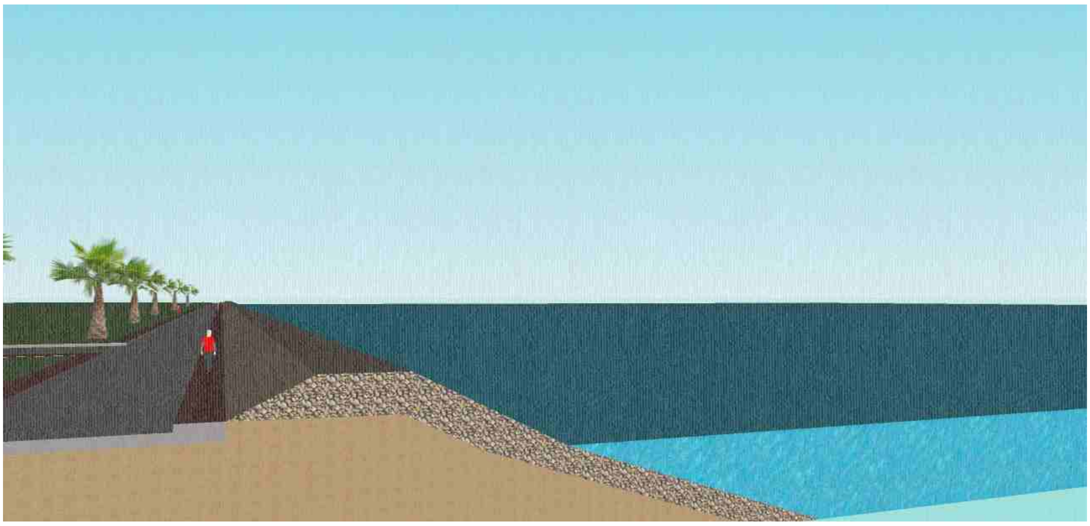


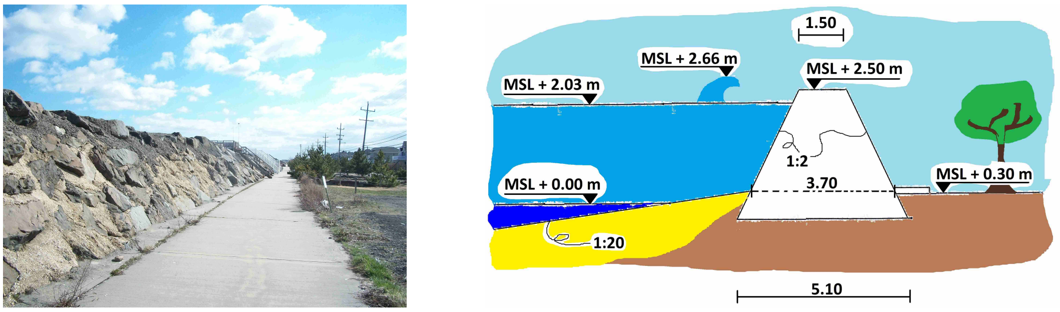
Figure 8.5: Artist impression of revetment

Sea wall, Castillo beach and El Laguito

The revetment will end at the El Laguito lake and from there a sea wall will be constructed over the beach over the stretch El Laguito (lake side) and Castillo beach till Punta Castillo. A sand nourishment will also be performed at Castillo beach to preserve the beach state, at El Laguito this is not performed as structural accretion already takes place. The nourishment will be also be discussed in section 8.3.

The required design height for the sea wall for Castillo beach and the lake side of El Laguito is **MSL + 2.5m** (table 8.2), to prevent seepage from occurring and to create stability the structure is also embedded **1.4m** into the subsoil.

To reduce the sea wall from becoming a great eyesore it will be constructed from natural appearing material. Also a walkway will be constructed on top of the sea wall to ensure that people are still able to jog along the beach and sea and enjoy its scenery as is now the case. The walkway has to be made of 1.5m to ensure two people can pass each other easily. To reduce the total width of the structure the slope will be constructed with a slope of 2:1. This will also give the seawall a more appealing view as the wall is not a direct vertival wall. The pavement on the structure will also need to be built under a small slope to facilitate runoff of water. The whole structure will be constructed on the sea side of the current tree line to reduce the view of the structure from the buildings, see figure 8.6b for an illustration.



(a) Example of natural sea wall (b) Sketch of proposed solution

Figure 8.6: Example of the designed sea wall

A calculation for the required volumes and a stability calculation has been made in the appendix. To give a view of how it will fit in the neighbourhood an artist impression is made.

Figure 8.7: Artist impression of the sea wall

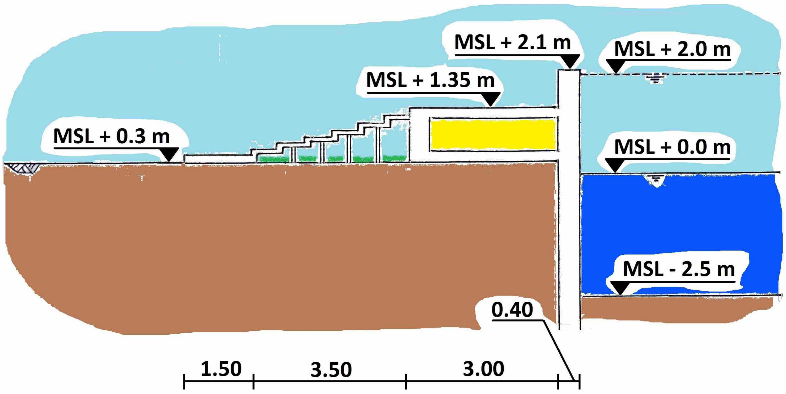
Retaining wall, Castillo bay

The revetment at Punta Castillo will be connected to a retaining wall on the Castillo bay. At this location a retaining wall will be implemented, as in front of it a marina will be constructed. The bay side is the best place to construct the marina as there are limited waves and there is currently no beach present.

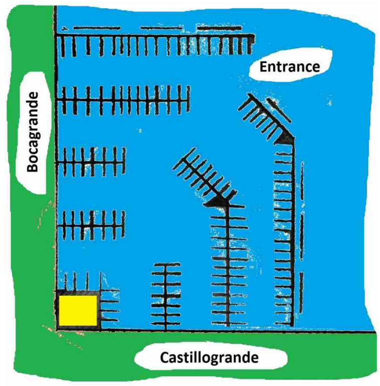
The retaining wall will have the function of both a retaining structure and a connecting element. To full fill both its functions it requires proper accessibility from both sides. At the land side enough space is available to construct stairs with a gentle slope (step width 0.50 m, step height 0.15 m). At the bay side a straight wall is required because of the floating jetty structure of the marina. Therefore the accessibility at the bay side is supplied by staircases. These staircases should be able to adjust to the changing water levels.

In order to create additional interaction between marina and land side the retaining wall has 3.00 meter wide walkway on top. At the bay side the walkway has a small wall with a height of

0.75 meter. The wall offers additional safety for users of the walkway, supplies the possibility to sit down and relax and it also results in less use of material. A sketch of the retaining wall is given in figure 8.8a.



(a) Retaining wall



(b) Topview marina

Figure 8.8: Sketches of marina area

Marina, Castillo bay

The marina in front of Castillo bay has the main function of increasing the value of the peninsula. It also needs to attract investors and create revenue.

To limit the walking distances from the moorings to the harbormaster office, the marina is located in the bay corner between Bocagrande and Castillogrande. This is also the location that has the best connection to the peninsula areas with a tourist function. It has short distances to shopping malls, hotels and beaches of both Bocagrande and Castillogrande.

After a quick inquiry of the current marina capacity (370 moorings) and a comparison to other popular marina cities (St. Tropéz: 2500+, Miami: 2500+, Tropea, 620) a capacity of 230 moorings is found to be feasible. In the current situation the marinas are occupied most of the time, a yearly occupancy of 70% is assumed as a conservative estimation.

Floating jetty walkways are constructed to be able to adapt to future water level rise and current fluctuations in water level. The location is fixed with piles that are driven into the bottom of the bay. The governing ship for the marina design has a LOA of 60 feet a maximum beam of 20 feet and a draft of 5 feet. In order to create easy access for sailing yachts no height restrictions are allowed. Larger ships can moor on the outer jetties. The dimensions are given in table 8.4 an elaboration of this can be found in the appendix.

Table 8.4: Measurements - Marina

Element	Width	Length
Main jetty walkway	3.00 m	2,300 m
Finger jetty walkway	3.00 m	1,725 m

To illustrate how this marina fits in the bay an artist impression has been made in figure 8.9 and 8.10.

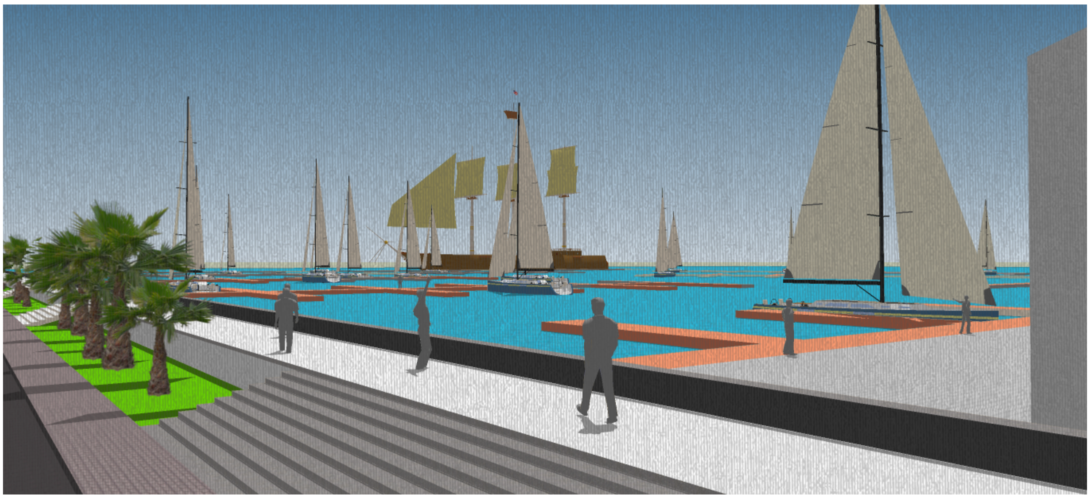


Figure 8.9: Artist impression of the entrance to the marina

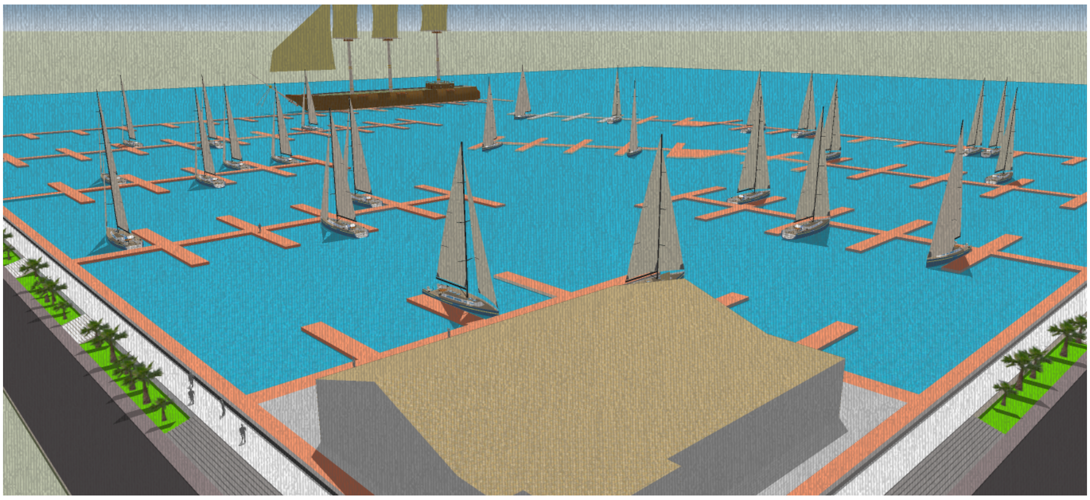


Figure 8.10: Artist impression of the layout of the marina

Retaining wall, Boca bay

The retaining wall at Castillo Bay will be extended by over the length of Boca bay. Almost the same requirements hold for the design, except for the surface level elevation, that is set to MSL + 0.5 m. The promenade will be constructed at the same height with respect to MSL, and therefore the retaining wall will be 0.2 m lower with respect to the promenade. However, the required material volumes will be the same as for the retaining wall at the marina, since it has to be designed for the same depth.

Quay wall, Centro bay

This design has been made as there is not much room for a different solution and because several boats depart from that area to the neighbouring islands that require a quay wall. The quay wall will also have the function of retaining the water level during extreme conditions. It will in that way protect the hinter laying roads and parts of the historical center.

At Centro bay the current structure consists of a gravity quay wall which already is close to the design level as it is at MSL +1.25m. This wall will be upgraded as this significantly decreases the costs. The extension will be built on top of the current structure and connected to the reinforcement. An illustration is made in 8.11.

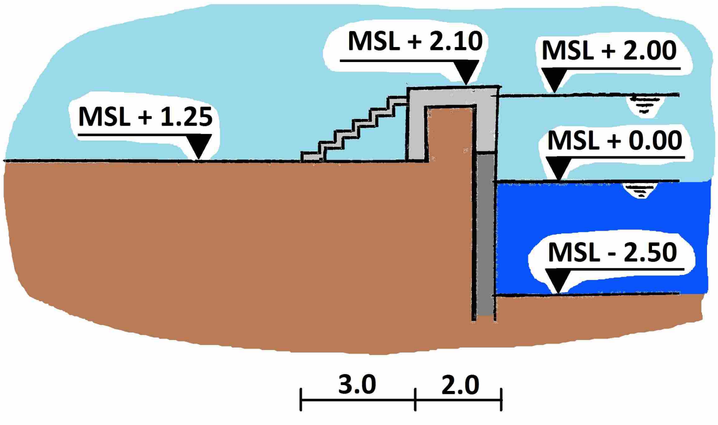


Figure 8.11: View of the quay wall

8.3 Nourishment and groynes

In addition to the retaining structures also several nourishments will take place at Boca Beach and Castillo Beach. The nourishments are implemented to compensate for the losses of the beaches due to erosion. At Boca Beacht the new structure is partly placed on the current beach so also these losses of beach space need to be compensated. Nourishing of the beach will also have the effect that incoming waves will have less run up. A similar nourishment is made to Castillo Beach, extending the beach and heightening it for future demand. The total increase for both sections is a broadening of **15m** and a heightening of **0.5m**.

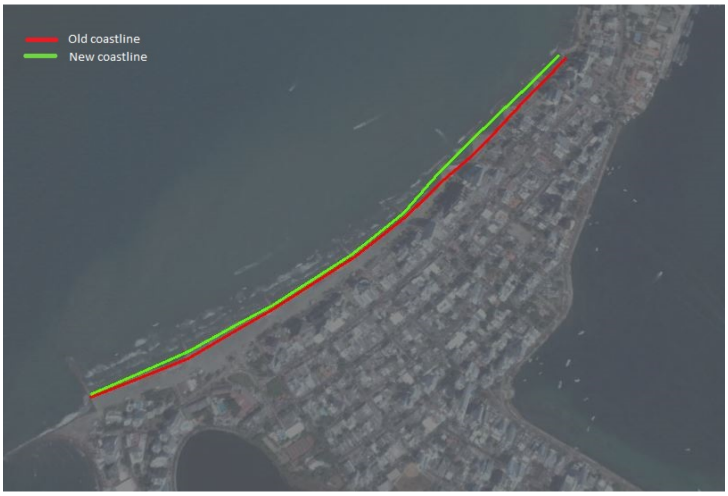


Figure 8.12: View of the nourishment

The current alongshore breakwaters are not sufficient in preventing erosion for the new design as they are located too close to the current beach. These breakwaters will be removed as they will no longer have a function. In order to keep the newly created beaches in place three new rock groynes will be constructed. The existing groynes will be extended to the same length the beaches will also be extended. The construction of the groynes could have a negative effect on the down drift side due to trapping of sediment. The longer groynes will trap more sediment, but due to the nourishing of the beaches they will soon be saturated. In the long term the sediment balance will therefore form a new equilibrium.

8.4 Drainage

Coastal protection on its own is not enough to prevent flooding from occurring. The heavy precipitation events also need to be dealt with by means of a proper drainage system. In this section the drainage system will be explained. The designed drainage system is based primarily on the Safe City variant, with a large amount of vegetation to create a politically desirable drainage solution. However no permeable pavements and green roofs are taken into account. The permeable roads were not feasible due to high groundwater levels in the future and high investment costs for a relatively small amount of water that could be retained. Green roofs were far too expensive for what they offered in retentive qualities.

8.4.1 Description drainage system

The drainage system is subdivided in the parts Centro and the peninsula. This subdivision has to be made because of the historic heritage that Centro contains. The differences between the two parts lie in the addition of vegetation on the Bocagrande peninsula which will act as extra retention to reduce peak flow. Also the raising of some roads in the peninsula is a point on which the solutions of the two areas differ.

Centro

In the Centro part of the city the only option that is feasible is to install pumps and check valves, without elevating the road. In the Safe City system already the surface elevation levels in Centro were investigated to determine what would be viable pump locations, figure 8.13a.

Bocagrande Peninsula

In the Bocagrande peninsula more options for drainage are possible. In addition to pumps and valves also extra vegetation will be installed. Furthermore the slope of the roads will be altered so that water flows off more easily. The Avenida San Martín and Calle 5 will be elevated for this purpose. In figure 8.13b the areas that drain off to the sea side and bay side of the peninsula are given.

(a) Elevation levels of Centro (b) Runoff areas to the sea and bay (c) Current inlets on the peninsula

Figure 8.13: Drainage system overview

8.4.2 Pumps

Locations

The valves will be integrated with the pumps. It therefore makes sense to place the pumps on the locations where valves should be placed. In the analysis the locations of the current inlets were already investigated. These inlets will have to be upgraded with check valves, to prevent tidal intrusion. At these locations also the pumps will be placed. In figure 8.13c the current locations of the inlets are given.

Capacities

In case of an excessive rain event that occurs 1/100 years, the pumping system capacity needs to designed in such a way that severe flooding is prevented. However not all the stormwater needs to be discharged directly. Several retaining elements have been implemented in the system to reduce the direct discharge.

In case of an extreme event it is not unthinkable that some water will be present in the streets. This does imply that some water is allowed to be stored on top of the concrete pavements for a limited amount of time, without inducing major problems. The amount of water should not exceed the levels of the sidewalks. The sidewalks are located at an average of about 100 mm above street level. After the rain event ends, the pumps should be able to drain the amount of water stored on top of the pavements. A calculation for the retention volumes and the capacity of the pumps per section has been made in the appendix. The locations of the pumps will be the same as the locations of the drainage outlets and thus the amount of pumps are known, figure 8.13c. For each of the discharge areas now the capacities of the pumps can be calculated as is done in table 8.5.

Table 8.5: Pump capacities

	Dicharge volume	**Number of pumps**	**Capacity**
Sea side	18,637 m^3	11	1,694 m^3/s
Bay side	60,429 m^3	19	4,316 m^3/s
Centro	34,714 m^3	4	8,678 m^3/s

8.4.3 Elevations

To get the desired runoff towards the pumps, roads in each part of the city will need to be elevated. It was already determined which parts of the city flow off towards the sea and bay side. This is again shown in figure 8.13b.

Centro

As said before Centro is a historic heritage site which can not be altered. The roads in Centro are however already built slightly sloping towards the four locations indicated in figure 8.13a. It is therefore not needed to alter the elevations of the roads.

Bocagrande Peninsula

In order to get the desired slopes it was determined that the Avenida San Martin will be elevated. For each of the indicated flow areas the longest flow length was measured. This length was then multiplied with the previously determined slope of 6.42e-4 to find the desired extra elevation of the Avenida San Martin.

Table 8.6: Desired elevations

	San Martin - Sea	**San Martin - Bay**	**Calle 5 - Bay**
Length	125 m	445 m	325 m
Δh	0.08 m	0.285 m	0.209 m

From the table it can be seen that the desired elevation for the Avenida San Martin is 0.285 m, which is more than the 0.2 m that the sidewalk is above the street level. For this design to work also the sidewalks will need to be elevated, otherwise these will be flooded.

8.4.4 Design of pumps and outlets

Water is conveyed from the drainage area to the critical points where pumping stations are located. The runoff water is primarily collected via the gutters on top of the pavements to a storage chamber at these pumping stations. This storage chamber is connected to a outlet drain and a pump. When low water levels at sea are present, drainage by gravitation is possible. If the water levels at sea are higher than the outlet drains, the check valves will be closed to prevent tidal intrusion. The water level in the wet well will rise until a critical level, which will automatically switch on the pumps. The required pump capacity is determined further on. The pumping station should be able to overcome the maximum hydraulic head, that is possibly induced during high water levels at sea. This should be no problem for pumping stations with such a capacity.

8.4.5 Integration drainage in coastal defence

The drainage system will need to be integrated with the coastal defence. This will be mostly done by constructing the drainage outlets through the defence structures. At the drainage outlets the check valves will be placed, so the tidal intrusion is prevented.

The pumps will be mostly embedded inside the defence structures. In this way the amount of space needed is reduced. The pumps will have to pump continuously but only when the drainage is bigger than can be discharged away by gravitational flow. To determine when the pumps need to start working a storage chamber will be build that, when filled up to a certain level, give a sign to the pump to start working. The pumps will be placed on top of the storage chambers. The storage chambers will be placed in line with the drainage pipes that run from the gutters to the outflow point.

In figure 8.14 one of the embedded drainage systems is shown. In this figure the pump, check valve and storage chamber are indicated.

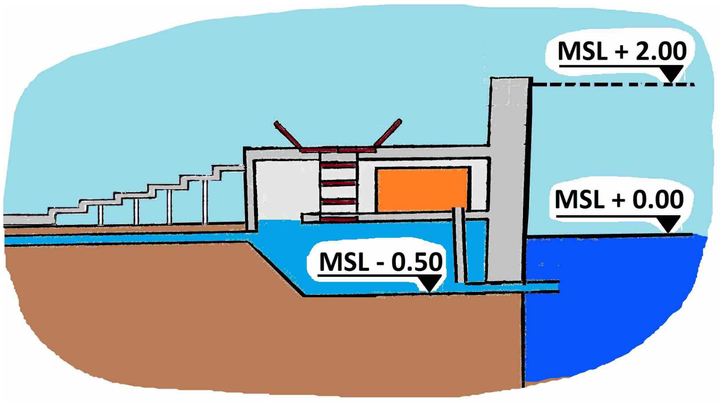


Figure 8.14: View of the drainage integration in the coastal protection

8.5 Construction method

The construction method of each section is discussed explaining what difficulties lie. Also a choice will be discussed whether to construct in-situ or prefab. Lastly a planning is made to show which parts can be made simultaneously and which section have the most priority.

8.5.1 Promenade, Boca beach

The promenade will be made with a step dike design where the body consists of sand. The sand core has a slope of 1:2 for the sand body to be stable. Over this body a layer of blinding concrete will be constructed as a foundation for the stairs [27]. The steps are constructed in-situ with reinforced concrete of which an example is shown in figure 8.15, as for pre-fab construction heavy cranes need to be used and this is not feasible at the beach. In this figure also clearly construction stages are noticeable.

As the soil of Bocagrande mainly exist of sand, it is assumed that the bearing capacity is sufficient to build the steps with a pile foundation. These have to be designed in a further stage

Figure 8.15: Construction stages of the promenade [28]

To prevent seepage, an additional vertical length of 0.5 m is needed according to figure 4.5. As this is only 0.5 m there are no sheet piles needed at the toe but the use of a deeper concrete toe structure is enough. Additionally, the structure will be build at the beach current level. After the nourishment is in place the structure will be embedded into the sand minimising the risk that the toe of the structure erode due to toe scour.

In the final construction stage the benches, street lightning and the vegetation can be implemented.

8.5.2 Seawall

To construct the seawall first a ditch will need to be excavated to a level of MSL-1.1m to embed the structure. At this point the sea wall can be constructed with loose rocks and binding material till it reaches a height of MSL+2.5m under a slope of 1 : 2.

Stairs will be constructed over the structure to reach the beach and the walkway on top of the sea wall. The drainage system will need to be constructed simultaneously and be embedded in the structure.

8.5.3 Retaining wall Centro

Along the bayside coastline of Centro the current retaining wall will be upgraded. To be able to connect the new structure to the current wall a small part of the concrete will need to be demolished and the rebar connected with the rebar from the extension. With this in place the concrete can be cast in-situ.

The concrete structure needs a minimum cover of 55 millimeter to avoid salt water reaching the reinforcement steel. Construction of the front wall is has to be build in-situ in a dry dock due to the direct presence of water.

8.5.4 Retaining wall Boca bay and Castillo bay

The current construction of the retaining wall at the Bocagrande and Castillogrande bay side are not expected to have a long lifetime (Appendix C). Instead a new structure will be build.

Figure 8.16: Different construction stages of a revetment in one picture

Like the retaining wall to be build near Centro, this structure will also have to be build in a dry dock, because it is directly in contact with the bay water. The front wall will be build first in-situ. The other parts of the quaywall will have to be connected to the front wall, so at both parts protruding rebar will be connected and concrete will be cast again in-situ.

At the places where valves and pumps are planned, the valves will be installed right after making the front wall. Then simultaneously with the other parts of the concrete construction the storage chambers will be build. The pumps will be installed before the final top slab is placed. The top slap will therefore be made prefab.

8.5.5 Marina

After the construction of the retaining wall is completed, work on the marina will be started by driving the piles for the jetties from a floating barge. Bottom protection will be laid to prevent scouring around the piles and at the basin of the quaywalls. The pre-assembled floating jetties can be then be connected to the piles.

8.5.6 Revetments

The revetments will have to be build in stages that follow up quickly, in order to prevent flushing away of material. The structure needs to be divided into section in the alongshore direction, so building stages can be simultaneously executed. The building stages consist of making the sand core, placment of the toe construction, applying the geotextile, placement of the filter layer and finally placing the armour stones. If one of the building stages is finished the next one should be started as soon as possible to retain the material. In the next section the previous stage then can be started. An example of different construction stages can be seen in figure 8.16.

The placement of the toe construction and armour stones can be best done from a floating structure. The other building stages are possible to execute form the land side.

8.5.7 Elevation of roads

To get the stormwater to drain of to the valves in the coastal protection the roads will need to be elevated. The avenida San Martin and calle 5 will be made the highest, as from these roads the stormwater needs to be drained to the sea and bay side. For this to be done the current roads need to be demolished and after an elevation with sand the roads will need to be reconstructed.

8.6 Maintenance

In the designed final system some maintenance does have to be done, but due to the past bad experiences with systems that require maintenance, the structures have been made in the most maintenance free way possible.

The promenade, seawall and different retaining walls can be considered almost completely maintenance free. These structures are mainly constructed in concrete that is expected to last for the chosen lifetime. At several locations along the retaining walls ships will moor. At these mooring places sometimes repairs will have to be made.

At the marina some more maintenance can be expected to have to be done. As a lot of mooring places will be present, regular small repairs will have to be made. The marina will be in ownership of a private party who will exploit the marina, so the small repairs will not pose a real problem.

The new nourished beaches are expected to erode away slowly over time. To counteract this loss of sediment additional nourishments will need to be done. The expected timescale between different nourishments is ten years.

Most maintenance, check ups and repairs will have to be done to the drainage system, the pumps in particular. At least every year before the rainy season the pumps will need to be checked on functionallity, as they are expected to work in this period. As most of the pumps will be embedded in the coastal defence structures maintenance hatches will be placed to get to the pumps.

8.7 Construction Planning

The construction planning of the project are together with the finances the main decisive criteria for a successful implementation of the project. Since most projects in Cartagena are executed during one term of the mayor, it is important that the construction of the project can be completed within four years.

Furthermore is of importance that the current commercial activities must be able to continue their operation. During the construction planning it must therefore be taken into account that activities can go on and not whole areas are deprived of connectivity. The construction planning is for this reason divided into phases.

8.7.1 Priorities

In order to decide which elements to be constructed first, priorities will be given to certain elements.

Elements with most priority:

- Improve weakest coastal protection first
- Construction works should only have minor influence on accessibility peninsula
- Same type of construction works in same phase or consecutively

For the accessibility of Bocagrande and Centro the main roads should be available during construction works by improving the roads lane by lane and no parallel main roads can be adjust at the same time. Moreover, it is essential that the drainage and coastal protection will be implemented at the same time. It is not desired constructing a coastal protection, without adapting the drainage system at the same time. Therefore the drainage elements must be started during the phase that the coastal protection is implemented.

8.7.2 Construction time

Combining all priorities and elements led to a final estimation of the planning, which is shown in figure 8.17. The total construction time is longer than 3 years, however many of the projects can be constructed simultaneously. This just gives an indication of the construction time with prioritized planning. The time is still shorter than the governing period of one mayor making it a feasible planning. If the decision is made to reduce the construction time that is easily implemented by constructing the different sections simultaneously. Therefore it makes the design still feasible in the term set. In appendix J.13 the planning considerations are explained more extensively

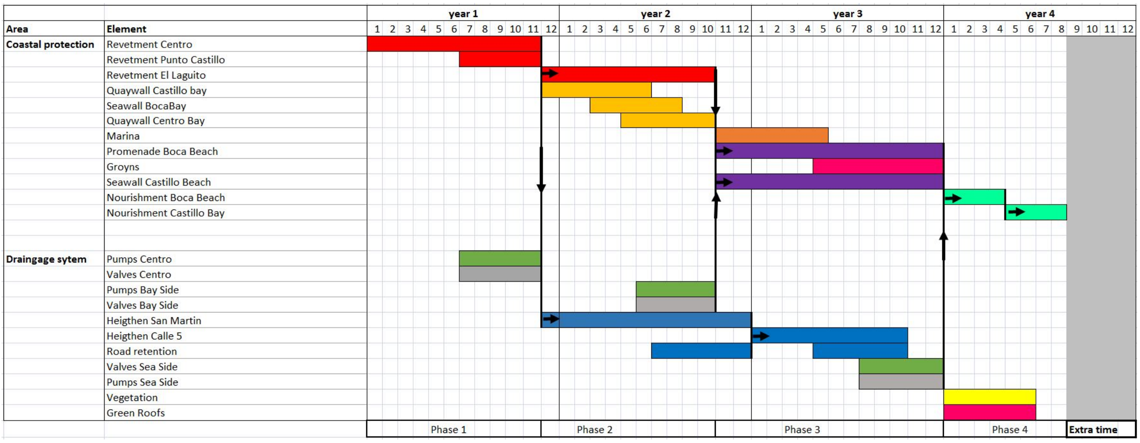


Figure 8.17: Planning of the elements

8.8 Costs and benefits

In order to determine the economic feasibility of the final designed system the costs and benefits are compared with each other. The project will be considered economically feasible if the considered benefits are more than the investments and costs. The benefits are subdivided into economic growth, marina income and non-financial benefits. Costs have been extracted from different reference projects and have been calculated in a more extensive way than was done for the global solutions. They have also been calculated back to Net Present Value(NPV). The thorough calculation of the costs and benefits can be found in Appendix J.

All calculated values of the costs and benefits are summarized in table 8.7.

Table 8.7: Total overview, net present values at an 4.5% interest rate

Expenses		**EUR**		**COP**
Coastal protection	€	73,221,960	$	237,166,658,702
Drainage	€	8,208,607	$	26,771,597,656
Maintenance	€	7,798,949	$	25,435,536,015
Total	€	89,229,515	$	291,013,658,702

Benefits		**EUR**		**COP**
Economic growth	€	22,447,319	$	73,209,817,393
Marina	€	16,219,408	$	52,898,072,635
Damage prevention	€	61,767,794	$	201,449,841,424
Total	€	100,434,522	$	327,557,731,452

Difference		**EUR**		**COP**
Total	€	+ 11,205,006	$	+ 36,544,072,749

From this calculations it follows that potential benefits will be higher than expenses. The project can therefore be seen as economic feasible. In addition to this the calculation has been performed conservatively by underestimating the damage that is prevented. This is because with calculating indirect damages back to NPV it has been done at the 50 year point when in reality it should be done annualy which leads to an underestimation of the actual damages. For the direct damage the economic growth is not taken into account for the value of the buildings etc. leading to an underestimation.

8.9 Risks

In this risk analysis the final solutions system will be considered. Although each part if the solution is designed to have a high enough protection level, still things could go wrong. These risks and their possible counter measures will be discussed.

8.9.1 Coastal Risks

Seepage

Although most of the coastal defence structures already takes measures to prevent seepage it is still possible that seepage will occur. Long term large head differences which the structures are not designed for can take place. This event will however not happen frequently. Structures where seepage can occur are the seawalls, the promenade and the quay walls of the marina. Counter measures are installing additional seepage screens or compacting the ground. The amount of seepage is however limited as the time in which high water levels are present is short.

Instability

From analysis it is determined that the ground consist mostly of sand. This means that the bearing capacity of the ground will be high. Still some instabilities can occur. Foundations need to be placed for some of the structures and to ensure the stability these foundations need to be placed with care.

Furthermore instability can occur as a result of seepage. The permeability of sand is high and if seepage starts to occur some of the sand can be flushed away. This will influence the stability of the structure on top, as the bearing capacity of the ground is lessened.

Overtopping

One of the design criteria is that overtopping rate is not more than the maximum allowable. It is probable however that a wave higher than the design condition is approaching the structure. This will mean that the amount of water that flows over the structure is higher than was taken into account during the design. This will influence the stability of the structure, but will also cause nuisance of water in the street.

Revetments

The revetments on the bay side of the peninsula are also subjected to waves and currents generated by ships sailing by. The current water retaining structure on the bay side of Bocagrande and Castillogrande is, although it is still under construction, already experiencing problems with these waves and currents. When more of these waves and currents are present than was expected the stability of the revetments will be less. To mitigate this problem it can be implemented that ships need to sail further away from the revetments, or heavier armour stone can be used.

8.9.2 Drainage Risks

Check valves

The primary function of the check valves is to prevent tidal intrusion. When one of these valves fails and the water level becomes higher, the streets will again be flooded. The check valves will be embedded in the coastal structures or be placed below the sidewalks, so they will not be easily accessible. The valves should therefore be made as redundant as possible, to prevent unwanted events from happening.

Pumps

The installed pumps will also, like the check valves, be embedded in the structures. But while the valves are expected to function without much attention, the valves will be needing some upkeep and repairs. If one of the pump locations is not functioning during a period with high precipitation rates the area around this location is likely to flood. To give the system more redundancy at each location two smaller pumps can be installed for example.

Maintenance

The system with a lot of pumps and vegetation will need some maintenance. From past project it is known that maintenance will not always be done and most of the times will only be done after certain parts are broken. This is however to late, as in the case of this project flooding will already have happened. For the whole system to function a more structured approach to maintenance will need to be implemented, as otherwise the system won't work.

8.9.3 Other risks

Marina

Other than structural risks also financial risks need to be taken into account. In the financing of the project it was assumed that there was desire for more mooring places in the Bocagrande bay. There is a possibility that this is overestimated. With reduced use of the marina the revenue will also be lower than anticipated and possible investors will be let down and potentially back out.

Promenade

The same is applicable for the promenade on Boca beach. To attract investors a prediction will be made about the extra venue that can be expected. If this turn out to be lower than predicted the investors will have to be let down and get a lower return.

Swimmer safety

The final risk is not a technical or financial risk, but more an operational risk. When the pumps are working swimmers need to be warned not to swim to close to the outflow points. It remains to be seen however how often swimmers will be present when the pumps are working, because the pumps only start working in extreme conditions. It's is not very likely that people will then want to enjoy a swim.

8.9.4 Overview

To categorize the risks an overview has been made. Each risk will be given a relative probability and relative consequences. From the overview it can be seen that especially seepage and pump failure has to be prevented. The total overview is given in table 8.8.

Table 8.8: Overview technical risks

Risk	Probability	Consequences	Affected structures
Seepage	medium	high	Seawall, quay wall, promenade
Instability	low	medium	Seawall, quay wall, promenade
Overtopping	low	low	Revetment
Horizontal current	low	low	Revetment, seawall
Valve failure	medium	medium	Check valves
Pump failure	medium	high	Pumps
Maintenance failure	medium	high	Check valves, pumps

8.10 Policy plan

The solution is designed to keep the water out of the city, however a lot of additional solutions like policy changes are also available. The policy changes aim not to retain water but create manners how to live with water. They can thereby contribute to a decrease in costs of the current proposed solutions.

The starting point is that there will be no abrupt changes in the appearance of the peninsula. The implementation of a new policy could reduce the consequences of floodings and possibly lead to a coastal protection system that is less expensive and less obstructive. Different types of policy are available, each having a different area of influence. Therefore the peninsula is not divided into sections for this option. Instead, the policies will be named with a brief explanation. The policy can influence both the coastal defence and the rainfall drainage.

8.10.1 Disaster management

In case of a catastrophic event the natural human panic reaction results in additional chaos which increases the consequences of flooding. By making sure there is a well organised disaster plan, drafting protocols and proper staff training the consequences will be reduced significantly. The introduction of a good awareness campaign will also result in better prepared residents. This will result in a reduced stress level which in turn reduces the consequences of floodings. This policy change will allow limited flooding, but due to evacuation plans reduce the fatalities. It could however increase indirect damages as people might be evacuated without proper cause.

8.10.2 Construction guidelines

By adjusting the construction guidelines to the specific situation of the Bocagrande peninsula, it is possible to reduce the consequences of flooding. For example, introducing a minimum construction height (relative to MSL) for the ground floor would reduce the consequences significantly. Subsequently specific guidelines can be formulated for the construction of garages and other underground constructions. This could also take into account that future land elevation would take place.

8.10.3 No-build areas / extinction policy

By appointing the most flood prone areas as no-build areas, the consequences of flooding are reduced significantly. However, some of the locations that qualify as no-build areas will probably contain structures in the current situation and are to valuable to set as no build areas. Demolishing is often a very time- and money consuming activity, and is in most cases juridically impossible as well.

In this case an extinction policy could offer the solution. By changing the zoning plans it can be prevented that new buildings will be constructed once a building has reached the end of its lifetime. This solution is a long-term run that mainly focuses on reducing the consequence of flooding.

Chapter 9

Conclusion

Main causes of flooding in the studied area are high tide and heavy precipitation. During high tide sea water overtops or overflows the coastal protection at specific locations. Tidal intrusion also occurs through the drainage system due to the lack of, or the proper functioning of check valves.

During heavy precipitation the gravity runoff of rain water is not sufficiently fast enough to drain all the water. This is mainly due to deficiencies in the drainage system and an unsatisfactory surface level gradient. When heavy precipitation and high tide occur simultaneously gravity runoff is impossible and the flooding problem aggravates.

A third cause of flooding are less frequent phenomena such as severe storm conditions (return period 1/100) and the La Niña occurrence. Together with expected sea level rise and land subsidence this leads to estimated design levels varying between MSL + 2.47 and MSL + 2.87 along the coastline.

Besides environmental boundary conditions a lot of important social-cultural and political boundary conditions are present. Only a few decision making stakeholders have the authority to initiate a project of this size. These stakeholders need a sense of urgency to set the wheels in motion, which is created by estimating the damage through flooding at COP $ 201 billion.

Due to the mayor's limited period in office the construction time of the final design is limited to a maximum of 4 years. For a successful creation of the project within such a small period a solid stakeholder management is required.

From interviews and own observations it has become clear that frequent maintenance is not a standard procedure. Therefore the final design contains a lot of hard structures that are low in maintenance as well as soft structures that are low in maintenance costs.

Investment costs should be kept low at all time to make the project beneficial. For both local as national decision makers this is a major requirement. By leaving out the out-of-the-box solutions such as 'Green Roofs' and 'Permeable Pavement' the investments costs of the final design have been reduced in comparison to preliminary designs.

The problem description requires a distinct solution for the coastal protection system and the drainage system. The final design is the result of combining the strengths of various preliminary designs for both systems. All boundary conditions are taken into account by grading the separate elements on selected criteria in two different stages of the design process

Eye-catchers of the coastal protection system are the promenade at Bocagrande Beach and the marina at Castillogrande Bay. The promenade is executed in combination with a nourishment that provides sufficient construction space and additional beach area. The promenade creates a safe barrier against high water levels, adds status to the (inter)national image of the city and provides for additional recreational activities.

Construction of a marina at the bay side of the peninsula will attract additional tourists to the city. The daily presence of yachts will generate direct income which by estimation will earn back the initial costs within a period of 8 years. In addition the attraction of more tourists will result in a more intensive use of shopping malls and other touristic activities on the peninsula. The coastal protection is provided by a retaining wall which also provides the connection between the peninsula and the marina.

Centro Historico has the UNESCO world heritage status and to retain its historic character only necessary coastal protection executed by means of a revetment. To minimize the costs of the total project also other locations around the studied area are protected structures without additional functions.

The drainage system has the main function of draining water originating from rainfall. In addition it should also be able to prevent tidal intrusion through its outlets. Gravity runoff is increased by elevating the crucial roads of the peninsula. The increased slope ensures a rapid runoff towards the coast where the water can be stored in the coastal protection works and is pumped into the sea. Elevation of the roads is not a possibility in the historic centre due to UNESCO restrictions. However, here the surface gradient should already be sufficient to ensure a sufficient runoff. Tidal intrusion is prevented by installing new check valves at the outlets.

In addition to the surface elevation and the installation of pumps, vegetation will be planted which reduces the peak flow during rainfall events. The contribution is mainly symbolic since it barely influences the pumping capacity. However, it gives the solution a more green and innovative character without a big increase of costs.

From a financial point of view it is expected that the benefits of the final design have a net present value that is approximately COP $ 36 billion larger than the net present value of the expenses on construction and maintenance.

With regard to the main question of this report it can be stated that flood problems in Cartagena de Indias can be mitigated by implementing a design that puts the improvement of the drainage and coastal protection system in the first place. In addition this design requires both financial and non-financial values in order to satisfy all stakeholders involved.

Chapter 10

Recommendation

Based on the research made some things have come forward that could be examined more closely. These are related to assumptions made and recommendations for further study in the final design. Also recommendations to reform parts of the organizational system in Cartagena were made.

Final design

In the program of requirements assumptions have been made regarding data that were outdated or not available. These assumptions should be checked by performing measurements to obtain these data. The most important assumptions that should be checked will be mentioned.

Since only wave data at the Caribbean sea were available and the bay side is located at the lee side of the peninsula, an assumption was made by reducing the wave heights by a factor, based on common sense. Therefore these wave heights should be checked. Also there were no elevation maps with respect to mean sea level available. From visual observations reasonable approximations could be made, but for an optimal design of the drainage critical points and heights of the retaining walls, a research should be executed.

In the final design, the shore will be extended at Boca beach and Castillo beach by a nourishment and extending the groynes. A study should be performed to the effectiveness of these modifications. The effects of the recently constructed groynes at the Crespo area should be taken into account by a model. Also the effects of seepage need to be taken into account, since its effects could cause serious problems with coastal structures in the future. With the expected water levels, this could prove to be the most critical factor for the technical feasibility.

The infrastructure was not taken into account in this study. However, during the project it became clear that the capacity of Carrera 1, along the Bocagrande beach side, is insufficient, creating an undesired bottleneck for the accessibility of the peninsula. Since the final design extends the shore along this alignment, it allows the possibility to add a lane to this road, to improve the capacity.

Organizational system

The relation to the stakeholders during the project is important. An unsatisfying stakeholder participation can create resistance. It is recommended to determine in advance what stakeholders are consulted on what subjects on at what time during the project. A clear stakeholder management and communication strategy should be made to get each relevant stakeholders on board and reduce the resistance or even to ease the process.

Large amount of institutions are working on their own field of specialization. These organizations operate separately from each other without interacting with other parties. This obstructs an integral cooperation between the different parties. If the communication and therefore cooperation between these institutions would improve, a more integral approach can be used.

Also a central point for all data is recommended. Since the institutes gather their own data, some parties work with different data on the same subject, or it is difficult to find out what data belongs to which institute. It takes too long to gather all required information in the current situation. Therefore it is advised to let a public institute, like the university, gather all data to make it easily accessible.

A clear responsibility should be established for the different subjects like drainage and the coastal protection. The different organisations should have their own responsibilities and where necessary merging organisations. Those responsibilities should be backup with laws and regulations.

The allocation of funding for maintenance should be clear in the beginning of the project. Thereby a constant maintenance of the drainage system and coastal protection should be executed.

Appendix A

Introduction

A.1 Analysis of current and past floods

The city of Cartagena suffers frequently from floods, in the lower areas of the city (Bocagrande, Castillogrando, El Laguito and Centro) especially between August and December [29]. The duration and water levels vary between these floods, and consequently also the damages are different for every flood. In this paragraph a distinction is made between three different classes of flooding: low, medium and high impact floods. These flood events differ in water level and duration. The frequency, duration and the damage per level of the floods are shown in table A.1. Below examples of the different classes are given.

Class	Frequency	Duration	Damage
1	2-3 times a month during rain season	1-3 days	-Minor damages to buildings -Some damages due to the intrusion of salt water in the drainage system -Cars affected by the salt water.
2	4-5 times a year during rainy season	2-6 days	-Minor damages to buildings -Some damages due to the intrusion of salt water in the drainage system -Cars affected by the salt water -Inundation of ground floor levels of buildings occurs. -Economic activities are hindered
3	once every 5-10 years	5-15 days	-Major structural and economic damages -Parts of the city only accessible by boat -Causes severe damages to public and private property -Economic activities are barely possible.

Table A.1: Frequency, duration and damage of the different flooding types

A.1.1 Class 1: Low impact flood

In case of a low impact flood, some of the streets are inundated by either the events of tidal intrusion or a peak rain discharge. In these low impact situations is referred to a minor flood event, where the sidewalks are not flooded but the main streets are inundated. Although the main streets are still accessible for cars and other vehicles. During observations every spring tide event, a class 1 flood was observed at Bocagrande, Castillogrande and parts of Centro.

Example: Flood at Castillogrande at December 16th 2014 (Figure A.1). Despite not having heavy rains or extreme water levels at the Bay of Cartagena, the streets at Castillogrande suffered a minor flood due to the high tidal water levels [30]. According to CIOH (El Centro de Investigaciones Oceanográficas e Hidrográicas del Caribe), the wind speed reached only 7-12 km/h, representing a slight breeze. Also, the wave height only reached 0.6m, normally not a significant height in coastal areas. Since the street levels on Castillogrande are lower than on Bocagrande, these conditions were severe enough to flood the streets, affecting the traffic significantly.

(a) Hinder to the traffic

(b) Inundated streets

Figure A.1: Flooding of Castillogrande, December 16th 2014

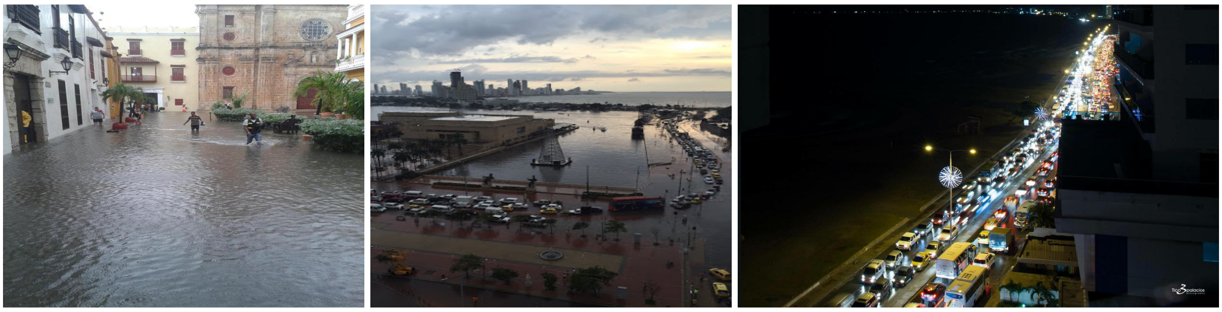
A.1.2 Class 2: Medium impact flood

In case of a medium impact flood, a more severe flood event is the case, induced by either a strong tidal component, a heavy peak rain discharge, or a combination of both. Most parts of the lower areas of Cartagena are flooded and cause significant hinder to most of the infrastructure. Most side walks are flooded and the duration of the flood is usually longer compared to a low impact flood.

Example: Floodings at several parts of Cartagena on December 10th 2014. A few days prior to the example discussed above, a peak rain discharge has caused flooding of most parts of the city of Cartagena. The focus in this report is to the areas of Centro, Bocagrande, Castillogrande and El Laguito, but during these floods also parts south in the city were flooded.

A.1.3 Class 3: High impact flood

When speaking of a high impact flood, there is a serious hinder from flooding. The main roads are inaccessible for traffic and the ground floor of numerous buildings are flooded.



(a) Flooded square in Centro (b) Hinder of infrastructure (c) Hinder to traffic at Bocagrande

Figure A.2: Medium impact flood at different parts of Cartagena [31]

Example: the 1988 flood event, when Bocagrande was closed of for one day from the rest of the city and was only accessible by boat. During this event hurricane Joan-Miriam raged through the Caribbean. Even though the hurricane did not make landfall in Colombia, Cartagena suffered from Joan-Miriam. It was causing the sea level to be pushed up directed to Cartagena. Also the hurricane caused the rain discharge to be immense. The combination of both factors occuring simultaneously caused a high flood impact. The example of Joan-Miriam is an exceptional event, since most hurricanes in the Caribbean tend to deflect to the north.

Appendix B

Analysis

B.1 Area Analysis

B.1.1 Historical Centre (Centro)

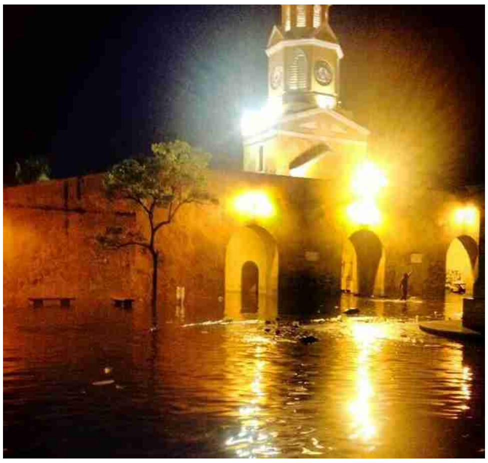
The historical centre is the oldest part of Cartagena and famous for its old characteristic colonial buildings. The origin of the centre dates to the 16th century. The centre is surrounded by a big city wall and within these walls several colonial buildings can be found. This area is a UNESCO world heritage site since 1984. Its cultural heritage makes the centre important for the attractiveness of the city, making it a popular tourist destination. The historic centre suffers from problems with flooding by tidal intrusion and peak rain discharges. At most buildings the ground floor is placed at a slightly higher level with respect to the sidewalks and street level. Therefore, the ground floor often stays dry during the floods. However, the buildings still suffer from structural damages. The floods also cause economic damages, since commercial activities are significantly hindered during these flood events. In Appendix A pictures of the flood events can be found.

Tidal intrusion

The historic centre is vulnerable to flooding when spring tide hits, especially in combination with storms generated at sea, causing even higher water levels. The coastal profile in front of Centro consists of a rocky revetment with various constructed breakwaters (figure B.2a). These are hard structures that barely contain a sandy beach. Due to the steepness of the profile, the waves are assumed to be plunging waves. There is a main road located outside the city walls, which has a bigger elevation height than the area inside the city walls. The incoming waves tend to start overtopping the revetment even when it isn't high tide yet (figure B.2c). The outflow of the drainage system is also located at the coast (figure B.2b). Through these outlets, seawater can enter the system in case of a high sea level induced by the tide.

Drainage

In Centro several water outlets from buildings runoff to the streets gutters (figure B.3a). The roads in the city are barely permeable so all the precipitation is discharged trough the gutters



(a) Flooding of historical centre within city walls [18]

(b) Flooding of historical centre within city walls [32]

(c) Tidal intrusion, outside the city walls [20]

(d) Tidal intrusion, outside the city walls [20]

Figure B.1: The city centre during different flood events

along the streets(Figure B.3b). The gutters get often clogged due to garbage on the street. The gutters dispose the water into drains or manholes that are built at the bigger intersections in the city (Figure B.3c). From these drains, the rainwater is guided directly towards the sea. During high sea water levels the hydraulic head is insufficient to open the valves for runoff. At some locations the valves are not functioning properly due to bad maintenance and the water is even forced onto the city streets.

Future developments

The height differences in the historical centre with respect to sea level are small, leading to a small available hydraulic head for the rain water to run off to the outlets. When taking into account the accelerated effect of sea level rise, the problems with flooding most likely will occur with a higher frequency and higher intensity if no precautions are taken. Over the last years, several proposals to improve the systems were made. Unfortunately all of these proposals find trouble with practicability or funding.

(a) Rocky revetment (b) outlet (c) Coastal view from city wall

Figure B.2: Conditions at revetment at 21 August 2015 10:42, between lowtide and moonrise

(a) Outlets onto the streets (b) The gutters (c) The drains

Figure B.3: Drainage system in historical centre

B.1.2 Bocagrande

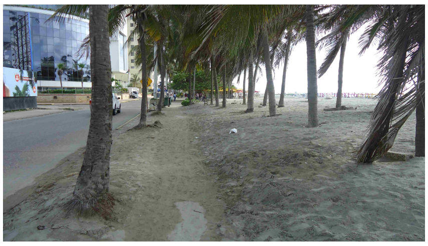
Bocagrande is situated south of the historical centre, shown in green in figure 2.1a. Although situated closely to the historical centre, Bocagrande gives a totally different experience of Cartagena. This part of the city is very modern and is almost completely filled with high-rise hotel buildings, which are all constructed close to the beach. In Bocagrande also a lot of shops and western restaurants chains, like McDonald's, are found. Bocagrande provides 21 percent of the employment of Cartagena and is therefore an important economic center for this growing city[33]. To maintain the growth of commercial activities, the reduction of floods has become more important.

The three major issues that lead to a serious flood problem in this area are:

- The land-sea gradient is too low
- Insufficient urban drainage system: water cannot runoff in Bocagrande during sea level rise or rain
- Inadequate coastal protection

The first problem is that the gradient from the land to the sea is too small. This causes the water to be trapped in the streets of Bocagrande after heavy rainfall. Moreover when there is a high sea level, the hydraulic head is too low to let the water runoff into the sea.

The second problem is the current state of the drainage system (figure B.4). The drainage systems have an open connection to the sea, which means at high tide the sea water is able



(a) Land gradient

(b) Insufficient drainage: Open drainage to the sea

(c) Insufficient drainage: garbage in drains

(d) Tideway

Figure B.4: Drainage system in Bocagrande

to freely enter the city and increase the effects of flooding by precipitation. An additional coagulation of the runoff system is that the gutters are full of garbage causing a poor water runoff capacity.

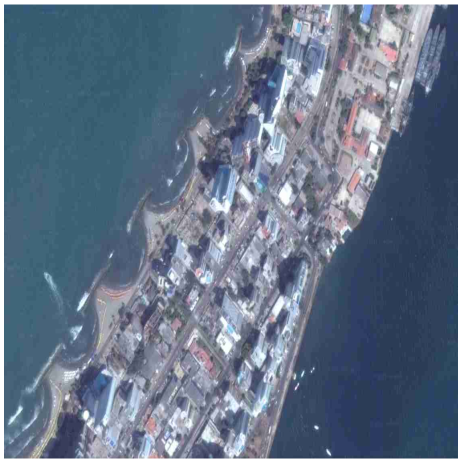
The third problem is the poor coastal protection. The lack of primary embankments affect the flooding from sea. There is not a retaining structure like a dike or seawall to retain high water levels. The water is free to intrude into the Bocagrande area during high water. During high tide the sea water can penetrate to the streets of Bocagrande causing limited accessibility for traffic.

Another important aspect about the Bocagrande area is that tourism is becoming very important. The tourists come for the beaches so these need to be preserved. A number of breakwaters have been installed at the sea side of Bocagrande to reduce possible erosion and to trap sediment in the beach area.

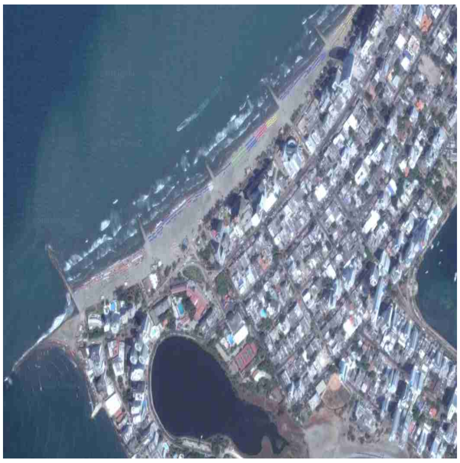
Coastal protection

At the northern and southern side of Bocagrande the breakwaters consist of groynes whereas at the middle part of Bocagrande the breakwater are alongshore with the coast as can be seen in figure B.5.

(a) Groynes in the Northern part of Bocagrande



(b) Tombolo formation in the middle part of Bocagrande



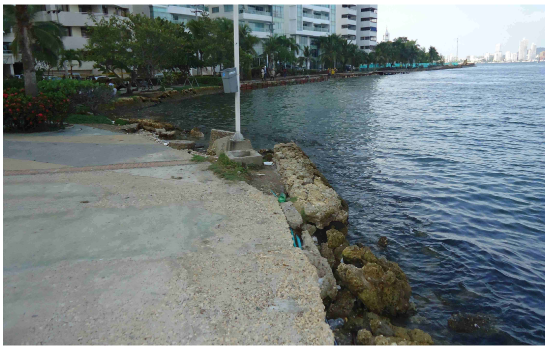
(c) Groynes in the southern part of Bocagrande and El Laguito

(d) Irribarren groyne

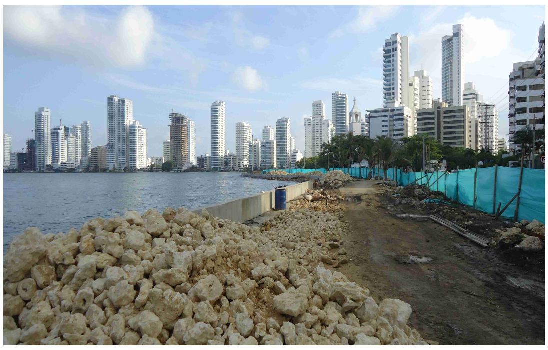
Figure B.5: Coastal protection of the Bocagrande area

These alongshore breakwaters have been situated very close to the coast and have formed into tombolos. The formation of tombolos is not a desirable effect as it diminishes the effect of the trapping sediment.

The bay side of Bocagrande is situated at a level lower than the sea side and therefore is much more vulnerable to flooding. It is protected by only a small retaining wall. Currently a new sea wall is being constructed that should be able to retain higher water levels with a sufficient drainage system as can be seen in figure B.6.



(a) Damaged protection with Bocagrande border



(b) Construction of sea wall bay side

Figure B.6: Bay side protection of the Bocagrande area

B.1.3 El Laguito

El Laguito is the area seen in the southwestern part of figure B.7. The area of El Laguito is not much different from the Bocagrande area. The skyline is also dominated with high rise buildings, built mainly for tourists and not for residents of Cartagena. The Hilton hotel is one of the largest hotels present on this newly constructed land. El laguito was constructed in the period of 1960 to 1964 and has several large groynes for the stabilisation of the land that has been constructed. The groynes are located on the western side of El Laguito. Currently, a new breakwater is being constructed at that location. With the construction of the El Laguito a tidal basin was created which inlet is sedimented over the years. This was probably caused due to the lake of ability to trap the sediment with the groynes. The lost ability to trap sediment was caused because the groynes were all filled up and the sediment can bypass the groynes and enter the tidal basin. In order to prevent further sedimentation to occur a groyne was constructed on the southern part of the tidal basin but this has not led to a significant decrease in accretion. Because of the accretion the tidal basin has slowly transformed into a lake (Figure B.7).

(a) Creation of the Laguito area (b) Development tidal basin (c) Current tidal basin

Figure B.7: Evolution of the El Laguito area

Water quality

The closure of El Laguito has led to a water quality problem in the lake since there is no interaction with sea water any more. An official investigation however states that the water quality is sufficient and no undesirable smells are present. The official investigation contradicts with the experience of local residents, who state the lake is literally rotting, since there is a lack of oxygen in the water [34]. Complaints are made about foul odors, proliferation of many mosquitos and rats around El Laguito and all kinds of waste discharged into the lake. During rain events, the rainwater mixes with waste of dust, paint and car tires and flows into El Laguito. These contaminants may cause serious risks to health [35].

The area of the lake is roughly 58 600 m^2. Interests for this area are high as several developers are interested in filling up the lake and using the new area for new high rises and hotels. There is opposition against this from local population as a large part of green would disappear. The El Laguito area is less prone to flooding than the Bocagrande, Castillogrande and Centro as El Laguito has a higher surface elevation than than the before mentioned areas. Flooding mainly occurs with high tidal intrusion in the El Laguito area similar to the Bocagrande area. As is seen in figure B.8a the lake has been enclosed by structural accretion and there is only a very shallow entrance channel for flow to go into the lake during high water.

(a) Lake view (b) Inflow and outflow (c) Revetment

Figure B.8: El Laguito lake enclosure

The western El Laguito area however has a lot of problems concerning erosion which occurs less in the Bocagrande area. Protection is in place by means of a rough stone revetment. At the tip of the Bocagrande/El Laguito area a lot of the existing beach has already been eroded to the point where it touches the stone revetment and restaurant and hotel owners are losing precious beach areas (figure B.8c).

Drainage

Not only tidal intrusion is a problem is the El Laguito area, but also lack of runoff of tidal water and precipitation. Due to the large lake this problem is considerably smaller than in the Bocagrande area. One thing to be considered is that due to the closure of the tidal basin the water cannot easily runoff through the channel. The drainage has the same problems as in the Bocagrande area. The drainage is limited by the mild slope that consists on the area. The drains that are in place are easily clogged and are generally insufficient.

(a) Stormwater drain

(b) Stormwater drain

(c) Street runoff

(d) Street runoff

(e) Clogged outlet drain

Figure B.9: Several drainage facilities in El Laguito

B.1.4 Castillogrande

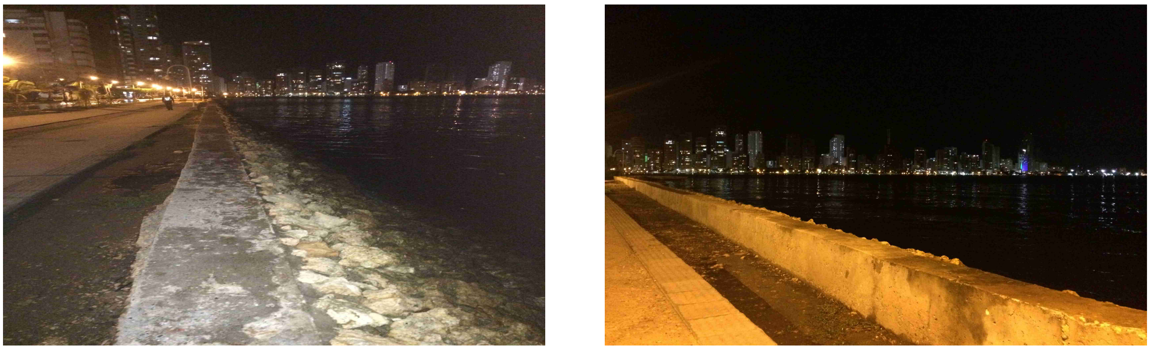
Castillogrande is also a part of Cartagena that is characterized by high rise buildings, although these are mainly meant for the richest families of Cartagena. The beaches that are now in place were formed around 1986 at the same time the lake at El Laguito started to close as well. Beaches that are found here are mostly visited by the families living there instead of tourists.

At the sea side of Castillogrande a number of small groynes have been constructed. These groynes have accumulated enough sediment in the time since construction that it no longer holds sediment and the groynes are full. The groynes are very small in length but are protecting the beach sufficiently, as shown in figure B.10.

(a) Beach accretion north side (b) Groynes fully sedimentated

Figure B.10: Groyne positioning at Castillogrande

The bay side of Castillogrande has just had an upgrade in flood protection. It is now protected by a sea wall with a protective layer of revetment. This sea wall is protecting against the sea, but with the runoff drains having an open connection to the bay it is not working sufficiently. (figure B.11)



(a) Revetment of the bay side (b) Sea wall on the bayside

Figure B.11: Bay side protection at Castillogrande

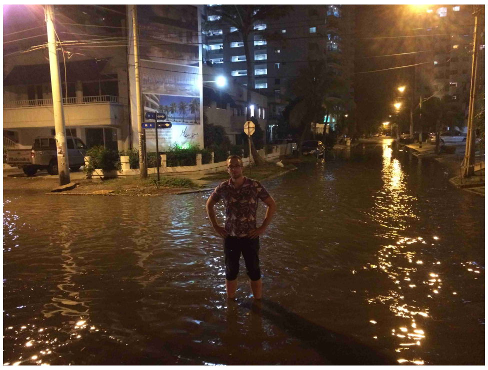
With the tidal intrusion is already leading to flooding problems entering via the drains, the problem will only enhance with the expected sea level rise in the future.

Drainage

Castillogrande has lower street levels than Bocagrande. The street levels are so low that in case of high water the streets flood very quickly as can be seen in figure B.12. With the occurrence of spring tide the streets are flooded with water, which occurs twice a month. During these periods the apartments at Castillogrande are not easily accessible due to the inundation. The drainage system is not able to let the water runoff due to the low head difference, which causes the water to pile up in the streets.

(a) Example of a flooded Castillogrande

(b) Car riding through flooded streets



(c) Flooded cross section

(d) Drain over maximum capacity

Figure B.12: Flooded Castillogrande

B.2 Sewer system

Most of the drainage systems in older cities have a combined system [36]. In this system there is one single pipe through which both the wastewater and rainwater is discharged. The water in the pipes flows via a network to the sanitary wastewater treatment plant where it will be treated before it flows back to the surface water. If overflow of the system occurs regularly, this could lead to environmental problems in the surface water.

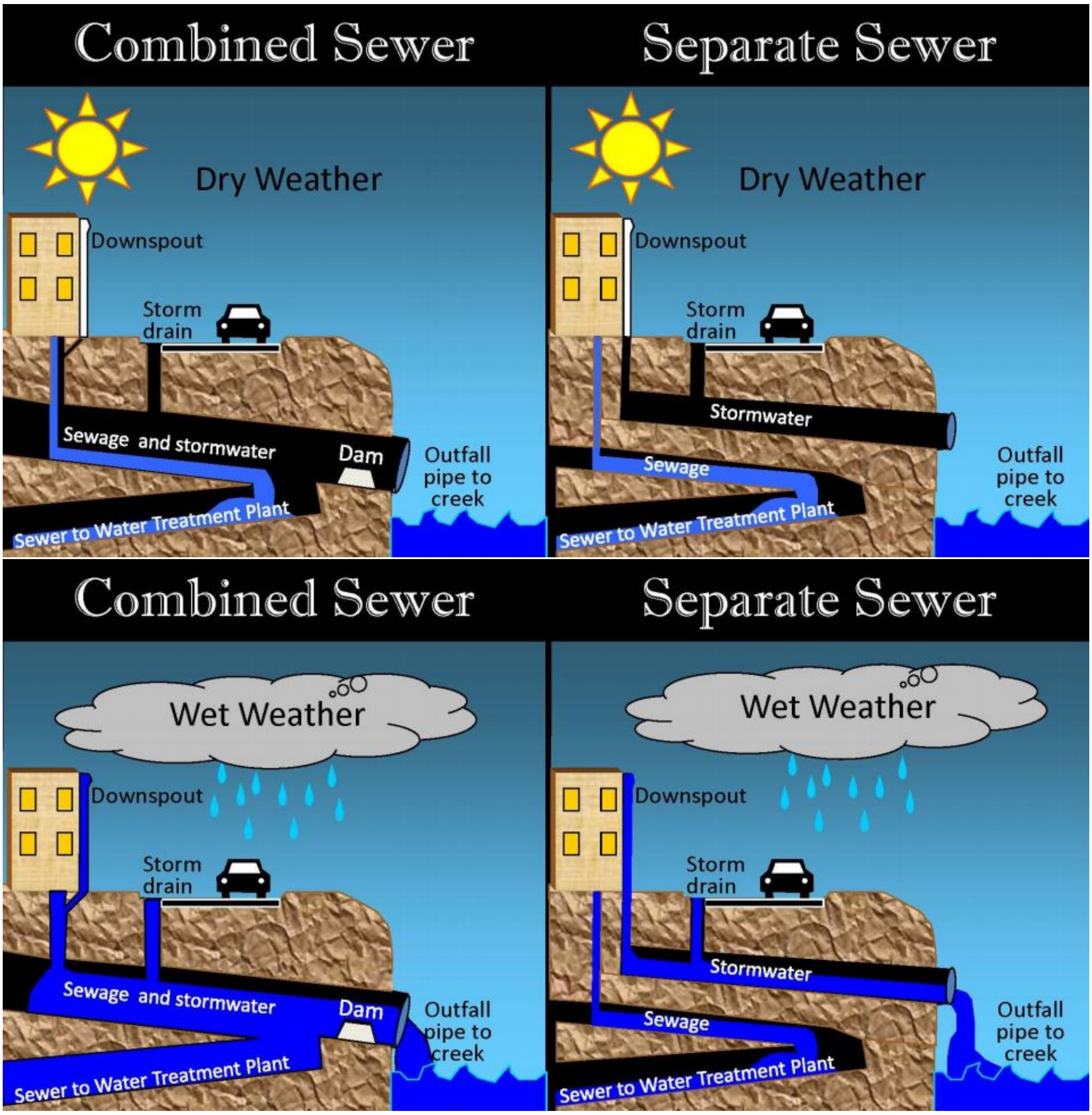


Figure B.13: Combined vs separate sewer system [37]

In a separated system the rainwater and the sanitary wastewater are kept separated by using two pipes [36]. The wastewater will run through one of the pipes to the treatment plant and after treatment it will flow into the surface water. The stormwater will runoff into the surface water without any treatment by using the other pipe. This way, overloading of the sanitary sewer system is prevented.

Both systems have their advantages and disadvantages. Currently there is already a separated sewer system in Cartagena. Therefore there is no reason to change this to a combined system. The wastewater is pumped through various pumps and eventually ends up in the deep end of the sea at Punta de Canoa, north of the city. With this system there are some issues that need to be taken into account. First, the stormwater system needs to be designed in such a way that the occurrence of stagnant water is kept at a minimum to avoid a hatchery for mosquitoes.

Furthermore, it is important that the wastewater cannot flow into the stormwater system due to wrong connections or leakage. Finally, it is important to do maintenance on the stormwater system during the dry season, so that in the wet season the system will work well and no flooding will occur.

Current drainage system

At the Bocagrande, Castillogrande and El Laguito areas, the stormwater drainage is entirely designed for runoff by gravitation. Not a single pump for stormwater is installed, even though in the past the Universidad de Cartagena advised to do so. The current drainage system proves to be insufficient, as can be noticed by the frequent floods in these areas. The proposal of the University was accepted by the municipality and even the funding was finalized. However, these pumps were never installed because of unclear governmental reasons.

There are some pumping stations installed in and around Centro Historico. In the past the squares had troubles with stagnant water after heavy rainfall, since the water was not able to runoff by gravitation. A pump was installed at Plaza De La Aduana [38] (figure B.14), that discharges into the water near Getsemani. Inside the city walls no other pumping stations are located. Another pumping station is installed near Parque Centario. This is located outside Centro Historico, so in this research this is not taken into account.

Figure B.14: Pumping station at Plaza De La Aduana, located at A1

B.3 Critical points

Bocagrande

In the Bocagrande area there is no proper drainage system. The Bocagrande neighbourhood can be defined as flat area. In this urban area the water runoff is determined by the slopes of the streets towards the sea. The street level gradients in Bocagrande are less then 0,5 % at most parts of the city and some streets even reach slopes with zero gradient. The drainage management in the flat areas is not only influenced by precipitation but also influenced by the tide, the channels and the lakes in the city. As a result, during the rising tide in the seasons, water is even present in the streets in absence of rainfall [39].

There are several critical points that flood when the tide is high. The floods occur when the tide enters via the sewers and drainage channels. The critical points in Bocagrande are between Calle 6 and Calle 10 where an outlet exists between the street and the sea. Clogging occurs due to transported sediment during high tide which prevents water from discharging normally into the sea [39] (Figure B.16a). The elevation of the land is also a problem, the low surface elevation at some points causes accumulation of water at those points, obstructing the water runoff. In figure B.15a, the critical point from the high tide intrusion is shown in blue. In green, the critical points due to the their low surface elevation are shown.

(a) Critical points Bocagrande

(b) Critical points Castillogrande

(c) Critical points El laguito

Figure B.15: Critical points at the peninsula

Castillogrande

The tidal intrusion in Castillogrande is most severe at the Club Naval, located at the southern tip of Castillogrande. Due to the fact that this land has the lowest surface elevation point, even a minimal elevation of the tide causes the streets of Castillogrande to be flooded, since the water cannot runoff (Figure B.16b). The point at Calle 6 has the lowest elevation in the area, so this point is likely to flood easily. See figure B.15b.

(a) Open mouth connection between the sea and street

(b) Drainagesystem Castillogrande during high tide

El Laguito

El Laguito's most critical point is at the south of the area at Calle 1B as indicated in figure B.15c. Here, the surface elevation is lower compared to the rest of El Laguito. Since the El Laguito lake is closed of from Cartagena Bay, during heavy rainfall events the inner lake is more likely to flood to the lowest point of the land. Like mentioned in the area analysis of El Laguito, the water quality of El Laguito lake is poor and a possible risk for health problems, which makes inundation of water from the lake very undesirable.

Centro Historico

The drainage system in the historical centre consists of several outlets from buildings to the streets gutters. These gutters are connected to drains or manholes at the intersections of the city. The gutters flush into the sea. But at high tide, due to the lack of valves the gutters can get flushed with backflow, causing sea water to enter the streets of the city. Also clogging of the gutters is a big problem, resulting in a decrease of the capacity of the drainage system.

Appendix C

Current construction works

The current state of the Cartagena coastal protection and drainage system is not sufficient to prevent flooding from tidal intrusion and peak rain discharges. The Department of Infrastructure of the Municipality of Cartagena is trying to solve these problems and has taken actions by constructing adjustments to the current system. In this section, the current construction works will be discussed.

C.1 Bocagrande pedestrian promenade

Along the Cartagena Bay side of the Bocagrande and Castillogrande, a renewed pedestrian promenade of 2.1 km is being built. The new promenade includes a retaining wall with a height of 80 cm and width of 30cm. Construction started in May 2015 and will be completed in December 2015. The investment in the intervention is 8,60 billion COP (2,3 million EUR) The old promenade was built 28 years ago and this is the first investment made in that area since its construction [40].

There was also a lot of resistance and criticism from different parties to the new pedestrian promenade project. First of all the design is not the most aesthetic and desired one, according to local residents and a group of architects. One of these architects, Fernando De La Vega, states that "a design in this important part of the city should compete at national and international awards for design, infrastructure and creativity" [41]. Other criticism came from the communities of Bocagrande and Castillogrande and The Society of Engineers and Architects of Bolivar (SIAB). Both parties met the Ministry of Infrastructure before construction to indicate their concerns in a proposal. After that meeting, the communities and SIAB claim they did not get any insights into the final design and whether their proposal was taken into account. Their main concerns are about the drainage of rain water from the streets, since the design mainly focuses on the problems with tidal intrusion. Also the quality of the concrete in combination with reinforcement is a point of concern since the intrusion of salt water has proven to affect the quality of the concrete in the past. In the past the salt intrusion caused the concrete of the retaining wall to be insufficient after a few years. The estimated lifetime of the structure is only 2 to 5 years according to prof. Javier Mouthon Bello [Appendix D.1].

According to Mario Ramos, secretary of Infrastructure, the problems that are mentioned are taken into account in the design. There are special duck valves (Figure C.1c) installed in the drainage system, so tidal intrusion is prevented and rain water can runoff. To guarantee the quality of the concrete, he states that the reinforcement is placed in a sufficient way, such that corrosion is prevented and the wall is protected in the best possible way [42]. About the aesthetic part of the design, he said that vegetation and ornaments will be used to decorate the work. This should meet the promenade standards for an area with the allure of Castillogrande.

(a) Construction new retaining wall (b) Progress construction at Bocagrande (c) New drains [43]

Figure C.1: Construction of new pedestrian promenada at Bocagrande and Castillogrande

C.2 Seepage and piping

The current solution is primarily based on the problems caused by tidal intrustion entering trough the outlet drains. However, other forms of tidal intrusion may be present at the current coastal defence system, being seepage and piping (Figure C.2). Seepage is a flow of water that is able to pass the coastal defence system via gaps, cracks or connections between structural parts. When the flow goes underneath the structure, carrying pieces of sediment, the process is called piping. Piping is potentially very dangerous, since once all the sediment is flushed away underneath the structure, the water is able to flow away the entire structure. The effects of seepage and piping did not have been investigated so far, since the problems of tidal intrusion entering via the drains is significantly larger. The effects of seepage and piping have to be taken in account for a final design. Sheetpiling would be a possibility, but expensive solution to prevent these effects.

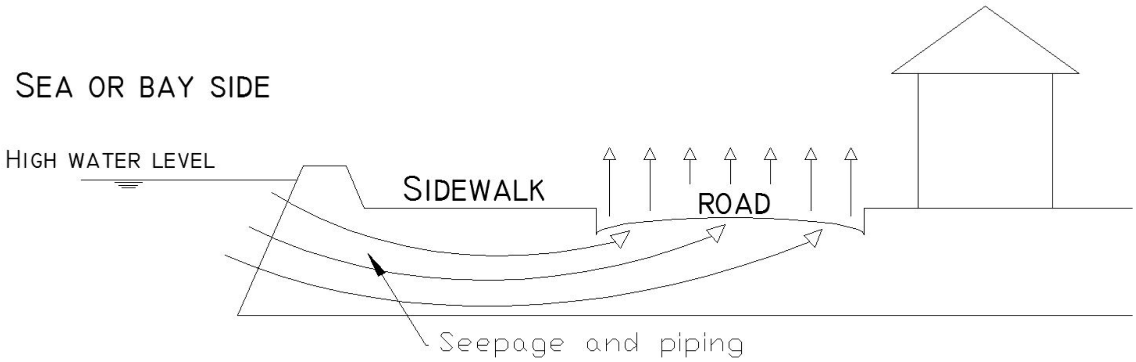


Figure C.2: Schematization of the effects of seepage and piping

C.3 Tunnel Anillo Vial De Crespo

In the Marbella area, located close to the airport in the northern part of the city, the Anillo Vial de Crespo project is being executed (see figure C.3). The project was initiated by congestion problems on the 'RUTA 90A', the highway that connects Cartagena and Barranquilla. Once RUTA 90A enters Cartagena, the traffic is guided through the smaller roads of Marbella which leads to congestion. The 'Annilo Vial de Crespo project' is a tunnel to bypass the Marbella district and establish a straight connection along the coast.

The main reason to bypass Marbella was the limited opportunity to expand the roads. Initially the space along the coastline was limited as well so the solution also includes the reclamation of new land. In order to create additional value and have maximum benefit of the newly created wide beaches the project has decided to opt for a tunnel. The reclamation solves local erosion problems as well and the design is therefore considered an integral solution [44].

Figure C.3: Location of Anillo Vial de Crespo project

The project is designed to create an integral solution that forms an improvement for the following problems:

- Solution to improve capacity RUTA 90A
- Local coastal protection
- Create new recreational area

C.3.1 Mobility

By upgrading the highway from 2 to 4 lanes, the capacity increases significantly, improving the capacity of RUTA 90A. To further increase the capacity the intersections and exits are being renewed as well. The tunnel should have been completed at the end of 2014, but difficulties with the quality of the concrete caused a delay. The construction of the diaphragm walls lacked accuracy which resulted in unacceptable leakage so an extra layer of reinforced concrete had to be installed. The consortium claims the problems are solved and do not obstruct the final result. However, the spaciousness of the width of the tunnel is reduced though, since the tunnel walls had to be applied bigger than initially was calculated.

Figure C.4: Impression of Anillo Vial De Crespo

C.3.2 Coastal works

In the past some groynes were constructed in order to reduce the coastal erosion. With the Anillo Vial de Crespo project these groynes have been replaced by seven larger groynes. A nourishment of 1.2 million m^3 of sand has been executed to create a reclaimed area of approximately 35 hectares. The coastline has moved $\pm$ 100 m seawards and the groynes are extending 100 m into the sea from the newly created coastline. Underneath the beach a 2.2 km revetment wall has been constructed to create an extra level of protection against erosion. Figure C.5 and figure C.6 show the coastlines in respectively 2009 and 2015.

Figure C.5: Marbella coastline in 2009 [45]

Figure C.6: Marbella coastline in 2015 (green line indicates 2009 coastline) [45]

C.3.3 At a larger scale

Marbella is definitely not the only location along the Colombian coastline that experiences erosion. The focus area of this research (Centro and Bocagrande peninsula) is experiencing the same kind of problems and largely depends on the sediment transported along the Marbella coastline [see section 'Coastal evolution' in chapter 4 'Boundary conditions']. The newly constructed groynes can be expected to catch sediment and therefore reduce the supply in the focus area. In figure C.5 and figure C.6 it can be seen that the coastline downstream (left side of the pciture) has already retreated by more than 30 meters [Google Earth measurements].

The real effect of the newly constructed groynes is important to produce a reliable solution.

However, this is very time consuming and the input parameters would contain a lot of uncertainties as well. Therefore we prefer a method with historical satellite images of the coastline at three different checkpoints. Since there is a strong difference over the seasons in bed profile it is preferred to only use data originating from the same time span.

From the available data, the pictures used all originate from the months January and December. The distance from a fixed land point to the start of the surf zone is measured. Measuring points are defined at Chiriguito Beach, Hotel Bocagrande and Hotel Dorado (see also figure C.7). The measuring points are defined at locations that are susceptible to erosion. The coastline around the historic center, for example, only consists of rock revetment and there is no sand to erode. Results are presented in meters in table C.1.

Figure C.7: Location of measuring points

Table C.1: Retrieving costline (m) [45]

	Jan '07	**Dec '09**	**Jan '12**	**Dec '12**	**Dec '13**	**Dec '14**	**Jan '15**
Chiriguito Beach	50	59	49	60	55	42	41
Hotel Bocagrande	27	33	30	31	35	25	23
Hotel Dorado	12	51	22	29	35	54	53

Interpretation of the measurements is difficult since they are only a snapshot in time. The values in table C.1 do not give away the conditions of that moment (high/low water, stormy/calm weather, etc). Assuming equal weather- and tidal conditions for the moments of measurement will lead to the conclusion that Chiriguito Beach and Hotel Bocagrande have experienced coastal retreat of more than 10 meters within one year. On the other hand, Hotel Dorado has experienced accretion of 20 meters in the same period of time. This conclusion seems odd and in combination with the false assumption of equal conditions it cannot hold. With the current available data we are unable to draw a straightforward conclusion. Therefore we will not take into account the possible influence of Anillo Vila de Crespo for our design. For a more accurate and dependable solution it is recommended to make a computational model of the situation.

Appendix D

Flood risk assessment

In order to determine the damage a flood causes it is necessary to assess the damage per area. Each area holds a different societal and economical value. It is important to have a level of protection that is in line with these values. Risk can be expressed as an expected amount of annual damage with the probability and the consequence of a scenario and can be defined as follows.

$$Risk = Probability \cdot Consequence$$

Not only material damage needs to be taken into account, but also the loss of working hours and possible loss of life. Material damagge is relatively easily to determine. Indirect damages and losses of life are however more difficult to give a quantitative value. Reasons for loss of life during a flood depend on a number of effects, being:

- Flood effects: Depth, velocity, rise rate
- Other factors: Exposed population, evacuation, collapse of buildings
- Mortality amongst exposed population

The damage to buildings and the loss of lives are considered direct damage due to a flood. High water in the city also hampers traffic and other everyday activities. Economic losses related to those are the indirect damages

D.0.4 Direct damage

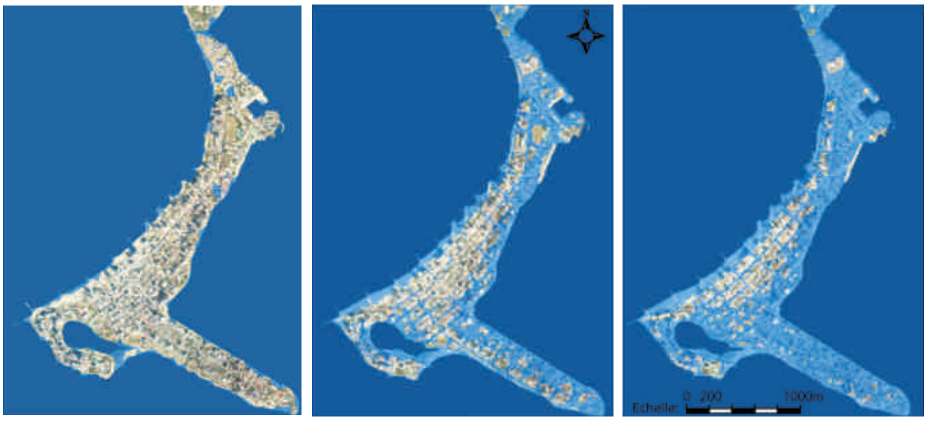
To determine the direct damages the flood levels in the city are related to inundated areas. The city is again devided into the parts Bocagrande, Castillogrande, El Laguito and Centro. Two situations are taken to asses the losses for. The first situation is the level of the sea in 50 years without waves. A total rise of 1.03 m is considered. The damages in this situation can be seen as damages that are more or less certain, as these conditions can be expected to occur frequently. The second situation also includes the waves, heightening the inundation level to 2.87 m. This can be considered as the extreme condition and long before this situation is reached all parts will already be flooded. All values can be found in table D.1.

The material damage per part of the city is determined by taking the surface areas of the flooded areas. These are multiplied with the economic value and a damage factor that is applicable for high rise buildings. In figure D.1 the inundated areas a for the Bocagrande peninsula are

Table D.1: Considered situations

Element	Height
High Tide	0.34 m
la Nina	0.30 m
SLR	0.28 m
Land subsidence	0.11 m
Total elevation in 50 years	1.03 m
Wave amplitude	0.84 m
Storm surge	1.00 m
Elavation incl wave	2.87 m

visually represented for both situations. From these the inundated areas are estimated. The same has been done for Centro. The damage factors are calculated according to Dutch theories [46]. These will overestimate the damages greatly, as inundations will not have the same effect in both countries. In Cartagena floods occur much more frequent so the populations is adjusted to them. Therefore only half of the calculated damage will be accounted for.



(a) Predicted flooded parts by 0.5 m rise of sea level (b) Predicted flooded parts by 1 m rise of sea level (c) Predicted flooded parts by 1.50 m rise of sea level

Figure D.1: Predicted flooded parts of Bocagrande [2]

The economic costs of the lives lost is also calculated on the basis of the inundated surface areas. The areas are multiplied with the population density, the statistical value of human life and a life loss factor. For Colombia the statistical value of $680.000 US dollars is taken [47]. The life loss factor is again calculated according to Dutch flood risk management [46]. These are in contrast to the material damage factors not modified. It can be argued that, although the population is accustomed to floods, the factor does not have to be modified when considering the greatly reduced accessibility.

Table D.2 show the total direct damages caused by floods in the two situations. The total calculation can be found in appendix D

D.0.5 Indirect damage

The amount of indirect damage is more difficult to assess as it can not be derived directly. The majority of indirect damage related to flooding in Cartagena would come from loss of income.

Table D.2: Direct damages due to floods in US Dollars

Part of the city	Situation without waves	Situation including waves
Bocagrande	$ 90,266,670	$ 615,607,582
Castillogrande	$ 4,732,619	$ 115,476,791
El Laguito	$ 1,289,191	$ 50,205,980
Centro	$ 41,790,125	$ 225,045,822
Total	**$ 138,078,606**	**$ 1,006,336,176**

This loss of income would not be instantaneously, but a gradual loss increasing over 50 years as the water level increases and thus the obstructing effects increase.

To quantify the loss of income the GDP will be used. In 2010 the department of Bolivar had an annual GDP of 12,230 million US dollar [48]. Cartagena's industry contributed 23% of the annual GDP. From the area analysis it came forward that the Bocagrande area alone takes care of 21% of the employment in Cartagena. This would imply that the Bocagrande area on its own has an annual GDP of 590.7 million US dollar.

For the areas of Centro, El Laguito and Castillogrande similar information is not available. To get an estimation of the loss of income in these areas a similar proportional GDP is assumed. Taking into account that Bocagrande has a surface area of 1090733 mÂš and the year consists of 242 working days the GDP per day per square meter can be calculated that will be used for all areas.

Table D.3: GDP per day of Bocagrande

Variable	Value
GDP per year	$ 590.7 million US dollar
GDP per workable day	$ 2.441 million US dollar
GDP per day per square meter	$ 2.238 US dollar

To estimate the loss of income per area the flooded areas must be known. This can be done by means of knowing the total elevation over a period of 50 years and the related flooded areas for these various elevations. A rough estimation has been made based on figure D.1a and figure D.1b to estimate what areas flood at given elevations. In the total elevation the effects of land subsidence, sea level rise and the high tide are taken into account. The La Nina effect and extreme wave conditions are not taken into account as they are assumed to be of short term effect on the loss of revenue.

The total damage that is caused by the flooding of these areas is found by multiplying the areas with the GDP, a correcting factor of 0.5 for the high tidal window and a correcting factor of 0.5 for the loss of income that is actually the case. This will result in a cumulative damage amount over 50 years shown in table D.4.

D.0.6 Total damage

The total damages can be found in table D.5. As is seen the damage that can be prevented is considerable. Things that need to be considered are that these values are rough estimates as specific values are not known at this time for the expected loss of business and are estimated

Table D.4: Indirect damages due to floods in US Dollars

Part of the city	Indirect damage after 50 years
Bocagrande	$ 348,169,592
Castillogrande	$ 44,532,054
El Laguito	$ 9,631,364
Centro	$ 183,478,373
Total	**$ 585,811,383**

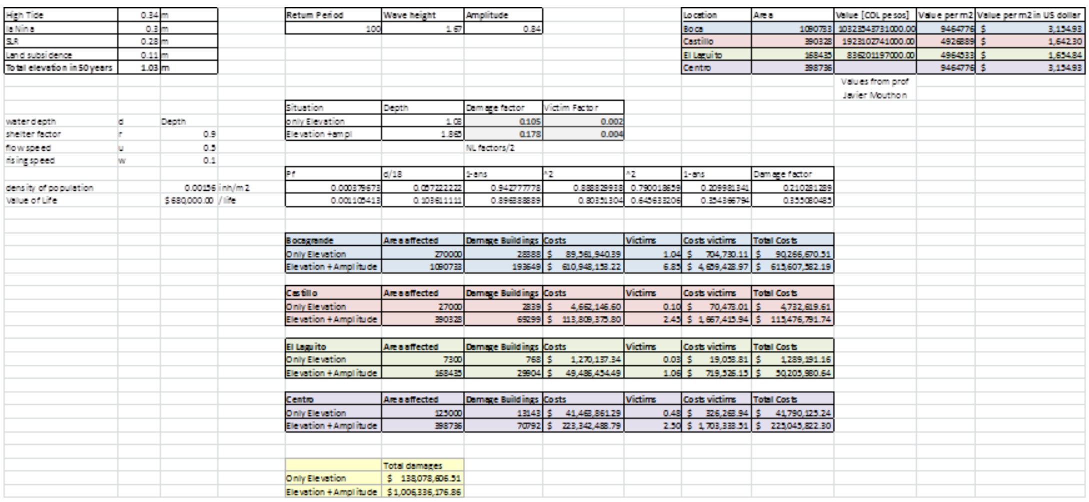
on the current GDP. As said before the situation without waves can be assumed to occur with high certainty, where the situation with waves represents the extreme condition.

Table D.5: Total flood damage caused by direct and indirect sources in US Dollars

Part of the city	Without waves	With waves
Bocagrande	$ 438,436,263	$ 963,777,174
Castillogrande	$ 49,264,674	$ 160,008,846
El Laguito	$ 10,920,555	$ 59,837,345
Centro	$ 225,268,498	$ 408,524,195
Total	**$ 723,889,989**	**$ 1,592,147,560**

D.0.7 Excel calculations flood risk analysis

To come to an estimation of the expected damage excel sheets were made for the direct and indirect damage. These can be found in figure D.2 and figure D.3.



High Tide	0.34	m
la Nina	0.3	m
SLR	0.28	m
Land subsidence	0.11	m
Total elevation in 50 years	1.03	m

water depth	d	Depth	
shelter factor	r	0.9	
flow speed	u	0.5	
rising speed	w	0.1	
density of population		0.00156	inh/m2
Value of Life		$ 680,000.00	/ life

Return Period	Wave height	Amplitude
100	1.67	0.84

Situation	Depth	Damage factor	Victim Factor
only Elevation	1.03	0.105	0.002
Elevation +ampl	1.865	0.178	0.004
		NL factors/2	

Pf	d/18	1-ans	^2	^2	1-ans	Damage factor
0.000379673	0.057222222	0.942777778	0.888829938	0.790018659	0.209981341	0.210281289
0.001105413	0.103611111	0.896388889	0.80351304	0.645633206	0.354366794	0.355080485

Location	Area	Value [COL pesos]	Value per m2	Value per m2 in US dollar
Boca	1090733	10323543731000.00	9464776	$ 3,154.93
Castillo	390328	1923102741000.00	4926889	$ 1,642.30
El Laguito	168435	836201197000.00	4964533	$ 1,654.84
Centro	398736		9464776	$ 3,154.93
		Values from prof Javier Mouthon		

Bocagrande	Area affected	Damage Buildings	Costs	Victims	Costs victims	Total Costs
Only Elevation	270000	28388	$ 89,561,940.39	1.04	$ 704,730.11	$ 90,266,670.51
Elevation + Amplitude	1090733	193649	$ 610,948,153.22	6.85	$ 4,659,428.97	$ 615,607,582.19

Castillo	Area affected	Damage Buildings	Costs	Victims	Costs victims	Total Costs
Only Elevation	27000	2839	$ 4,662,146.60	0.10	$ 70,473.01	$ 4,732,619.61
Elevation + Amplitude	390328	69299	$ 113,809,375.80	2.45	$ 1,667,415.94	$ 115,476,791.74

El Laguito	Area affected	Damage Buildings	Costs	Victims	Costs victims	Total Costs
Only Elevation	7300	768	$ 1,270,137.34	0.03	$ 19,053.81	$ 1,289,191.16
Elevation + Amplitude	168435	29904	$ 49,486,454.49	1.06	$ 719,526.15	$ 50,205,980.64

Centro	Area affected	Damage Buildings	Costs	Victims	Costs victims	Total Costs
Only Elevation	125000	13143	$ 41,463,861.29	0.48	$ 326,263.94	$ 41,790,125.24
Elevation + Amplitude	398736	70792	$ 223,342,488.79	2.50	$ 1,703,333.51	$ 225,045,822.30

	Total damages
Only Elevation	$ 138,078,606.51
Elevation + Amplitude	$ 1,006,336,176.86

Figure D.2: Direct damage calculation

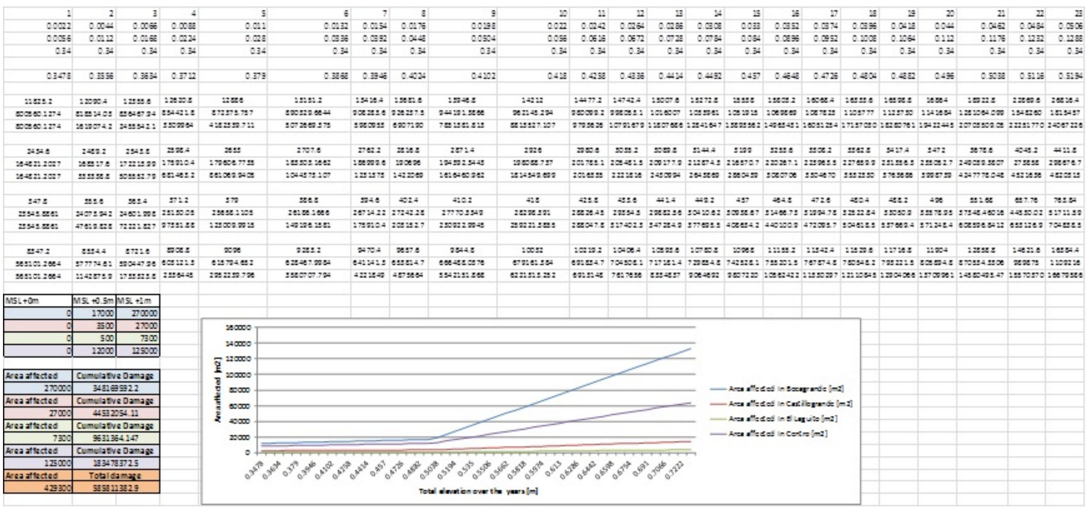


Figure D.3: Indirect damage calculation, only the 23 first years are shown

Appendix E

Stakeholderanalysis

The stakeholder analysis process is based on documents that were provided by Erik Waumans (Van Oord, project sponsor). Going through four basic steps results in a good insight of how each stakeholder has to be managed.

1. Identify stakeholders
2. Understanding stakeholders
3. Prioritize stakeholders
4. Define specific actions to influence stakeholders

E.1 Identify stakeholders

In total a number of 30 stakeholders has been identified. These are subdivided in the following categories of which an overview is given in figure E.1 .

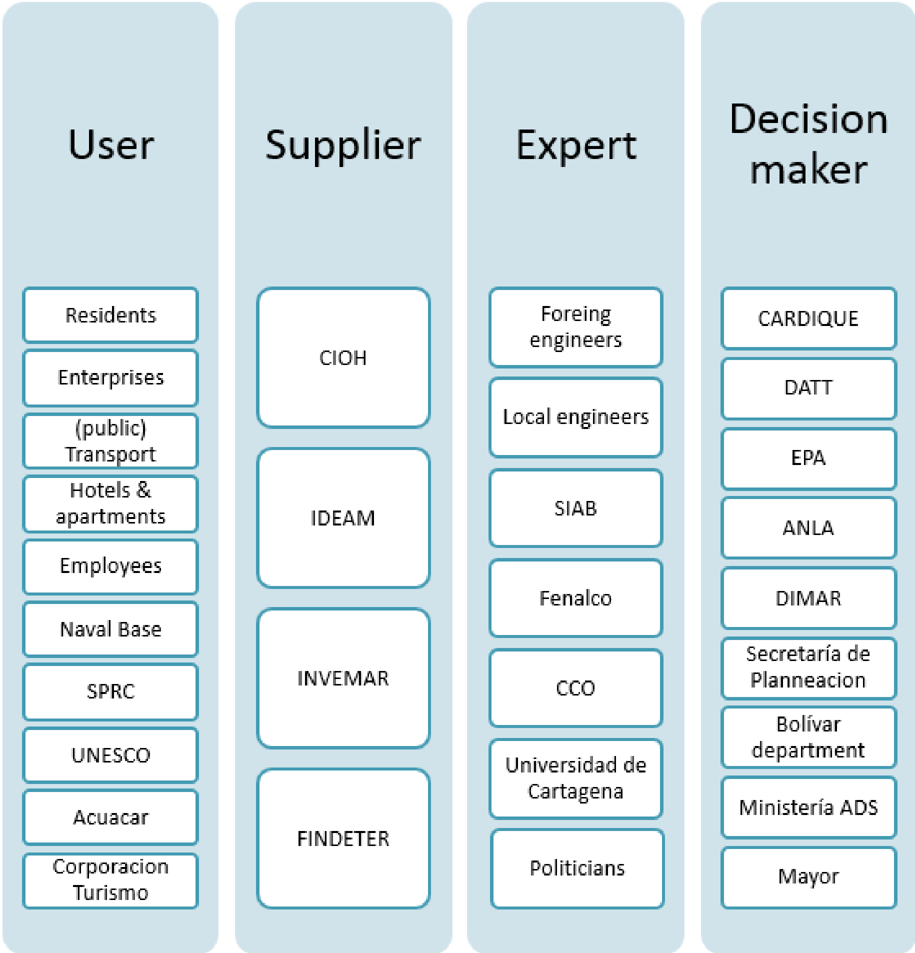


Figure E.1: Overview stakeholders per category

1. **Users**: Centro and the peninsula are home to a wide variety of (general) activities. Stakeholders are defined as 'users' when they participate in these activities.
2. **Decision makers**: Decision makers are defined as the group of stakeholders that have influence on the policy and licenses in the area. There is no distinction between high and low power yet.
3. **Experts**: The experts are local parties with knowledge of the problem and the political situation. These stakeholders have great insight in the feasibility of possible solutions as well.
4. **Suppliers**: These are stakeholders that are of critical importance for the execution of the project. They supply construction materials, workers, equipment etc.

E.2 Understanding stakeholders

In order to be able to understand the stakeholders an assessment has been performed of their mission, vision, involvement, influence and opinion with respect to the project. For each stakeholder this has resulted in a qualitative description in the context of the project.

Mayor of Cartagena

”Build collectively and with equality for everyone. The proposed Cartagena is a city to dream, to enhance its geographic, ecological, cultural, historical and tourist wealth port, and projecting into the future with an inclusive urban development, urban infrastructure that favors natural vocation to strengthen 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 encounter, enjoyment and collective ownership. A city in which citizens coexist peacefully, are quiet and calm, respect the rules, protect their environment, recognize and respect the diversity, compliance agreements and self-regulate their behavior to ensure the full exercise of freedoms and rights of everyone” (cited from http://www.cartagena.gov.co/).

Interface: Liveability, economic growth, city status, personal status

Opportunities: Financing of the project, green or red light for the project

Influence: All institutions

Influenced by: National government, the Bolivar department, politicians, residents, unions, media

DATT - Departemento Administrativo de Transito y Transporte

”Ensure road safety to preserve the life and agile mobility of citizens, educating and enforcing traffic rules as a result of an efficient teamwork” (cited from http://www.transitocartagena.gov.co/).

Interface: Accessibility

Opportunities: Endorse the problem, financing of the project

Influence: Local government

Influenced by: Local government

Secrataria de Planeaccion

”Bring back power to the citizens, through the collective construction of the city, respecting and enforcing the public, preserving their natural resources and their Caribbean identity; engaging citizens, in their diversity, to meet its obligations and efforts, achieving significantly improve economic and social conditions of everyone and Cartageneras the Carthaginians” (cited from http://planeacion.cartagena.gov.co/).

Interface: Economic growth, liveability

Opportunities: Endorse the problem, financing of the project

Influence: Major, Entrepeneurs, Hotels, Local firms

Influenced by: Bolivar department, national government, mayor

Fenalco Presidencia Nacional

”We represent the trade and service sector and work for sustainable development, the general interests of the country and strengthening the private sector and institutions. We provide leading and innovative products and services that drive business competitiveness and are a forum for thought and reflection on the challenges of the country" (cited from http://www.fenalco.com.co/).

Interface: Sustainable solution, economic growth

Opportunities: Endorse solutions, endorse the problem

Influence: Local government, BolÃŋvar department, national government

Influenced by: The trade sector
"Represent the voice of the citizens. Indicate problems that are not being dealt with by the seated government and influence the governmental decisions." (self defined)

Politicians

Interface: Liveability, personal status

Opportunities: Endorse the problem

Influence: Major, seated government

Influenced by: Residents, unions, the trade sector, media

Corporacion Turismo Cartagena de Indias

"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/).

Interface: Liveability, recreation, accessibility, tourism

Opportunities: Endorse the problem, endorse solutions, financing of the project

Influence: Local government

Influenced by: Hotels, tourist sector

EPA - Establecimiente Público Ambiental Cartagena

"EPA - CARTAGENA , will be consolidated as the environmental authority of the District of Cartagena generating changes in attitudes in the community about the use of natural resources and the environment , building a participatory sustainable development , to ensure liveability in the population, and leading processes development through a planned and concerted environmental management stakeholders" (cited from http://www.epacartagena.gov.co/).

Interface: Liveability, sustainable development

Opportunities: Endorse the problem

Influence: Local government

Influenced by: Local government, companies

Residents

”A comfortable area to live and recreate, without paying additional taxes. A good connection with the rest of the city (and country)” (self defined).

Interface: Liveability, accessibility, property value

Opportunities: Endorse the problem, financing of the project

Influence: Local government

Influenced by: Local government

Employees

”A job that provides a secure income and is easy to be accessed” (self defined).

Interface: Job opportunities, accessibility

Opportunities: Endorse possible solutions

Influence: Local government, major

Influenced by: Local government

Public transport / taxis

”Make money by transporting people from one location to another. Preferably as fast as possible” (self defined).

Interface: Employment, recreation, tourism, accessibility

Opportunities: Endorse solutions, endorse the problem

Influence: -

Influenced by: Local government

Hotels and apartments

”Take care of a good accommodation for tourists where they feel safe and home. An easily accessible environment which offers a lot of activities which attract tourists” (self defined).

Interface: Recreation, tourism, accessibility, liveability

Opportunities: Endorse the problem, endorse possible solutions, finance the project

Influence: Local government

Influenced by: -

Bolivar department

”The government of the Department of Bolivar assumed as its original responsibility, building conditions to generate well-being and human development, regional and local levels in its territory and community, and exercise with efficiency, equity and development orientation probity Department Bolivar, complementing the efforts of local authorities, for the allocation of productive resources between different groups in society, involving all public, private and community actors” (cited from http://www.bolivar.gov.co/).

Interface: Liveability, economic growth

Opportunities: Financing of the project

Influence: Local governments

Influenced by: National government, SEA

ANLA - Autoridad Nacional de Licencias Ambientales

"Ensure that the assessment, monitoring and control of projects , works or activities subject to licensing, permits or environmental procedures of our competition is conducted in a transparent, objective and timely manner, with highest standards of technical and legal quality, to contribute to balancing environmental protection and development of the country for the benefit of society" (cited from http://www.anla.gov.co/).

Interface: Liveability, economic growth, legally good designs

Opportunities: Endorse solutions

Influence: Contractors with licensing

Influenced by: Local government, Regional Government, national government

Local engineering firms

"Execute projects that generate income and add prestige to the engineering firm. At the same time the local engineering firms are also really committed to the city's future" (self defined).

Interface: Liveability, business

Opportunities: Endorse solutions, endorse the problem

Influence: Local government

Influenced by: -

Universidad de Cartagena

"The University of Cartagena is, as a public institution, by the completion of its substantive functions of teaching, research and extension, and its internationalization process, competent professional way in different areas of knowledge, scientific, humanistic, ethical, cultural and axiological foundation. This allows them to exercise responsible citizenship, contribute to social transformation, and leadership development processes business, environmental and cultural contexts of institutional action.

In 2027, the University of Cartagena will continue to consolidate as one of the most important institutions of higher education in the country, with a broad international presence. To do this, it works on continuous improvement of its academic, research , administrative, financial, social outreach, technology, internationalization development; with a clear link to, political, cultural, environmental and social economic development of Cartagena, Bolivar, Colombia and the Caribbean region" (cited from http://www.unicartagena.edu.co/).

Interface: Economic growth, liveability, business, status

Opportunities: Endorse the problem, endorse solutions

Influence: Local and national government

Influenced by: Local and national government

Foreign engineering firms

"Generate income by implementing Dutch knowledge abroad. Continuously keep in touch with national and local government and private parties in order to keep up-to-date" (self defined).

Interface: Get insight in local stakeholders, generate business

Opportunities: Endorse the problem, local contacts

Influence: -

Influenced by: Law institutions, users, government

Politicians

Interface: Liveability

Opportunities: -

Influence: Local government

Influenced by: Local, regional governments

CARDIQUE - Corporación Autónoma Regional del Canal del Dique

"The Autonomous Regional Corporation of the Canal del Dique -Cardique- in its area of jurisdiction as highest environmental authority in charge of managing the environment and natural resources, aims for sustainable development of communities and productive sectors in his Four (4) ecoregions: Zona Marino - Costera, Canal del Dique, Montes de María and Ciénaga de La Virgen, through the implementation of plans, programs and environmental projects, using innovative, human and technical capacity research" (cited from http://www.cardique.gov.co/). * They do not have any jurisdiction within the city.

Interface: Liveability

Opportunities: -

Influence: Local government

Influenced by: Local, regional governments

CIOH - Centro de Investigaciones Oceanográficas e Hidrográficas del Caribe

"Develop programs of basic and applied marine scientific research DG Maritime and Navy; provide technical and scientific advice to other national authorities with the aim of contributing to the knowledge and use of our seas, as well as the safety of life at sea" (cited from http://www.cioh.org.co/)

Interface: Put data into use for development of the country

Opportunities: Endorse the problem, retrieve data

Influence: -

Influenced by: DIMAR

CCO - Comisión Colombiana del Océano

”Advise the Government on marine and coastal issues and on issues related to the National Policy of the Ocean and Coastal Zones - PNOEC, planned and coordinated with various agencies and institutions of the State; in order to raise awareness and maritime culture in Colombian and help the recognition of our oceans as a sustainable resource use for socio- economic development of the nation” (cited from http://www.cco.gov.co).

Interface: Liveability, economic growth, cultural heritage

Opportunities: Endorse the problem

Influence: National government

Influenced by:

IDEAM - Instituto de Hidrología, Meteorologia y Estudios Ambientales

”The IDEAM is a public institution of scientific and technical support to the National Environmental System, which generates knowledge, produces reliable, consistent and timely information on the status and dynamics of natural resources and the environment, to facilitate the definition and settings environmental policies and decision- making by the public, private and the public sectors in general” (cited from http://www.ideam.gov.co/).

Interface: Provide data, gain status

Opportunities: Endorse the problem, providing data

Influence: -

Influenced by: -

INVEMAR - Instituto de Investigaciones Marinas y Costeras

”Perform basic and applied research of renewable natural resources and the environment in coastal and marine ecosystems and ocean of national interest in order to provide the necessary scientific knowledge to policy, decision -making and the development of plans and projects leading to the development of these, toward the sustainable management of resources, the recovery of the marine and coastal environment and improving the liveability of Colombians, through the rational use of the scientific capacity of the Institute and its articulation with other public and private entities” (cited from http://www.invemar.org.co/).

Interface: Liveability, sustainable solution

Opportunities: Endorse the problem, provide data

Influence: Local government.

Influenced by: Public and private entities

Naval Base ”The contribution to the defence of Colombia through effective use of naval power in a maritime, rivers and land to fulfil the constitutional role and participate in the development of naval power and the protection of Colombian interests”.

Interface: Defence of Colombia, good accessibility of the Base

Opportunities: Endorse the problem, move to other place, part of the budget, block projects

Influence: -

Influenced by: National government

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/).

Interface: Sustainable solutions, healthy environment

Opportunities: Endorse the problem, part of the budget, policies

Influence: The policy making, the local governments

Influenced by: National parliaments

FINDETER

”Promoting economic sectors in the country to control the environmental impact, thereby doing the administrative activities of entity and the financing of the projects” (cited from http://www.findeter.gov.co/).

Interface: Sustainable solutions, liveability, health environment

Opportunities: Financing projects, influence policies, endorse the problem

Influence: Local governments, regional governments, the world bank

Influenced by: National government, the world bank

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/).

Interface: Wellbeing citizens, endorse the problem, risk Management

Opportunities: Influence policies, endorse the problem

Influence: CIOH

Influenced by: Ministry of Defence

Sociedad Portuaria regional de Cartagena

”The port groups is an organization which dedicated its recourses to logistic services that add value and create a viable port to compete in the international market” (self defined).

Interface: Economic development

Opportunities: Stop certain proposed solutions, financing of the project

Influence: Local government, regional government

Influenced by: Local government, national government

SIAB

"An advisory of the government on engineering and architecture to come up with sustainable solutions with minimal resources and maximal added value" (self defined).

Interface: Sustainable development, liveability

Opportunities: Endorse the problem, endorse solutions

Influence: Local government

Influenced by: -

Aguas de Cartagena Aguar

"The mission o Aguas the Cartagena is improve the liveability in the municipality by offering high end water supply and sewer systems with reliable technical process and a durable business model" (self defined).

Interface: Sustainable city, liveability, healthy environment, make money

Opportunities: Endorse problem, stop certain proposed solutions

Influence: Local government

Influenced by: Local government, users

E.3 Prioritize stakeholders

Stakeholders are ranked on three criteria to quantify their level of importance. The scales used for the quantification are presented below. Figure E.2 gives an overview of the results for all 30 stakeholders.

E.3.1 Influence scale

Influence is an indication of the position that the stakeholder has within the network of all stakeholders. How many other stakeholders does it influence and in what way? Here it is also important to note whether the stakeholder is influenced by other stakeholders.

1. Stakeholders that have no significant influence at all
2. Stakeholders that can put pressure through unions or institutes
3. Stakeholders that control (part of) the budget or legislation procedure
4. Stakeholders that have direct influence on the 'shot-callers'
5. Stakeholders that have the authority to call the shots

E.3.2 Opinion scale

Opinion is a reflection of the stakeholder's point of view on the problem, not its opinion on possible solutions. Stakeholders that experience the problem as significant get a high rating, stakeholders that do not acknowledge the problem score low.

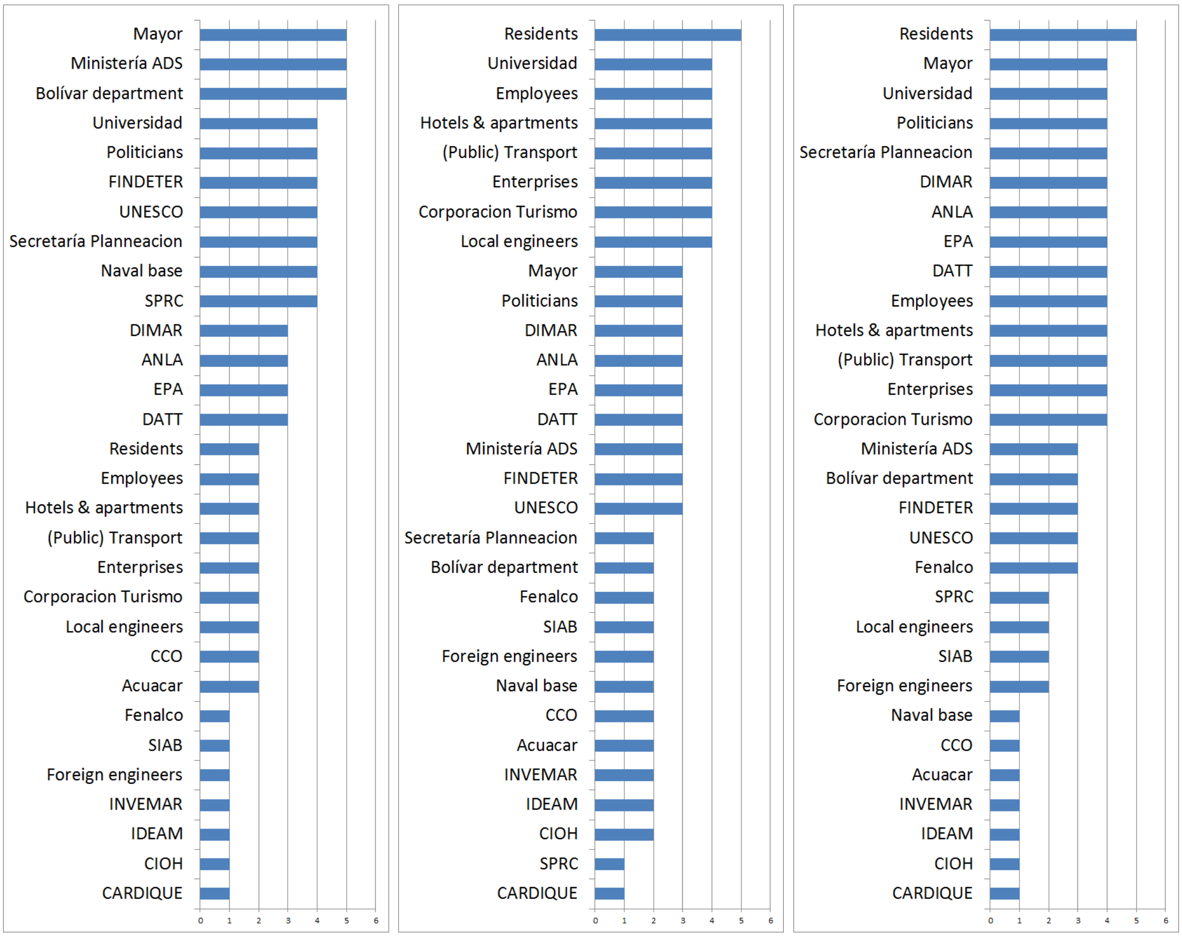
1. Stakeholders that think there is no problem / has no priority
2. Stakeholders that are passively interested in a solution
3. Stakeholders that want to solve the problem but also may have to contribute to the financing
4. Stakeholders that want to solve the problem and have a direct profit from a solution
5. Stakeholders that deeply desire a solution

E.3.3 Involvement scale

The involvement of stakeholders is partly intertwined with their opinion. However, there are some differences. The involvement is focused on the stakeholder's responsibilities and the positive and/or negative effects that the problem and/or the solution can have on the stakeholders. Things like status, benefit, etc. play an important role.

1. Stakeholders that do not have a direct profit
2. Stakeholders that are interested in making profit
3. Stakeholders that are interested in increasing the well-being on a national scale
4. Stakeholders that are interested in increasing the well-being on a local scale

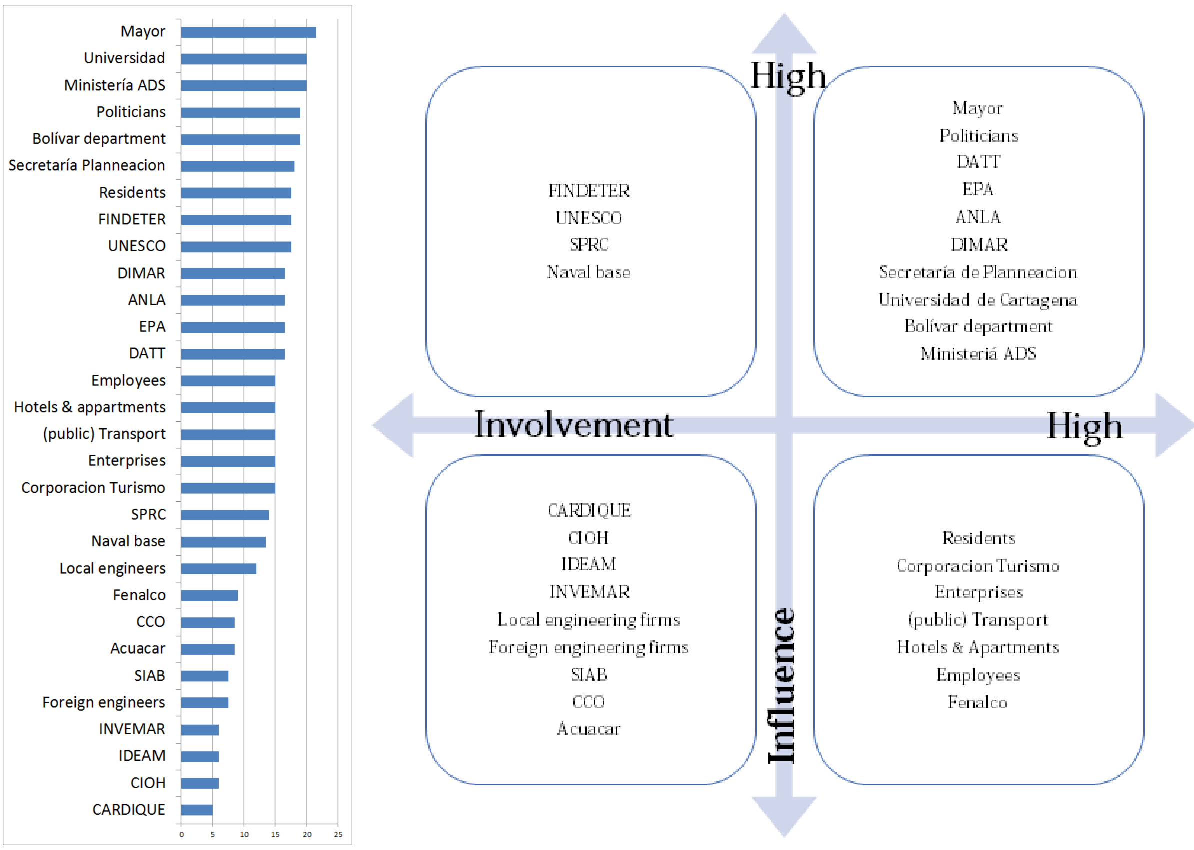
5. Stakeholders that suffer frequently from the problem



(a) Influence (b) Opinion (c) Involvement

Figure E.2: Quantification of stakeholder characteristics

The quantitative values for all three criteria are combined in one value that reflects the level of importance of the stakeholder. From interviews and the analysis of the political system it has become clear that especially 'influence' is a key criteria for projects within Colombia. In comparison to 'opinion', the 'involvement' of stakeholders will also have more impact on a positive result. Based on this information the following weights are given to the criteria: influence (2.5), opinion (1.0) and involvement (1.5). This results in a hierarchy of stakeholders as presented in figure **??**.



(a) Importance of stakeholders

(b) Influence vs. involvement

Figure E.3: Hierarchy of stakeholders

E.4 Conclusions

From the stakeholder analysis and additional interviews it has become clear that there are three parties that have the authority to start a project: the Ministry of ADS (National Environmental Policy), the Bolivar department and the mayor of Cartagena. At this moment in time they do acknowledge that the flooding of the peninsula and the historic center is a problem. However, the authorities do not see the urgency of the problem. This results in continuous postponement of a durable solution.

The shortest route to increase the sense of urgency is through the local government, since this is the area where the (future) problem has the largest impact. Therefore the mayor of Cartagena is the most important stakeholder within this project. This is also confirmed by what was heard in several interviews: ”if the mayor does not acknowledge the problem, then there is no problem”.

There are several stakeholders that have influence on the mayor such as the Bolivar department and the Ministry of ADS. Other parties that can put some significant pressure on the mayor are the secretaries of the municipality, UNESCO and the University. Also FINDETER could be of great value once it is convinced about a solution.

Colombia no longer is a development country. High investment costs are possible as long as they can be substantiated and the benefits and/or revenues are made clear.

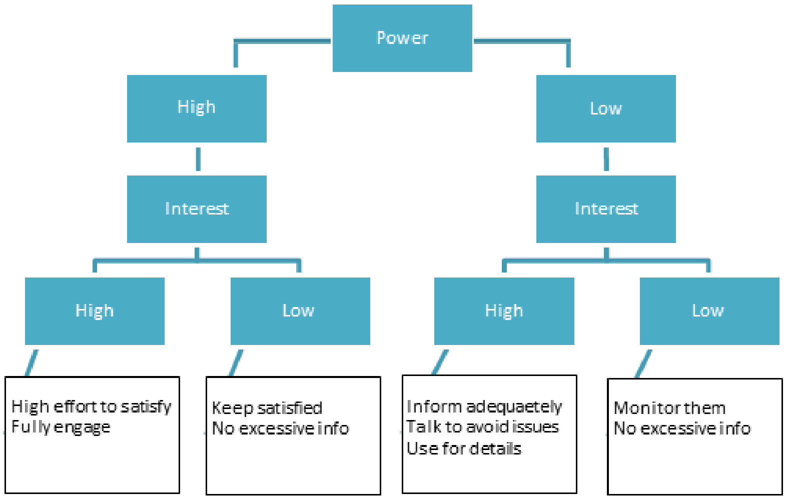


Figure E.4: General stakeholder management strategy

Another thing which cannot be concluded clearly from the stakeholder analysis is the influence of the press (newspapers, radio stations, etc). This is a powerful medium to explain the problem, the urgency and the benefits of a solution. Especially for stakeholders in the category 'Users' this might be a good tool to create some support.

It should be kept in mind that the network of stakeholders is a dynamic network. The importance of stakeholders might change over time, or new stakeholders might arise. This makes it a very complex task to accurately manage and satisfy all stakeholders. Also the concept and technical details of a design influence the opinion of stakeholders.

A general strategy of stakeholder management is deducted from the documents provided by Erik Waumans. This is shown in figure E.4.

Especially the contact with the local government and university should be intensified for the preliminary state of the design. Once there is a conceptual design, also other parties such as FINDETER, Ministery of ADS and the Bolivar department have to be involved in process in order to create wide support for a solution. Another important medium to create additional support is the use of the press.

Appendix F

Political system

F.1 History of coastal mangement

The need for coastal protection is only recorded the last 30 year and only recent the importance of coastal protection is seen as an important topic in Colombia [7]. Therefore, the institutions that deal with those problems are often quit young.

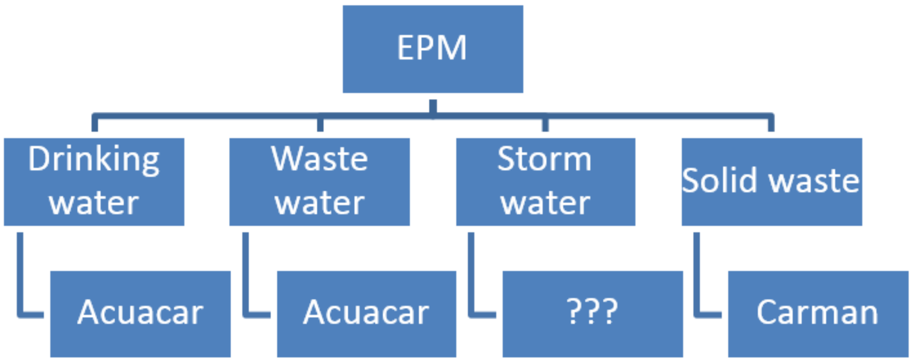


Figure F.1: The division of the tasks of EPM after splitting

Another important remark is the history of the ”Empresa Publica” (EPM) which was mentioned by Prof Javier Mouthon Bello in the interview K. There used to be an institute that took care of all water related problems and solid waste disposal in Cartagena. The local government decided to split up the institute separate it into different disciplines as shown in figure F.1. Three of the four branches turned out to be suitable for a profitable business plan and were taken over by other companies. The stormwater management was not taken over by a private party, nonetheless the local government decided to drop it anyway. At the moment, no one in Cartagena is legally responsible for the drainage of stormwater.

F.2 Coastal management

All organisations are working in slightly different areas. A short explanation about their responsibilities and work field is given below:

MAD A national public agency that is responsible for matters related to the environment and sustainable development.

ANLA Responsible for the projects, works or activities subject to licensing, permit or environmental process comply with environmental regulations. The goal is to contribute to the sustainable environmental development of the country.

IVEMAR National Research Center is responsible for conducting basic and applied research on the natural renewable resources and the environment of coastal and oceanic ecosystems of the seas of Colombia

IDEAM In charge of producing and managing the scientific and technical information on the environment of Colombia, and its territorial composition. The IDEAM also serves as the Colombian institute of meteorology and studies the climate of Colombia.

DIMAR Executing government maritime policy and maritime activities. Administration and collective goods in coastal areas are among DOMAR responsibilities. However, coastal erosion and climate change are not one of the responsibilities

CIOH Prepares official nautical charting and does research in the disciplines of oceanography.

CCO Consult, planning and coordination of the National Government. It only is an consultant and advisory board regarding policies related to coatsal and environmental issues, so decisions they make are only guidelines.

Appendix G

Boundary conditions

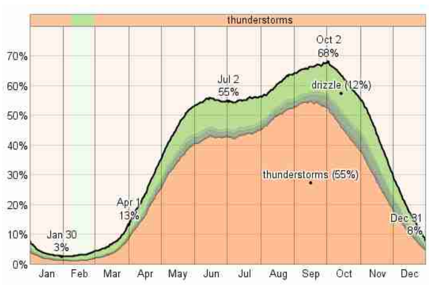
G.1 Precipitation

G.1.1 Explanation dry and wet season

This clear distinction between dry and wet season can be explained by the changes in the trade wind and the Intertropical Convergence Zone(ITCZ) [49]. The ITCZ, also known as doldrums, is a low pressure belt near the equator where the trade winds of the Northen and Southern trade winds come together. If in wet season the ITCZ moves north, the wind dies away and the ITCZ clouds produces heavy precipitation. In the dry season, the ITCZ moves a bit south which leads to very windy and dry weather.

Types of precipitation

Figure G.1 shows the types of precipitation and the percentage of the different types. The largest contribution to the precipitation comes from thunderstorms flowed by drizzle. Thunderstorms are most likely to happen half September with 74 % chance whereas the chance on drizzle rain is highest in October with a chance of 12 %.



(a) Probability of precipitation and the form of precipitation [10]

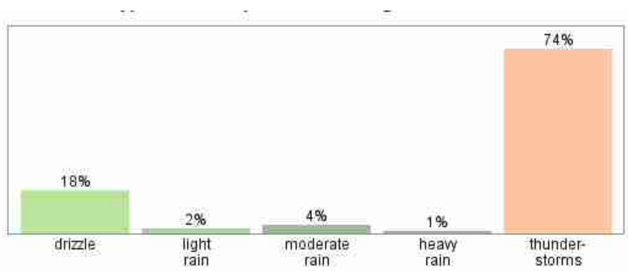


Figure G.1: Type of precipitation averaged over the year [10]

A weather station at the airport "Rafael Nùñez International Airport" in Cartagena started measuring the rain in 1982. Figure G.2 shows the average precipitation in mm and the average amount of rainfall days based on data from 2000 until 2012.

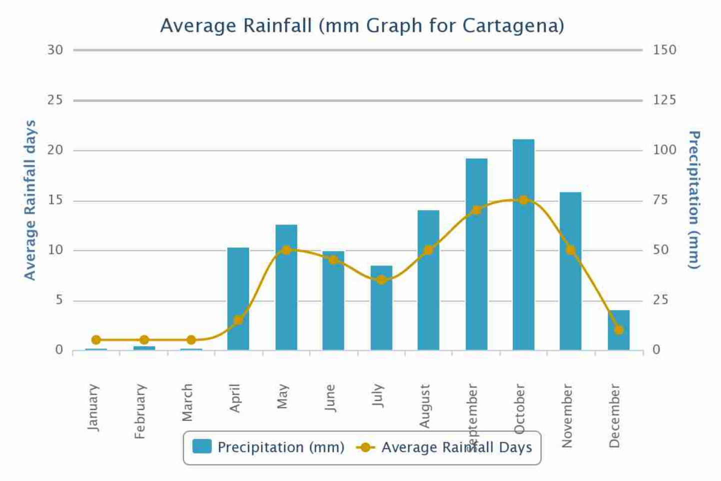


Figure G.2: Precipitation and amount of rainy days [9]

The annual rainfall of Cartagena is around 1000 mm which does not differ a lot from the global average annual precipitation over the earth, which is 990 mm. The problem is that the rain is mostly falling in the wet season when the intensity of the rain is very large. Most precipitation falls in the form of thunderstorms. More explanation about the types of rain can be found in the appendix.

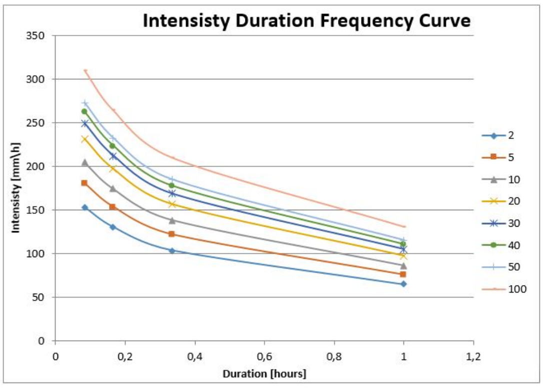
G.1.2 Prediction precipitation rate

In this report the data records of the Istituto de Hidrología, Meteorologia y Estudios Ambientales (IDEAM) were used to make a simplified forecast on the future developments in rainfall. The measurements originate from 1947 up to 2013. Unfortunately, the data are not complete for all years since the results for some months are missing. Years with more than 3 blank months have been left out of the analysis in order to make the simplified forecast.

The simplified forecast is performed by calculating a linear trend line over the remaining data.

G.1.3 Duration Frequency

For the design of an appropriate drainage system the rainfall Intensity Duration Frequency (IDF) and the rainfall mass curves must be known. The IDF curves give information about the occurrence of the rainfall intensities over a given period of time for certain return period. In the following figures the IDF curve is given and the return periods calculated with the Gumbel and logaritmic distribution method. These curves give a good representation of the precipitation conditions in the studied areas [39].



(a) IDF curve Cartagena

T*	P (X=>Xi)**	Ajuste Gumbel		Ajuste Logarítmico
años	%	Yi*** = - Ln(-Ln(T-1/T))	Precipitación (mm)	Precipitación (mm)
2	50,00	0,3665	75,04	70,66
5	80,00	1,4999	104,48	101,48
10	90,00	2,2504	123,97	124,80
15	93,33	2,6738	134,97	138,44
20	95,00	2,9702	142,66	148,11
25	96,00	3,1985	148,60	155,62
50	98,00	3,9019	166,87	178,94
100	99,00	4,6001	185,00	202,25
120	99,17	4,7833	189,76	208,39

* Periodo de Retorno en años

** Probabilidad de no ocurrencia del evento Xi

*** Variable Reducida (Monsalve, 1999)

(b) The return periods

Figure G.3: Precipitation conditions [39]

The rain intensity can be calculated according to [36] with the following formula:

$I = \frac{616.97 * T^{0.18}}{t_c * 60 + 10^{0.561}}$

where T is the return period and t_c is the duration of the rainfall. The intensity is obtained by the Gumbel method.

G.1.4 Time concentration method

The total peak discharge of the system is determined by the concentration principal. The total runoff is related to the total precipitation. The areas are divided in parts with the same time concentration principle. The rational method is used in relative small urban areas and paved surfaces. The areas of Cartagena will be divided in the neighbourhoods and also these neighbourhoods will be divided in two areas with constant time concentrations.

The time concentration method describes the total discharge of an area by the surface and an intentsity multiplied by the reduction coefficient, which takes into account losses.

The surface area of the regions are presented in table G.1.

Table G.1: Surface areas

Area	Km^2
Centro Historico	0.667
Bocagrande	1.064
Castillogrande	0.370
El Laguito	0.172

G.1.5 Amount of rainfall

The normative rainfall that will be taken into account is for a return period of 1/100. Depending on the duration different volumes of precipitation must be drained. A list of volumes is given in table G.2. In this calculation only the peak precipitation discharge is known therefore the assumption is made that the rainfall has a constant distribution. This leads to an over estimation of the total amount of rainfall that will occur. For a fully functioning design this value is however not unreasonable as the design of the drainage system will have to function when a 1/100 event occurs. A possible gamma or lognormal distribution could be applied, however the amount of data is too limited to give an accurate distribution.

Table G.2: Peak and total amount of precipitation

Duration	Peak precipitation discharge[mm/h]	Total volume during event [mm]
0.083333	309.369	25.7807534
0.166667	263.2608	43.87680231
0.333333	209.7003	69.9000954
1	130.3659	130.3659118
2	92.11743	184.2348657
3	74.45318	223.3595529

G.2 Sea level

G.2.1 Meteorological effects

Due to the strong seasonal effects in the Caribbean climate there is a noticeable effect on the mean sea level. This variation in the sea level is around 40 cm through the year. At the end of November the sea level is lower when the windy season starts. By the arrival of the 'Veranillo', the short period of finer weather during the summer wet season, in July or August the sea level rises until the maximum level in October. After this the sea level will start to go down again.

G.2.2 Sea level rise

According to the first NCAP project, Cartagena is one of the cities in Colombia that is highly vulnerable to the sea level rise[13]. The NOAA, National Oceanic and Atmosphercic Administration, has made a long term expectation based on the monthly mean sea level based on data from 1949 to 1992 [14]. According to the graph the sea level will be 5.31 mm/yr +- 0.37 mm/yr with a 95 % confidence interval.

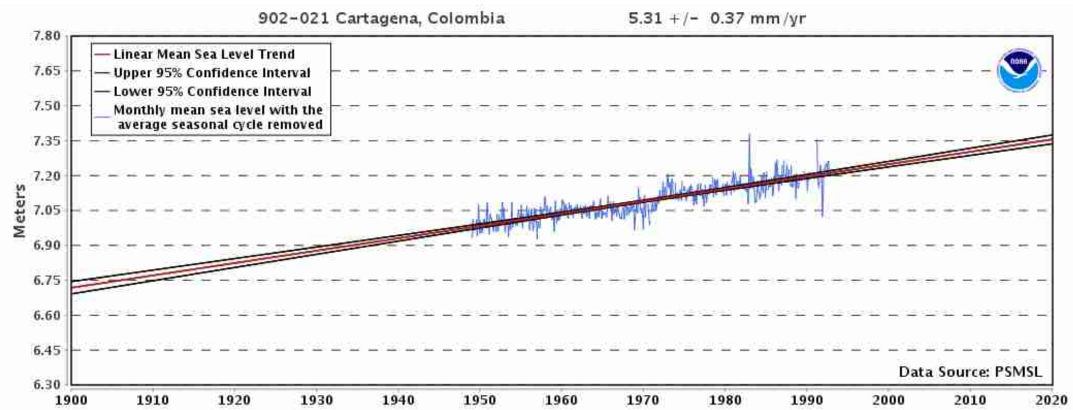


Figure G.4: Sea-level rise in Cartagena relative to the RLR datum based on NOAA data [14]

According to the data of the UHSLC (University of Hawaii Sea Level Center [15]) the sea level rise will be 5.98 mm/yr a bit more that estimated with the NOAA. If we assume a sea level rise of 5.6 mm/yr, the sea level will rise 0.28 m in the coming 50 years. The municipality of Cartagena has made their own predictions of the flood prone areas for moderate en strong see level rise [16], see figure 4.1.

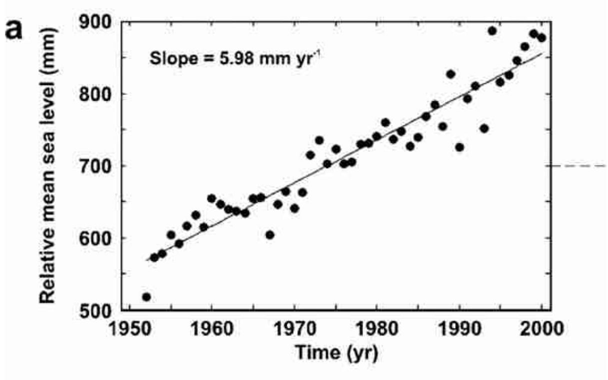


Figure G.5: Sea-level rise according to UHSLC data[13]

G.2.3 La Niña

The ENSO effect (better known as El Niño Southern Oscillation) affects Cartagena as well. For Cartagena the cooling phase, La Niña should be considered instead of El Niño. On the Pacific coast of Colombia the sea level can rise 20-30 cm due to the effects La Niña [13]. The effect on the Cartagena coast is normally negligible. Only in 1982 and 1995 there was a bigger sea lever rise of 15 cm and 25 cm, respectively. Therefore, a possible sea level heightening during El Niño should be taken into account.

G.3 Tide

From human observations it has become clear that tidal intrusion is a big problem for the districts Bocagrande and Centro Historico. In case of high water levels, some places in these districts do not have sufficient elevation and get flooded due to the lack of check valves.

G.3.1 Tidal analysis

For the Cartagena coast, a tidal analysis has been performed by Torres and Tsimpli [12]. They used hourly measurements gathered over a time span of 49 years. Based on these measurements they made a calculation of the tidal constituents, their results are shown in Table G.3.

Table G.3: Tidal constituents at Cartagena [12]

	K1	O1	P1	M2	N2	S2	M_f
Amplitude (mm)	98	59	29	74	26	16	17
Phase lag (deg)	241	241	242	137	111	47	358

The coastal area of Cartagena seems to be influenced by a predominantly semi-diurnal tide. As can be seen in Figure G.6 the tide presents two low waters and two high waters within a day. The maximum range between these two level is no more than 60 cm, therefore the tide can be categorized as micro-tidal [6].

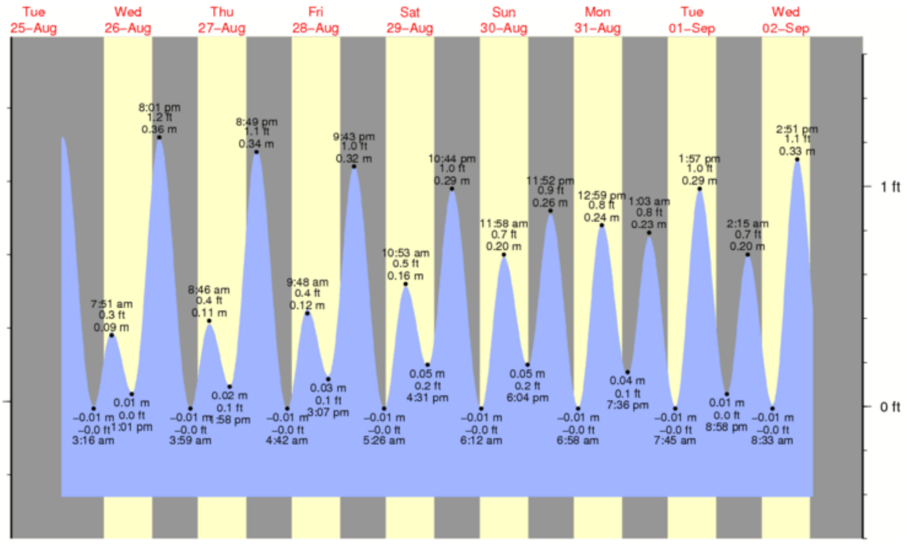


Figure G.6: Predominantly semi-diurnal tidal movement (25/08/2015)[50]

G.3.2 Long-term tidal cycle

The analysis also presents a visualization of the long-term tidal cycles of the amplitude and the phase lag. Both graphs are presented in figure G.7 below. It becomes clear that at this moment of research (August 2015) the long-term tidal cycle has a minimum. Current observations will therefore not be representative for the expected problems.

After some calculations the study shows that the highest astronomical tide (HAT) is 502 mm and the lowest astronomical tide (LAT) has a value of 418 mm. The maximum tidal range is calculated as the difference between these two values and amounts 84 mm. When designing solutions for the future this margin has to be taken into account as well.

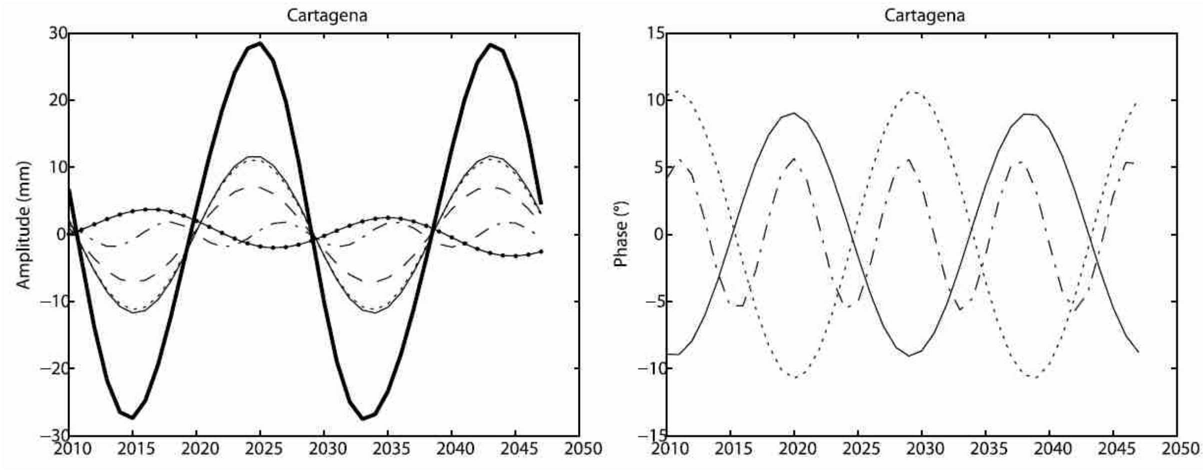


Figure G.7: Long-term tidal cycle [12]

G.4 Land elevation

The City of Cartagena is built on a very low elevation in relation to the sea level. This can be seen as one of the causes for the flooding problems of the city. To get more insight the elevation of the land above sea level is examined.

G.4.1 Elevation map

There are no clear data of the land elevation in relation to mean sea level. For some reasons these values are not given free by the authorities. However from physical observations it has been concluded that land level is approximately equal to mean see level. Figure G.8 shows that the differences on land are almost negligible.

The areas of Bocagrande and Centro are depicted below on a smaller scale. From these images it can be seen that the elevation of the land is almost the same as sealevel. It should be noted that the range has also changed in comparison to the previous figure.

(a) Elevation Bocagrande

(b) Elevation Centro

Figure G.9: Elevation map [51]

A rough estimation is given below for the relative areas.

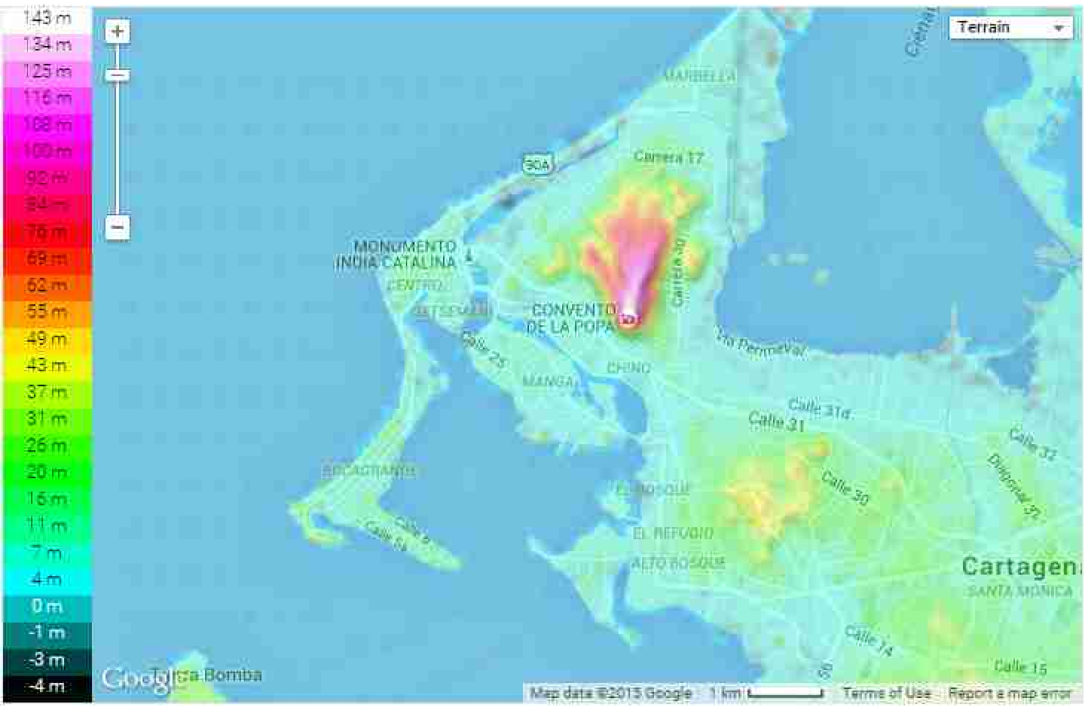


Figure G.8: Elevation Cartagena [51]

Table G.4: Surface elevations in reference to MSL

Area	Surface level
Centro	MSL + 1.25m
Bocagrande	MSL + 0.5m
El Laguito	MSL + 0.7m
Castillogrande	MSL + 0.3m
Punta Castillo	MSL + 0m

G.5 Wind and wave conditions

Two periods can be distinguished: one from November-July, the other from August-October. Both the wind and waves conditions are characterized by these two periods.

G.5.1 Wind

The windspeed reaching the coast of Cartagena depends on the season. The maximum daily windspeed around March can reach up to 11 m/s, where in the season around October the windspeed does not exceed 8 m/s. These values originate from observations of various weather stations.

The direction from which the wind is coming is also greatly dependent on the season change. In the first period of November-July the wind is coming predominantly from the Northern/North-Eastern direction, where in the second period also wind is coming from the Western direction. This is illustrated in figure G.11.

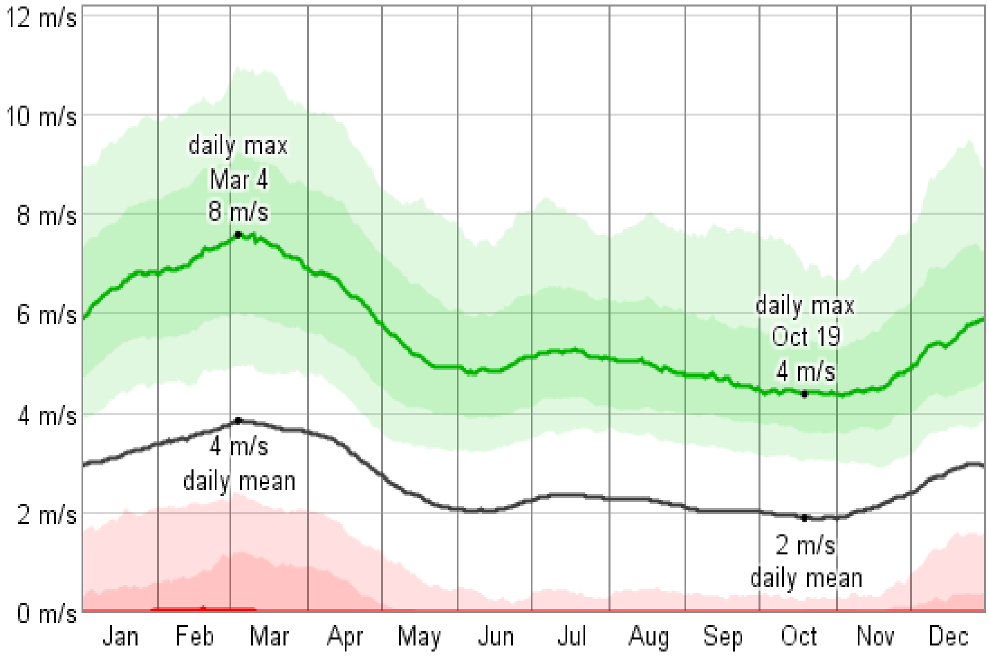


Figure G.10: Maximum wind speeds throughout the years [10]

G.5.2 Comparison with Argoss Data

To check if these numbers are acceptable values, the Argoss database [52] was consulted. In the Appendix a detailed description in which way the Weibull distribution was used to get to the wind speed values.

The wind data was taken at the location indicated in figure G.12a. The windspeed data belonging to this area can be found in figure G.13.

With this data a Weibull analysis was performed. From this analysis the wind speeds for certain return periods are calculated. For a couple of return periods the found values are given in table G.5. The resulting trendline is given in figure G.14.

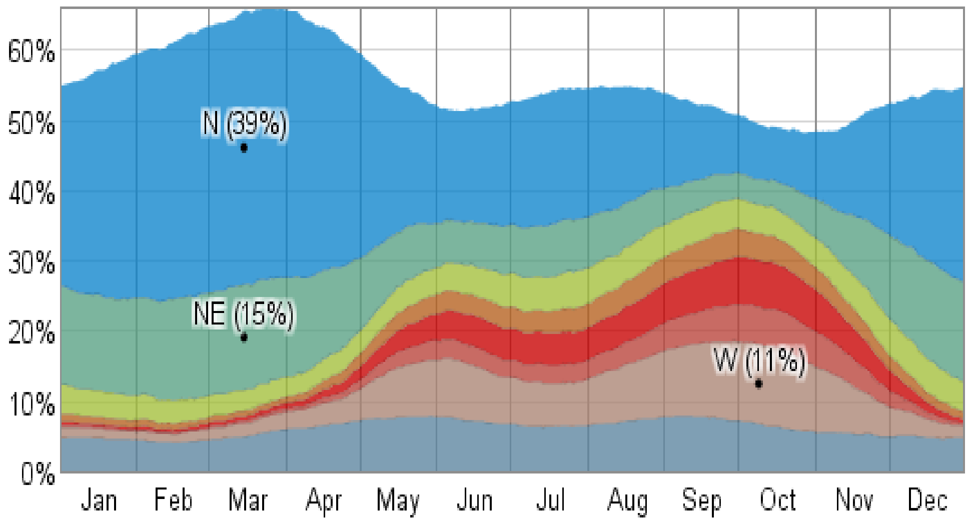


Figure G.11: Direction windspeeds throughout the year

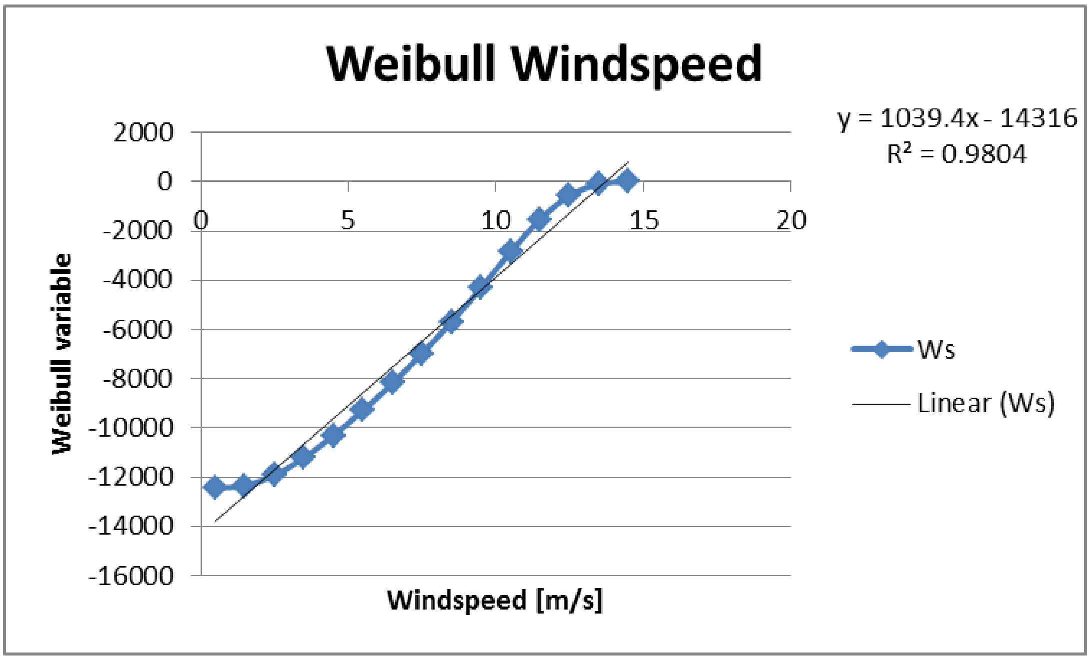
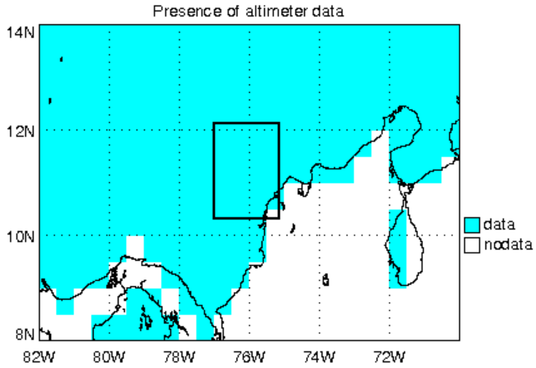
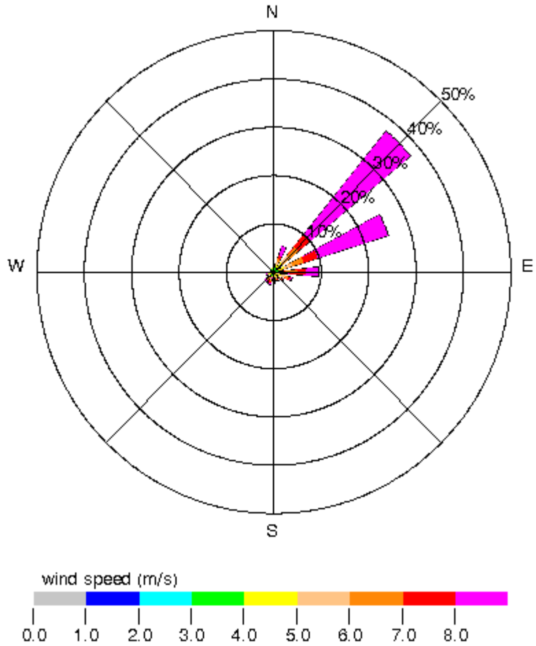


Figure G.14: Trendline resulting from the Weibull analysis for the wind data

The values calculated with the Argoss data are shown in table G.5. These values are clearly higher than the observed values of the weather stations. This can be attributed to the fact that with a Weibull an extreme value analysis is done and the results are extrapolated. For further calculations in this report the extrapolated values will therefore be used, as these values give expected values, rather than values based on past observations.



(a) Indication of the location where the data is taken from. Model output point is taken from 11° 00'N, 76° 15'W [52]



(b) Windrose according to Argoss database [52]

Figure G.12: Location and windrose according to Argoss database

Table G.5: Wind speeds found from the Weibull analysis

Period of return (years)	Wind speed (m/s)
5	13.78
10	13.83
25	14.11
50	14.56
100	15.76

Hurricanes

Another contributor to high wind speeds are the hurricanes, which are known to occur in the Caribbean sea area. In the Argoss database these values are taken into account, so in the extrapolated wind speeds these should also be represented.

G.5.3 Waves

The same location as used to find the data for the winds speed was taken. The values found are given in figure G.15. The trendline found from the Weibull analysis can be found in figure G.16.

	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	1	0	0	0	0	0	0	0	0	0
1	2	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	1.1
2	3	0.5	0.6	0.6	0.6	0.6	0.6	0.5	0.4	4.4
3	4	0.8	1.3	1.4	1	1	0.8	0.6	0.5	7.3
4	5	0.7	2.1	2.1	1.2	1.2	0.9	0.5	0.3	8.9
5	6	0.6	3.1	2.9	1.1	0.9	0.8	0.2	0.1	9.6
6	7	0.4	4.1	3.5	0.6	0.6	0.5	0.1	0	9.9
7	8	0.3	5.4	3.5	0.3	0.3	0.3	0.1	0	10.2
8	9	0.2	6.6	3	0.1	0.1	0.2	0	0	10.1
9	10	0.2	7.5	2.4	0	0.1	0.1	0	0	10.2
10	11	0.1	8	1.6	0	0	0	0	0	9.7
11	12	0	7.3	0.7	0	0	0	0	0	8.1
12	13	0	5.3	0.3	0	0	0	0	0	5.7
13	14	0	3	0.1	0	0	0	0	0	3.1
14	15	0	1.2	0	0	0	0	0	0	1.2
15	16	0	0.4	0	0	0	0	0	0	0.4
16	17	0	0.1	0	0	0	0	0	0	0.1
17	18	0	0	0	0	0	0	0	0	0
18	19	0	0	0	0	0	0	0	0	0
19	20	0	0	0	0	0	0	0	0	0
total		3.8	56.3	22.2	4.9	4.8	4.4	2.1	1.4	100

Figure G.13: Windspeed data as found in the Argoss database [52]

	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 G.15: Wave data, as found in the Argoss database [52]

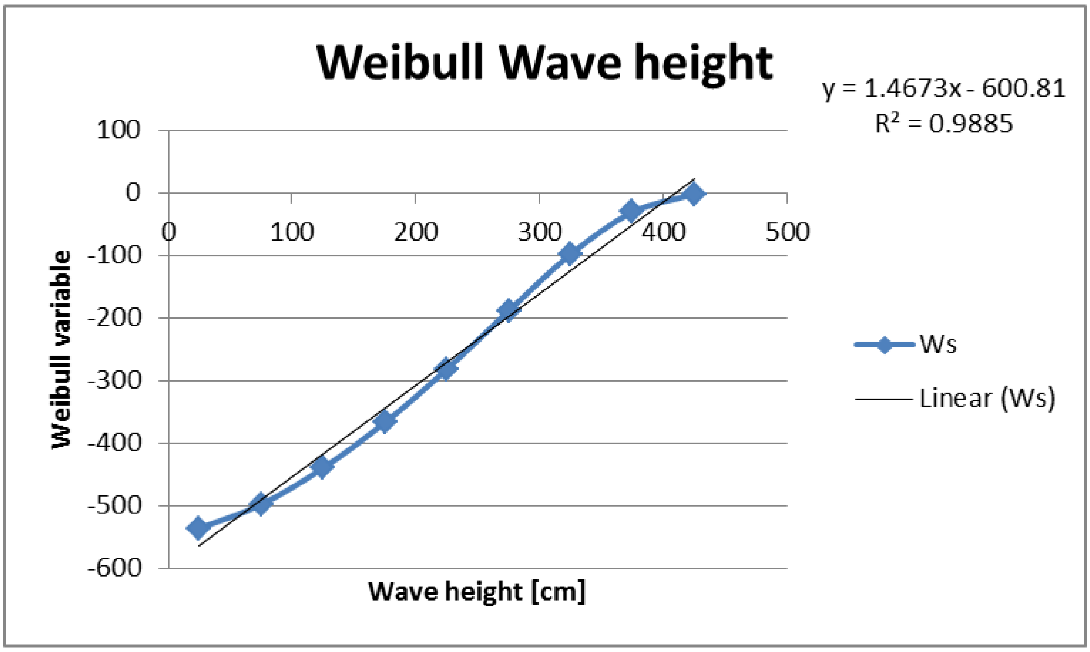


Figure G.16: Trend line resulting from the Weibull analysis for the wind data

The same return periods as were done for the wind data were taken as to give resulting wave heights. The results can be found in table G.6.

Table G.6: Wave heights found from the Weibull analysis

Period of return (years)	Wave height (m)
5	4.13
10	4.20
25	4.43
50	4.74
100	5.20

The values obtained are much higher than described by Alexandre et al. [2]. This can be explained by the fact that the found wave heights are for open sea and not close to the coast. The values need to be transformed to wave heights in shallow water close to the coastline.

G.5.4 SwanOne

The transformation of the deep water wave heights to shallow water wave heights is done with SwanOne. SwanOne uses the bathymetry as one of the input parameters. To get a basic idea about the bathymetry a map was used from the site of Navionics [53]. The results of the SwanOne calculations can be found in table G.8.

Table G.7: Shallow water wave heights calculated with SwanOne

Period of return (years)	Shallow water wave height (m)
5	1.59
10	1.60
25	1.62
50	1.63
100	1.67

The wave height acquired with SwanOne are a bit lower than the previously mentiond maximum wave heights observerd. Still it is chosen to use the shallow wave heights calculated with SwanOne, as the represent expected significant wave heights

During the period of November-July the wave climate is predominatly dependent from swell waves coming from the NNE. The average height is 0.71 ± 0.4 m, where the highest waves exceed 2m. The period of August-October also waves of coming from the WSW are present. The highest waves in this period are 1.5 m. Direction and magnitude are displayed in a wave rose in figure G.17.

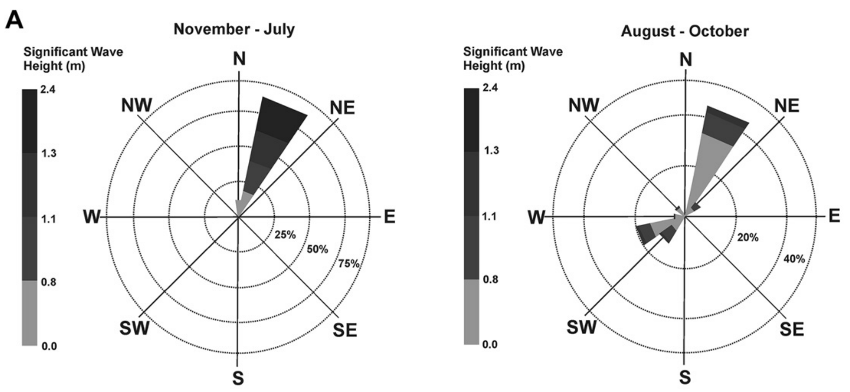


Figure G.17: Waverose, indicating direction and height [2]

G.5.5 Comparison with Argoss Data

Following the procedure as for the wind speed data, the values found for wave heights were also checked with a Weibull analysis performed with values found from the Argoss database [52]. This data is transformed from deep water to shallow water with SwanOne. The detailed description can again be found in the appendix. The results of the SwanOne calculations can be found in table G.8.

Table G.8: Shallow water wave heights calculated with SwanOne

Period of return (years)	Shallow water wave height (m)
5	1.59
10	1.60
25	1.62
50	1.63
100	1.67

The wave height acquired with SwanOne are a bit lower than the previously mentiond maximum wave heights observerd. Still it is chosen to use the shallow wave heights calculated with SwanOne, as the represent expected significant wave heights.

G.6 Coastal evolution

In this section an explanation is found on where the sediment sinks and sources originate, what the human induced changes are, what the effect of subsidence are and what future developments can be expected.

G.6.1 Sediment sources and sinks

A quick study of drawings and photographs of the Cartagena coastlines leads to the conclusion that the coastline is virtually in an equilibrium state. A quick scan performed by Deltares [54] as well as the study of Martha P. Vides [6] shows the sediment transport system at macro-level. Summarized, on a yearly basis there are two net flows that join each other at the opening between Tierra Bomba and the Bocagrande. From there the sediment flows into the Caribbean Sea.

Most of the sediment transport towards Cartagena originates from up north. Sediment from the Magdalena river is an important source for the coastline of Cartagena. The Magdalena flows into the Caribbean Sea at Barranquilla, where the sediment continues its travelling. The other source of sediment is coming from the south, from the peninsula of Barú. See figure G.18 for an overview sketch.

Up to 1936 there used to be an additional sediment source from the peninsula of La Guajira. This area is located northeast of Barranquilla, drawing a line between the borders of Colombia and Venezuela. In 1936 a jetty, named Bocas de Cenizas, was constructed in order to reduce sedimentation problems and improve the navigation at the port of Barranquilla. This jetty is now (partially) blocking the sediment coming from La Guajira. Moreover, the jetty forces the sediments from the Magdalena river so far into the Caribbean Sea over a steep continental slope towards a submarine canyon [6].

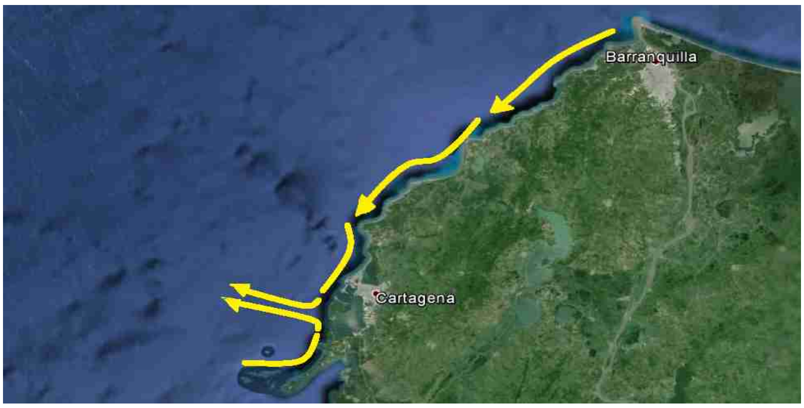


Figure G.18: Main transport direction of sediment [54]

This reduction of incoming sediment has not yet effected the coastline of Cartagena. However it is expected that some effect will become noticeable in the near future. From drawings and satellite pictures it can be seen that some islands along the coastline between Barranquilla and Cartagena started eroding due to the deficiency of sediment.

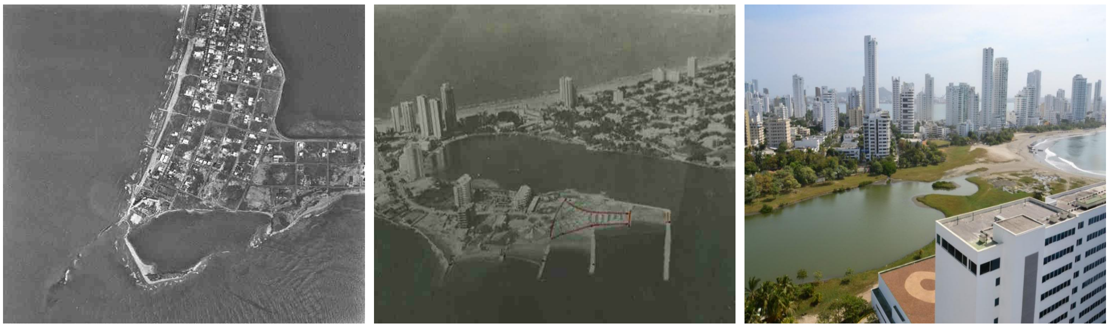
For example the island 'Isla Verde' experienced so much erosion that has completely vanished. Islands such as 'Isla Verde' can thus only function as a temporary source of sediment. In the long run a structural deficiency will be present, which is most likely to effect the coastline of Cartagena.

G.6.2 Human-induced changes

At a more local scale, drawings and photographs of the Cartagena coastline do not show large changes over the past centuries. However there still are two eye-catching, human-induced changes. The first significant change to address is the construction of groynes along Bocagrande.

The original dune system is completely replaced by buildings and other structures. This has significantly reduced the buffer zone in case of incidental erosion (e.g. storms), especially for the Bocagrande peninsula. This erosion creates large problems for adjacent infrastructure and buildings. To mitigate these problems the first groynes were constructed. Later on the groynes were extended and new and larger groynes were constructed. As a result larger and wider beaches have formed at Bocagrande.

The second human-induced change is the formation of El Laguito. This part of the peninsula has its origin as a natural sand spit at the tip of Bocagrande. Somewhere around 1960 the sand spit was further filled by human work. To protect this new land groynes were constructed. Due to natural accretion and the construction of additional groynes a lot of new land has been created from the mid-60's up to the late 70's. The development of El Laguito is shown below in Figure G.19. In the years after, the accretion continued which resulted in a complete closing of the El Laguito lake. Nowadays people are complaining about a bad water quality and stench of the lake, however local authorities claim that the water quality is still okay.



(a) Begin 60's (b) Late 70's (c) Nowadays

Figure G.19: Impression of the El Laguito development [20]

G.6.3 Subsidence

The last years SIGRAS is a reference system identical to the International Terrestrial Reference System (ITRS). Reference stations are positioned all over America to identify the tectonic plate moments and crustal deformation. From those data the subsidence is extracted from the station in Cartagena the discrete station velocities in relation to the land subsidence. According to figure G.20 it can be concluded that the relative subsidence is 22 mm/year. In the figure the vertical component from 2000 until 2014 is shown.

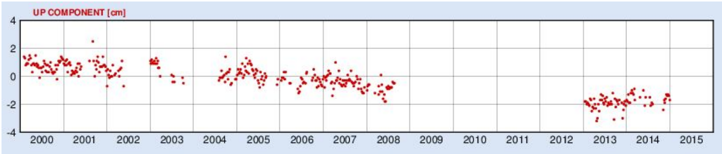


Figure G.20: Subsidence from 2000 until 2014[55]

G.6.4 Future developments

At this moment in time a large groyne is being constructed north of the Bocagrande peninsula. Since the majority of waves is coming in from the northeast this groyne will be likely to capture a large part of the sediment, causing a disruption of the equilibrium downstream. The dimensions of the groyne indicate that the associated erosion problems will be significant.

Another issue is the increase of sea level rise. According to a research of Restrepo and Lopez [13] the current trend is a sea level rise of about 6 mm/year. They expect the sea level to rise with 50 cm in the next 50 years which roughly represents a mean see level rise of 10 mm/year. According to calculations based on Bruun's rule performed by Wanders et al [56] this additional see level rise will lead to a structural retreat of the coastline of 40 cm per year.

G.7 Water quality & health

Cartagena, as a city by the sea, has a lot of open water. The largest surfaces are the Ciénaga de la Virgen at the North side of the city and the Cartagena Bay located south of the city. In and around the historic center there are some wide channels located. The rest of the city has some smaller channels flowing through. In general these water bodies have a really bad water quality and stagnant water is continuous thread for stench and health issues.

G.7.1 Ciénaga de la Virgen

The growing population was accompanied by a growth of sewerage. Due to the lack of an organized sewage system the sewerage was dumped into the water bodies. In 1980 about 60% of Cartagena's sewerage was discharged in the Ciénaga de la Virgen. As a result the city was dealing with heavy stench problems and mosquito invasions, affecting the population's health [57].

In 2000 the 'La Bocana' tidal inlet was constructed by Boskalis in order to improve the water quality. Already, within 3 weeks the water quality reached its desired value. The first 5 years Boskalis carried out the operation and maintenance of the structure and it was then consigned to the Colombian government. Unfortunately, the maintenance was omitted by the government and the structure deteriorated heavily. Within a short period of time the water quality was back to square one [57].

Figure G.21: La Bocana

However, the Ciénaga de la Virgen problems also gave rise to the creation of a sewerage masterplan. Nowadays a submarine outfall is located at Punta de Canoa which discontinues the sewerage disposal in the lagoon.

G.7.2 Cartagena Bay

The Cartagena Bay is located south of Cartagena. It is home to 62th largests container port in the world [58]. The tide of the Carribean Sea comes in through two entrances named Bocachica ('small mouth') and Bocagrande ('big mouth'). The Bocagrande entrance is only open for small boats because of an historic underwater wall constructed between 1771 and 1778 by the Spanish in order to stop pirating ships from plundering the city. Therefore all the navigation from and towards the port is forced through the Bocachica entrance [59].

In 1582 the Canal del Dique was constructed as a channel from the Magdalena river towards Cartagena. It deposits large amounts of sediment in the Cartagena Bay. Since construction it has been impassable for some times due to the high sedimentation rates. However, to keep improving the trade in the port of Cartagena the Colombians are working on plans to keep the channel open.

According to the World Resources Institute the Cartagena Bay is classified as 'hypoxic' [60]. As defined by the USGS: "Hypoxia is the condition in which dissolved oxygen is below the level necessary to sustain most animal life" [61].

G.8 Materials

A quick scan of available construction resources at the local market gives knowledge of feasible solutions. Resources that are abundantly available in the country can be supplied quickly and the money flows back into the own economy. Local workers mostly have experience with these material and know how to apply them in an accurate way.

The construction industry in Colombia is the third largest in Latin America (after Brazil and Mexico). It is even expected to be doubled in 2020 with a total revenue of $ 52 billion USD. Over the last five years the demand has shown a 5.8 % average growth. A specification of the demand for construction materials is given in figure G.22.

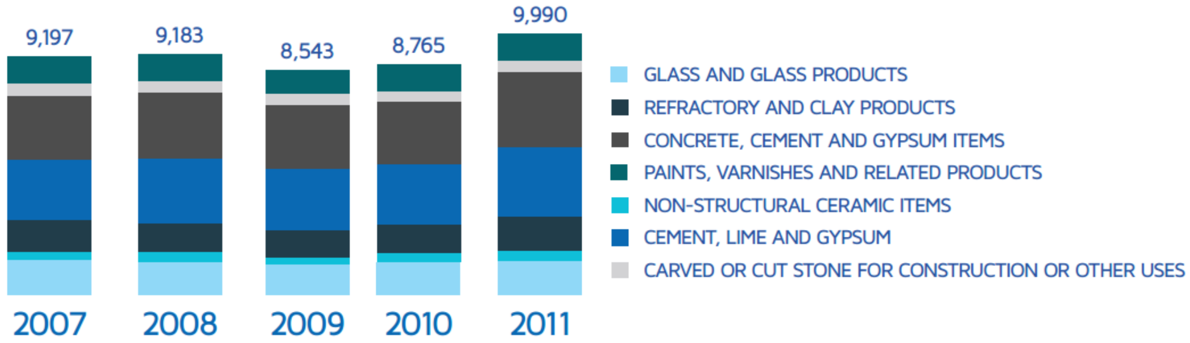


Figure G.22: Demand for construction materials in Colombia (in USD) [62])

It can be seen that a lot of a large part of the demand consists of the categories 'Cement, lime and gypsum', 'Concrete, cement and gypsum items' and 'Refractory and clay products'. Although not a significant amount, the 'Carved or cut stone' has a steady demand every year. These are the most commonly used construction materials in Colombia.

The country also exports a lot of construction materials to other countries in the Caribbean and Latin America. After Brazil and Argentina it is the largest exporter country of materials in the region. In 2012 the export of construction materials grew by 8 percent. Nonetheless, the current demand for materials is higher than the national production capacity. The government is now trying to close the gap by attracting international companies to Colombia with tax benefits and lobbying campaigns.

According to the interviews with Santiago Rizo (CARINSA, appendix K) and Klaas de Bruijn (ARCADIS, appendix K) it should not be a problem to obtain any kind of material for a construction project.

Appendix H

Elements of solution

In this part an elaboration is made on the elements of solution. A short description explains each possibilities, advantages and possible capacities.

H.1 Storage, retention and infiltration

The storage of water by retention or infiltration is one of the three main processes that was examined to improve the drainage system in Cartagena. The storage distributes the peak rain discharge into a longer time span, reducing the peak and therefore reducing the amount of runoff required by gravitation and pumping. This is illustrated in figure H.1.

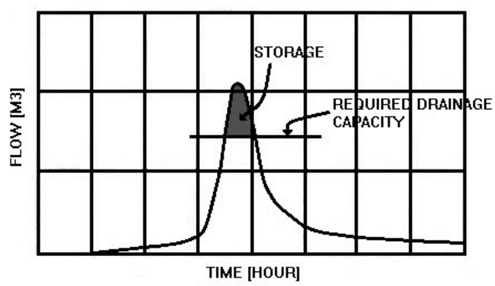


Figure H.1: Reduced required drainage capacity, due to storage

H.1.1 Amount of water

Before possible solutions will be looked after further, the total amount of water that has to be discharge after an extreme rainfall event will be calculated first. In this way the effect of the proposed solutions will become clear.

The normative event that the design will be adjusted to, is an excessive rainfall event with a duration of 3 hours that will occur once every 100 years. The total cumulative intensity that will fall in these 3 hours was found to be 223 mm, following appendix G.

For the Bocagrande peninsula with a total surface area of 1 600 000 m^2, the volume of this normative event will come done to: 0.223 m x 1 600 000 m^2 = 356 800 m^3. In the same way will the total volume that pours down in Centro, with a surface area of 667 000 m^2 is determined to be 0.223 m x 66 700 m^2 = 148 741 m^3.

H.1.2 Rooftop retention

From visual observation it is known that a few buildings at Bocagrande already contain storage basins on their rooftop. On average these consist of 4 storage basins with a total of 2000 liters, or 2 m^3.

To estimate the number of buildings on the peninsula, it is assumed that for every Calle (roads perpendicular to the main rooads), there are 10 buildings that are able to install storage basins on their rooftop. There are 15 Calles in Bocagrande, 7 in Castillogrande and 5 in Lagito. If each stores 2 m^3, then a total volume of 540 m^3 can be stored.

H.1.3 Green roofs

The implementation of green roofs brings a number of advantages next to retention of water.

Advantages green roofs:

- Water storage and reduction of peak drainage volume
- Aesthetic value, it gives a greener and more appealing view to the city
- Reduction of noises from environment
- Protection roof from sunlight and rain
- Isolating effect against the heat

The key advantage of the green roof would be that of water storage. Even when saturated the green roofs still reduce and slow down the peak amount of drainage water. An 8 - 10 cm thick green layer can retain about 10 mm of precipitation in a single event before becoming saturated [63]. This will partly runoff later and it will partly evaporate, but most importantly it will not instantly charge the surface area, and therefore reduce the discharge peak. Considering that Bocagrande consists mainly of high rise buildings with flat roofs this could be implementable.

H.1.4 Underground storage

From aerial pictures it is estimated that 15% of the built area is occupied by low rise buildings. That would mean that 186 900 m^2 is can be used for storage area.

The surface area of the Bocagrande peninsula is approximately 1 780 000 m^2. Of this area it is estimated that at least 70% is covered with buildings. That would mean that a total area of 1 246 000 m^2 is being occupied by buildings. If every building were to have an underground storage of 0.5 m designed to retain drainage water fallen during a storm already 623 000 m^3 could be retained.

However, this amount of underground storage does not seem feasable. Big disadvantage is that the stored water needs to be pumped out after the rain event. Besides, most of the buildings were constructed a long time ago with no underground storage in mind. It should also be noted that most of the buildings are high rise buildings, which require a deep foundation. If underground storage is to be installed now, it seems unrealistic to do this underneath these high rise buildings.

H.1.5 Vegetation

Capacity In order to determine if vegetation can be of considerable influence the drainage, an estimation o the amount of water that vegetation can retain has to be made.

The amount of moisture that can be stored within the plants is dependent on the volume of the body of the plant. Up to 90% of the mass volume of a cactus can be formed of water, but not all of this water will be drained. After a long dry spell the cactus can be shrivelled to 50% of its original volume, but can also take in as much water after a rainfall event [64]. A cactus one foot wide and six feet tall (30 cm width and 2 m tall) is roughly 3.5 gallons water. This converts to 0.013 m^3 of water.

To transform this quantity to a the surface area needed for one full grown cactus is assumed to be 0.3 x 0.3 = 0.09 m^2. This surface of cactus will absorb 0.013 m^3 of water. That converts to the unit of one square meter of cacti to be able to absorb 0.14 m^3 of water. This figure shows that a lot of cacti are needed to be off any influence on the amount of water that needs to be drained after a heavy rainfall event.

Vegetation Fortunately a lot of species of cacti are already growing in Colombia. It was found that in the part of Colombia near the Caribbean coast the species *cereus*, *monvillea*, *pilocereus*, *stenocereus* and *subpilocereus* are already present [65]. For this (part of) the solution to work, the vegetation will have to grow into a plant with a large volume. Of the before mentioned species, the stenocereus and subpilocereus seem to be the most promising choices.

(a) Stenocereus

(b) Subpilocereus

Figure H.2: Suitable indigenous cacti species

Parks More extensively than only planting some vegetation, also some parks can be constructed. These parks will have a slightly higher capacity for retaining water, as in parks also larger kinds of vegetation will grow. It remains a question however how much space is available.

H.1.6 Roads and permeable pavements

Permeable pavements A permeable pavement is a method that allows rainwater to seep into the ground instead of being discharged through the gutters of the street into the drains. This allows a peak discharge to distribute the load to both the underlying soil and the drains onto the streets. Peak flows will be reduced, and therefore the water runoff is more consistently over a longer time span, reducing the maximum capacity asked from the drainage system. An example illustration of permeable pavement with all its optional elements is given in figure H.3.

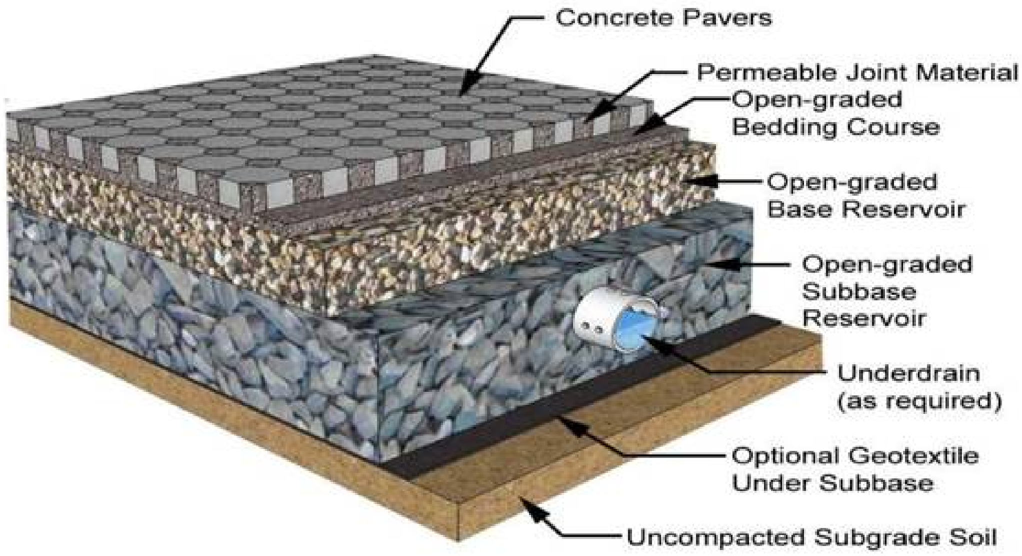


Figure H.3: Example of permeable pavement, image from vwrrc.vt.edu

An additional advantage of a permeable pavement is its functioning of filtering the infiltrated water. After long periods of drought, all kinds of pollutants are present on the streets that would otherwise be discharged directly to the surface water. The permeable pavement forces the water to pass through different aggregate sizes and typically form some sort of filter. When raining, it infiltrates down into a storage basin, after which it is released into the surrounding soil. They have been showed effective in the removal of pollutants like suspended solids, phosphorous and oil. In void spaces, naturally micro-organisms break down the pollutants. Therefore, it contributes to a healthier ecosystem [66]. This seems like a promising solution, but a site note must be made that these pavements do require some maintenance, specially when there is a long period without rain.

Another problem for implementation of permeable pavements in the Bocagrande peninsula, are the phreatic levels. According to Carinsa (Engineering consultant firm) [21], the phreatic levels at San Martin avenue vary between 0.3 and 0.45 depth and the corridor between Glorieta Satander and Castillogrande was determined in all surveys at an average depth of 0.7m.

For a proper design of an impermeable pavement following [67], [68] and [69], several impermeable base layers need to be installed below the surface layer as a foundation and to create sufficient reservoir storage immediately after a storm event. The surface is layer is made of either asphalt or concrete, and has a minimum thickness of 15 cm. The thickness of the required base layers is therefore limited by runoff storage needs. If for the surface layer a pervious concrete with 15% porosity is assumed and a 15 cm subbase stone layer with a porosity of 40%, a maximum storage capacity of 8.4 cm would be possible.

Gutters Instead of draining the water directly through the road it is also possible to install improved gutters. The considered gutters are to be installed next to the road or underneath the existing roads.

To place better gutters next to the road it is proposed to take a look at gutters that drain quickly to the underlaying grounds. This can be done by transforming the existing gutters from a closed concrete one, to an open trench filled with rocks as can be seen in figure H.4

Figure H.4: Example open trench drain [70]

Another possible way is by placing the flow gutters underneath the roads. This will allow the water to run off quickly to a possible retention facility. Benefit of these measures would be that traffic will not be hindered by the inundated streets, since the water flows gets collected beneath the roas. Disadvantage are the high investment costs and limited available space available beneath the roads, due to high groundwater levels.

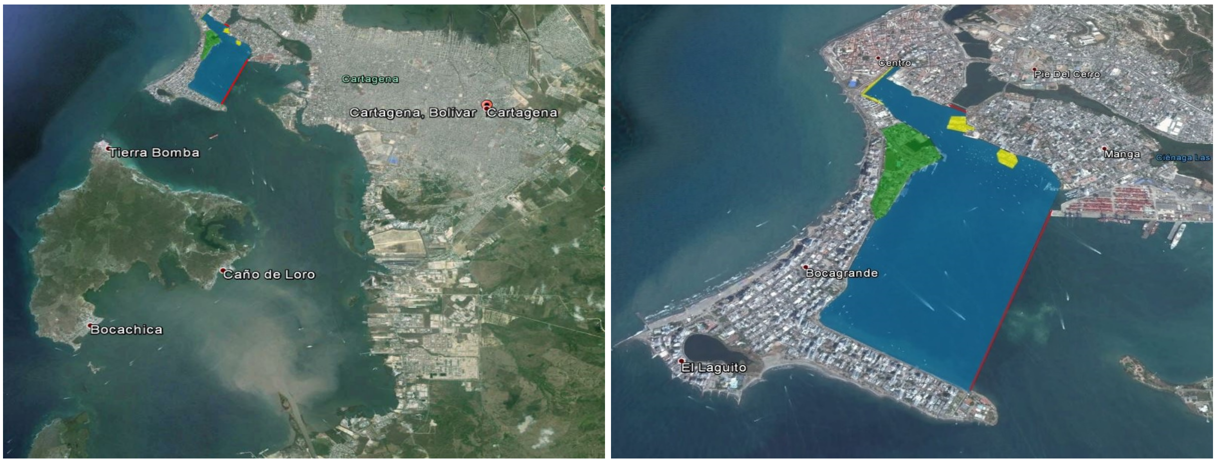
H.2 Closing of Cartagena bay

H.2.1 Cartagena Bay

Cartagena Bay is approximately 14 km long and 6 km wide with an average depth of about 20m [71]. The bay consists of two connections with the Caribean Sea. The southern connection at Bocachica is used intensively for shipping, including important trade for the port of Cartagena. The northern connection cannot be used by large vessels. At the south of the bay, also the debouchment of the Canal del Dique is present, providing a supply of fresh water and sediment into the bay (Figure H.5a). More details about Cartagena Bay can be found in appendix G.

H.2.2 The concept

The bay side of Bocagrande and Castillogrande suffers frequently from tidal intrusion and has trouble with drainage. Since at this side of the peninsula no beaches are present, it is desired to be able to let the water runoff at this side of the peninsula. In order to prevent serious hinder of important port activities, the location of the possible closure is restricted to the inner side between Castillogrande and Manga, creating a new basin where the water level can be artificially controlled (Figure H.5b). The new created basin will be about 2.2 km long and 1 km wide. When lowering the water level inside the new basin, a significant storage volume is created as well as a larger gradient for the water runoff. This way, the water level can be controlled autonomous of the water levels at sea. Therefore tidal intrustion and blockage of the outlets of the drainage system are prevented during high water levels.



(a) Overview of Cartagena Bay

(b) The considered retention basin

Figure H.5: Concept of closing off Cartagena Bay

H.2.3 Current facilities

The current facilities in the considered basin area consist of the naval base at Bocagrande (green area), a quaywall destined for tourist boat trips and luxury yachts at Centro and two important marinas at Manga (yellow area). It can be concluded that navigability for shipping is very important in this area. Therefore, a proper navigation connection with Cartagena Bay is required.

H.2.4 Water quality

The current condition of the water quality is 'hypoxic' [60], meaning that the dissolved oxygen is below the level necessary to sustain most animal life. After closure, tidal interaction will be hindered, just as the freshwater supply from the Canal del Dique. No other sources than rainwater are available. In order to prevent the water quality to deteriorate, measures will have to be taken to preserve interaction with surrounding waters.

H.2.5 Feasibility

The closure of the basin will be conducted by a hard structure that has to meet the following requirements:

- Control of water level
- Navigability for shipping

- Interaction with surrounding water

The first two requirements can be found by installing a pumping system and a lock. The last requirement is hard to accomplish and preservation of the water quality is presumably going to be problematic without proper measures.

The available retention volume that is created by the new basin is more than sufficient to allow all rainwater from the areas considered to runoff. Also the gradient that is created will reduce the problems of stagnant water. Moreover, tidal intrusion is prevented at the bay side between Castillogrande and Manga. Downside of this intervention is the hinder of navigability and the problems of preservation of the water quality. To determine measures that has to be taken to prevent the latter, an expanded study should be performed. The concept is anticipated to be feasable, but only at very high investment and operational costs

Closed structure

A closed structure can be performed by constructing a dike are a seawall that closes off the basin from Cartagena Bay. For the water quality to be guaranteed, a water supply and discharge has to be created. This can be done by constructing a pumping system that produces sufficient water circulation.

Shipping lock

For the navigability of the basin, a lock needs to be constructed. The lock can follow its operational time with the semi-closed structure, meaning that the gates are only in operation when the valves of the semi-closes structure are closed. The capacity of the lock has to be investigated. If needed, a system of locks can be installed.

H.3 Polders

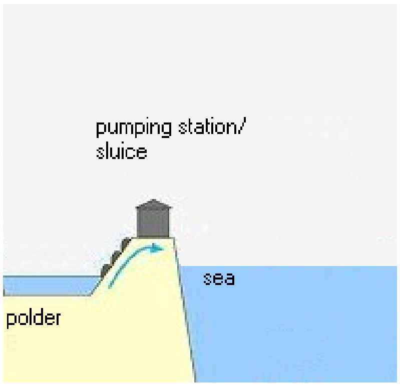


Figure H.6: Concept of a polder

H.3.1 Poldering in Cartagena

The neighbourhoods of Bocagrande, Castillogrande, El Laguito and Centro are low-lying areas of land that have trouble with drainage of rainwater, due to the surrounding waters that have about the same level. By making a polder of these areas, the storage and drainage of water can be controlled artificially. When lowering the groundwater levels, additional storage for rainwater is created, after which the water can be discharged to the sea or bay.

H.3.2 Structure

The current embankments exist of a rocky revetment, quaywalls and concrete retaining walls. Crossing through these embankments the drainage outlets are located. To create a polder, most parts of this revetment has to replaced with a new embankment, that allows the water level inside the polder to be disconnected from the surrounding waters. Also the effects of seepage and piping has to be taken into account. This can be done for example by applying sheet piling or diaphragm walls that reach deep enough into the soil. Drainage of the water can be done by applying a sluice that discharges during low or by pumping.

H.3.3 Feasibility

In order to let the polder be an effective measure to prevent tidal intrusion and solve the drainage problems, a combination of the following aspects needs to be fulfilled:

- A maintained enclosed embankment system
- Sufficient pumping and storage capacity

To realise the construction of the enclosed embankment system, significant investment costs are required, but once in place, maintenance will be minor. The capacity of the pumping and storage is determined by a combination of both. The maintenance and operational costs of the pumps will be significant, since there is no drainage by gravitation possible anymore. If the water level is lowered, more storage capacity is created. By doing so, it has to be taken into account that the subsoil can subside.

H.4 Drainage by gravitation

The current drainage system by gravitation is described in appendix B. One of the weak points is the tidal intrusion entering via the outlet drains. This can be solved by installing valves at these outlets. Another weak point is the surface level gradient which creates runoff to the surrounding waters. When increasing the gradient, the runoff capacity will increase as well.

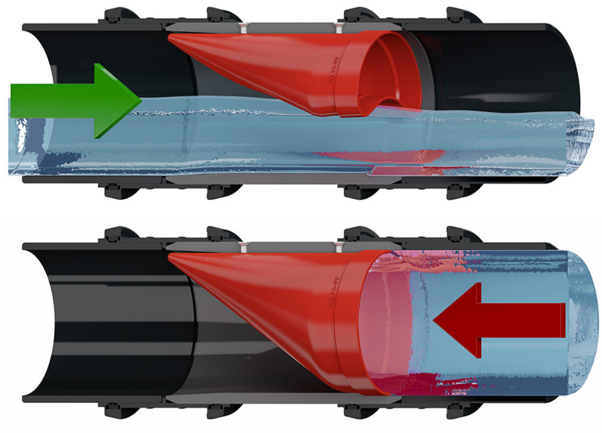
H.4.1 Valves

The current system is designed to discharge stormwater by gravity into the Caribbean Sea or Cartagena Bay during low water levels in the surrounding waters. To prevent tidal intrusion during high water levels, a check valve has to be included. A check valve is a valve that only allows flow in one direction. There are many different types of valves available to process the stormwater. The best available options will be discussed in this section.

Check valves are applied in many ways in engineering purposes. A valve that is desired in the Cartagena drainage system should be as maintenance-free as possible. Therefore no mechanical parts are required and the lifetime of the used materials should last for at least more than a decade. When analysing available solutions, a corrosion free option consisting of an elastomer construction is obtained. Two types of checks valves are distinguished: Inline- and duckbill check valves.

Inline check valves

These valves consist of a flexible elastomer valve, placed in direction with the water runoff, such that it opens when rain water has to be discharged. It seals tightly along the tube when backflow water from the Caribbean Sea or Cartagena Bay wants to enter. Two examples of these inline check valves are depicted in figure H.7.



(a) WaStop PVC range [72]

(b) Tideflex CheckMate [73]

Figure H.7: two available solutions for inline check valves

Duckbill valves

The duckbill valve consists of a one-piece flexible sleeve made of reinforced elastomer material. The sleeve is shaped like the beak of a duck, that will open once there is an upstream pressure present due to discharging stormwater. When there is a backpressure from the sea side, the flexible sleeve will squeeze tightly together, preventing backflow. Examples of duckbill valves are given in figure H.8.

(a) Closed, no discharge (b) Low discharge (c) High discharge

Figure H.8: Example of duckbill valve, by Tideflex [73]

H.4.2 Surface level elevations

Land elevation could contribute to an improved drainage system. With the use of the Chézy formula it is possible to determine the required elevation level:

$$v = C\sqrt{Ri}$$

Where v = flow velocity, C = chezy coefficient, R = hydraulic radius and i = the gradient. In situations where the width is much larger than the depth to hydraulic radius can be approximated to be equal to the flow depth d. This is the case as the width of the roads is in the order of meters and the flow depth in the order of centimeters.

Considering a Manning-Strickler roughness coefficient for concrete 'n' equal to 0.013, the chezy roughness coefficient can be determined with the following formula:

$$C = \frac{1}{n} R^{\frac{1}{6}}$$

Start of gradient driven transport is considered to be when the flow velocity is higher than 0.5 m/s. By putting all the values into the Chézy formula it is obtained that i $\geq 6.42 \cdot 10^{-4}$ (roughly equal to 1:1600).

H.5 MCA

H.5.1 Explanation MCA results

In this section an explanation is found for the MCA values found in the MCA of elements of solution. It is subdivided into a two parts, one for coastal protection and one for drainage which are seen below.

H.5.2 Building with nature, Added value and Hard structures

H.5.3 Building with nature

Geohooks The geohooks have been found to be a neutral solution that does not provide for a much desired construction. Residents and tourism entrepreneurs would find this solution to be an undesirable eyesore and would probably oppose it. Also the amount of sediment that it would catch would be insufficient to gain political support for the alternative. Even though it is cost efficient, it does not seem to excel for any area.

Vegetation With the eye on durability this seems an viable option to attract certain environmental stakeholders and by that way gain political support and financing. In addition to this it is an aesthetically well performing alternative which would prevent opposition from tourism agencies. The technical aspects of this alternative are however a bit more difficult to implement as you would have to create an ecosystem. All in all it is an option to consider for the areas of Centro Historico, Centro sea and El Laguito.

Nourishment Tourism stakeholders would greatly appreciate a nourishment on the beaches of Boca bay and El Laguito. In addition residents of Castillogrande would also prefer a nourishment on their beach to a different solution. Politically it would be easily implemented as it is a sound technological alternative with great benefits. Financially and environmentally it is a less attractive option as it would not receive much subsidiaries, but could possible enlist support of private investors. For the El Laguito area however there would be difficulties with erosion and if this was implemented an additional design must be made to prevent erosion from occurring.

Reefs Reefs are like vegetation a very durable solution which could attract subsidiaries and give way to political support. However the reefs do not pose a solution on its own, it would make a good addition to a coastal protection system. Possibly it could be very difficult convincing people of the actual effect it would pose as it is not visible and would only slightly decrease wave impact. In the Colombian culture this could be seen as

Wetlands Wetlands could give a lot beautiful nature with intertidal areas enhancing the appear of the Centro Historico area. This could lead to financing from a lot of private stakeholder in addition to possible government agencies who would appreciate the biodiversity in Cartagena. The technical aspects however cause that this project would not get approved easily by the relevant institutions as this is a difficult system to to construct and could erode easily especially in the construction phase.

Sea Grass Another neutral solution as it would not cause great public or political support as it is not visible and the effects might be overlooked. It would receive some support from environmental agencies, but not being a stand alone solution it does not seem to be a substantial addition to the coastal protection.

Rich revetment This solution would not find any opposition in terms of residents or tourism stakeholders as it is aesthetically pleasing. It would be easily implemented in the political environment and maintenance friendly which is important in the Colombian atmosphere. Financially it would be able to get funding from the government as it is one of the technically more sustainable alternatives and might be admissible for subsidiaries as it is environmentally friendly.

H.5.4 Added value

Promenade A promenade would bring in a lot of private investment in the Boca Bay area and the Castillo bay and Boca bay area as a lot of money could be made with an extra set of commercial activities. Also political support would be easy to find if it appears to be attracting new venue. In Centro it would be less desirable as it would distract from the world heritage colonial town. The technical feasibility would be strong, but it would be an financially and environmentally undesirable option.

Retention dike The Retention dike comes across as a neutral solution. The aesthetics do not work in its favour as it is very prominent in the line of view. This would cause residents and tourism entrepreneurs to be hesitant to support this project and therefore political support would be difficult to find. In addition to that the technical feasibility and maintenance demanding design do not seem fitting for the Colombian culture.

Stepdike The stepdike, similar to the promenade, would make a great addition to the areas of Centro historico and El Laguito. The increase in revenue would also enlist the support of political parties as well as private investors. The execution of the construction would be expensive, but would definitely ensure safety for the city as well as increase revenue.

Marina This is one of the most profitable possibilities as an added marina would greatly increase the land price of the relevant areas. This would entice a multitude of private investors to take part in this project and greatly please the current residents as well as the municipality as a nice marina would also bring rich patrons with it. It could pose some problems with shipping routes and possible permits, but with a profitable project this can be forgiven.

H.5.5 Hard structures

Sea wall A seal wall is an appealing for each section as it provides a direct solution to the problem. This will please the governmental institutes as well as the residents. It could be easily implemented and has a proven technical feasibility. It is however costly and would not generate value that would attract private investors.

Revetment For revetment the same appeal exists as for the sea wall, only at a slightly lower price making it more desirable for the municipality.

Groynes Groynes are a very desirable option for the tourism industry as it would protect their beaches and make it more pleasant to swim. It would however not have the same protection against floods as the other hard structures. It also has a slightly higher environmental impact which could lead to opposition for the project.

Breakwater Breakwater are similarly attractive to the tourism industry, but have proven to be less effective in Cartagena. This might lead to a lower interest in the government agencies to support construction of another breakwater. Also the lack of flood protection would be a lacking point.

H.5.6 Retention, Prevention, Runoff

H.5.7 Retention

Multi purpose areas The multi purpose areas will not find any social resistance but the **Rooftop** For the rooftop retention owners of the buildings need to cooperate this will cause not the social support. Thereby the policies have to be changed to let everybody cooperate, this will read to some resistance. Moreover the solution is not very economic, because it stores less water then green roofs. **Green roofs** For green roofs the legal and social issues are the same, only that the maintenance of the grasses on the **Underground** The underground retention needs a lot of adaptations of the current constructions in the city, this will lead to lot of resistance on the social area. The maintenance after a flooding is very high, the muds, waste needed to be removed from the retention basis. The realisation of the retention basis is very costly. **Absorbing flora** Absorbing flora is very good for the environment, but the advantages is that there will not be a lot of public support and the maintenance of the flora is very high. **Channels** Channels are technically not possible due to the low land gradient, thereby the health risk is very high, the channels attract insects and other pests. **Roads** The roads are made of permeable top layer which stores water, there by the social cooperation is much lower. The legal and political obstacles minor compared to the other solutions because owners does not have to cooperate .

H.5.8 Prevention

Close the bay To close of the bay, lots of companies have to remove to maintain their interest. Thereby to costs for the realisation will be not beneficial to the benefits gained by it. **Elevation roads** The total appearance of Bocagrande will change if the elevated road is created, so the social acceptance will not be high. The costs of the project are very high. **Valves** Valves are an economical viable solution, thereby the environment is not harmed. The importance for the functioning of the valves is the maintenance, if this is not properly done the valves wont function any more.

H.5.9 Runoff

Elevation for gradient This solution is not economically desirable because it will coast a lot of money and the main roads will be closed for a long time. The **Mobile pumps** Mobile pumps are not very reliable, because the pumps should be placed. A lot of labour is needed so not economically preferable. **Pumping system** A pumping system is a very reliable system, which is technical very achievable. The political and legeal issues do not appear because it has no major influences on the daily use of the roads or buildings.

H.5.10 Coastal MCA

In this section the values for each MCA executed are found. Both of the drainage as the coastal protection.

Coastal protectection

Building with nature

Table H.1: Centro historico

Centro Historico	Geohooks		Vegetation		Reefs		Wetland		Sea grass			
	factor	weight	factor	weight	factor	weight	factor	weight	factor	weight	factor	weight
Social	2	0.18	4	0.36	3	0.27	4	0.36	3	0.27	3	0.27
Technical	2	0.27	2	0.27	1	0.13	1	0.13	2	0.27	3	0.40
Administrative	2	0.31	2	0.31	1	0.16	2	0.31	2	0.31	4	0.62
Political	3	0.60	3	0.60	3	0.60	2	0.40	3	0.60	3	0.60
Legal	5	0.56	5	0.56	4	0.44	4	0.44	5	0.56	5	0.56
Economic	4	0.89	4	0.89	2	0.44	1	0.22	3	0.67	3	0.67
Environmental	2	0.18	3	0.27	5	0.44	4	0.36	4	0.36	4	0.36
		2.98		3.24		2.49		2.22		3.02		3.47

Table H.2: Centro sea

Centro Sea	Geohooks		Vegetation		Reefs		Sea Grass		Rich revetment	
	factor	weight	factor	weight	factor	weight	factor	weight	factor	weight
Social	3	0.27	3	0.27	3	0.27	3	0.27	3	0.27
Technical	2	0.27	2	0.27	1	0.13	2	0.27	3	0.40
Administrative	2	0.31	2	0.31	1	0.16	2	0.31	4	0.62
Political	3	0.60	3	0.60	3	0.60	3	0.60	3	0.60
Legal	5	0.56	5	0.56	4	0.44	5	0.56	5	0.56
Economic	4	0.89	4	0.89	2	0.44	3	0.67	3	0.67
Environmental	2	0.18	3	0.27	5	0.44	4	0.36	4	0.36
		3.07		3.16		2.49		3.02		3.47

Table H.3: Boca beach

Bocabeach	Nourishment		Sea Grass		Reefs	
	factor	weight	factor	weight	factor	weight
Social	4	0.36	3	0.27	2	0.18
Technical	4	0.53	2	0.27	1	0.13
Administrative	3	0.47	2	0.31	1	0.16
Political	4	0.80	3	0.60	2	0.40
Legal	3	0.33	5	0.56	2	0.22
Economic	2	0.44	3	0.67	2	0.44
Environmental	3	0.27	4	0.36	5	0.44
		3.20		3.02		1.98

Table H.4: El Laguito

El laguito	Nourishment		Vegetation		Sea grass		Rich revetment	
	factor	weight	factor	weight	factor	weight	factor	weight
Social	4	0.36	3	0.27	3	0.27	3	0.27
Technical	1	0.13	2	0.27	2	0.27	4	0.53
Administrative	2	0.31	2	0.31	2	0.31	3	0.47
Political	3	0.60	3	0.60	3	0.60	3	0.60
Legal	3	0.33	3	0.33	3	0.33	3	0.33
Economic	2	0.44	2	0.44	2	0.44	3	0.67
Environmental	3	0.27	3	0.27	3	0.27	3	0.27
		2.44		2.49		2.49		3.13

Table H.5: Castillo beach

Castillo beach	Nourishment		Reefs		Sea grass	
	factor	weight	factor	weight	factor	weight
Social	4	0.36	2	0.18	2	0.18
Technical	4	0.53	1	0.13	3	0.40
Administrative	3	0.47	2	0.31	3	0.47
Political	4	0.80	2	0.40	3	0.60
Legal	3	0.33	2	0.22	3	0.33
Economic	2	0.44	2	0.44	2	0.44
Environmental	3	0.27	5	0.44	3	0.27
		3.20		2.13		2.69

Table H.6: Punta Castillo

Punta Castillo	Nourishment		Reefs		Rich revetment	
	factor	weight	factor	weight	factor	weight
Social	4	0.36	3	0.27	3	0.27
Technical	4	0.53	1	0.13	4	0.53
Administrative	2	0.31	2	0.31	3	0.47
Political	4	0.80	2	0.40	3	0.60
Legal	3	0.33	2	0.22	3	0.33
Economic	2	0.44	2	0.44	3	0.67
Environmental	3	0.27	5	0.44	3	0.27
		3.04		2.22		3.13

Table H.7: Centro bay, Castillo bay and Boca bay

Castillo Bay	Reefs		Boca Bay	Reefs		Centro Bay	Reefs	
	factor	weight		factor	weight		factor	weight
Social	3	0.27	Social	3	0.27	Social	3	0.27
Technical	1	0.13	Technical	1	0.13	Technical	1	0.13
Administrative	2	0.31	Administrative	2	0.31	Administrative	2	0.31
Political	2	0.40	Political	2	0.40	Political	2	0.40
Legal	2	0.22	Legal	2	0.22	Legal	2	0.22
Economic	2	0.44	Economic	2	0.44	Economic	2	0.44
Environmental	5	0.44	Environmental	5	0.44	Environmental	0.44	0.44
		2.22			2.22			2.22

Added value

Table H.8: Centro Historico

Centro Historico	Promenade		Retention dike		Stepdike	
	factor	weigth	factor	weigth	factor	weigth
Social	3	0.27	3	0.27	4	0.36
Technical	4	0.53	2	0.27	3	0.4
Administrative	3	0.47	2	0.31	3	0.47
Political	4	0.80	3	0.60	3	0.6
Legal	3	0.33	2	0.22	4	0.4
Economic	2	0.44	3	0.67	3	0.67
Environmental	2	0.18	3	0.27	3	0.27
		3.02		2.6		3.2

Table H.9: Centro Sea

Centro Sea	Retention dike	
factor	weigth	weigth
Social	3	0.27
Technical	2	0.27
Administrative	2	0.31
Political	3	0.60
Legal	2	0.22
Economic	3	0.67
Environmental	3	0.27
		2.60

Table H.10: Bocabeach

Bocabeach	Promenade	
	factor	weigth
Social	4	0.36
Technical	4	0.53
Administrative	3	0.47
Political	4	0.80
Legal	3	0.33
Economic	3	0.67
Environmental	2	0.18
		3.33

Table H.11: El Laguito

El Laguito	Promenade		Stepdike	
	factor	weigth	factor	weigth
Social	3	0.27	3	0.27
Technical	1	0.13	2	0.27
Administrative	3	0.47	3	0.47
Political	3	0.60	3	0.60
Legal	3	0.33	3	0.33
Economic	2	0.44	3	0.67
Environmental	2	0.18	2	0.18
		2.42		2.777777778

Table H.12: Punta Castillo

Punta Castillo	Retention dike	
	factor	weigth
Social	3	0.27
Technical	2	0.27
Administrative	3	0.47
Political	3	0.60
Legal	2	0.22
Economic	2	0.44
Environmental	2	0.18
		2.44

Table H.13: Castillo Bay

Castillo Bay	Promenade		Marina		Retention dike	
	factor	weigth	factor	weigth	factor	weigth
Social	4	0.36	5	0.44	3	0.27
Technical	4	0.53	3	0.40	2	0.27
Administrative	3	0.47	2	0.31	3	0.47
Political	4	0.80	4	0.80	3	0.60
Legal	3	0.33	2	0.22	3	0.33
Economic	3	0.67	4	0.89	2	0.44
Environmental	2	0.18	2	0.18	2	0.18
		3.33		3.244444444		2.555555556

Table H.14: Bocabay

Bocabay	Promenade		Marina		Retention dike	
	factor	weigth	factor	weigth	factor	weigth
Social	4	0.36	5	0.44	3	0.27
Technical	4	0.53	3	0.40	2	0.27
Administrative	3	0.47	2	0.31	3	0.47
Political	4	0.80	4	0.80	3	0.60
Legal	3	0.33	2	0.22	3	0.33
Economic	3	0.67	4	0.89	2	0.44
Environmental	2	0.18	2	0.18	2	0.18
		3.33		3.244444444		2.555555556

Table H.15: Centro bay

Centro bay	Marina	
	factor	weigth
Social	4	0.36
Technical	2	0.27
Administrative	2	0.31
Political	4	0.80
Legal	2	0.22
Economic	3	0.67
Environmental	2	0.18
		2.80

Hard structure

Table H.16: Centro Historico

Centro Historico	Seawall		Revetment		Groynes		Breakwater	
	factor	weigth	factor	weigth	factor	weigth	factor	weigth
Social	4	0.36	4	0.36	4	0.36	4	0.36
Technical	5	0.67	5	0.67	3	0.40	3	0.40
Administrative	4	0.62	4	0.62	4	0.62	4	0.62
Political	3	0.60	3	0.60	3	0.60	2	0.40
Legal	3	0.33	3	0.33	3	0.33	3	0.33
Economic	3	0.67	4	0.89	4	0.89	4	0.89
Environmental	3	0.27	3	0.27	2	0.18	2	0.18
		3.51		3.73		3.38		3.18

Table H.17: Centro Sea

Centro Sea	Seawall		Revetment		Groynes		Breakwater	
	factor	weigth	factor	weigth	factor	weigth	factor	weigth
Social	4	0.36	4	0.36	4	0.36	4	0.36
Technical	5	0.67	5	0.67	3	0.40	3	0.40
Administrative	4	0.62	4	0.62	4	0.62	4	0.62
Political	3	0.60	3	0.60	3	0.60	2	0.40
Legal	3	0.33	3	0.33	3	0.33	3	0.33
Economic	3	0.67	4	0.89	4	0.89	4	0.89
Environmental	3	0.27	3	0.27	2	0.18	2	0.18
		3.51		3.73		3.38		3.18

Table H.18: Boca beach

Boca beach	Groynes		Breakwater	
	factor	weigth	factor	weigth
Social	4	0.36	4	0.36
Technical	3	0.40	3	0.40
Administrative	4	0.62	4	0.62
Political	3	0.60	2	0.40
Legal	3	0.33	3	0.33
Economic	4	0.89	4	0.89
Environmental	2	0.18	2	0.18
		3.38		3.18

Table H.19: El Laguito

El Laguito	Seawall		Revetment		Groynes		Breakwater	
	factor	weigth	factor	weigth	factor	weigth	factor	weigth
Social	4	0.36	4	0.36	4	0.36	4	0.36
Technical	5	0.67	5	0.67	2	0.27	3	0.40
Administrative	4	0.62	4	0.62	2	0.31	2	0.31
Political	3	0.60	3	0.60	3	0.60	2	0.40
Legal	3	0.33	3	0.33	3	0.33	3	0.33
Economic	3	0.67	4	0.89	4	0.89	4	0.89
Environmental	3	0.27	3	0.27	2	0.18	2	0.18
		3.51		3.73		2.93		2.87

Table H.20: Castillo Beach

Castillo Beach	Groynes	
	factor	weigth
Social	4	0.36
Technical	2	0.27
Administrative	2	0.31
Political	3	0.60
Legal	3	0.33
Economic	4	0.89
Environmental	2	0.18
		2.93

Table H.21: Centro Bay, Castillo bay and Boca Bay

Castillo bay	Sea wall		Boca Bay	Sea wall		Centro Bay	Sea wall	
	factor	weigth		factor	weigth		factor	weigth
Social	4	0.355555556	Social	4	0.355555556	Social	4	0.355555556
Technical	5	0.666666667	Technical	5	0.666666667	Technical	5	0.666666667
Administrative	5	0.777777778	Administrative	5	0.777777778	Administrative	5	0.777777778
Political	3	0.6	Political	3	0.6	Political	3	0.6
Legal	3	0.333333333	Legal	3	0.333333333	Legal	3	0.333333333
Economic	3	0.666666667	Economic	3	0.666666667	Economic	3	0.666666667
Environmental	3	0.266666667	Environmental	3	0.266666667	Environmental	3	0.266666667
		3.666666667			3.666666667			3.666666667

Table H.22: Punto Castillo

Punto Castillo	Sea wall		Revetment	
	factor	weigth	factor	weigth
Social	4	0.36	4	0.36
Technical	5	0.67	5	0.67
Administrative	5	0.78	4	0.62
Political	3	0.60	3	0.60
Legal	3	0.33	3	0.33
Economic	3	0.67	4	0.89
Environmental	3	0.27	3	0.27
		3.67		3.73

Drainage

Retention

Table H.23: Centro

Centro	Underground retention		Absorbing flora	
	factor	weigth	factor	weigth
Social	4	0.36	1	0.09
Technical	2	0.27	2	0.27
Administrative	2	0.31	1	0.16
Political	3	0.60	2	0.40
Legal	3	0.33	3	0.33
Economic	2	0.44	2	0.44
Environmental	3	0.27	4	0.36
		2.58		2.04

Table H.24: Seaside

Seaside	Rooftop retention		Green roofs		Underground retention		Absorbing flora		Cannels		Roads retention	
	factor	weigth	factor	weigth	factor	weigth	factor	weigth	factor	weigth	factor	weigth
Social	2	0.18	2	0.18	2	0.18	1	0.09	1	0.09	3	0.27
Technical	2	0.27	2	0.27	2	0.27	2	0.27	1	0.13	2	0.27
Administrative	2	0.31	1	0.16	2	0.31	1	0.16	2	0.31	2	0.31
Political	3	0.60	3	0.60	2	0.40	2	0.40	1	0.20	3	0.60
Legal	2	0.22	2	0.22	2	0.22	3	0.33	3	0.33	3	0.33
Economic	3	0.67	2	0.44	2	0.44	2	0.44	2	0.44	2	0.44
Environmental	3	0.27	3	0.27	3	0.27	4	0.36	2	0.18	3	0.27
		2.51		2.13		2.09		2.04		1.69		2.49

Table H.25: My caption

Bay side	Multi purpose area's		Rooftop retention		Green roofs		Underground retention		Absorbing flora		Cannels		Roads retention	
	factor	weigth	factor	weigth	factor	weigth	factor	weigth	factor	weigth	factor	weigth	factor	weigth
Social	2	0.18	2	0.18	2	0.18	2	0.18	1	0.09	1	0.09	3	0.27
Technical	2	0.27	2	0.27	2	0.27	2	0.27	2	0.27	1	0.13	2	0.27
Administrative	3	0.47	2	0.31	1	0.16	2	0.31	1	0.16	2	0.31	2	0.31
Political	2	0.40	3	0.60	3	0.60	2	0.40	2	0.40	1	0.20	3	0.60
Legal	2	0.22	2	0.22	2	0.22	2	0.22	3	0.33	3	0.33	3	0.33
Economic	2	0.44	3	0.67	2	0.44	2	0.44	2	0.44	2	0.44	2	0.44
Environmental	3	0.27	3	0.27	3	0.27	3	0.27	4	0.36	2	0.18	3	0.27
		2.24		2.51		2.13		2.09		2.04		1.69		2.49

Prevention

Table H.26: Centro

Centro	Elevation of roads		Valves	
	factor	weigth	factor	weigth
Social	2	0.18	2	0.18
Technical	1	0.13	2	0.27
Administrative	2	0.31	2	0.31
Political	2	0.40	3	0.60
Legal	2	0.22	3	0.33
Economic	2	0.44	3	0.67
Environmental	3	0.27	3	0.27
		1.96		2.62

Table H.27: Sea side

Sea side	Elevation of roads		Valves	
	factor	weigth	factor	weigth
Social	2	0.18	2	0.18
Technical	2	0.27	2	0.27
Administrative	3	0.47	2	0.31
Political	2	0.40	3	0.60
Legal	3	0.33	3	0.33
Economic	2	0.44	3	0.67
Environmental	3	0.27	3	0.27
		2.36		2.62

Table H.28: Bayside

Bayside	Close of bay		Elevation of roads		Valves	
	factor	weigth	factor	weigth	factor	weigth
Social	1	0.09	2	0.18	2	0.18
Technical	2	0.27	2	0.27	2	0.27
Administrative	2	0.31	3	0.47	2	0.31
Political	2	0.40	2	0.40	3	0.60
Legal	2	0.22	3	0.33	3	0.33
Economic	1	0.22	2	0.44	3	0.67
Environmental	2	0.18	3	0.27	3	0.27
		1.69		2.36		2.62

Runoff

Table H.29: Centro

Centro	Elevation		Mobile pumps		Pumping system	
	factor	weigth	factor	weigth	factor	weigth
Social	2	0.18	2	0.18	4	0.36
Technical	1	0.13	2	0.27	3	0.40
Administrative	3	0.47	2	0.31	2	0.31
Political	3	0.60	2	0.40	3	0.60
Legal	2	0.22	2	0.22	3	0.33
Economic	1	0.22	3	0.67	1	0.22
Environmental	2	0.18	3	0.27	3	0.27
		2.00		2.31		2.49

Table H.30: Sea side

Sea side	Elevation		Mobile pumps		Pumping system	
	factor	weigth	factor	weigth	factor	weigth
Social	2	0.18	2	0.18	4	0.36
Technical	2	0.27	2	0.27	3	0.40
Administrative	3	0.47	2	0.31	2	0.31
Political	3	0.60	2	0.40	3	0.60
Legal	2	0.22	2	0.22	3	0.33
Economic	1	0.22	3	0.67	1	0.22
Environmental	2	0.18	3	0.27	3	0.27
		2.13		2.31		2.49

Table H.31: Bay side

Bay side	Elevation		Mobile pumps		Pumping system	
	factor	weigth	factor	weigth	factor	weigth
Social	2	0.18	2	0.18	4	0.36
Technical	2	0.27	2	0.27	3	0.40
Administrative	3	0.47	2	0.31	2	0.31
Political	3	0.60	2	0.40	3	0.60
Legal	2	0.22	2	0.22	3	0.33
Economic	1	0.22	3	0.67	1	0.22
Environmental	2	0.18	3	0.27	3	0.27
		2.13		2.31		2.49

Overview

Table H.32: Overview drainage

Retention							Prevention			Runoff			
	Multi purpose area's	Rooftop	Green roofs	Underground	Absorbing flora	Cannels	Road	Close of bay	Elevation of roads	Valves	Elevation for gradrient	Mobile pumps	Pumping system
Centro				2.58	2.044				1.96	2.62	2.00	2.31	2.49
Sea side		2.51	2.13	2.09	2.044	1.69	2.49		2.36	2.62	2.13	2.31	2.49
Bay side	2.24	2.51	2.13	2.09	2.04	1.69	2.49	1.69	2.36	2.62	2.13	2.31	2.49

Table H.33: Coastal overview

	Building with nature							Added value				Hardstructures			
	Geohooks	Vegetation	Reefs	Wetland	Sea grass	Rich Revetment	Nourischment	Promenade	Marina	Rentention dike	Step dike	Seawall	Revetment	Groynes	Breakwater
Centro historico	2.98	3.24	2.49	2.22	3.02	3.47		3.02		2.60	3.20	3.51	3.73	3.38	3.18
Centro sea	3.07	3.16	2.49			3.47				2.60		3.51	3.73	3.38	3.18
Boca beach	3.02		1.98				3.20	3.33						3.38	3.18
El laguito		2.49			2.49	3.13	3.20	2.42			2.78	3.51	3.73	2.93	2.87
Castillo beach			2.13		2.69		3.20							2.93	
Punta Castillo			2.22			3.13	3.04			2.44		3.67	3.73		
Castillo bay			2.22					3.33	3.24	2.56		3.67			
Boca bay			2.22					3.33	3.24	2.56		3.67			
Centro bay									2.80			3.67			

Appendix I

Global solutions

A brief explanation is made for each choice of coastal protection.

I.1 System 1: Green city

I.1.1 Design of the coastal protection

The coastal protection however is especially important for the road connection between Bocagrande and Centro. Therefore a rich revetment is constructed. This will ensure the safety against flooding, but will also have a natural appeal as well as having ecological benefits. This can be made as one long revetment between Boca beach and Centro, as is seen in figure 7.2.

At the part of Boca Beach the beaches will be extended by nourishments. This will also mean that the breakwaters and groynes in this region need to be extended/replaced. On both sides the beaches will have to be connected to revetments. This can be done best at the points where there are groynes. The sand nourishments will reduce wave influence, but with expected sea level rise etc. there will still need to be a small sea wall to prevent flooding.

The coastline near El Laguito is exposed to high erosion rates. Beaches have been eroded away and the high erosion rates also prevents new beaches from forming. Nourishing in this part would therefore not be a very sustainable option and to protect the coast a rich revetment will be constructed.

At Castillo Beach the beaches are still present. For further protection and to add extra recreational value the beaches will be nourished and extended. Similar to Boca beach the groynes will need to be extended for this to occur as they are currently 'full' and will require a small sea wall to facilitate with the rise of sea level.

Around the tip of the Castillogrande peninsula lays Punta Castillo where erosion rates higher than in the bay. Currently no beaches are present and a rich revetment will be constructed for protection.

In front of the parts of Castillo Bay and Boca Bay the foreshore will be extended with intertidal areas and mangroves forests. These extended foreshores will decrease the tidal intrusion by trapping some of the water and reducing run up. This in addition with the current construction works should lead to sufficient flood protection. Also tourism can be increased in the area if people are allowed to visit the mangrove forests and natural areas. This will be one of the selling points of the coastal protection as it would give a very nice intertidal area for recreation as well as ecological biodiversity.

Finally at the bay side of Centro the existing seawall will be heightened. This is to prevent water from entering the area connecting Centro and Bocagrande.

I.2 System 2: Safe city

I.2.1 Design of the coastal protection

Figure 7.3 gives an overview of the selected elements per area. Along the coastline around Centro a revetment is constructed that prevents waves from running up and overtop onto the streets. It is a straight forward upgrade of the existing revetment that does not do any harm to the city its historic appearance.

Further downstream the revetment continues along Bocagrande. For traffic this location is the biggest bottleneck in the current situation.

At Boca Beach the current groynes will be redesigned and breakwaters will be placed where necessary. This will be combined with a nourishment to increase the width of the beach that results in a higher dissipation of wave energy. Only a redesign of the breakwater structures and a widening of the beach will not satisfy in case of very high water events. Therefore a seawall is constructed between the beach and the road to prevent flooding. The function of the groynes and breakwaters is to keep the beach in place, the seawall should prevent tidal intrusion. The seawall will be connected groynes.

At El Laguito the coastline is exposed to high erosion conditions. Nourishment at this location will probably result in a maintenance intensive solution. The construction of a seawall at this location is difficult due to the absence of sufficient land. Moreover there are no problems with tidal intrusion at this location since the land elevation is larger than at other parts. Problems that occur are induced by wave conditions. Therefore a revetment will be placed that dissipates energy from the waves and prevents them from overtopping.

At Castillo Beach the current beach will be extended by a nourishment and backed up by a seawall along the road, in order to protect a normative storm. Similar to the solution at Boca Beach but without additional works on the existing groynes.

Punta Castillo will be equipped with a seawall that merges with the seawalls of Castillo Bay and Boca Bay which are currently under construction. The current construction height does not satisfy for the determined boundary conditions and has to be increased.

I.3 System 3: Showpiece

I.3.1 Design of the coastal protection

Figure 7.5b gives an overview of the coastal elements. At the Centro a revetment will be constructed which is designed in such a way that the UNESCO heritage is emphasized. With the historic center as the main eye-catcher its original character stays intact. The drainage for stormwater will be managed with the use of pumps and valves, similar to the 'Green City' solution.

The revetment of Centro extends to Boca Beach where it will slowly transforms into a promenade. The promenade serves both a recreational function and a protective function. The beach in front of the promenade will be nourished to create enough construction space for the promenade and maintain the current width of the beach. Furthermore, the breakwaters parallel to the coast will be demolished and replaced with groynes to maintain and create extra beaches. Due to the large construction height and limited available width parallel slopes and stairs are installed to enable a connection from the road to the beaches. At the seaside a stair will be constructed which gradually blends into the beach. The stairs have a positive effect on wave run-up and therefore decrease the the required construction height. A seawall on top of the promenade decreases the required construction height even more.

At the end of Boca Beach the promenade will smoothly develop into a seawall with a walkway on top of it. The walkway runs up to the Hilton Hotel. From the Hilton up to Punta Castillo a nourishment will be executed to create additional beaches. The beaches provide a natural coastal defense for the hinterland. The walkway provides some sidewalk cafes with a great view on the bay, while the beaches give additional value to the surrounding apartments and hotels. For extreme conditions a small seawall separates the road from the beaches.

This small seawall merges into the seawall at Punta Castillo. Club Naval, located at Punta Castillo, is completely protected by the seawall. In front of the seawall a jetty structure is present which adds additional capacity and flair to the private marina. At the bay side the seawall gradually lowers as the wave conditions are more favorable.

At Castillo bay a marina arises with a capacity of 230 moorings, the total capacity in Cartagena now increases to 600 moorings. The marina consists of a floating jetty structure which is connected to the current seawall. The seawall is improved in order to fulfill the project standards. Besides the additional land value and touristic activity that is generated by the marina, the marina itself should be profitable as well. With a occupancy of 70% it is expected to generate a yearly turnover of approximately €1.700.000.

The seawall extends further along Boca Bay. The seawall that is currently under construction is improved in order to fulfill the project standards. It also contains a small promenade which provides space for running, skating, street vendors etc.

Further along the coast it is unclear what the destination plan of the Naval Base is. At the bay side of Centro the marina and restaurant are kept intact and a second line of defense is constructed around it by raising a small sea wall.

The drainage at the sea and bay side is fully performed by pumps and valves. To create extra retention and give a greener look to the city this will be done with green roofs and permeable pavements. In the option 'Green City' this concept is further elaborated on.

I.4 Drainage

I.4.1 Permeable roads

Permeable roads increase the infiltration capacity and offer additional retention, this reduces the required pumping capacity. Another advantage is that the purifying effect adds to the sustainable image of the city. Disadvantages are that they are expensive to construct and it will take up a lot of time to perform the upgrade for the whole city without causing severe congestion. The pavement is able to absorb 8.4 centimeter during a single rainfall event. Table 7.11 gives an overview of the capacity in relation to the volume of a single rainfall event. However with the effect of sea level rise the ground water level will also rise leading to a reduced capability of infiltration through the pavement.

The capacity of permeable pavement on the long term is not known. The above calculations are based on the current situation. Since the subsoil mainly consists of sand, the ground water level will most probably increase due to sea level rise. This will significantly reduce the capacity of the permeable pavement.

I.4.2 Green roofs

Green roofs increase the infiltration capacity and offer additional retention, this reduces the required pumping capacity. A green roof can retain 10 mm during a single rainfall event. Roughly 25% of the Bocagrande area contains roofs that can be used for this solution. Table 7.12 shows a calculation of the possible volume.

I.4.3 Vegetation

Vegetation can be used to absorb water and reduce the discharge peak and required pumping capacity. For an estimation of the capacity the most absorbing vegetation species are assumed. Cacti can absorb $\mathbf{0.14\ m^3/m^2}$.

To estimate the available area a division is made between vegetation along roads and vegetation in urban areas. A continuous strip of approximately 40 cm is available along the roads. It is difficult to substantiate the available area in urban areas, estimated is that 5% of the peninsula is suitable for redesign. An overview of the vegetation retaining capacities is given in table 7.13.

I.5 Construction time

To compare the construction times for the different solutions the elements are ranked from 1-5, where 5 stands for a very long construction time and 1 for a very short construction time. This can be found in table **??** for the coastal elements and in table I.1 for the drainage elements.

Next, the ranking is used to see which solution will have the most expansive drainage and coastal system. This can be found in the table I.2.

I.6 MCA

I.6.1 Clarification

This section gives a substantiation of the assigned scores in the MCA.

Coastal solution	Ranking	Drainage solution	Ranking
Promanade	4	Pumps and valvues	5
Rich Revetment	3	Green roof	3
Revetment	2	Vegetation	1
Nourishment	1	Permeable roads	2
Foreshore extension	2		
Sea wall	3		
Groynes	2		
Wall	1		
Marina	5		

Table I.1: Construction time ranking per solution

Coastal solution	Green city	Safe city	Show piece
Centro	3	2	2
Centro sea	3	1	2
Boca beach	1	3	3
El laguito	3	2	3
Castillo beach	1	3	2
Puncta Castillo	3	2	3
Castillo bay	2	1	5
Boca bay	2	3	7
Centro bay	3	3	3
Total	21	20	30

Table I.2: Ranking coastal elements

Coastal protection

Social: All concepts have a positive social image, the city will be better protected against flooding. However, the GreenCity and Showpiece will also have a significant side effect on the daily quality of life. Therefore theyscore equally well on social criteria, the Safe City scores somewhat lower.

Technical: All concepts contain elements which are technically feasible. The Green City is the only concept that scores significantly lower. The option to create an extended foreshore at the bay is very hard to execute. Moreover natural growth is needed which induces that the concept is not offering protection on the short term. Also the protection in the long term is uncertain. Showpiece scores lower in comparison to Safe City since it contains elements which take a long construction time.

Administrative: Safe City and Showpiece score equally well on administrative criteria. Both options contain elements that are low in maintenance and that merge well with existing coastal works. Green City scores slightly lower, again due to the foreshore extension which will require intensive monitoring and maintenance.

Political: Green City has a maximum score on political criteria. With some stakeholders present that are specifically interested in sustainability, this concept looks promising. Besides, there are no stakeholders specifically against sustainability. Showpiece scores higher than Safe City because it creates a lot of additional opportunities to generate additional revenue.

Drainage solution	Green city	Safe city	Show piece
Centro	5	5	5
Sea side	11	7	11
Bay side	11	7	11
Total	27	19	30

Table I.3: Ranking drainage elements

Legal: Legally there are the most challenges for the Showpiece concept. For example caused by the interests of stakeholders, such as the nature organizations (beach extensions) and the current marinas (marina construction). Green City scores higher, but again the construction of an extended foreshore is an obstacle. Safe City does not contain significant complications on a legal aspect and has the best score.

Economic: Showpiece has a maximum score on economic criteria. Although the initial costs are 10-15 % higher than the other concepts, the additional revenue and opportunities for private investors result in a solution that is very cost beneficial. Neither Green City nor Safe City generates additional revenue or creates opportunities for private investors. Green City scores slightly lower because of the difference in initial costs.

Environmental: Green City again has a maximum score. The concept enhances the existing environment and adds additional environmental value. Both other concepts do not add any additional environmental value, however they will not negatively effect the existing environment. Therefore they both score neutral.

Drainage

Social: Both concepts have a positive social image, there are no extreme differences. Green City and Showpiece will slightly improve the daily quality of life by introducing more flora in the city. However the extra retention will also require some offers from residents. Therefore all three concepts score equal.

Technical: The additional capacity created by the permeable pavement turns out to be insignificant on the long term. Moreover the construction time for this drainage solution is larger. Therefore Green City and Showpiece score significantly lower than the more straight forward Safe City concept.

Administrative: Both concepts require a lot of maintenance in order to keep sufficient capacity in the long term. Safe City requires a minimum of pipe infrastructure and scores higher. The permeable pavement requires additional maintenance which increases the difference in score.

Political: Green City and Showpiece will both generate a more sustainable image for the city. This adds to the status and attractiveness of a modern city. Politicians will be susceptible to this argument. Safe City does not has this, but it still offers an effective solution. Therefore there is only a slight different in score.

Legal: A metamorphosis of the streets surfaces into permeable pavements requires a lot of legal procedures. The same goes for the implementation of green retention. Safe City does not contain these elements, however the implementation of a completely new drainage system will also require legal procedures.

Economic: Safe City is by far the cheapest concept for drainage. The large difference is especially caused by the permeable pavement that is included in Green City and Showpiece. Use of green retention does not add a lot to the initial costs. There are no real opportunities for funding by private parties in either of the concepts.

Environmental: Green City and Showpiece will probably contribute to the environmental goals of the community. The exact impact is hard to estimate. Safe City does not contribute to the environmental goals nor does it negatively influence them.

Appendix J

Final design

A more extensive elaboration about each choice of retaining structure per section is given in this appendix.

Centro: The view of Centro is recognized by its famous city walls, something that cannot be disturbed by an eye-catching coastal defence. Since the current coastal protection consists of a revetment that does not interfere with the view of the city, it has been chosen that a similar revetment should be applied. It has to be heightened to meet the requirements of a 1/100 year storm condition.

Boca sea: To implement a coastal protection that includes additional value for hotel owners, a nourishment and promenade solution will be applied. The nourishment extends the available beach and the promenade adds an attractive walkway for pedestrians. Both of them will attract tourists. Since commercial activities will expand, it is possible to approach private investors for funding part of the coastal protection.

El Laguito (sea side): Due to severe erosion, it is not possible to restore the beach that once was available here. Implementation of a revetment has been chosen to protect the residents against high water levels at sea. The revetment will be aligned more into the sea than the current one, to regain part of the land.

El Laguito (lake side) and Castillo beach: Currently a lot of accretion has caused closure of lake El Laguito and a wide beach at Castillo beach. To prevent excessive adjustments to the coast, it seems better to keep lake El Laguito closed and extend the beach toward Castillo beach. In order to satisfy the programme of requirements, an additional seawall has to be placed at the back of the beach, to withstand a normative storm.

Punta Castillo: The lowest part of the peninsula is Punta Castilo which suffers from erosion. Therefore heightening of the revetment is the best solution to implement at this location.

Castillo bay: Cartagena bay provides a lot of opportunities to implement additional value with an improved coastal protection by constructing a marina. Currently, there is a lot of recreational shipping in Cartagena bay, but there are no possibilities to moor at the peninsula. Implementation of a marina will increase the value of the peninsula significantly, making it interesting for private investors to participate in the funding of this solution

Boca bay: This part of the peninsula suffers most from frequent flooding. There is enough space available to construct a quay wall which will not obstruct the view of the lake.

Centro bay: Large yachts frequently moor at Centro bay. Therefore the presence of a sufficient quay wall is important to remain intact. An upgrade by heightening the quay wall is a desired solution, to meet the programme of requirements.

J.1 Technical design

The required height has been calculated with the overtopping demand of 200 l/s/m. An elaboration of the exact calculation is made is this section.

J.1.1 Model

The calculation tool of the HRWallingford Ltd UK is used to calculate the wave overtopping. The model uses the formula's form the in 2007 published, âĂIJWave Overtopping of Sea Defences and Related Structures - Assessment Manual". This model will include the techniques described in the Dutch (TAW) and German (EAK) overtopping manuals, in addition to the method of Owen. In the calculation done below the the empirical models are used.

J.1.2 Calculations

For all calculations the following boundary conditions are used:

- The average wave period T_m is 4 seconds
- The significant wave height H_s is 1.68 m for the Sea side, 1.28 m for the Punta Castillo and the Bay Side is 0.84 m.

Revetment For the revetment is chosen to use the Armoured Composite Slope with Crest Berm model. The model represents the reduction due to the amour stones the best. There is chosen to design the revetment with two different slopes to reduce the overtopping as much as possible.

The additional assumptions for the calculation:

- The coefficient for reduction factor is 0.6 (Rocks, 1 layer, impermeable core).
- The lower slope is chosen on 1:3 the upper slope is chosen on 1:2

Stepdike For the step dike at Boca Beach the Composite Slope with (Small Vertical) Wall and Vertical wall is used. The additional assumptions for the calculation:

- The beach slope is 1:10 based the graph of Wiegel (1964) as the beach consist of fine sediment and has a more reflective character.
- The wave depth at toe of the structure is MSL +1.53m which is the height at extreme water level minus the nourishment of the beach.

Wall For the marina in Castillo Grande and Quay wall in Centro the Vertical Wall model is used.

- The toe of the structure at Castilo grande and Centro is MSL - 2.5 m. This is based on the minimal draft of 1.5 m needed for the boats in the marina, the water level at low tide, the space needed between the ground and the bottom of the ships and some space for possible measures against scours. This depth is also assumed at the wall of boca bay and the q-wall at centro.
- The design height is calculated with a water height of 1.53 m above the toe. This is based on assumption that he current beach is 0.5 m above MSL and the nourishment will also be 0.5 m.

With the assumptions the calculations are made. The height of the structure is based on the summation of the MSL + tide + la nina + Sea level rise + land subsidence + storm surge + Freeboard. In table 8.2 the required heights for the different structures can be found.

J.2 Promenade, Boca beach

The three rough designs for the promenade are described in this section as well as the volumes for the final design.

Possible designs

Each design will consists of a retaining structure and a promenade. For the retaining structure two types of walls are considered, the stepped face wall and the vertical wall. The required retaining height is different for each structure. The height above the current street level is + 1.8 m for a step face and + 2.3 m for a vertical wall.

Stepped face structure The stepped face structure is used frequently, because it requires less height than the vertical wall and low maintenance is needed. Possibility for a sheet pile wall are present to prevent seepage. To prevent possible scour the toe of the structure is embedded in the soil [74]. To prevent undesired settlements it is constructed on a pile foundation for which the soil conditions in Bocagrande are adequate.

As the stepped face not only has the function of retaining the water, but also as a stairs to the beach, the slope of the structure is designed at 35 degrees [75]. To lower the cost of the promenade a concrete wall is constructed with a height of 0.45 meter on top of the structure. In this way the small wall can also be used as a place to sit on. In addition some place for vegetation is created in the wall.

Vertical wall The main advantage of the vertical wall is that it requires much less space than the sloped stepped wall. Still, stairs or ramps are needed on regular intervals to get up to the to promenade. As the wall needs to retain the water it needs to be non-porous. There are different types of vertical non porous walls but in this case a gravity based wall, a concrete sheet pile wall and a L-shaped wall are used for the design.

Three designs have been made to explore options for the promenade. The three design are shortly discussed below and the sketches of the designs are made to give a rough impression.

Extra space: In this design extra space is created on top of the promenade so besides strolling public, some vegetation etc. there is also space for some small restaurant and other types of shops. On the sea side a stepped wall is constructed to get access to the beach and on the road side a vertical wall with stairs and ramps to get up to the promenade.

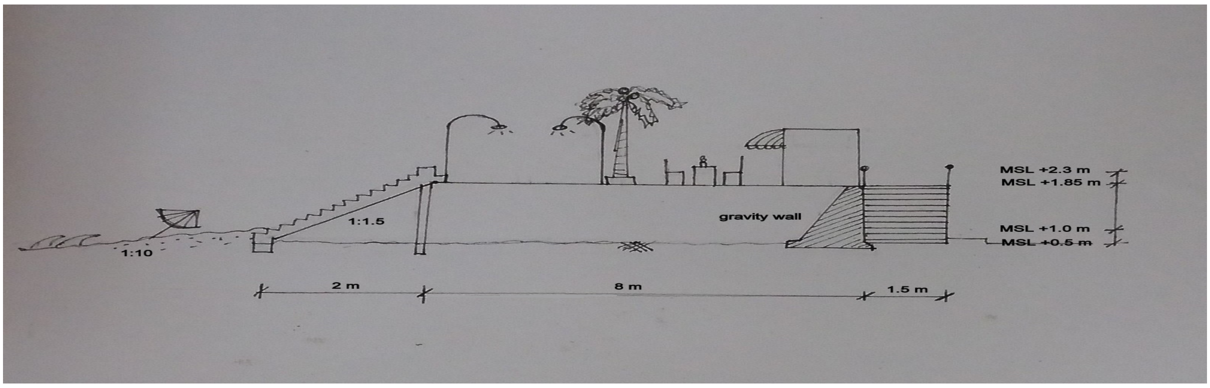


Figure J.1: Design 1: Extra space

Stairs: In this design is chosen to construct a stepped face at both sides of the promenade to access the beach. The profile of the top will have a width of 3.5 m where there is space for a walkway, vegetation lighting etc. [26].

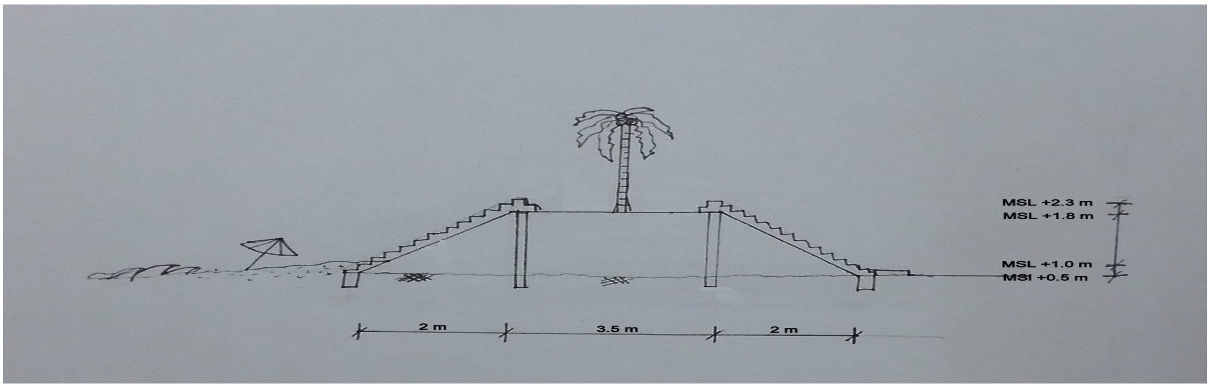


Figure J.2: Design 2: stairs

Less space: In the last design the space required for the promenade is kept to a minimum by constructing two vertical walls. The stairs to get up the promenade are designed with a width of 150 cm to have some space for railing and for people to use it in both directions [26].

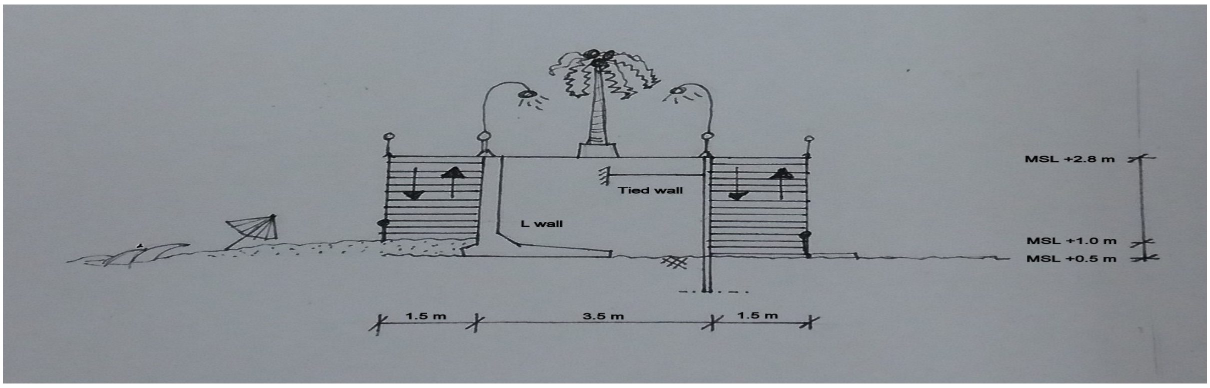


Figure J.3: Design 3: Less space

The stairs design has been chosen to be the most fitting design based on its aesthatetics and will be further designed.

J.2.1 Volumes

For a detailed design the amount of volumes required for the structure is calculated and is listed in table J.1. These are used for the costs calculation. The structure will be constructed for a large part on a sand basis.

Type	Volume	
Sand	13365	m3
Concrete	5039	m3
Pavement	6300	m2
Groyne	270	m

Table J.1: Volumes

J.3 Revetment, Centro, El Laguito and Punta Castillo

For the revetment a calculation for the necessary armour stones and the total volumes is given in this section.

J.3.1 Material

The size of the armour stones depends on the direct wave attack. The submerged part of the structures is designed on the stability of the armour stones. Statically stable structure are structures where no damages to the armour is layer is allowed. The stability can be determined as a function of the relative crest height based on the ratio H_c/D_{n50}.

$$\frac{H_s}{\Delta D_{n50}} = A + B\frac{R_c}{D_{n50}} + C(\frac{R_c}{D_{n50}})^2 \quad \text{(J.1)}$$

The calculation tool of the Cress.nl is used to calculate nominal mean diameter of the armour stones. The model used is submerged structures statically stable. The Equation J.1 is used in de model to calculate the nominal mean stone size. This model will includes the approach of Videl(1999) to determine the constants A, B and C

The stone size for the different revetments can be found in the following Table 8.3.

Table J.2: The armourstone sieze used in revetment

	D_{n50} **[m]**	M_{50} **[kg/m^3]**
Centro	1.04	2571
El Laguito	0.77	1087
Punta Castillo	0.77	1087

J.3.2 Volumes

The volumes of the amount of armour stones and the volume of sand that is required for the construction of the revetment is given in table J.3. The volumes are quite high as the length of coastal protection around Centro is quite high. The areas are calculated by figure 8.4.

Table J.3: Total volumes of the revetment

	Crest height [m +MSL]	**Crest width [m]**	**Volume total [m^3]**	**Volume Sand [m^3]**
Centro	2.33	2.5	121821	78743
El Laguito	2.13	2.0	42827	27513
Punta Castillo	2.13	2.0	25429	16260

J.4 Sea wall, Castillo beach and El Laguito

A calculation has been made to assess the total volume of the required sea wall in order to give an estimate of the cost. Also a stability check has been made to ensure that it will not slide away or tip over.

The Castillo beach area has a length of 1000m and the lake side of El Laguito has a length of 500m that needs to be protected by a sea wall. The total dimensions are given in table J.4.

Table J.4: Dimensions sea wall Castillo beach and El Laguito

Area	**Retaining height**	**Construction height**	**Toe width above ground**	**Volume per meter**	**Length**	**Volume**
Castillo beach	MSL + 2.5m	3.6m	3.7m	11.9 m^3	1000m	11,900 m^3
El Laguito	MSL + 2.5m	3.6m	3.7m	11.9 m^3	500	5950 m^3

Stability

To ensure the stability a stability check is made. The structure will be tested on horizontal and rotational stability [22]. The sea wall will be constructed from rocks and binding material.

The total density of the structure is therefore estimated at 2650 kg/m^3, the density of seawater is 1025 kg/m^3 and the density of sand is taken to be 2000kg/m^3 with an active soil pressure coefficient of Ka = 0.3333 and a passive soil pressure coefficient of Kp = 3.

Horizontal stability

$\sum H < f \cdot \sum V$ with f = 0.5 for a rubble mound sea wall.

$\sum H = F_w + F_s a - F_s p$

$\sum H = 0.5 \cdot \rho_w \cdot g \cdot h_w^2 + K_a \cdot 0.5 \cdot \rho_s \cdot g \cdot h_s^2 - K_p \cdot 0.5 \cdot \rho_s \cdot g \cdot h_s^2$

$\sum H = 0.5 \cdot 1025 \cdot 9.81 \cdot 2.2^2 + 1/3 \cdot 0.5 \cdot 2000 \cdot 9.81 \cdot 1.4^2 - 3 \cdot 0.5 \cdot 2000 \cdot 9.81 \cdot 1.4^2 = -31.062 kN/m$

$\sum V = V_s \cdot \gamma_c = 11.9 \cdot 2650 = 31.482 kN/m$

$f \cdot \sum V = 0.5 \cdot 31.482 = 15.741 kN/m$

$-31.062 < 15.741$ Therefore the horizontal check is satisfied

Rotational stability

$e_R = \sum M / \sum V \leq 1/6 \cdot b$

$\sum M = F_w \cdot 1/3 \cdot h_w + F_s a \cdot 1/3 \cdot h_s a - F_s p \cdot 1/3 \cdot h_s p$

$\sum M = 26060 kN/m$

$\sum M / \sum V = 26060/31482 = 0.83$

$0.83 \leq 1/6 * 5.1 = 0.85$

Also for rotational stability it is sufficient.

Vertical stability The maximum bearing capacity of the soil is 500kN/m^2. The vertical effective stress must not exceed this [22].

$\sigma_k max < p_s$

$\sigma_k max = \sum V/b + \sum M/(1/6 \cdot b^2)$

$\sigma_k max = 12185 < 500000$

The vertical stability also is fulfilled. This implies that it is technically feasible design that can be executed.

Volumes

The volumes of material needed are very simple for this design, it completely consists of large rocks with binding material and therefore a total volume of **11,900 m^3** is needed for the sea wall in Castillo beach and a total volume of **5950m^3** is needed for the lake side at El Laguito.

J.5 Retaining wall, Castillo bay

A summation of the quay wall functions is given in table J.5

Table J.5: Requirements - Quay wall, Castillogrande

Techical	Functional
Design level at MSL + 2.10 meter	Connection between peninsula and marina
Horizontal stability	Drainage connection
Rotational stability	Low maintenance
Vertical stability	Stability of revetment
Walkway width of 2.00 meter	Max. available width is 8.00 meter

J.5.1 Volumes

Also a calculation has been made for the total volumes of the quay wall in order to estimate the costs which is given in table J.6.

Table J.6: Volumes - Quay wall, Castillogrande

Element	Per meter	Length	Required
Front wall (concrete)	2,24 m^3/m	1.000 m	2.240 m^3
Back wall (concrete)	0,42 m^3/m	1.000 m	420 m^3
Top slab (concrete)	0,60 m^3/m	1.000 m	600 m^3
Bottom slab (concrete)	0,60 m^3/m	1.000 m	600 m^3
Sand fill	1,95 m^3/m	1.000 m	1.950 m^3

J.6 Marina, Castillo bay

The required functions and apropriate volume for the jetty structure have been determined and calculated in this section and have been used in the final design of the marina.

J.6.1 Functions

Some of the required functions the jetty structure must fulfil are given in table J.7.

Table J.7: Requirements - Marina

Technical	Functional
Inner channel width min. 37,00 meter	Capacity of 230 moorings
Main jetty walkway length max. 300,00 meter	2500.00 m^2 for additional facilities
Main jetty walkway width 3.00 meter	Easy access to the peninsula
Finger jetty length 15.00 meter	No height restrictions
Finger jetty width 3.00 meter	Low maintenance
Finger jetty spacing 18.10 meter	Structure able to adapt to water level rise
Draft min. 2.00 meter	Space for (un)loading

J.6.2 Volumes

Volumes required for the jetty structure of the marina are given in the following table.

Table J.8: Volumes - Marina

Element	Width	Length	Required
Main jetty walkway	3.00 m	2.300 m	6.900 m^3
Finger jetty walkway	3.00 m	1.725 m	5.175 m^3

J.7 Quay wall, Centro bay

For the cost estimation the total volume of the extension of the quay wall has been made.

J.7.1 Volumes

Table J.9: Volume of the quay wall

Element	Width [m]	Height [m]	Length [m]	Volume m^3
Top step	0.425	0.425	1300	234.8
Bottom step	0.85	0.425	1300	469.6
Total				704.5

J.8 Nourishments

The total nourishment amount is explained in this section as well as the necessary amount of maintenance nourishment that is required.

The expected sea level rise is 0.28m and land subsidence is 0.11m for the next 50 years so the current beach needs to be at least heightened with 0.39m. The beach will be heightened with **0.5m**. The beach from calle 8 till calle 1 has a minimum width of 40 m so there is enough space to create a promenade. From calle 8 till calle 10 the beach width gets so small that there is not enough space for the promenade. Therefore, additional land should be created at this part. An additional width of **15 meters** will be constructed to have enough space for the promenade and create some extra beach. The possibility of widening the carerra 1 is not taken into account into this design. If this is desired this could be easily implemented by widening the beach even more.

The volumes of the nourishments of Boca Beach en Castillo Beach are presented in Table J.10.

Table J.10: Volumes nourishment

	Extension [m]	Increased height [m]	Volume [m^3]
Boca Beach	15	0.5	40000
Castillo Beach	15	0.5	35000

J.8.1 Maintenance

Due to loss of sediment the current beaches have to be maintained every ten years. The amount of sediment that is lost each year is calculated by means of the Bruun Rule and can be found in Appendix J. This determines the rate in which the shoreline retreats and therefore gives an estimation of the necessary nourishment volume required to maintain the shore line. Table J.11 presents the volume of eroded sediment per ten years.

Table J.11: Maintenance volumes per 10 years

	Volume [m^3]
Boca Beach	16398
Castillo Beach	9958

In figure J.4, the calculation of the volumes of nourishments of the revetments are given.

In figure J.5, the calculation of the volumes of maintenance of the revetments are given.

J.9 Drainage

J.9.1 Pumps

In this section a calculation of the required pumping capacity is given. The total area of the streets is given in table 7.11. The reduction of the required drainage capacity is also given in table J.12.

Table J.12: Retained storm water

	Sea side	**Bay side**	**Centro**
Volume pavement [m^3]	8490	13810	14 852
Vegetation [m^3]	6958	18984	0
Total [m^3]	15448	32794	14852

The total amount of stormwater that can be retained can be subtracted from the total volume of stormwater. The resulting volume needs to be able to drained off.

Discharge volumes

The remaining discharges that are required are given in table J.13. To discharge these amounts, a system of pumps has to be installed.

Table J.13: Volumes to be discharged

	Sea side	**Bay side**	**Centro**
Total precipitation volume[m^3]	71360	214080	118993
Total retention volume[m^3]	15448	32794	14852
Volume to be discharged[m^3]	55912	181286	104141
Hourly discharge volume[m^3/h]	18637	60429	34714

J.9.2 Integration drainage in coastal defence

The drainage outlets will have to be constructed through the coastal defence system. Because not everywhere along the coast there is much space to implement extensive pumping stations, the pumps and check valves need to be embedded in the defence structures.

Promenade

The promenade itself already is quite a big structure. To be able to place this structure extra beach will be created. To conserve the space created and to keep the aesthetic view also created by the promenade the pumps and valves will be embedded in and underneath the structure.

The storm water will flow towards the promenade over the streets and enter the storage chambers build partly under the pavement and partly under the promenade. From here the storm water can be drained with the use of the pumps also installed inside the promenade. The water will flow over the beach towards the sea, as it also does now. This will mean that trenches again will come to exist on the beaches.

Seawall

The integration of the drainage system in the seawall is comparable with the integration in the promenade. Also to conserve space the pumps valves and storage chambers will be constructed in or underneath the structure.

Drainage water will also enter the drainage system through gutters where under normal circumstances the water will be discharged by gravitational flow. During storm conditions the water will be termporary stored in the storage basins untill the pumps start working. The water will then be pump through the same discharge tube and will end up at the beach.

Marina

Outflow of drainage water is not preferred in the marina. The outflow of water from the valves will create currents that will make it difficult for ships to manoeuvre inside the harbour. The current will also increase the hawser forces on of the moored ships. At the marina therefore no outlets will be constructed.

Quay wall

At the sections of Boca Bay where no marina is in front the drainage system can again be integrated inside the structure. Inside the hollow stability structure room can be made for the pumps. The storage chamber can again be placed underneath the construction or be integrated in the bottom floor slab.

Revetment

The revetments used are solid structures. So in contrast to the other coastal defence structures the drainage solutions can not be integrated much. Pumping stations will therefore have to be placed behind the revetments. To be able to discharge drainage water still pipes will have to be made through the revetment. A storage chamber will be build underneath the pumping stations.

J.10 Construction method

J.11 Maintenance

In the designed final system some maintenance does have to be done. For each structure the expected services that need to be done are described.

J.11.1 Promenade, Boca beach

The promenade is expected to not need a lot maintenance of its own. The structure itself is when well constructed almost maintenance free and erosion is also not expected as it is not in constant contact with the sea. The check ups and repairs will have to deal with the pumps that have to drain out the storm water. At least each year before the rain season the pumps will have to be checked.

J.11.2 Seawall

The sea wall is very maintenance low as no real erosion takes place. The sea wall primarily exists for extreme conditions and therefore does not suffer from structural erosion. During an extreme event some rocks might be damaged and perhaps be replaced. The pumps need the same amount of maintenance as was described for the promenade.

J.11.3 Retainingwall Centro

As the seawall, the retainingwall at centro is also very maintenance low. It is expected that ships will moor in this area, so the mooring places will sometimes need repairs. Only one pumplocation is planned for this area, however this is an important one as it drains a large part of the Centro. Regular maintenance is required for this pump.

J.11.4 Retainingwall Bocabay and Castillobay

At this part of the coastal defence many boats will dock at the quay wall. Also many people are expected to walk over it to access the boats. The structure will be able to handle the amount of people, but as at the retainingwall at Centro some repairs will have to be done at the mooring places.

J.11.5 Marina

Regular maintenance can be expected to be done in the marina. The marina will however be in the ownership of a private party, so the regularity of the maintenance will not pose a very serious problem. Furthermore is the amount and frequency of maintenance dependend on the choice of material.

J.11.6 Revetments

Revetment are in general maintenance free structures. The armour stones are designed for the extreme conditions and are therefore not expected to break or replace at less severe circumstances. Only after an extreme event the revetment should be checked.

J.11.7 Nourishments

Due to loss of sediment the current beaches have to be maintained every ten years. The amount of sediment that is lost each year is calculated by means of the Bruun Rule and can be found in Appendix J. This determines the rate in which the shoreline retreats and therefore gives an estimation of the necessary nourishment volume required to maintain the shore line. Table J.11 presents the volume of eroded sediment per ten years.

J.12 Construction planning

J.13 Planning construction

The planning is divided in 4 phases, the idea behind each phase is that when completed: that part of the city is protected against tidal intrusion and the drainage of the area is sufficient. In the following figure the areas protected after each phase are shown.

In the first phase the main bottleneck for the accessibility of the peninsula is addressed. In this phase the revetment around Centro and Centro Sea is constructed. The road from Centro leading to the peninsula will in this way be protected. During the construction of the revetment around Centro the needed pumps and valves will also be installed as they need to be embedded in the construction. The revetment of Punta Castillo is also constructed. This is an area where a lot of scour is expected and therefore needs to be protected.

Phase 2 will deal mostly with the protection of the bay side of the peninsula. The construction of the revetments at El Laguito will start. Work will also be started on the retainingwalls at Castillo Bay, Boca Bay and Centro Bay. To let all the parts of the peninsula still be accessible the seaside protection will be done in the next phase. The construction of the pumps, valves and storage chambers will be implemented.

In Phase 3 the Seaside will be addressed, the promenade of Boca Beach as well as the seawall at Castillo Beach will be constructed. Firstly the drainage system will have to be implemented as also the elevation of the roads will start in this phase. This will ensure that drainage can continue in the normal way.

After finishing the structures on the bay side in Castillo Bay and Boca Bay the construction of the marina will be started. Last stage in phase 3 consists of the groins that will be placed.

Phase 4 is the finishing phase in which the nourishing of the beaches will be started. The final stage of this phase consists of implementing the vegetation. There is also some room for delay in that phase as the current planning shows that the project will be finished three months before the end of the term of the mayor.

J.14 Costs and benefits

This section gives a more extensive costs and benefit calculation in comparison to the conceptual design. The costs are split up in initial costs and maintenance costs. For both the calculation method is described before the results are presented. The benefits are subdivided into economic growth, marina income and non-financial benefits.

Costs have been extracted from different reference projects. These projects are located in different countries and subsequently different currencies are used. In order to compare the costs the below conversion rates have been used (6th of October, 2015).

- 1 GBP = 1.35491774 EUR
- 1 USD = 0.88831247 EUR
- 1 COP = 0.00030873 EUR

J.14.1 Initial costs

The initial costs estimation includes all costs related to the project from scratch to finish. Costs during the operational phase are separately substantiated. Costs from scratch to finish include the costs for among others project coordination, collection of data, model studies, license procedures, administration, construction material, construction equipment, etc.

Method

The costs estimation is based on reference projects. Each project has its own specific characteristics and as a result each project has a unique price. Import parameters that effect the total price are the global dimensions and the environmental boundary conditions. Both these parameters as well as the costs from scratch to finish are known for the reference projects.

All costs for the reference projects are extracted from the report 'Cost estimation for coastal protection - summary of evidence' as published by the British Environmental Agency [76]. The document does not contain reference projects for construction of marinas. These costs have been estimated based on market prices for construction materials.

Environmental boundary conditions are assumed to be equal for equal types of designs. Therefore no changes are made to the estimation of the costs. Moreover, it is assumed that all initial expenses are made at day 1 of construction. Therefore no net present value calculation is required.

Revetments

For revetments a lot of information is available on dimensions and prices. Based on the values supplied by the Environmental Agency it is estimated that the rock revetment along Centro and Centro Sea will cost approximately €6,300 per meter. Due to less intense wave conditions and smaller lengths the revetments at El Laguito (€5,000/m) and Punta Castillo (€2,200/m) are less expensive.

Nourishment

Three reference projects have been considered for beach nourishment. However all three projects consider very large amount of sand compared to the final solution. The price per cubic meter will be higher for smaller volumes. As a result the price is assumed at €22.00/m^3 compared to the average of €14.91/m^3 for the three reference projects.

Promenade

It is hard to find characteristic values for structures with comparable features. As a result the used reference project is a quay wall structure roughly the same dimensions. It consists of reinforced concrete, a masonry facing and its founded on piles which makes it an expensive structure. Just like the proposed promenade. The costs for the promenade are estimated at €11,000/m.

Seawall

A lot of reference projects where available for the seawall, however not all characteristics are known. The costs are therefore estimated based on the height and the complexity of the structure. The seawall along El Laguito and Castillo Beach is estimated at €3,000/m. The seawall at Centro Bay is much smaller and is estimated at €1,500/m.

Retaining wall

The retaining wall along Castillo- and Boca Bay is a structure that is hard to compare to the reference projects. In this way it is assumed to be similar to the Promenade at Boca Beach but with a smaller volume. The costs are estimated to be €8,000/m.

Groynes

Also for the groyne structures a lot of reference projects are available. However a lot of them seem unrealistically inexpensive and were not taken into account. For Boca Beach a realistic value has been estimated at €6.500/m. For Castillo Beach less intense wave conditions apply and the groynes are estimated at €5,500/m.

Marina

As already stated, no reliable reference project has been found for the marina. Instead the cost estimation is based on the sum of costs for the jetty structure (€280/m^2) and required additional infrastructure / facilities (± €1,500,000). Overhead and construction costs are estimated at 20% of the total costs.

Overview coastal protection costs

Per element the costs are calculated based on its specific dimensions. An overview of the total costs is shown in table J.14. For unforeseen expenses a margin of 5% is added.

Table J.14: Total coastal protection costs

Location	Structure		EUR		COP
Centro & Centro Sea	Rock revetment	€	11,340,000	$	36,984,341,772
Boca Beach	Nourishment	€	693,000	$	2,260,154,219
Boca Beach	Promenade	€	19,800,000	$	64,575,834,840
Boca Beach	Groynes	€	2,080,000	$	6,783,724,064
El Laguito	Rock revetment	€	3,500,000	$	11,414,920,300
Castillo Beach	Nourishment	€	847,000	$	2,762,410,713
Castillo Beach	Seawall	€	4,500,000	$	14,676,326,100
Castillo Beach	Groynes	€	1,760,000	$	5,740,074,208
Punta Castillo	Rock revetment	€	1,408,000	$	4,592,059,366
Castillo Bay	Marina	€	5,857,200	$	19,102,706,052
Castillo Bay	Retaining wall	€	8,000,000	$	26,091,246,400
Boca Bay	Retaining wall	€	8,000,000	$	26,091,246,400
Centro Bay	Seawall	€	1,950,000	$	6,359,741,310
5% of total		€	3,486,760	$	11,371,739,287
Total		€	73,221,960	$	291,013,658,702

Pumps

Costs for pumping installations are estimated based on information supplied by manufacturers. Pumps at Centro with a capacity of 9,000 m^3/h are installed at costs of €80,000 per pump. At the peninsula pumps of 1,700 and 4,300 m^3/h are installed at costs of respectively €20,000 and €45,000 per pump.

Surface elevation

The road surface elevation is estimated to cost €1,557.55 per stretching meter. The value is based on the construction of a complete new road in an urban area [78].

Valves

The number of valves is equal to the total number of pumps. Costs are estimated based on a reference project where 140 valves where installed at the Seaford and Wantagh coastline [80]. The average cost per valve is €12,690.

Vegetation

A total area of 140,000 m^2 will be planted with vegetation at a cost of only €0.31 per m^2. These costs are based on a research of the Australian Agricultural and Resource Economics Society [79].

Overview drainage costs

The total drainage costs are calculated based on the specific characteristics of the individual elements. An overview of the drainage costs is shown in table J.15.

Table J.15: Total drainage costs

Location		EUR		COP
Pumps	€	1,170,000	$	3,815,844,786
Surface elevation	€	6,230,000	$	20,319,262,206
Valves	€	370,000	$	1,200,246,801
Vegetation	€	50,000	$	161,405,879
5% of total	€	390,886	$	1,274,837,984
Total	€	8,208,607	$	26,771,597,656

J.14.2 Maintenance costs

The maintenance costs cover the costs for repairs that are required to maintain a specific level of protection. Additional maintenance for green maintenance, cleaning, etc. are not included. These are considered to included within the standard tasks of the local government.

Method

Again the report 'Cost estimation for coastal protection - summary of evidence' [76] is used to estimate the costs. Each structure is scored as high, medium or low maintenance costs, based on table 1.1 of the report. A single maintenance event is assumed to cost 15% of the initial costs when it is classified as low. For medium and high classification a single maintenance event respectively costs 25% and 35%.

Besides the costs of a single maintenance event the number of maintenance events during lifetime has been determined. Since the expenses for maintenance will be made in the future it is necessary to calculate the net present value of these costs. Therefore an interest rate of 4.5% is used [81]. Also, the environmental boundary conditions will have an influence on the required amount of maintenance, in contrast to the initial costs.

Revetments

Table 1.11 of the report [76] shows the deterioration rates in years for revetments in coastal environments. A division is made from Grade 1 up to Grade 5, in which Grade 1 is directly after construction or maintenance. Maintenance is assumed to be necessary at Grade 3, for revetments without any maintenance this is after approximately 19 years. Since climatic circumstances in Cartagena differ a lot from the English climate a period of 15 years is taken into account. This results in a number of 3 maintenance events during lifetime. According to the Environmental Agency revetment maintenance costs are indicated as low.

Nourishment

Nourishment maintenance costs are based on the calculated recharge volumes in the final design. However, the required volumes are a lot lower than the required volume of the initial nourishment. This results in a higher estimated cost of €25.00/m^3.

Promenade, seawall and retaining wall

Table 1.10 of the report [76] shows the deterioration rates in years for revetments in coastal environments. A division is made from Grade 1 up to Grade 5, in which Grade 1 is directly after construction or maintenance. Maintenance is assumed to be necessary at Grade 3, for concrete structures without any maintenance this is after approximately 30 years. Since climatic circumstances in Cartagena differ a lot from the English climate a period of 25 years is taken into account. This is results in a single maintenance event during lifetime (after exactly 50 years a second maintenance event is necessary). According to the Environmental Agency concrete structure maintenance costs are indicated as low.

Groynes

Paragraph 1.8.3 of the report [76] states that the average design life of rock groynes is in the region of 50 years. Since climatic circumstances in Cartagena differ a lot from the English climate a period of 40 years is taken into account. This results in a single maintenance event during lifetime. According to the Environmental Agency groynes maintenance costs are indicated as medium.

Marina

The marina is assumed to be maintained by the party that will be coordinating daily operations (municipality or investor). Maintenance costs are therefore not taken into account.

Drainage

Except for the surface elevation all drainage elements need continues maintenance. For the vegetation this is already included in the initial costs. It is assumed that yearly 10% of the initial costs are required for maintenance purposes. This leads to a yearly maintenance cost of €158,750.

Overview maintenance costs

Per element the costs are calculated based on its specific deterioration rates. An overview of the maintenance costs is shown in table J.16. A quick calculation shows that the net present value of the total maintenance is 11% of the total initial costs.

Table J.16: Total maintenance costs (net present value)

Location	Structure		EUR		COP
Centro & Centro Sea	Rock revetment	€	1,567,786	$	5,113,185,980
Boca Beach	Nourishment	€	491,120	$	1,601,741,149
Boca Beach	Promenade	€	510,628	$	1,665,365,911
Boca Beach	Groynes	€	89,403	$	291,579,217
El Laguito	Rock revetment	€	483,885	$	1,578,143,821
Castillo Beach	Nourishment	€	75,649	$	246,720,876
Castillo Beach	Seawall	€	116,052	$	378,492,252
Castillo Beach	Groynes	€	298,242	$	972,688,033
Punta Castillo	Rock revetment	€	194,660	$	634,864,714
Castillo Bay	Retaining wall	€	206,314	$	672,875,115
Boca Bay	Retaining wall	€	206,314	$	672,875,115
Centro Bay	Seawall	€	50,289	$	164,013,309
Drainage	All elements	€	3,137,228	$	10,231,774,520
5% of total		€	371,379	$	1,211,216,001
Total		€	7,798,949	$	25,435,536,015

J.14.3 Benefits

Since it is difficult to forecast the real impact of the solution, the benefit calculations are largely based on common sense and quantitative expectations. The three main financial aspect are economic growth, revenue of the marina and prevented damage. Also the non-financial benefits will be discussed briefly.

Economic growth

The Bolívar Department has a gross domestic product (GDP) of $ 12,230 million Colombian pesos. In the analysis it is stated that the city of Cartagena contributes to 23% of this GPD. Bocagrande, El Laguito, Castillogrande and Centro are important contributors within the city. For example; 21% of the registered jobs in the city are located at Bocagrande. It is hard to directly relate this percentage to a contribution to the GDP. However, including the other areas it is assumed to be conservative that together they contribute to 10% of the city's GDP.

A forecast of the effect of the solution on the economic growth of the area is not within the range of the skill set of the team. However, it is very feasible that economic growth will occur due to better traffic flow, less corrosion through tidal intrusion and more attractive locations for tourists.

To put a value on the economic growth it is assumed that the GPD of the focus area will increase with 0.5%. This increases the GDP of the project area with €1,247,400. Accounting this additional GDP for each year of the lifetime results in a net present value of €22,447,319.31.

Marina

For the marina two scenarios are considered: a worst case and a best case. In both scenarios the expected yearly occupancy is 70% of the capacity. However, the worst case scenario assumes a price of €30.00 er night, where the best case assumes a price of €60.00 per night. The price range is extracted from current prices of marinas at Miami, St. Tropéz and Tropea. Also there is difference in expected profit margin: 20% for the worst case scenario and 60% for the best case scenario.

Each scenario separately, it would take the worst case scenario 41 years to earn back the investment costs (after converting to the net present value). For the best case scenario this is only 5.5 year.

For this rough revenue estimation the average situation is considered. This results in a period of 8 years to earn back the initial investment. Including extraction of the initial costs the income of the marina over a lifetime of 50 years represents a net present value of €16,220,000. See also figure J.8.

The benefits estimation does not include the increase of land value due to the marina. Although it has been shown in other cases that this could increase the land value up to double of the original value. It might be possible to finance part of the project with this increase of value. However, the complex juridical paperwork and the amount of lobbying that will be required make the feasibility of such a construction questionable.

Prevented damage

The calculated damage is with respect to current economical values of the focus area, which implies no net present value calculation is required. However, the flood risk analysis is performed with expected storm conditions for over 50 years. The net present value is calculated by assuming the current economic values are still valid at the end of the design it's lifetime. Economical development is not included in the calculation.

To determine the net present value, first the probability of occurrence of the extreme event during lifetime of the construction has been determined. The return period of the considered extreme event is: 1/100 years. This gives a probability of occurrence of p = 0.02. The lifetime of the structures is set to N = 50 years. The probability of the extreme event occurring in this 50 years is calculated with:

$$pN = 1 - (1-p)^N = 1 - (1-0.2)^{50} = 0.395.$$

The current interest rate in Colombia is: i = 4.5 % [81]. The net present value is calculated for each of the values found in the flood risk analysis with the formula:

$$\Sigma \frac{R}{(1+i)^t}$$

For both the expected probability that the extreme conditions will occur as well as the event that the extreme condition will occur with 100% certainty the net present values have been calculated. The first condition can be seen as a lower boundary and the second condition as an upper boundary to the amount of economic value that is justified to invest. The values are listed in table J.17.

Table J.17: Net present value of prevented damage

Value		**EUR**		**COP**
Expected damage	€	1,412,492,622	$	4,606,711,631,090
NPV for pN	€	61,767,794	$	201,449,841,424
NPV for one extreme event	€	156,376,564	$	510,007,432,176

J.14.4 Remarks

The estimated initial costs for the coastal protection are mainly based on reference projects in the United Kingdom. Conditions for construction works are not directly comparable. For example labour costs in Colombia will probably be lower compared to labour costs in the United Kingdom. Moreover, the design has been fitted to the local available construction materials which reduces transport costs in comparison to some of the used reference projects. As a result the cost estimation is considered conservative.

The final solution does not only financially generate benefits. For example the quality of life will improve significantly due to the prevention of floods and the additional opportunities of recreation. Besides, the final solution includes a lot of elements that will positively effect the opinion of many stakeholders. For example residents, employees, hotels and restaurants will gladly cheer for a solution that solves their problems without raising additional taxes. For the mayor, the department and the national government it is an excellent opportunity to improve their status. On a local level as well as on a national and maybe international level.

J.14.5 Conclusion

All calculated values of the costs and benefits are summarized in table J.18. Compared to the global solutions the costs have increased significantly for the coastal protection part. One of the explanations is the increase of costs for the construction of new groynes. Also the costs for the promenade are significantly larger.

On the other hand, costs for the drainage system are lower than calculated for the global solutions. This difference is solely induced by the fact that in the final design water is able to runoff over the streets and a extensive system of sewer pipes is no longer necessary.

Another contribution of the total costs is the inclusion of unforeseen expenses that are taken equal to 5% of the total initial costs. Also the inclusions of maintenance costs increases the total investment.

Table J.18: Total overview, net present values at an 4.5% interest rate

Expenses		**EUR**		**COP**
Coastal protection	€	73,221,960	$	237,166,658,702
Drainage	€	8,208,607	$	26,771,597,656
Maintenance	€	7,798,949	$	25,435,536,015
Total	€	89,229,515	$	291,013,658,702
Benefits		**EUR**		**COP**
Economic growth	€	22,447,319	$	73,209,817,393
Marina	€	16,219,408	$	52,898,072,635
Damage prevention	€	61,767,794	$	201,449,841,424
Total	€	100,434,522	$	327,557,731,452
Difference		**EUR**		**COP**
Total	€	+ 11,205,006	$	+ 36,544,072,749

Although not substantiated by an extensive model, an economic growth of 0.5% seems logical.

An increase of the GDP with such a percentage will result in a high added value to the focus area. This outcome is especially important for governmental institutions that are interested in sustainable development on local and/or national level.

The revenues of the marina have been further detailed compared to the global solution. As a result the net present value is calculated at €16,219,408 (or COP $52,898,072,635) after extraction of the initial costs. The expectation is that it will take 8 years to get to a break-even point. This makes the marina an interesting project for investors. Governmental institutions can also decide to exploit the marina themselves.

For the prevented damage a lower bound value is taken into account, based on a probability of occurrence of 2%. The probability of occurrence does not give an indication of the moment in time that a storm will strike. If maximum storm conditions occur in an early stadium of the lifetime, the theoretical damage prevention is a lot higher because economical growth is not taking into account for this calculation.

All costs compared to the benefits result in a design with an added value expressed in monetary value of €11,205,006 (or COP $ 36,544,072,749). This is an important outcome to convince stakeholders that are not daily inconvenienced by the problem.

Volumes Nourishment		
Bocaay		
Length area	1000,00	m
	800,00	
Slope	0,10	
Thickness nourischmer	0,50	m
Extra beach korte	25,00	
Volumes	12,50	
Extra beach lange	60,00	
Volumes	30,00	
Totale volume	40000,00	m^3

Volumes Nourishment	
Castillo Beach	
Length area	1400,00
Slope	0,10
Thickness nourischmer	0,50
Extra beach	50,00
Volumes	25,00
Totale volume	35000,00

Maintenance			
beach retreat			
sea level rise	5,6	mm/year	
sediment scale parameter	0,0872	(1/3)	
depth of closure hc	2,598657	m	
Berm height	0,5	m	
width shore of active nearshore zone boca	162,6854	m	
width shore of active nearshore zone castillo	127,0158		
erosion Boca Beach	0,911038	m^3/m/year	
erosion Castillo Grande	0,711288	m^3/m/year	Tc
Total volume Boca Beach/ 10year	16398,69	m^3	Hc
Total volume Castillo Beach/ 10 yr	9958,039	m^3	hc
Sealevelirse	0,0056		
		closure depts	

Figure J.6: Overview phases and areas

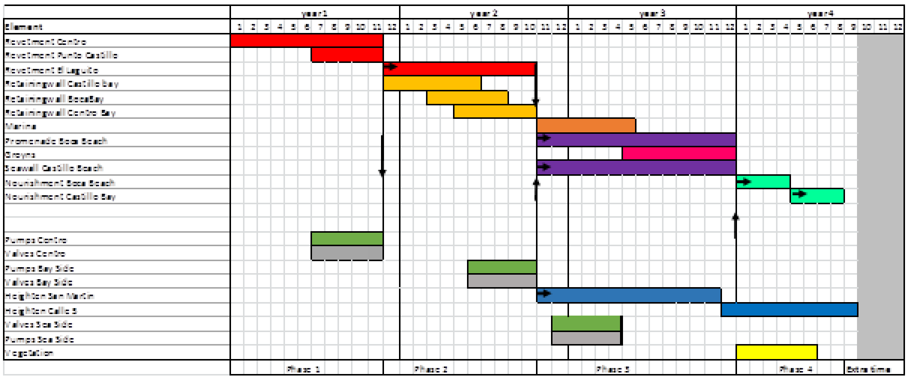


Figure J.7: Planning of the elements

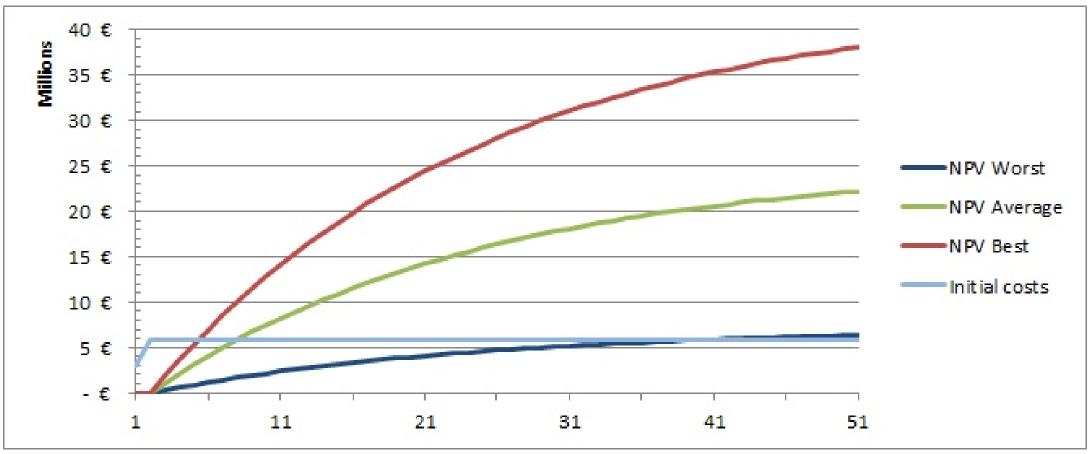


Figure J.8: Marina net present value estimations

Appendix K

Interviews

K.1 Istituto Hydraulica y Saneamiento Ambiental (IHSA)

Interview with	Prof. Javier Mouthon Bello
Date	25/08/2015
Location	Universidad de Cartagena Piedra de Bolivar, Cartagena
Present	Daan Cornelissen Rolf Ziel

K.1.1 Topics

Prof. Javier Mouthon Bello is the head of the IHSA. The institute is part of the Universidad de Cartagena and helps local governments and associations by doing research and offering consultancy. The civil engineering students at the University make use of the archives and have the possibility to graduate in watermanagement or hydraulic engineering at the institute.

1. Drainage network/system of the Historic Center
2. Flooding: damages and frequency
3. Current construction works
4. Politics in Colombia
5. Construction of new groynes at Marbella district
6. Water quality / health

K.1.2 Drainage network/system of the Historic Center

The drainage system of Cartagena used to be interconnected in the past. Before the airport was constructed, the channels through the Historic Center connected the bay to the CiÃľnaga de la Virgen, a large brackish water in the north. About 60% of the total city water used to runoff via this route. Construction of the airport caused a blockage of the water flow, which was initially resolved by means of a culvert. Due to the presence of guerilla troops it was no longer possible to perform maintenance and the connection was closed off.

Now the most important runoff is provided by the San Anastasio channel through La Matuna district. This commercial area with its triangular shape connects the Historic Center to the inner waters of Cartagena at Monumento India Catalina. From here it is finally pumped away to an ocean outlet at Punta de Canoa, approximately 10 kilometers away from the city borders. The reason to choose the San Anastasio channel connection is the presence of a large head difference in contrast to the former bay connection. The steeper slope allows a more rapid water runoff in case of floods.

K.1.3 Floods: damages and frequency

In order to be able make a good quantification of the flooding severities and consequences we divided them into three different classes:

- Class 1: Tidal intrusion, a water layer of ± 15 cm on the streets
- Class 2: Heavy tidal intrusion, a water layer that would also flood the sidewalks
- Class 3: Heavy tidal intrusion combined with rain, complete shutdown of Bocagrande

A class 1 flooding usually leads to damage to cars and infrastructure. Some Colombian drivers don't even realize that the salt water splashes on their chassis and speeds up to eroding. The infrastructure, mostly constructed from concrete, is also deteriorating due to the salt intrusion. In the long run, stones from revetments will get loose and the reinforcement in elements is exposed through large cracks in the concrete.

There is no institute, department or whatsoever that keeps track of all the flooding. There are however possibilities to get records of the rainfall/weather conditions (IDEAM) and records of the tidal motion (CIOH). Combining these records would give great insight in the flooding conditions of the period over which these records run. Below is an estimation by prof. Javier in relation to our flood classes based on his own experiences and observations(started his studies at Universidad de Cartagena mid-70's).

- Class 1: 5 to 10 times a month
- Class 2: 4 to 5 times a year
- Class 3: once in 5 to 10 years

The latest Class 3 flood that prof. Javier was able to remember was the flood in 1988 caused by hurricane Joan-Miriam. In 2010 a big flooding occurred as well, however this one has to be contributed particularly to the heavy rainfall. The complete peninsula of Bocagrande and Castillogrande was closed off from the city. At that time prof. Javier used a helicopter to fly over the city to make photographs and an overview of the affected area. He will send these by e-mail.

K.1.4 Current construction works

Besides the developments at the airport area (point 5) one other major construction work is being carried out at the moment. Along the bayside coastline of Bocagrande and Castillogrande a 2.1 kilometer long seawall is being constructed. It is a modest wall, no more than 1 meter high with a small revetment strip in front of it. According to estimations of the university the wall will only function for 2 to 5 years. This is due to the expected deterioration of the revetment. Moreover, the university has advised to use pumping stations but for unknown reasons the city has chosen to apply 'duck valves'. In other parts of Cartagena these type of valves have already proven to get clogged very quickly.

K.1.5 Politics

During the interview it has become more and more clear how the Colombian politics work. Javier gave us some revealing examples of how thinks work in Cartagena.

A first example is a law the prohibits the major to execute plans that were not yet on the planning of his predecessor. This leads to a delay in political decision making and in some cases the plans won't ever be executed.

Economically there are quite some possibilities to raise a budget for big flood preventing and mitigating projects. A lot of people in Cartagena think that flooding is a small problem, but these are mostly the people that don directly profit from the income from tourism. The local government also raises a lot of money from taxes on property. High land prices are being paid for this area and the taxes are being paid accordingly.

Especially in the Bocagrande, Castillogrande and El Laguito area the inhabitants have high value properties at risk that they want to protect, thus they are willing to contribute to the solution. However they do not want to pay the money directly, prof. Javier is confident that they will be open to other payment constructions. By creating a better protected peninsula, the value of their properties will increase accordingly. This added value will earn them profit once they sell their property, land owners have already openly announced that they are willing to address this profit to payback the investments.

In addition to the above prof. Javier told us about his former job in the economical department were they used the rule of thumb that an apartment close a marina has twice the value of a apartment close to the beach. With this knowledge it might be interesting to investigate the option to create a marina area. Also a graduate student invested the relation between value of property and the distance towards the beach. He advised to check the online .PDF file of 'GEO Cartagena' published by PNUMA.

Another important remark is the history of the 'Empresa Publica' (EPM). This used to be an institute that took care of all water related problems and solid waste disposal. At one moment in time the local government decided to split up the institute and it was separated into different identities as shown below. Three of the four branches turned out to be suitable for a profitable business plan and were taken over by other companies. The storm water management was taken over by a private party, nonetheless the local government decided to drop it anyway. At the moment, no one in Cartagena is responsible for the drainage of storm water.

K.1.6 Construction of new groynes at Marbella district

Unfortunately prof. Javier was not directly involved in this project. However he knows a lot of people that have a lot of knowledge about the breakwater / groynes project.

The structures are being built in order to enable the construction of a tunnel along the coastline of Marbella district. The road from Barranquilla to Cartagena is planned to be expanded to a 4-lane highway. Since there was not enough space available they decided to go underground and construct a beach on top.

For more information we can try contacting the ’Atlante Proyectos’ company. Furthermore he will try to arrange a meeting for us with Santiago Rizo of CARINSA. He is (one of) the most experienced engineer in Cartagena and involved in almost every large project. He will try to arrange a meeting with Alfredo Pineda and Pedro Fabris as well. Both men are well up-to-date about the tunnel project.

K.1.7 Water quality / health

Finally, prof. Javier also made the remark that we should be careful with stagnant water. A couple of years ago some culverts got clogged, combined with the temperatures in Cartagena these are the ideal circumstances for mosquitos to live. At that time they had an epidemic of Chikungunya.

K.2 La Vecina primary school

Interview with	Nathalie Rietman
Date	28/08/2015
Location	La Vecina primary school La Boquilla, Cartagena
Present	Marlies van Miltenburg Maartje van de Ven Martijn de Way Rolf Ziel

Nathalie Rietman was in Colombia on study related business. During this period she was shocked by the amount of children living on the streets. She always had the idea of doing something related to children after her studies so when she finished her degree she came back to set up La Vecina 8 years ago. At the start there where 15 children that would go to school there. Now there are 115 children and 17 people in employment for the foundation. The children get education, 2 meals a day and after school activities such as music lessons, a soccer team and English lessons. In the neighbourhood the children have to deal with violence, drugs, alcohol and sexual violation. Therefore also a psychologist is working at the school to assist with the possible trauma that can occur with the children. The neighbourhood La Boquilla, where the school is located is one of the many neighbourhoods where most of the poor people of Cartagena live. The view from this poor neighbourhood on the skyline of the rich Bocagrande area clearly depicts the big difference between the rich and poor people.

Also this part of the city has a lot of water related problems. There is a sewerage system in this part of the city but often it gets clogged by rubbish. Also in the rainy season the neighbourhood often gets flooded and all the dirt and debris flows from the sewage system onto the streets. This creates a very poor living environment. The neighbourhood is located on very shallow flat land like Bocogrande and located just above sea-level. When the sea-level will rise further these parts of the city will be flooded first as there is no protection against the sea.

Also Nathalie explained that the city of Cartagena is the most corrupt city in Colombia. If you have money you can get everything done but otherwise it will take a lot of time and will most likely result in nothing happening. Most donations she gets come from Holland as a lot of foundation in Colombia are using 'foundations' as money laundering and none of the money reaches the intended goal. After eight years of working in Colombia, people have started to trust Nathalie and realize that she does good work and also Colombian companies, like the water company, start to donate money. The things Nathalie explained, shows that the city still has a lot of problems and that the flooding problems are only a small part of all the problem.

K.3 Santiago Rizo

Interview with	Santiago Rizo
Date	09/09/2015
Location	Office of CARINSA Bocagrande, Cartagena
Present	Daan Cornelissen Martijn de Way

K.3.1 Topics

CARINSA is a Cartagena based engineering firm. The owners, Jaime and Santiago have a lot of experience within the Cartagena construction sector. For example they worked on prestigious projects such as the 'La Bocana' tidal inlet and the 'Annilo Vial de Crespo' highway tunnel connection. The following topics have been discussed.

1. Drainage of Bocagrande and Castillogrande
2. Politics in Colombia
3. Dutch water management model
4. Maintenance
5. Possible solutions
6. Seepage due to sea level rise
7. CiÃĬnaga de la Virgen

K.3.2 Drainage of Bocagrande and Castillogrande

The current drainage network is fully based on gravity. There are slight differences between the districts of Castillogrande and Bocagrande. Figure K.1 gives a global overview of the direction in which the water (should) run off, darkblue flows to the sea and lightblue flows to the bay.

In Castillogrande culverts are located in every street transverse to the coastline. The water is running off towards the bay side which is lower than the beach side. Nonetheless, the slope will not be steeper than 1 percent. Santiago and his wife live in Castillogrande, close to the Club Naval. In some cases the water level on the streets can reach 40 centimeters.

A few yours ago new duck valves were installed on the culverts by a private initiative. This was working perfectly for one year, not a single flood due to tidal intrusion was recorded. Only some problems with rainfall runoff were still present due to the limited slope of the culverts. Unfortunately the tidal intrusion problems are back again because the municipality decided to upgrade the seawall along the bay. The new construction will have sufficient capacity to retain high tides combined with storm situations. Rain water will still be drained by gravity through culverts with duck valves. Santiago expects that in the future water from the bay will leak

Figure K.1: Drainage directions Bocagrande and Castillogrande

underneath the structure through the sand into the district. In the long term this should also be taken into account for the beach side of Castillogrande! E.g. by using a screen that lengthens the travel time for the water.

The Bocagrande drainage is quite similar to that of Castillogrande. But here the area is split up by the Avenido St. Martin (Carrera 2). On half of the district is drained towards the sea, and the other half is drained towards the bay. Also in Bocagrande the slope of the culverts is not always sufficient to drain the water within a limited period. One of the solutions that Santiago suggested was to raise the Carrera 1 (at the beach side) and turn the runoff fully directed to the bay.

K.3.3 Politics in Colombia

In General the national government is responsible for the coastal protection of the country. It is really rare the the Bolivar Department is involved in construction projects in Cartagena. Most of the construction works are ordered by the municipality. Also some coastal protection projects are carried out under the flag of the municipality. This is for example the case for the seawall that is being constructed along the Castillogrande and Bocagrande bayside. The project was sold as an 'architectural' project so that it wouldn't fall under the jurisdiction of the national government. So in the design the focus has also been on the aesthetics instead of on the water retaining capacity.

According to Jaime, Santiago and his wife the single most important person within this process is the mayor. The mayor can single handedly order or obstruct construction works without any interference of the city council. They also told about the corruption culture that is still embedded within Colombian politics. A lot of the projects (if not, all) are already sold before the new mayor gets elected for a 4-year term. Inhabitants of Cartagena do not feel like the local government gives priority to the public interests. Instead they are thought to be more interested in image and personal winnings. For example Santiago's wife told about the construction works that are being carried out in the streets of Bocagrande at moment. She thinks that these works are mainly due to the upcoming elections and that the current mayor only wants to be remembered as the mayor who did a lot of work. In the meantime nothing is really happening. These feelings also have the result that the residents of Castillogrande and Bocagrande refuse to pay additional taxes for a special coastal protection budget. They are afraid it will only get into politician pockets.

K.3.4 Dutch water management model

We briefly discussed the Dutch water management model were the guidelines and regulations are established by the 'Rijkswaterstaat'. The practical works are carried out to the local water districts (called 'Waterschappen'). Santiago already knew a lot about this system and had some slides from powerpoint presentations given by Dutch engineering companies.

Jaime and Santiago were both fairly enthusiastic about the system. But within their current horizon they couldn't see a way to fit parts of the Dutch system within the Colombian system. Their vision is that more and more projects should be carried out by the government instead of the municipality. This has for example been the case for the 'La Bocana' tidal inlet and the 'Annilo Vial de Crespo' highway tunnel connection. However these projects were of national importance. At the moment the government in Bogota does not yet see the problems of Bocagrande as of national importance. Since the main period of the year the peninsula is functioning perfectly, the floods are only inducing discomfort.

K.3.5 Maintenance

We can keep this part short: in the end everything is about money. So generally maintenance is not carried out since it only costs money. Some parts such as the cultural heritage are maintained by an association called 'Sociadad de Mejoras Publicas'. They make money by asking for entrance fees for visiting the fort for example. This money is used for the maintenance.

K.3.6 Possible solutions

The two most important design criteria according to Santiago are that is should require as less as possible maintenance. Secondly it should be able to be constructed within a period of only 2 years. This gives enough time to complete construction with in the term of a single mayor and eliminates the risk of the next mayor shutting down the project.

Other possible solutions for drainage and seepage are mentioned in the respective sections.

K.3.7 Seepage due to sea level rise

As already mentioned above; the sea level rise is expected to cause seepage. The sandy subsoil has a very porous character which doesn't give a lot of resistance against seepage. Water going underneath the structure instead of over it will result in comparable problems. It would also cause stability problems in case of high water (storm) levels which significantly reduces the level of safety.

The most common solution according to Santiago is the construction of screen in front of the current structures deep into the ground. This is also the strategy that has been used for the 'Annilo Vial de Crespo' tunnel, see figure K.2.

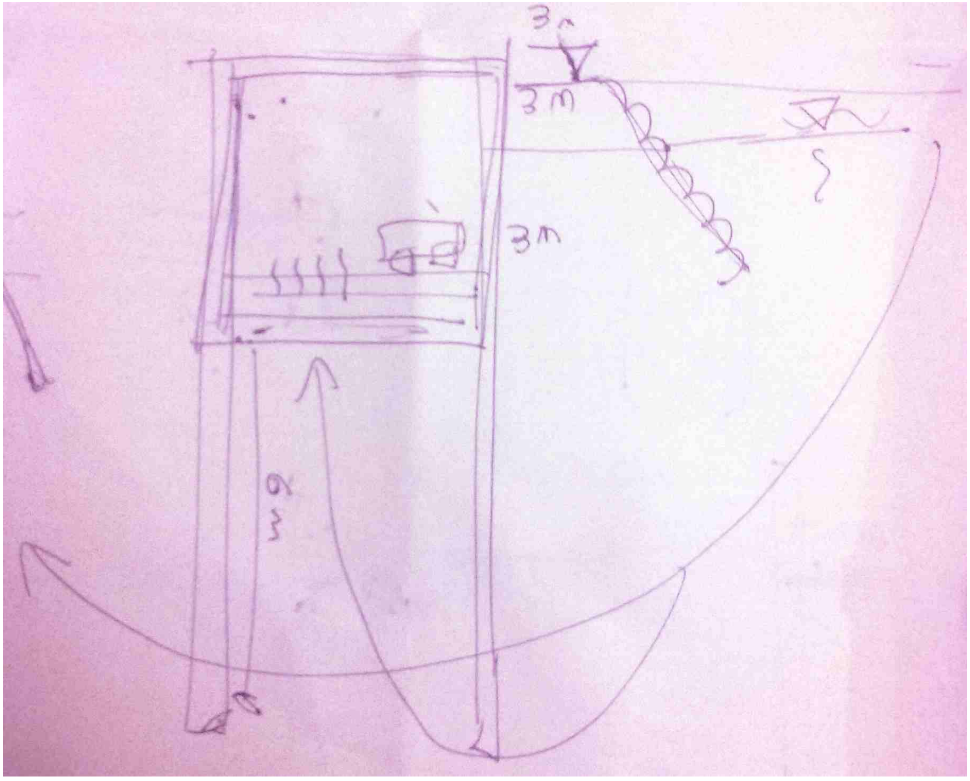


Figure K.2: Seepage screen, sketch by Santiago Rizo

K.3.8 Ciénaga de la Virgen

CiÃĺnaga de la Virgen is a widely stretched lagoon located at the north side of the city. Due to waste disposal (both water and trash) the lagoon has become contaminated. The intensive waste disposal also resulted in reclamation of land and the districts on the south bank started to grow in population. Between 1989 and 2004 the average land reclamation rate was 25 meters per year. Eventually the growth was stopped by the municipality. A road was constructed which has a double function as a physical barrier. The wastewater management of Cartagena has improved significantly, however still 10 percent of the city its total wastewater is disposed in to the Ciénaga de la Virgen.

According to Santiago the city of Cartagena is most prone to flooding due to climate change in the whole of Latin America. Especially the districts on the south bank will encounter drastic floods. The current protection level ranges from 0.40 to 1.00 meter with respect to MSL. Taking into account high tides, setup and sea level rise this results in a doomsday scenario for a population of nearly 400.000 people. Santiago wanted to tell us this to put the problems of Bocagrande and Castillogrande in the right perspective.

K.4 Javier López Grau

- Important aspects of the presentations of projects is the money involved to realise it.
- The important institutions which can execute a project are the major, the governor, of the minister of the infrastructure.

Interview with	Javier López Grau
Date	18/09/2015
Location	Universidad de Cartagena Piedra de Bolivar, Cartagena
Present	Daan Cornelissen Maartje van de Ven

- A clear image of the problem needs to be produced, the floodingâĂŹs are not really seen as a problem and the cause of the problem is not clear
- To present a project a concessive format should be used (where to find not clear)
- CAP had minor influence on the project. It includes only the dike and the municipalities around not the city Cartagena
- Media is an important factor in influencing the major and government
- To present the project a non-governmental institution should be back up, for example an local engineering company of university.

K.5 Klaas de Groot (ARCADIS)

Interview with	Klaas de Groot ARCADIS
Date	16/09/2015
Location	Interview via Skype
Present	Daan Cornelissen

Klaas de Groot is Senior Advisor on Business Development at ARCADIS. ARCADIS is a major engineering company with approximately 28.000 employees worldwide. They work with local offices that have a lot of autonomy. Within his function he explored business opportunities in countries all around the world. Relevant for the project are his experiences in Latin American countries such as Panama, Mexico and Colombia.

Through the Dutch Risk Reduction Team (initiative of MINBUZA & I&M and managed by RVO Netherlands) there is the possibility to directly react on global water related issues. As team leader he performed projects in Panama and Mexico. He also lived in Panama for four years as an employee of UNESCO. Within Colombia his experience is focused on the ”Rio Cauca” project, in some way comparable to the Dutch ”Room for the River” project. For these type of international project ARCADIS identifies three levels:

- Relational: how to deal with local culture and emotions
- Institutional: how are responsibilities divided and recorded in the law
- Knowledge: in what amount is knowledge available

The ”Rio Cauca” project is mainly on a regional level. Most important are the Department and the Corporacion Autonomas Regional (CAR). Interaction with the national government is solely governed by the regulations that are prescribed by the MADS which also finances part of the budget. The rest of the budget is coming from the exploitation of water power. It is not common that CAR's raise taxes like the Waterschappen in the Netherlands.

Colombia has around 34 CAR's. The CAR 'Valle de Cauca (CVC) is on of the most professionalized ones in Colombia. However it is still not comparable to a Dutch Waterschap. They have to manage an area that has half the area of the Netherlands with only a fraction of the resources.

Local engineers are involved in the project through the CVC. Also public institutes such as universities are closely involved. The use of consultancy firms is not common because this requires an official and extensive tender procedure. Universities can be given an assignment without such a procedure.

Finally, Colombia is a well developed country and it has all the resources available for innovative projects. However costs should always be realistic.

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