The future of Bocagrande

An exploratory study on the coastal and accessibility problems of the Bocagrande peninsula

Multidisciplinary Project - TU Delft

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Preface

As part of the curriculum of the Master in Civil Engineering at the Delft University of Technology, our team consisting of five students, have finished a multidisciplinary project in Cartagena, Colombia. Using the University of Cartagena as our home base, we focused on the Peninsula of Bocagrande. During our two months full-time project, we investigated coastal erosion, overtopping and flooding in Bocagrande as well as accessibility of the Bocagrande area. Based on our findings we gave an advice to the city of Cartagena how to cope with these problems.

First of all, we would like to thank the University of Cartagena for accommodating and supporting us with an office at their University in the city centre. For initiating this contact we would like to thank ir. H.J. Verhagen.

Regarding on how to approach the project, we would like to thank Drs.Ir. J.G. Verlaan (Construction Management and Engineering), Prof.dr.ir. M.J.F. Stive (Hydraulic Engineering), Ir. J. van Overeem (Hydraulic Engineering) and Dr.ir.R. van Nes (Transport & Planning).

For the support and the help by gathering information and data we would like to thank our two supervisors, Dalia Moreno and Adriana Puello.

Thanks goes out to all of our sponsors for supporting us in a financial way. Special thanks go out to Boskalis and CB&I for being our main sponsors.

Cartagena, Colombia, 27 June 2013

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Executive summary

Cartagena is the number one touristic attraction of Colombia due to its well preserved city center which is designated as a UNESCO world heritage site and its famous beaches around the peninsula of Bocagrande. Bocagrande is therefore of great social-economic value to the city. Almost all the beaches of Cartagena are located around the peninsula which attracts more and more tourists every year.

However, Bocagrande is coping with several issues which affect the social economic value of the peninsula. Flooding, coastal erosion, overtopping waves and lack of accessibility are the general issues mentioned by the stakeholders. They all seem to be interrelated and therefore all these issues are taken into account in this project. In order to capture the overall problem that will be investigated in this study the following research question is formulated:

> *What is the best integral solution for Bocagrande, concerning the problems of coastal erosion, flooding, overtopping waves and lack of accessibility, in order to secure the social and economic value that the peninsula has for the city of Cartagena?*

One of the major issues is the poor accessibility of Bocagrande. Since the increase of hotels and apartment buildings, nothing has been done to the infrastructure. There is one road that connects the peninsula to the city, of which the capacity is too low for the amount of traffic, resulting in congestion. This gets even worse when the streets are flooded. There are two types of floods, small scale and large scale. Small scale flooding happens every month on a part of Bocagrande, the bayside, due to high tide. This small scale flooding decreases the velocity and the capacity of the roads. There is no protection and no drainage system so the sea water can only be discharged with low tide. The sea water also causes damage to cars and property, since the basements of the hotels and apartments get flooded. Heavy precipitation also causes small scale flooding and decreases the road capacity and velocity. When high tide and heavy precipitation coincide with storm conditions, large scale flooding occur, which means that the whole of Bocagrande is flooded. The peninsula is then completely cut off from the city and nobody can leave or enter the peninsula without a boat.

On the seaside the beach is the only coastal protection there is. However due to incidental erosion the beach shows variety in beach widths. Especially during ´winter´ or storm conditions the beach becomes small enough to threaten infrastructure and buildings adjacent to the beach. The history of the coast shows that the shape of Bocagrande stays roughly the same and no real structural erosion occurs. The changes that are visible compared to the current situation have arisen from human interference. Along the coast multiple groynes have been placed to protect the beaches from incidental erosion. This is done by the hotel owners themselves to create a beach. Due to human interference El Laguito lake has formed and the beach on the south west side of El Laguito has completely eroded. The lake is now completely cut off from the sea and the water quality is deteriorating. Because of the erosion on the south west side, buildings near the beach are being damaged and restaurants and small vendors lose customers.

Another issue which affects the accessibility of Bocagrande is the overtopping of waves on the coastal road along the city centre. The seawall has been constructed to protect the road from the sea and consists of rocks and concrete debris with no beach in front of it. Waves break on the steep slope causing overtopping of the footpath and road. Even during relatively mild waves the overtopping of the seawall is significant enough to affect the road. The overtopping water causes damage to the

infrastructure and reduces the road capacity from a two lane road to a one lane road. During stormy weather the road cannot be used at all. This coastal road is one of the most important connections between Bocagrande and the North of the city where the airport is located.

Overtopping waves on the coastal roads and small scale flooding reduce the accessibility of Bocagrande significantly. All stakeholders acknowledge these issues and all have the same problem perception. It however lacks responsibility among the actors to take real action. Hotel owners solve their own issues by building some groynes in front of their hotel and installing pumps in their basements. It is therefore important to involve the actors with decision power by creating sense of urgency, or by bypassing them and making them redundant.

With the climate change, relative sea level rise and the increase of the amount of tourism for the next 50 years in mind, several solutions to solve the technical side of the problems are generated and some are chosen for the integral solution to limit the effects of the issues. The solutions do not only solve the problem but in some cases also add value.

This integral solution consists of the following parts:

- Construction of a berm and a raise of the seawall near Punta Santo Domingo to reduce overtopping. This will reduce damage to the road and increase accessibility by making both of the two lanes available.
- A wall with vegetated dunes along the seaside coast of Bocagrande will reduce future erosion and prevent flooding. The resulting availability of a beach during the tourist season will add value for the hotels, restaurants and the small vendors.
- Construction of T-groynes and nourishment near El Laguito create a beach, preventing flooding and reducing erosion. The beach restores the old situation where restaurants are located. It also protects the buildings from damage due to erosion.
- Filling the lake on El Laguito economically solves the degrading water quality problem and adds valuable land to Bocagrande.
- A wall along the bayside of Bocagrande prevents flooding which reduces the amount of damage to property behind the wall and increases the road capacity.
- The accessibility of Bocagrande increases by the previous solutions. However constructing a tunnel from Bocagrande to Manga increases the accessibility even more. The increase of accessibility of Bocagrande, decreases the total travel time.

The integral solution covers all the problem areas indicated by the system analyses and secures the social and economic value of Bocagrande by limiting the effects and adding value where possible.

Content

1. Introduction

Cartagena is a large industrial port city on the northern coast of Colombia with a population of 967.103 (DANE, 2012), making it the fifth-largest city of Colombia. It was founded in 1533 by Don Pedro de Heredia, a Spaniard conqueror. Cartagena became the most important Spanish port in America. The beautiful colonial walled city has become the city center of today´s Cartagena. The well preserved center is a great tourist attraction and since 1984 designated as a UNESCO world heritage site (UNESCO, 2013). Attached to the old city center lies the peninsula of Bocagrande. The old walled city and Bocagrande are the areas where most of the city's tourist facilities are, such as: hotels, shops, restaurants and bars (Jorge David Quintero Otero, 2008). This makes Bocagrande an important economic area for the city and for the country. The ministry of Commerce, Industry and Tourism indicated the tourism in Cartagena as one of the most important and dynamic economic activity of the city (Yanes Contreras, 2009). Figure 1.1 shows three images to indicate in geographical terms where Cartagena and Bocagrande are located. Starting at the top left the location of Cartagena along the Caribbean coast of Colombia is pointed out. The picture on the bottom left zooms in some more and shows the whole city of Cartagena and the Cartagena bay. On the right there is a picture of the old City center, Bocagrande, Castillogrande and El Laguito. To be exact Bocagrande is officially not the name for the full Peninsula. The little piece of land forming a curve at the end of Bocagrande is called El Laguito and the long stretch of land perpendicular to Bocagrande is called Castillogrande. However, in this report the name Bocagrande will refer to the complete peninsula, unless specifically mentioned otherwise.

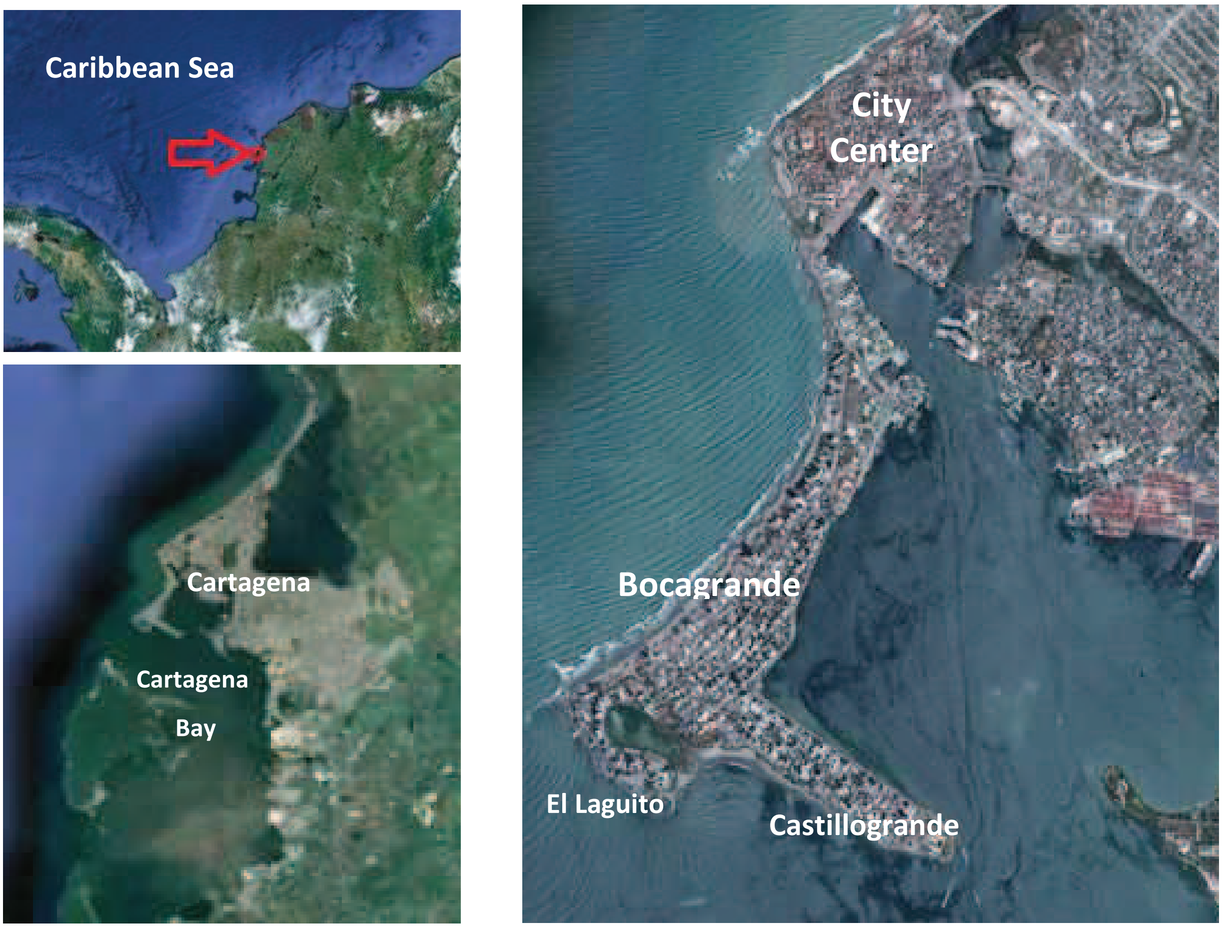


Figure 1.1 Geographic location

1.1 Problem description

Bocagrande is of great social-economic value to the city because of its tourist attractiveness. Almost all the beaches of Cartagena are located around the peninsula which attracts more and more tourists every year. Since 2007 the number of tourists has increased by 55%, with a growth of 16% last year. 40% of all the rooms available in Cartagena are located on Bocagrande and this number will increase due to the building of 7 more hotels in the upcoming 3 years, which will increase the number of rooms by 43% (Salazar Fuentes, Resultados Indicadores Turismo Enero a abril 213, 2013). But there are problems that Bocagrande is coping with; flooding, overtopping of waves, coastal erosion and poor accessibility. These problems have their impacts on the area, and it seems that without proper intervention the problems will get larger in the future considering the climate change and the increase of the amount of tourists.

Flooding

Bocagrande deals with a substantial amount of flooding every year (appendix B.2). This causes several problems such as inaccessible roads and water damage to structures and properties. Figure 1.2 shows a flooded road on Castillogrande. Under certain circumstances the area of Bocagrande is flooded. Local people indicate that heavy rains, storms and high tide are the most important factors regarding the floods. Each of them can be enough to cause flooding. When they occur simultaneously the problems increase significantly. Great amounts of water should not necessarily mean that severe floods occur. But it seems that there are no sufficient measurements in place to cope with a lot of water on the peninsula. As captain R. Molares (sarcastically) answered to the question whether there are any draining measures: “Of course… It is called the sun!” There is no better way to describe the lack of a sound system of measures.

Figure 1.2 Flooding of a road on Castillogrande

Overtopping waves

The shore along the old center of Cartagena consists of a steep seawall made of loose rocks and concrete debris with no beaches in front of it. A low concrete wall separates the seawall from the adjacent footpath and a two-by-two lane road. During normal weather conditions waves are breaking on the sea wall and causing overtopping of the footpath and road. The overtopping causes damage to the footpath and road. During storm conditions the road is not accessible due to heavy overtopping.

Erosion

Another problem is the coastal erosion along the coastline of Cartagena. The beaches are a great touristic attraction and a lot of economic activities are concentrated around the beaches and rely for a great deal on its presence. Hotels for example benefit from a

Figure 1.3 Groynes along the coast of Bocagrande

large beach in front of their hotel. Erosion is therefore a threat for the business on Bocagrande and for the attractiveness of the city as a tourist destination. A lot of measures have already been taken to prevent erosion. Structures such as groynes and breakwater are in place along the coast of Bocagrande and the centre of Cartagena. Figure 1.3 shows a picture of current measures along the coast of Bocagrande. A detailed analysis of the measures and their effects over the years is needed to see what the effect of erosion is on the beaches of Bocagrande and to discuss the possible solutions.

Accessibility

Bocagrande also has problems with its accessibility. The First Avenue (the road along the coastline), the road along the Cartagena Bay and the road which connects Bocagrande with the old city, all two-lane roads, cope with a lot of traffic. The accessibility problems are greater during the peaks of the touristic seasons (July, August, December and January) because of the increase in the amount of people wanting to travel to and from Bocagrande (appendix B.2).

Figure 1.4 Congestion between Bocagrande and centre

When parts of Bocagrande are flooded the accessibility worsens significantly. Coincidently the period of the year that flooding is most likely is during the touristic season (appendix B.2). Almost every year this results in a short but very intense extra problematic period for the Bocagrande peninsula. The rest of the year the traffic is also bad, but not as drastically. Figure 1.4 shows a common situation on the road between Bocagrande and the center.

1.2 Scope

This project will focus on the effect of three main problems; coastal erosion, flooding and accessibility. These three problem areas are causing several issues and problems for different stakeholders. An accurate and precise scope is necessary to be able to establish a clear and complete report.

The aim of this project is to design an appropriate and feasible long-term (50 years) solution for the region of Bocagrande. The deliverable is a complete and comprehensive advisory report in which the current situation is described and where appropriate solutions are formulated. Based on several analyses the best integral solution will be proposed.

1.3 Research approach

The goal of this study is to explore the indicated problems, concerning erosion, flooding, overtopping and accessibility around the peninsula of Bocagrande, in order to come up with solutions to the identified problems. In order to capture the overall problem that will be investigated in this study the following research question is formulated:

> *What is the best integral solution for Bocagrande, concerning the problems of coastal erosion, flood, overtopping waves and accessibility, in order to secure the social and economic value that the peninsula has for the city of Cartagena?*

To answer this question some sub questions are defined.

- *Which issues affect the social and economic value of Bocagrande?*
- *What are the main causes of the coastal erosion, flooding, overtopping waves and poor accessibility of Bocagrande?*
- *What are the effects of the coastal erosion, flooding, overtopping waves and poor accessibility?*
- *What has to be done to limit the effects, considering the next 50 years?*
- *What is the impact of different solutions on the social and economic value of Bocagrande?*

The sub questions will be answered based on several analyses. The social and economic values of Bocagrande arise from the stakeholder analysis and the system analysis. Which will also determine the more detailed problem areas. The system analysis will also describe the causes of the issues and the effect they have on the social and economic value of Bocagrande. Several solutions will be generated and discussed. Via a multi-criteria analysis, based upon the social and economic criteria, the preferred solutions will be elaborated in a conceptual design. Figure 1.5 visualizes how the different analyses and methods come together in an overall framework for the project.

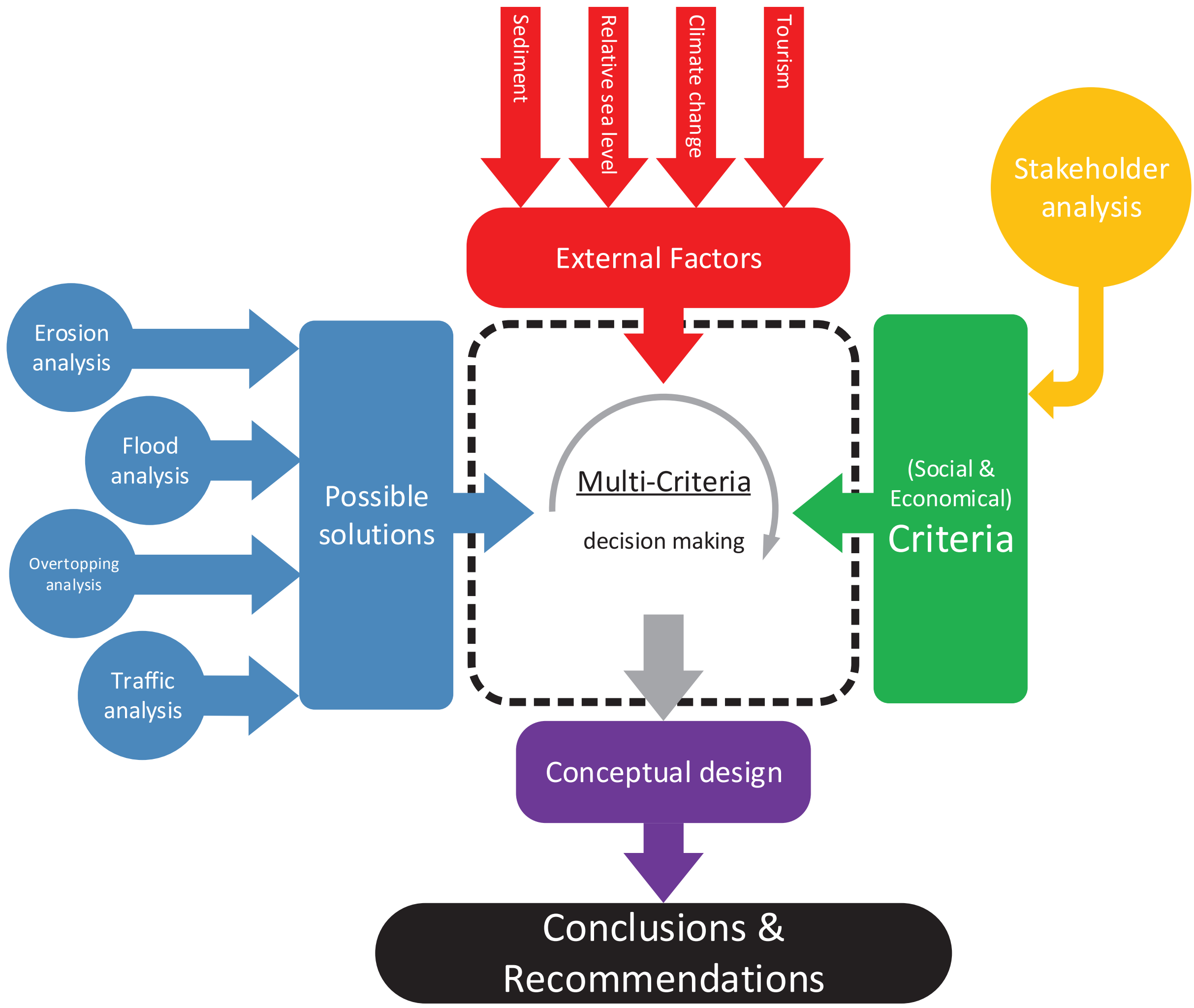


Figure 1.5 Project framework

2. Stakeholder analysis

In order to get a better understanding of the dynamics of the problem(s) and the system, a stakeholder analysis is conducted. It will give insight in different perspectives towards the problems regarding Bocagrande. In order to get a good overview of all the stakeholders and their perception of the problems multiple analyses have been conducted. A stakeholder is any person, organization or group who can place a claim, has power to respond or is affected by the organization's objectives (Bryson, 2004). By analyzing the stakeholders, you gain insight in the different views and stakes that play a role in the process. The network analyses shows the informal and formal relations between the stakeholders, this shows how some stakeholders can influence other stakeholders through different ways. For a clear overview of all the stakeholders and there formal and informal relations a hierarchical chart is available in appendix A. The stakeholder analyses are based on interviews with several different stakeholders. There will be a distinction between actors that are directly affected by the problems and actors that are indirectly or less effected (Table 2.1). This difference is made because the roles they (can) play are very different.

Directly affected stakeholders	Indirectly affected stakeholders
• **Municipality** ▪ Secretary of infrastructure ▪ Public services office ▪ Secretary of planning ▪ DATT • **Hotel owners** • **Public transport providers** • **Residents of Bocagrande** • **Part-time residents of Bocagrande** • **Tourists & visitors** • **Naval base Cartagena** • **SMEs** (Small and Medium Enterprises) • **SPRC** (Regional Port Society) • **Employees Bocagrande**	• **National government** ▪ National Planning Department ▪ Ministry of Transport ▪ Ministry of Environment and sustainable development ▪ Ministry of internal affairs ▪ Ministry of Defence ▪ Ministry of Commerce, Industry and Tourism • **Department of Bolivar** • **DIMAR** (Maritime and Ports Authority) • **ARMADA** (Colombian Navy) • **PROEXPORT** • **ANLA** (National Environmental Licensing Authority) • **UNGRD** (National Risk Management Department) • **CIOH** (Center of Oceanographic & Hydrographic research) • **INVEMAR** (Institute for Marine and Coastal investigations) • **IDEAM** (Institute for Hydrology, Meteorology and Environmental studies) • **University of Cartagena** • **Society of engineers and architects** • **Cartagena tourism corporation** • **COTELCO** (Hotel and Tourism Association of Colombia) • **ASOTELCA** (Hotel and Tourism Association of Colombia)

Table 2.1 Direct and indirect Stakeholders

The directly involved actors actually experience the problems and therefore their perceptions of the problems have a big influence on the requirements for the establishment of solutions. The other stakeholders are more external to the actual problems but do have a connection to the area or the problems and might have important resources and power that can make or break solutions. The analyses are performed separately for the direct and indirect stakeholders.

2.1 Direct stakeholders

In table A.1 of appendix A the interests, goals, and problem perceptions of all the directly affected stakeholders are described and analyzed regarding the problems of Bocagrande. It shows that almost all stakeholders have the same problem perception. The problems are widely acknowledged and there seems to be an understanding about the need to do something about them.

From meetings with stakeholders it became clear that the inaccessibility of Bocagrande seems to be the most important problem for most stakeholders. Especially the hotel owners, SMEs and the residents indicate that the accessibility of Bocagrande is a major problem for them. They indicate that the accessibility deteriorated since the increase of the apartment buildings and hotels in the last 10 years. According to them the road capacity is insufficient for the amount of travelers, especially the road capacity of the connection between Bocagrande and the old city. The regional port society (SPRC) is also affected by the bad accessibility of Bocagrande. A part of the harbor is located on Manga, which is a neighborhood where a lot of traffic passes through on their way to Bocagrande. This causes a lot of traffic jams on Manga which affects the accessibility of the harbor. By improving the accessibility of Bocagrande the SPRC wants to improve the accessibility of the harbor.

Another issue that is indicated by the direct actors is the floods. A flooding occurs due to heavy rainfall, high tide and severe storms. The seriousness of the flooding determines who is affected by it and in what way. With only high tide, some residents are affected because they have to pass salt water on the streets before entering their apartment. With only heavy rainfall, the streets are covered with a layer of water. The water affects the speed limit which has a negative impact on the road capacity and the accessibility of Bocagrande. If these two causes coincide with a severe storm, whole Bocagrande is inundated and everyone in the area is affected by it. Floods cause damage to infrastructure and buildings. Additionally, salt water causes corrosion to vehicles. The public transport providers, like taxies and busses, will therefore avoid places that are flooded. Most of the hotels have installed pumps in their basement to avoid damage due to salt water. In addition to that, the Hilton even constructed groynes along the beaches of their hotel to improve coastal protection and reduce the impact of severe storms.

2.1.1 Criticality and Dedication

The table below shows the dedication and the perception of the direct actors. As shown in the table all the actor have the same perception, interest and goals. The actors may differ in who they think is responsible for the problems, but they all seem to see the urgency of the problems. In addition to the criticality in table A.2 of appendix A this table shows the dedication of the actors. The dedicated actors are the actors who are actively concerned and involved in the problems and try to do something to improve the current situation. The non-dedicated actors are those actors who are not continuously busy with the problems, like the tourists and the part-time residents. Most striking is that the Municipality is placed as a non-dedicated actor. The reason for this is that it seems that local government has not shown any commitment to help solve the issues that are being researched in this study. The lack of political stability contributes negatively to this. But also the unwillingness to take decisions that might be unpopular, such as removing the street vendors in the Bazurto area for the Trans Caribe project, see appendix B.4. The critical and dedicated actors are the residents, the hotel owners and the regional port society. They are dedicated because of the direct effect the issues have on their business and home situation.

	Dedicated actors		**Non-dedicated actors**	
	Critical actors	*Non-critical actors*	*Critical actors*	*Non-critical actors*
Actors with same perception, interests and goals	- Residents of Bocagrande - Regional Port society - Hotel Owners	- SMEs	- Tourists & visitors - Municipality of Cartagena - Naval base	- Part-time residents - Employees Bocagrande - Public transport providers
Actors with different perception, interest and goals				

Table 2.2 Directly affected stakeholders dedications and direction of perception, interest and goals

2.1.2 Power and interest

The power interest grid (Figure 2.1) shows the interest in combination with the power an actor has. The grid shows that the regional port society and the municipality have the most power. The municipality has to approve every plan concerning public space and therefore has the power to approve a plan and execute a project. The municipality also has the link to the department of Bolivar and other non-local institutions for funding a project. The regional port society has power because of the connection to the national government. The captain of the port is a high ranked officer and a well-known man in Cartagena. The other actors have less power. The hotel owners have the money to fix damage to their property and some have even enough money to build groynes to protect and increase their beaches. Some of the hotel owners have connections with the national government and have the opportunity to address their problems to them. The residents have no real power, only the power to block a certain plan and voting power. The residents have the same power as the part-time residents, however they are more interested because they have to deal with the problems every day.

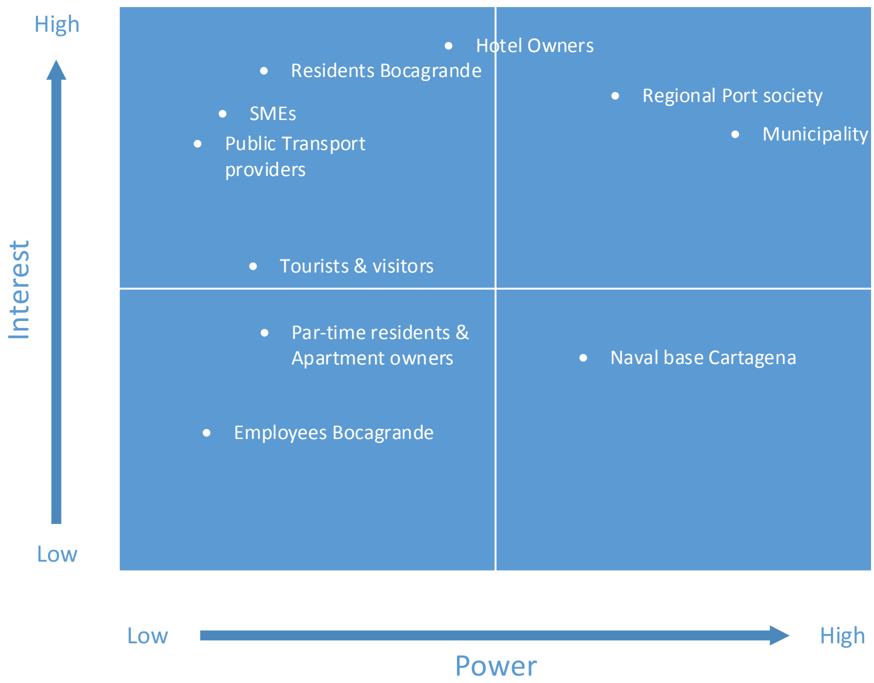


Figure 2.1 Power-interest grid directly affected stakeholders

2.1.3 Support

Figure 2.2 shows the direct actors in a grid where power and opposition/support are indicated. As the figure shows, all the actors are on the supporting side. This is expected because previous analyses have shown that all the actors seems to recognise the problems and want to solve them. Because the actors are directly involved, the expected support will be high, especially for those who live on Bocagrande and who have direct damage caused by the problems, like the hotel owners and SMEs.

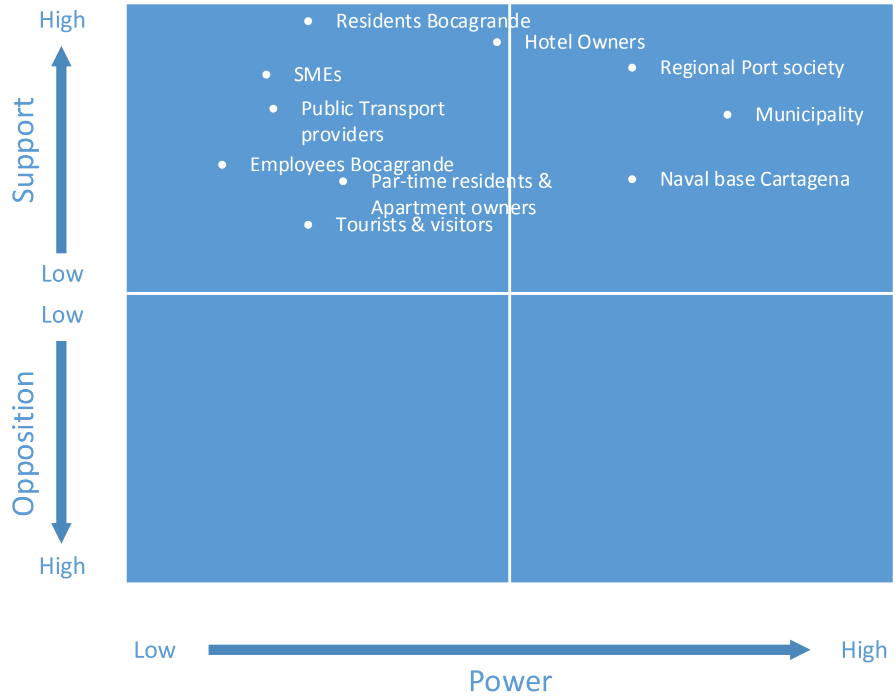


Figure 2.2 Problem-frame stakeholder map directly affected stakeholders

2.2 Indirect stakeholders

In table A.3 of appendix A the interests, goals, and problem perceptions of all the directly affected stakeholders are described and analyzed regarding the problems of Bocagrande. In this particular analysis the indirectly affected stakeholders are categorized into three group; Governance, Supporting institutes, and Representative bodies. This is done because of the great resemblance in interests, goals and perceptions among some stakeholders. The governance category has a lot of stakeholders, most of them are national government ministries and institutes. Their main interest is the national wellbeing of Colombia, and as a part of that they are also concerned about the wellbeing of Cartagena and Bocagrande. The supporting institutions are all institutes that have the main task of supporting actors in the governance category. They want their knowledge and expertise to be of service to the development of Colombia, and to be recognized as a quality institute. Representative bodies are institutes that represent public or private entities, or a combination of both. They try to improve the position of their members or an industry.

2.2.1 Criticality and Dedication

The most striking thing about Table 2.3 is that again there are no actors with different perception, interest and goals. This is because the problems are very obviously present and everyone wants them to be dealt with. In addition to the criticality of actors this table shows the dedication of the actors. The dedicated actors are the actors that are 'closest' to the problem. And the non-dedicated actors have less local connection to Bocagrande and Cartagena. Several actors indicated that national governments and supporting institutes are not so much concerned about local situations. One might say: the weaker the connection to Cartagena the less the dedication.

	Dedicated actors		Non-dedicated actors	
	Critical actors	*Non-critical actors*	*Critical actors*	*Non-critical actors*
Actors with same perception, interests and goals	- Department of Bolivar	- Cartagena Tourism Corporation - Universities of Cartagena - CIOH - COTELCO - ASOTELCO	- National government - DIMAR - ANLA	- ARMADA - PROEXPORT - UNGRD - INVEMAR - IDEAM - Society of Engineers and Architects
Actors with different perception, interest and goals				

Table 2.3 Indirectly affected stakeholders dedications and direction of perception, interest and goals

2.2.2 Power and interest

The power-interest grid shows where the actors are placed according to their power and interest regarding the problems at hand. The most important indirect actors are the National government, Department of Bolivar, DIMAR and ANLA. These actors are in the high power and high interest quadrant of the grid, and were also identified as critical actors. The main problem with these stakeholders seems to be that their interest is not very high. But since they have most of the decision power it can be very important to involve them and try to increase their interest. On the other hand there are the more locally involved actors: Cartagena tourist corporation, COTELCO, ASOTELCO and the universities. These actors have more interest but little power. The rest of the actors play a role that is more on the sidelines. They are more passive but can become more involved when addressed or informed about their expertise or interests.

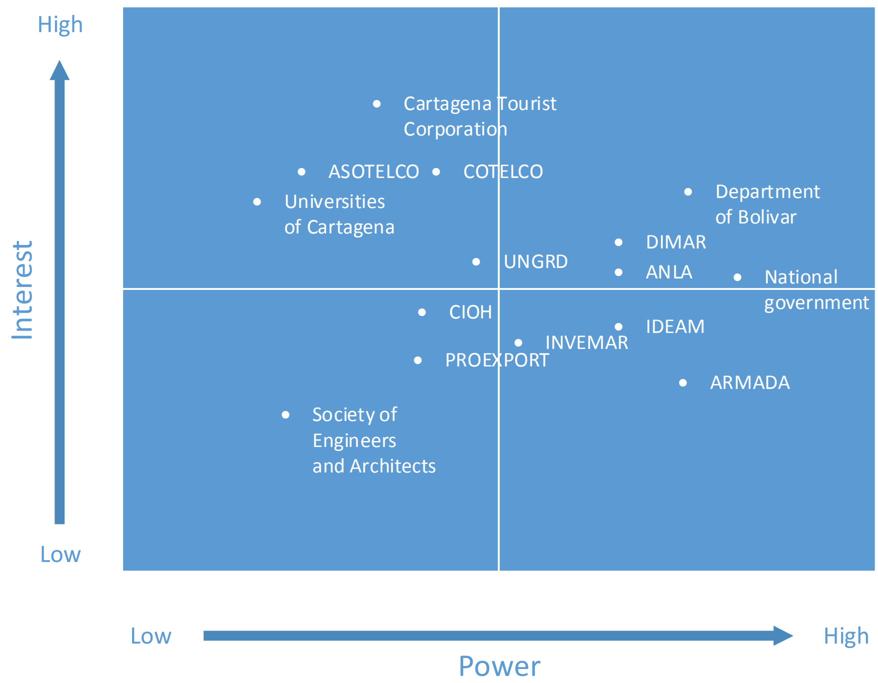


Figure 2.3 Power-interest grid indirectly affected stakeholders

2.2.3 Support

The problem-frame stakeholder map shows the actors in a grid where power and opposition/support are indicated. All the indirect stakeholders are placed on the support side of the grid. This is due to the fact that actually everyone recognizes the need to solve the problems stated in this report. But nevertheless the expected support is not very high among most of the indirect actors. As mentioned before the amount of support weakens when an actor has less direct connection to Cartagena, and most of these actors are national governments and supporting institutes. The odd one out might be the department of Bolivar. In a meeting with Ligia Salazar she gave an example that showed support and interest of the department of Bolivar (appendix B.3).

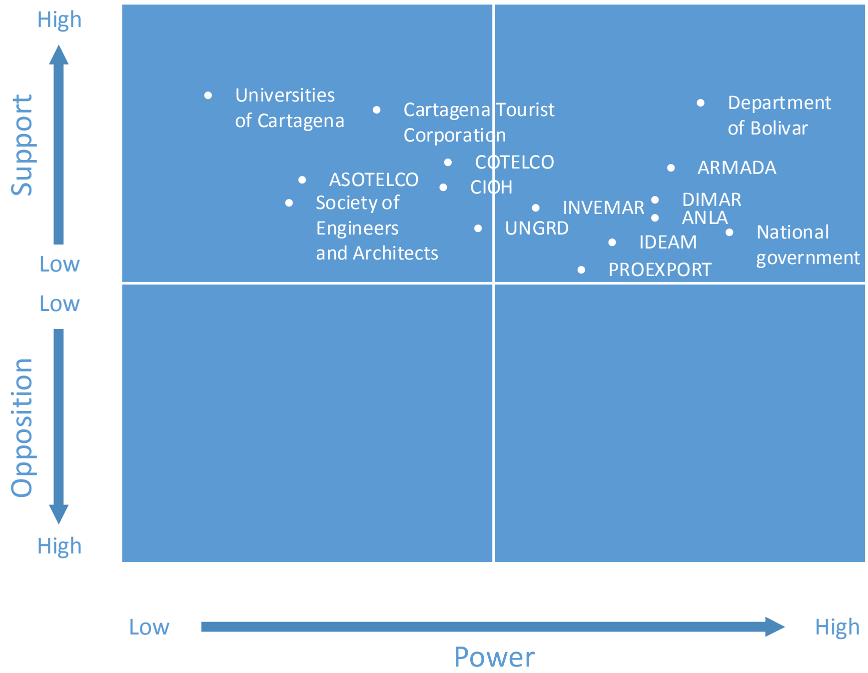


Figure 2.4 Problem-frame stakeholder map indirectly affected stakeholders

2.3 Politics & mind-set

Apart from the (technical) problems as formulated and acknowledged by the stakeholders there are also some problems concerning the (local) political situation and mind-set that came to light when talking to stakeholders.

2.3.1 Political

It can be said that the local political situation in Cartagena is not very stable. At this moment there is an interim-mayor until a new mayor is chosen in July 2013. The previous mayor handed in his resignation in November 2012, within a year after he started, due to his battle with lung cancer. But for several reasons none of the chosen mayors since 1988 have completed the full 4 year term of office (Vamos, 2012). This does not have a positive effect on the political stability of the city and the faith in good leadership has seemingly only become worse in Cartagena. And even if a mayor would complete the four years it is not possible to be re-elected. No re-elections is not necessarily harmful for long-term stability, but it seems that most mayors of Cartagena were not keen on going on with policies and projects that were initiated in a previous tenure. Mayors want to start fresh and implement their own ideas. This does not help to create a stable local political climate as a backbone for a more structured system. A striking example of ineffective local governance was given by Amalia Toro about the political troubles concerning the TransCaribe project in Cartagena (see appendix B.4)

2.3.2 Mind-set

There are a few mind-set issues that do not help the situation in Cartagena and Colombia. The first thing that came to light was the short-term thinking. This matter is very much entwined with politics but it is also very recognizable in everyday life. Several stakeholders gave examples, but the most striking example was illustrated by a visit to La Bocana, a tidal inlet constructed by Boskalis in 2000.

Now, almost 13 years later, the state of the construction is shocking. Figure 2.5 shows pictures taken during the visit.

Figure 2.5 La Bocana

The story is that Boskalis took care of the maintenance and monitoring the first 5 years after construction, and after that it was handed over to the national government. From this point on the deterioration began because the national government did not continue with the maintenance and monitoring in a sufficient manner. Especially the large wall that runs into the estuary to guide the tidal flushing mechanism is in bad shape.

Ironically, there are still soldiers guarding the construction. This was necessary when the structure was still maintained and monitored with expensive equipment. Now the soldiers, who are supplied by the local government, are only guarding a deteriorating piece of concrete that is managed by a governmental institute in Bogota. The distance does enlarges the lack of interest and commitment to manage things in a sufficient way. But the real problem is that the lack of long-term thinking seems to be very much ingrained in the Colombian society. This deterioration really is a shame because the tidal inlet had a great positive impact on the water quality of the estuary, and therefore on the quality of life of a lot of people living around it. Within 3 weeks the lagoon had obtained the desired water quality (Cohen, 2002). This 'distant' management of local issues and projects is very common in Colombia.

Another typical example was given by Amalia Toro (appendix B) concerning the current bus service providers in Cartagena. It seems very hard to get them involved in the transformation that the TransCaribe project will cause to the city. After 8 years she indicates that there has been close to no improvement in their understanding that things are going to change for them. And that they could be a part of the new, more organized and efficient system. It seems that they do not (want to) see the value of efficiency and organization.

2.3.3 Promising development

To counter the problems stated above there are also developments that look promising and provide positive perspective for the future. Various institutions around the mayor have created an inter-institutional Commission on Climate Change. This is a development that makes possible solutions that deal with future climate change less reliable on the power and policies of a mayor. This was actually one of the reasons for the creation of the commission (Network, 2013). The commission consists of both public and private entities.

Another development is that the national government has decentralized the incomes from oil. This entails that oil royalties are distributed over the departments, so the department of Bolivar also has its share of these funds. This decentralization brings the money closer to the problems so to speak. Ligia Salazar gave an example (Appendix B.3) about a recent plan for a drainage system on Bocagrande which the department knows about and supports. But the local government of Cartagena must submit it to the department in order for them to fund it. And even though they asked the local government to hand it in, for some reason, they have not done it yet. The fact that the department even asks for a plan to be submitted for funding shows that they are interested in the local situation and are dedicated to help solve problems. Apart from the opportunity that this example shows at the department of Bolivar it also reinforces the argument of a lack of stable local governance stated earlier.

2.4 Conclusion

The stakeholder analyses have shown that there are several issues regarding flooding, erosion and accessibility on Bocagrande. The main issue, according to the direct stakeholders, is the accessibility. Due to the increase of new apartments and hotels and the lagging of road capacity, the accessibility of Bocagrande deteriorated. The accessibility becomes even worse if the streets are flooded. Floods occur in some areas every month due to high tide and in other areas the streets are flooded due to a heavy precipitation. The whole of Bocagrande is flooded around once a year due to a combinations of stormy weather, high tide and a small beach to protect the peninsula, which causes damage to property and infrastructure. All direct involved actors seems to acknowledge these issues, however little is done about it. Individual actors, like residents and hotel owners try to solve their own issues by installing pumps in their basements or building groynes to increase the beach in front of their hotels. This has resulted in a beach with a lot of groynes. A structural long-term plan seems to be missing.

The support and interest of all actors is high, however nobody wants to take any responsibility. Supporting institutions have the knowledge and are aware of the urge of the issues, but do not want to take any responsibility by introducing a project. The municipality, especially the mayor, has the power to initiate and execute projects concerning public interest. The mayor also has the connection with several governmental institutions to finance such a project. He seems however not dedicated to the issues raised by the actors. Because of the power the mayor has, it is important to make him dedicated to the issues or to find another way to initiate and execute projects to improve the current situation at Bocagrande. Making the mayor dedicated to the issues is a difficult task, because the mayor seems to change every 2-3 years, and any project will take more than that. By lobbying through the representative bodies like Cotelco, Asotelco and through connections with national government, it may be possible to put pressure on the local government to actually do something. Another option is to get around the mayor and to execute a project through an organisation like the inter-institutional Commission on Climate Change.

The issues regarding Bocagrande are urgent and both direct as indirect actors seem to acknowledge the issues. It lacks however decisiveness to really do something about it. Everybody is pointing to the local government and nobody actually takes the initiative and act. Organisations like the Commission on Climate Change are for those reasons important organizations to take into account while initiating projects.

3. System analysis

In this phase of the research, the problem(s) will be made clear in a qualitative way. A system analysis is carried out per problem area to understand the broader picture and find the real issues per problem area. The four considered problem areas are: erosion, flooding, accessibility, and overtopping waves.

3.1 Erosion

One of the problems defined by some of the actors, like the hotel owners and the University of Cartagena, is the erosion along the coast of the old city (Centro) and Bocagrande. First a geographical analysis is carried out in which for both a global and a local point of view the coastal development over time is investigated. Secondly, structural and incidental erosion are separately analyzed to understand the dominating mechanisms for coastal changes. Finally a conclusion is drawn which states the detailed problems that are identified in this analysis. The result of the analysis will be used as a starting point for the formulation of possible solutions.

3.1.1 Geographical analysis

The geographical analysis is divided in two sections: one with a global perspective and the other with a local perspective. The global part covers the sources and sinks of the coastal system while in the local part the changes to very specific parts of the coast are treated.

Global perspective

The global coast that is considered consists of a large part of the Caribbean coast of Colombia. The considered global coast stretches from the mouth of the Magdalena River to the island of Barú in the south, see Figure 3.1. The overall sediment transport direction along the coast is indicated with white arrows in the figure, as well as the most important sources of sediment of the system. The Magdalena River in the North and the Dique Channel in the south are considered to be the most important sources for the coastal system. See appendix C for the full analysis. The main sediment source for the Caribbean coast is the Magdalena River. The Magdalena River has a considerably fluctuating sediment transport rate; on average it supplies around $130*10^6$ t/year of sediment to the coastal system.

Figure 3.1 Global coast system

However, in 1936 two breakwaters were constructed at the mouth of the river to reduce sedimentation problems and increase navigation near the port of Barranquilla, which is located close to the mouth of the Magdalena River. Since the construction of the breakwaters, sediment is discharged over the continental shelf on a steep slope (40°) (Restrepo & López, 2007). Less sediment reaches the coast, as a significant amount is discharged offshore. This has caused severe erosion just downstream of the river mouth. Considering the large amount of sediment that is supplied by the Magdalena River it is concluded that a large part of the Caribbean coast is affected by the reduction of sediment, possibly even until Cartagena. One of the impacts of the reduction of sediment by the Magdalena River is the disappearance of some islands along the coast. One of these islands is Isla Verde. In the 1940's this island experienced so much erosion that it has disappeared (Universidad del Norte, 2004)and worked as a new input of sediment for the system since then, see Figure 3.2.

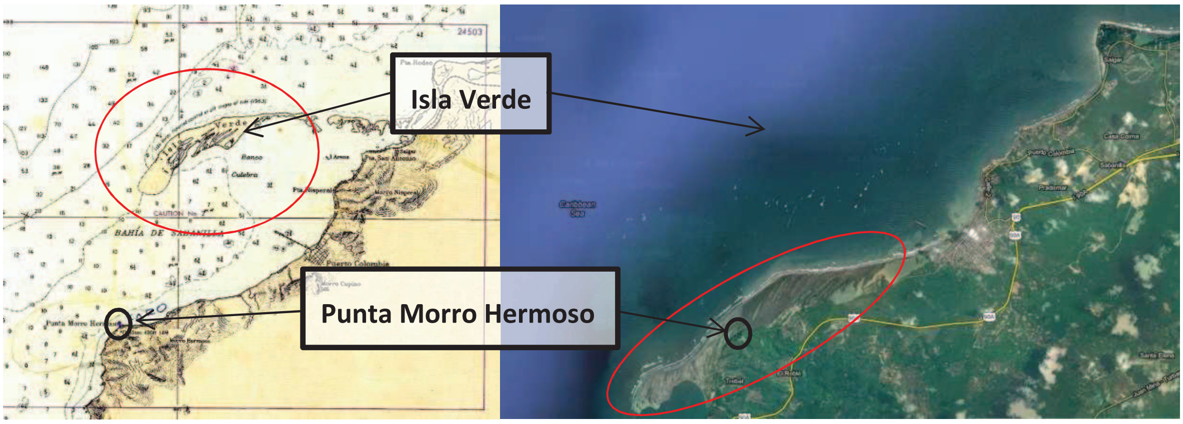


Figure 3.2 Isla Verde before and after disappearance

Even though a reduction of sediment supply from the Magdalena River has been caused by the construction of the groyne, it seems that erosion of the coast and islands have compensated for the reduced sediment that reaches Cartagena.

The Dique Channel is a man-made branch of the Magdalena River, constructed in 1630, and discharges approximately 10% of the Magdalena River's flow and sediment in the Cartagena Bay (Restrepo & López, 2007). Considering the high sediment content of the Dique Channel the sediment discharged in the Cartagena Bay could have impacts on the coast of Cartagena. However, it is assumed that the sediment discharged by the Dique Channel does not affect the beaches of Bocagrande and Castillogrande, because there is not enough current and wave action in the bay to transport significant amounts of sediments to the outer coast.

Local perspective history

In order to get an idea of what is happening to the coast on a local scale its history is investigated. The history of the coast is researched by examining aerial photos and old maps of the coast of Cartagena. The results of the analysis of the history of the coast are presented in Figure 3.3.The full research of the history of the coast see appendix C.

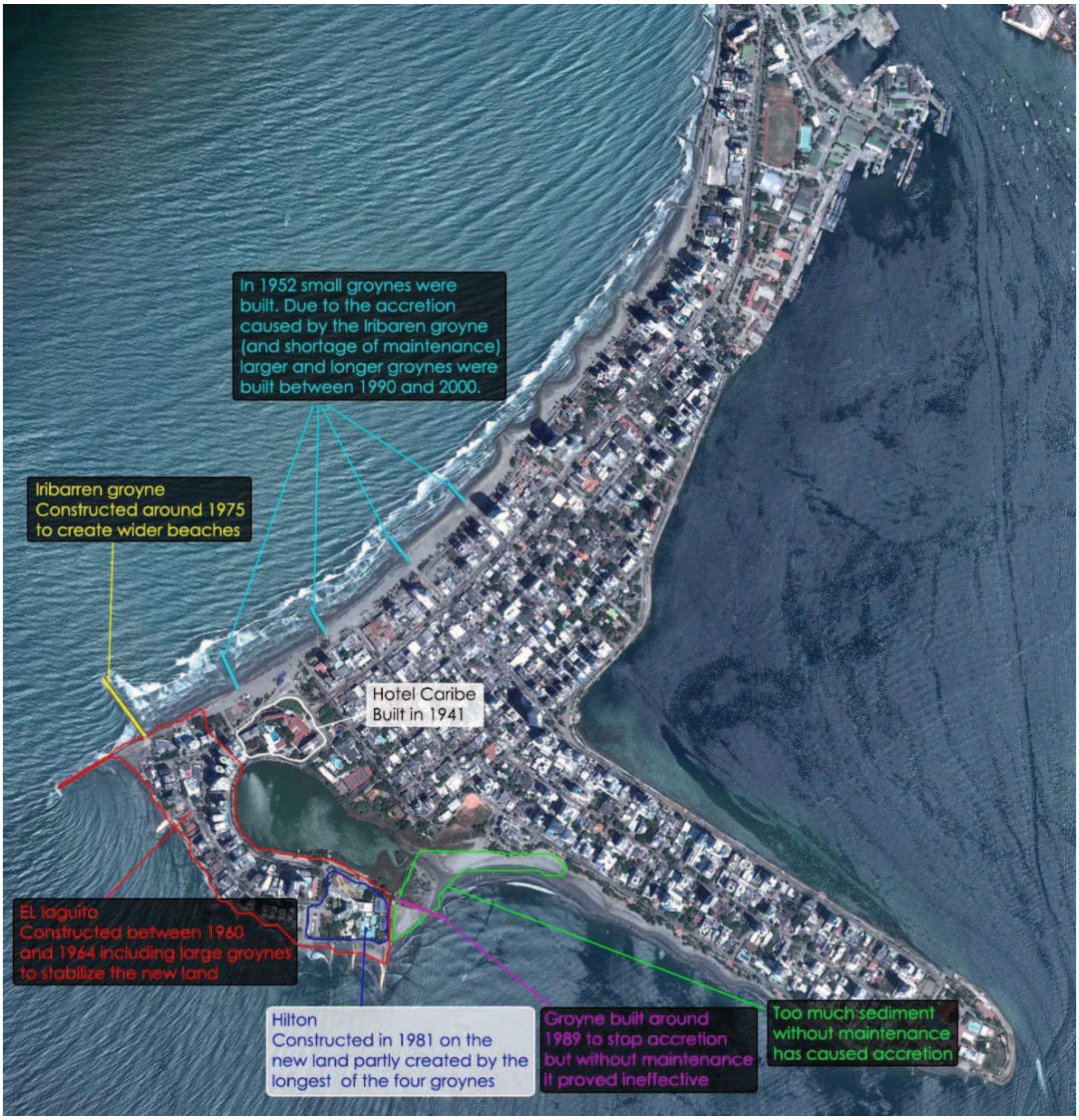


Figure 3.3 Most important changes over the years

The results of the research can be summarized as follows:

- Even when going back multiple centuries, the shape of the coast of Cartagena (and Bocagrande) is roughly the same as it is today. The changes that are visible compared to the current situation have arisen from human interference. The coast might therefore be assumed to be in a rough equilibrium.
- Hotel Caribe was the first hotel at the end of Bocagrande and thus an important landmark, it was built in 1941.
- In 1932 small groynes were placed along the coast of Bocagrande, probably to stabilize the coast.
- The sandspit at the end of Bocagrande (now called El Laguito) was relatively unstable. Its shape has been built and stabilized by human interference. The time it was built is between

1960 and 1964. El Laguito was first stabilized with four groynes. Later a few smaller ones were added at the end in order to create beaches.

- Around 1973 the Iribarren groyne at the end of Bocagrande was constructed in order to create a wider beach. Later, between 1990 and 2000, the other groynes that used to be on Bocagrande were rebuilt and made longer.
- In 1981 the Hilton constructed its hotel at the end of El Laguito.
- Around the year 1986, due to the sediment availability, the beaches of Castillogrande started to form and the lake started to close as well.
- To counteract the accretion of sediment next to the Hilton another groyne was constructed, it however did not stop the accretion sufficiently and nowadays the lake is closed off from the open sea. Due to its closure it seems the water quality of the lake is deteriorating.
- Just around the tip of Bocagrande where the Iribarren groyne and the Escollera groyne are located there used to be beaches, now only some restaurants are still there. The shoreline is reinforced with rocks to prevent damage to buildings caused by more erosion.
- Before Bocagrande was urbanized, dunes were located on the shoreline. These dunes were mostly generated by wind induced sand transport. However, when Bocagrande was becoming a more popular location dunes were removed and buildings were constructed close to the shoreline (appendix B.6)

Local perspective - Current situation

The changes to the coast in the past have resulted in the shape of the coast as it is today. The resulting coast, with emphasis on certain areas, is presented in a series of images. The image sequence starts geographically at the most southern tip of Castillogrande moving along the western side of Castillogrande following the coastline until the seaside of Bocagrande near hotel El Caribe.

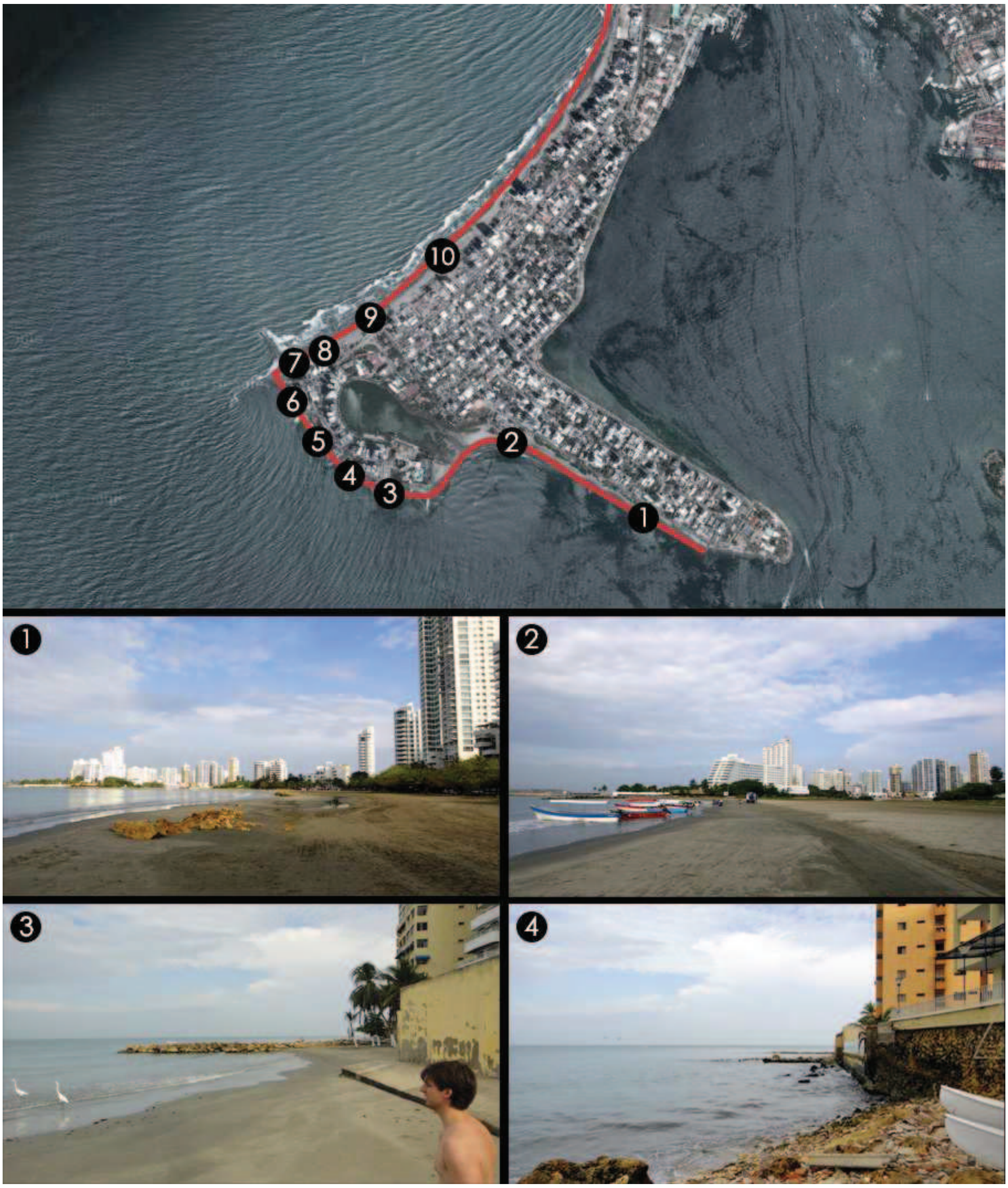


Figure 3.4 Current local situation erosion I

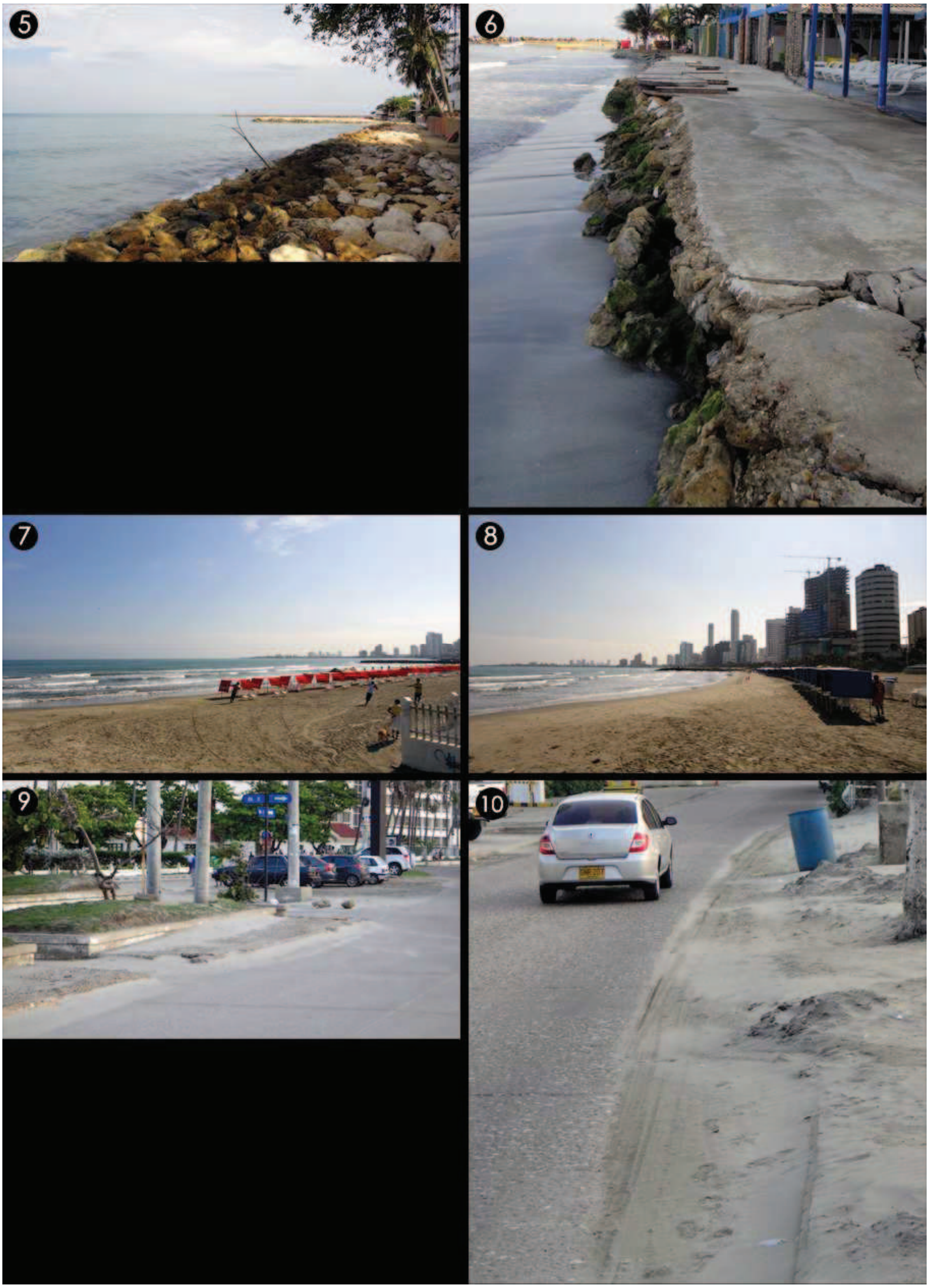


Figure 3.5 Current local situation erosion II

Starting with photo 1 and photo 2 the accretion on this part is clearly visible. Photo 1 shows a T-groyne that, due to accretion, has been partly covered with sand. Along this stretch of coast more T-groynes can be found, most of them old, eroded and embedded in the beach (covered partly with sand). Photo 2 shows the beach that has closed the entrance of El Laguito.

Moving along the coast from photo 3 to photo 4 and 5 the beach width decreases rapidly. Where photo 3 still shows some sediment forming a small beach, it is all gone in photo 4 and 5. This part is very badly protected from waves and the buildings flood regularly. Near photo 5 part of the coast is protected by a seawall constructed from rocks. Although a little better than the situation in photo 4 this protection is not able to protect the buildings behind it in case of storm waves.

Photo 6, taken close to the Escollera shows the severe erosion that has taken place. There used to be a wider beach here and some restaurants close to the shoreline. These restaurants have not survived the erosion and are not present anymore. The restaurants that used to be behind these are currently the ones that are along the shoreline. Due to the lack of a beach, also these restaurants try to protect their business using sandbags on which concrete is poured. These concrete “structures” are clearly shown in photo 6. Needless to say they do not suffice in storm conditions.

Photo 7 shows the corner of El Laguito. In the bottom right hand corner the hotel’s wall is visible. The beach is, as it is visible in the photo, wide enough in the current season. During storm season this is however not sufficient and all the sediment erodes until the entire beach is gone. In this season the “beach” width is hardly a meter from the wall.

An overview of the beach of Bocagrande is visible in photo 8.

The last two pictures, 9 and 10, show the sand gets blown off/over the beach onto the roads. The effect of the lack of a dune is clearly visible. In order to keep the road clear the sand is removed, stopping the formation of dunes.

3.1.2 Erosion time scales

When taking a look at the width of a beach in a short interval one might think that there is either a lot of erosion or accretion, either induced by man or by nature. However when one takes a much longer period into account, it is easy to see that the coast of Bocagrande is actually fairly stable. There is a little more coast on Bocagrande which is the result of human interference. However, since there are problems with incidental erosion, the erosion is separated in two distinctively different timescales: Structural erosion/accretion which happens over a long period (years) and incidental erosion which has a timescale of days to months.

Structural erosion

Considering the whole peninsula of Bocagrande (including Castillogrande and El Laguito) the only large change that can be witnessed (see Appendix C) is the creation of El Laguito. This area is manmade and has been stabilized using groynes. Less large of a difference is the width of the beach of Bocagrande that has slightly increased due to the construction of groynes. Beside these man induced changes not much has changed and the coast seems to be close to an equilibrium state. After multiple conversations with actors in the area, the assumption that the coast has not received periodic nourishments can be considered as correct. This means that the current state the coast is in can be considered natural. The only part that is not in equilibrium is between El Laguito and Castillogrande. In this section the sediment accretes just after the Hilton hotel up to the end of the

beaches of Castillogrande. It is very likely that the sand eventually moves of the tip of Castillogrande and settles in the deeper water of the bay.

When we look further north (near Centro and La Bocana) we find no difference compared to Bocagrande. At this location of the coast the only changes are human induced as well (Huertas, 2011)as can be seen in Figure 3.6. The blue line represents the coastline in 1961 and the red line shows the coastline in 2003.

A conclusion can be drawn when the global perspective of the coast is taken back into account. Until now Cartagena does not seem to suffer structural lack of sediment due to the changes of the mouth of the Magdalena River. In the future these problems might however occur, as can be seen closer to the Magdalena River. Erosion near Cartagena can be expected if the additional input of sediment, due to the disappearance of islands or other parts of the coast, stops.

Incidental erosion

As is discussed in the previous part, there are no signs of serious erosion on the long term. This paragraph discusses incidental erosion along the coast of Bocagrande due to seasonal variations and storms. See appendix D for the full analysis.

The wave climate changes over the year, with higher waves during the months of December – March, and lower waves in the rest of the year, specifically from August – October. These changes in wave climate generate different beach profiles. Winter profiles are created during higher wave conditions and summer profiles during lower wave conditions, see Figure 3.7.

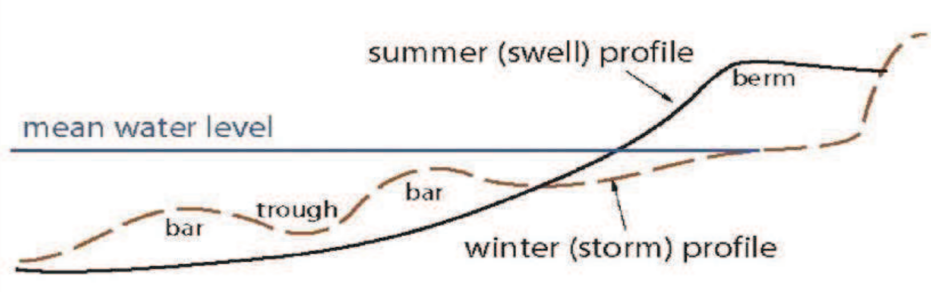


Figure 3.7 Summer and winter profiles

A comparable situation to seasonal changes happens during storm conditions, although on a shorter time scale. Storms can be caused by hurricanes on the Caribbean during the hurricane season (June – November), or storms can be more locally generated. Higher waves form the storm (or winter) beach profile. During storms, however, storm surges might occur as well, causing additional erosion

(Bruun’s rule, see appendix E). These effects are temporary and require a buffer of sand (i.e. dunes) to account for the change in beach profile. On Bocagrande, many buildings have been constructed close to the beach. Especially during ´winter´ or storm conditions the beach becomes small enough to threaten infrastructure and buildings adjacent to the beach.

3.1.3 Conclusion erosion

The analysis has shown that no significant structural erosion is present, the current problems of erosion are mostly local and man induced. The global analysis of the coast does also show that the main source of sediment to the coastal system has a reduced input, but the effects of this have not been noticed with respect to erosion along the coast of Cartagena. The problems that occur as a result of erosion are;

- Due to the human interference, a stagnant lake has formed, El Laguito. It is closed off from the sea, and it seems that the water quality of the lake is deteriorating.
- Just around the tip of Bocagrande where the Iribarren groyne and the Escollera groyne are located, at El Laguito, there used to be beaches. Due to erosion the beaches disappeared, now only some apartments and restaurants are still there, at some places the shoreline is reinforced with rocks to prevent damage to buildings caused by more erosion.
- The beaches are too small and too low to have a buffer for incidental erosion caused by storms or seasonal changes. Therefore damage can be caused to buildings and infrastructure adjacent to the coast.

3.2 Flooding

Another problem area raised by the actors is the flooding. Flooding occurs frequently on the peninsula of Bocagrande. Even though certain parts are affected more heavily and more frequently than others the whole peninsula suffers from this problem. The water that causes flooding comes from two different sources, one being precipitation and the other being the sea. These two causes of flooding are explained in more detail, after which a conclusion is drawn on the problems of the current situation.

3.2.1 Precipitation

Colombia being in the tropics, it has a very distinct seasonal variation of precipitation. During the months of December until the first half of April there is hardly any precipitation with the months of January and February having an average of zero millimeter of rain. The other months have a similar amount of rainfall except for October when precipitation is at its heaviest.

Período de Retorno	Pmáx	Pmáx	P48/P24
	48 Horas	24 Horas	
1	71.38	60.06	1.19
2	113.82	90.76	1.23
3	169.66	131.34	1.29
10	211.9	162.04	1.31
20	234.14	192.73	1.32
30	309.98	233.31	1.33
100	332.23	260.01	1.33

Table 3.1 Amount of precipitation versus return period

Although the total amount of rain over a month is not exceptional the problem lies in the focus over a small time period. Most of the rain of a month is spread over several days. At least once a year one can expect precipitation of 60mm in 24 hours. Table 3.1 shows the amount of precipitation in either 24 or 48 hours versus the return period (Universidad de Cartagena, 2009).

These downpours are short and intense; in fact more than 99% of the precipitation takes place in less than 3.3 hours (Arrieta Pastrana, Moreno Egel, Agámez Anillo, Bustillo Lecompte, & Mercado Palencia, 2009). The rain that needs to be drained falls on an area of 939400m^2. For a once a year downpour this results in a volume of 37622m^3 in a 24-hour period.

Currently, no sophisticated system is present that deals with the removal of the rainwater. Part of the volume evaporates; the other part has to be removed differently. The only measure that is taken to get rid of the rainwater is drainage pipes along the coast from the road towards the sea. As most of the roads are currently above mean sea level rainwater can flow directly out to sea.

However, the roads that are not adjacent to the coast do not always slope towards shore. Therefore some roads are flooded heavily after rainfall and are only released from the water through evaporation.

3.2.2 Seawater

Seawater intrusion occurs very frequently. Depending on the location of Bocagrande the circumstances that cause the flooding are different. Therefore the peninsula is divided in three parts: the bay side, the side of the open sea and El Laguito (Figure 3.8).

Figure 3.8 Division between bayside (red) and seaside (yellow) El Laguito (orange)

Bay side

The side of the bay lies much lower than the seaside. Due to this difference the bay side floods much more often, even though it does not have to withstand the waves as the seaside does. In fact, the levels of the streets, especially on Castillogrande, are so low that in case of a high water solely due to the tides the streets flood. A small protective perimeter dike exists along the larger part of the bayside which is currently in poor condition. This dike contains holes which function as outlets to drain rainwater. Since these holes do not have valves in them they do not only function as outlets for rainwater, but also as inlets for seawater. The flooding caused by a higher tide, not even being spring tide, can be observed often as is shown in Figure 3.9. The flooding due to high tide occurs at least twice a month, during spring tide. During a flooding the accessibility of the region decreases some places are even not accessible and the salt water is inconvenience for the residents.

Seaside

Figure 3.9 Outlets working as inlets and insufficient dike

The seaside has higher elevations and is thus less often the victim of flooding. However, in more severe conditions where the elements (for example the high tide and stormy weather) meet, also this side is known to experience flooding. On average once a year the whole of Bocagrande is flooded due to tide, extreme precipitation, and stormy weather all at once. This occurs during the winter months when the beaches are small and do not properly protect the peninsula (Rojas, Wit, & Navarrete, 2012). This kind of flooding causes inundation of the roads and apartments and causes damage to infrastructure.

Currently the sea side of Bocagrande has no accurately functioning system to remove water. There is no drainage system to speak of. Currently the water gets drained by evaporation and at some parts the water can flow into the sea if the water level difference is large enough. In order to remove water from the streets, improvised drainage systems are made, see Figure 3.10. This is an example of the seriousness of the problem and the lack of organised efforts to solve the flooding problems.

Figure 3.10 Improvised drainage gully Bocagrande

Before the extensive construction on Bocagrande a natural dune (appendix C and meeting with Mr. Rizo Pombo in appendix B.6) protected the coast on the seaside. Currently the dune is gone and what remains is a slightly higher elevation than the bay side. This, however, does not give enough protection. The only protection against the sea is the beach. In some places groynes are constructed to increase the amount of beach, however this is not enough to protect Bocagrande against a flooding under more severe conditions.

El Laguito

Flooding of El Laguito due to seawater intrusion has not been observed during the project. This is mainly because the elevation of El Laguito is significantly higher than Castillogrande and most of Bocagrande (see appendix E). However, with sea level rise in mind flooding might become a problem in the future.

3.2.3 Conclusion flooding

The flooding on Bocagrande can be divided into two kinds of flooding, occasionally flooding on the bay side due to high tide and/or precipitation and heavy flooding once a year due to a combination of elements and no proper sea protection. The flooding on the bay side causes inconvenience for the residents. The heavy flooding that happens approximately once a year causes flooding of all the roads and ground floors of buildings on Bocagrande. Unfortunately it is not known how much the value of the damage is.

Flooding in itself is a problem, but it is also a cause for additional problems. Due to the flooding the accessibility of the peninsula deteriorates and the infrastructure and properties get damaged.

As the expertise of the project group is not in the field of water management, the flooding due to precipitation and associated drainage system are not extensively considered. The design report of a drainage system by (Arrieta Pastrana, Moreno Egel, Agámez Anillo, Bustillo Lecompte, & Mercado Palencia, 2009) provides a sound solution to the flooding problems due to precipitation. It is assumed that a drainage system is installed to deal with flooding problems caused by precipitation in further chapters of this report.

3.3 Overtopping waves

This chapter discusses the overtopping problem in Cartagena along the old center of Cartagena on the 'Avenida Santander'. The considered stretch of coast is shown in Figure 3.11.The road around the city center is built on land that was reclaimed in the 1960's. Originally the old city wall was located directly on the shore.

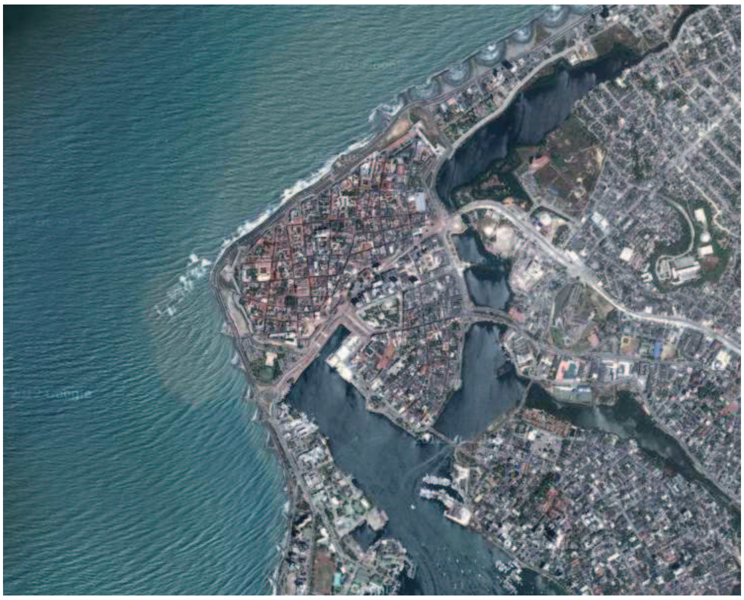


Figure 3.11 Overtopping considered road

3.3.1 Current situation

The shore along the old center of Cartagena consists of a steep seawall made of loose rocks and concrete debris with no beaches in front of it. A low concrete wall separates the seawall from the adjacent footpath and a two-by-two lane road. Figure 3.12 shows an image of the seawall, footpath and road.

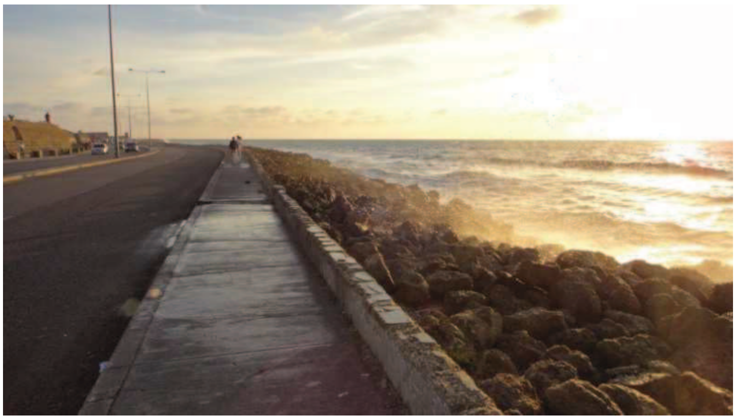


Figure 3.12 Shore build-up

Waves breaking on the steep seawall cause overtopping of the footpath and road. The overtopping water causes damage to the footpath and road, thereby reducing the capacity of the infrastructure. Even during relatively mild waves the overtopping of the seawall is significant enough to affect the road. During the execution of the project, multiple times wave overtopping has been observed. During these events the wave heights did not seem to be high. This indicates the frequency of the occurrence of wave overtopping. The overtopping causes damage to the road, which causes a decrease of road capacity because the traffic avoids the damage parts. Resulting in the 2 lane road becoming a 1 lane road.

The holes in the road cause the water to accumulate in the damaged parts, even though drainage pipes are present. The drainage pipes are simple pipes constructed in the curb to let water out in the case of high water levels on the streets. However, high water levels at sea or severe wave attack might cause water to flow onto the streets through these pipes. This has not been observed, but in the case of a severe storm surge this is considered to be a possibility.

In an interview with a hydraulic engineer from the University of Cartagena (Adriana Puello) some more information about the seawall became available. "*In the year 2001 a project was carried out to maintain the seawall. A new protection was applied with a slope of 1:1.5 – 1:2. However, at Punta Santo Domingo the underwater slope was too steep to place the rocks on the seabed without additional measures. The rocks that were placed rolled towards deeper water, which finally resulted in a steeper slope at Punta Santo Domingo of 1:1*." Since the measures in 2001 the seawall has experienced damage and degradation without appropriate maintenance to repair the seawall. This has led to increased overtopping rates at some locations where the seawall has experienced the most severe damage (own observations).Some loose rocks on the slope of the seawall have come off and are now in front of the seawall. This has also led to exposure of underlying smaller rocks, see Figure 3.13. The reason some rocks have come off the slope could have to do with the slope being too steep (up to 1:1) at some locations. Also a lack of decent toe structure might have caused instability of the slope. It is clear that the water depth just in front of the seawall is small, as the rocks seem to rest on the seabed. The shallow foreshore of the seawall cause (larger) waves to break before they hit the seawall. However, in the case of a storm surge larger waves could hit the seawall directly.

Figure 3.13 Loose rocks have come off the seawall slope (left) and exposure of underlying smaller rocks (right)

During storms the overtopping is significantly increased and driving on the road adjacent to the sea wall is not possible. The storm waves induce damage to the sea wall at places where rocks are nog large enough to withstand the high waves. Figure 3.14 shows pictures taken during and after storm conditions at the sea wall respectively.

Figure 3.14 Storm conditions (left) damage to sea wall due to storm (right)

Overtopping quantities

The theoretical current overtopping rates are calculated. These quantities are verified by observations. Overtopping quantities have been calculated using the Van der Meer overtopping formula: Eq 6.5 (EurOtop, 2007)

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.2 \cdot \exp\left(-2.3 \frac{R_C}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta}\right)$$

To this formula a reduction factor is added for the crest of the sea wall because the road is not located directly adjacent to the sea wall (eq. 6.7 (EurOtop, 2007)).

$$C_r = 3.06\exp(-1.5G_c/H_{m0})$$

The conditions that are used for overtopping are normal conditions and 1/year storm conditions. The conditions that are considered to be representative for this area are shown in Table 3.2 (for full description see appendix E.

	Normal conditions	1/year storm conditions
Storm surge	0m	0,5m
Tide	0,35m	0,35m
Waves	1m	2,5m

Table 3.2 Local normal and storm conditions

The dimensions of the seawall are given in Table 3.3. Figure 3.15 shows a cross section of the sea wall with the water levels per condition and corresponding crest heights.

	Value
Crest height w.r.t. MSL R_c	2m
Crest width G_c	4m

Table 3.3 Dimensions current situation

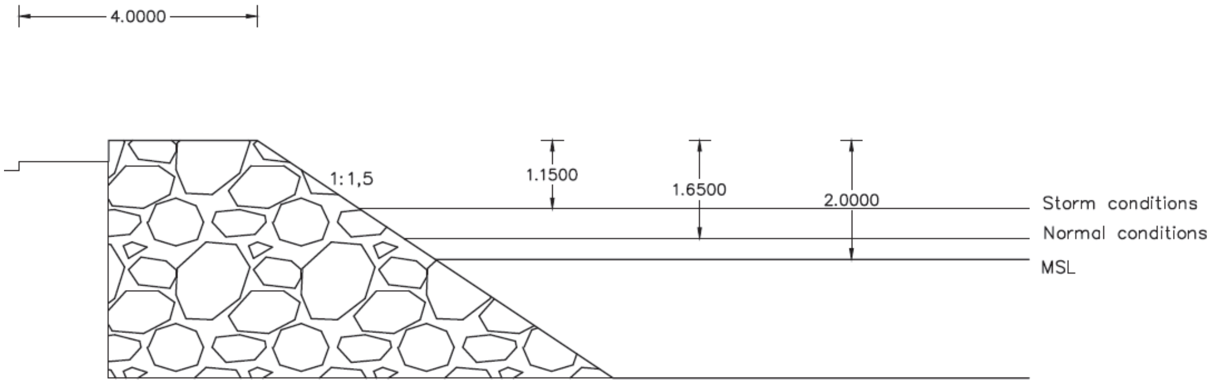


Figure 3.15 Cross section sea wall

The overtopping quantities based on normal and storm conditions are shown in Table 3.4. For the full calculation see appendix F.

	Normal conditions	Storm conditions
Overtopping volume q	$4*10^{-6}$ $m^3/s/m$	0,09 $m^3/s/m$

Table 3.4 Overtopping quantities

These outcomes seem plausible, as under normal conditions observations have shown that some overtopping is present. Passing cars along the sea wall are not directly affected by the overtopping water. However, the water has damaged the road because of the very long time the overtopping has been present. During storm conditions the overtopping becomes too much for cars to drive along the sea wall.

3.3.2 Conclusion overtopping

The seawall that protects the coast around the old city Center for erosion and flooding permits too much overtopping to avoid problems with adjacent infrastructure. The overtopping of the seawall causes damage to the infrastructure on the coast, and thereby reduces the capacity of the important 'Avenida Santander'. Even during mild wave conditions overtopping is present at certain locations along the coast.

The seawall is in a bad shape, loose rocks have come off the slope and underlying smaller rocks are exposed to direct wave attack. The damage to the seawall causes increased overtopping at the affected locations. Too steep slopes, poor structures and too small armor stones have probably caused damage to the seawall that was rebuild in 2001. Furthermore, the seawall has a very low crest height to prevent overtopping in stormy conditions.

3.4 Accessibility

The accessibility of Bocagrande is a major problem according the majority of the direct stakeholders. The fact that only one access road to Bocagrande exists and the popularity of the peninsula is rising, results in more accessibility problem.

To get a general idea of the traffic situation in Cartagena, a TRAIL-layer model will be presented first, in which the (im)balance between travel demand and infrastructure supply is analyzed. After that, the supply and demand side of traffic flows are investigated in more depth.

Based on that analysis, and by using an OmniTRANS Transport model, the major problems in the Cartagena transport network during the morning peak are identified. In chapter 5 solutions for these problems are proposed and tested.

3.4.1 TRAIL-layer model

The TRAIL-layer model values the quality of a transportation system from a market perspective. In the layer model, two markets can be distinguished: the transport and traffic market. When a balance exists between the demand and supply of transport and traffic, the transport system performs well. When demand increases, an imbalance on the market is created and congestion emerges.

Transport market

The transport market emerges between the activities that the citizens of Cartagena want to exploit and the transport services that exist to reach the activity destination. Since this accessibility study focuses at the capacity problems on the Cartagena road network, the morning peak will function as the study time range.

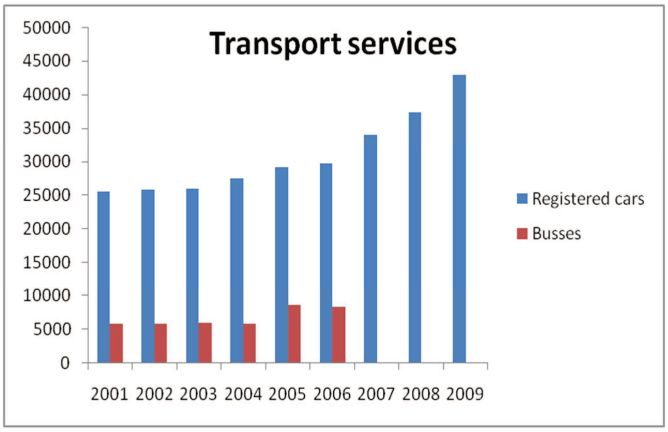


Figure 3.16 Amount of transport services

The inhabitants of Cartagena in 2009 together owned almost 43.000 cars, as can be seen in Figure 3.16. This results in a low car occupancy rate of 1 car per 20 inhabitants. But Figure 3.16 shows as well that the car occupancy rate is rapidly rising, showing the increased popularity of cars as a transportation mode.

Since 2007 the local government of Cartagena is also working on the bus system Transcaribe. It hasn't been finished yet, due to some land owning issues, but the development of the transport system did initiate the collection of traffic data on public transport travelers. Another problem that prevents the Transcaribe-project from implementation is the fact that all current bus services are provided unofficially. Bus owners start their own bus line, without a central planning. Bus stops do not exist, but a bus conductor simply calls people into the bus. The lack of a central bus organization and having to cope with many different bus 'companies' makes it so difficult to have all stakeholders accept the new centrally organized public transport system.

In 2012, 5800 licenses for taxis were awarded, meaning that almost 15% of all cars in Cartagena functions as a taxi. Assuming that taxis in general make more kilometers per day than personal owned cars, the contribution of taxis to the total amount of traffic will be higher than the 15% earlier mentioned. Taxis are relatively cheap and easy accessible, therefore becoming a popular transport service for both locals as tourists.

Making trips during the morning peak can be based on different purposes: commuting, going to the university, shopping or performing touristic activities. Based on the zonal data in appendix G.2, it can be concluded more than 21% of all jobs is located in Bocagrande and Centro area, while only 4% of the total population of Cartagena lives in these two areas. Also, more than 60% of all university students goes to the city Centre (Centro) to reach his or her university.

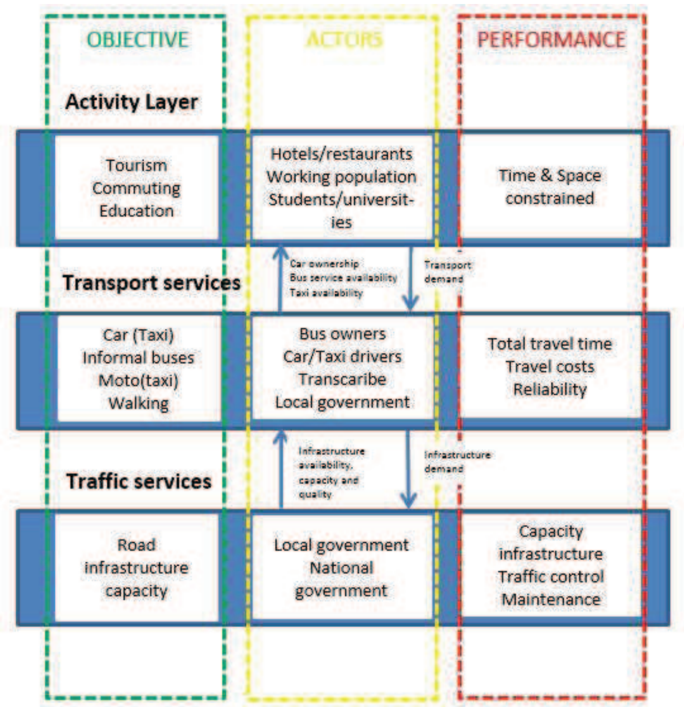
When looking at the touristic attractions, it can be seen that they are mainly located in city centre. Also beaches, for which Cartagena is highly appreciated by tourists, can only be found along the coast where Bocagrande is located.

It can be concluded that cars form the biggest transport service. Also taxis, buses and motorcycles are used as transport modes in Cartagena. Based on the zonal data on the amount of inhabitants, jobs, university places and touristic sights it is shown that many activities are centre-oriented, resulting in traffic towards the city centre. Outside the touristic peak period this is caused by the high amount of university places and jobs in the city centre, within the touristic season the amount of centre-oriented activities even increases.

Traffic market

The traffic market describes the (im)balance between the demand for and availability of infrastructure. As can be seen from Figure 3.17 all cars, buses, taxis and motorcycles demand for infrastructure capacity. Pedestrians and cyclists are not taken into account, because their capacity demand is negligibly small.

Figure 3.17 Trail layer model



The capacity performance of an infrastructure network is dependent on the amount of infrastructure, the way the capacity is controlled and to what extend capacity is maintained throughout the years.

In this study, no solutions will be presented that have to do with traffic control, but the research' focus is on capacity use and expansion.

From Figure 3.17 it can be seen that the local government is responsible for the city roads, while the national government maintains the national ones. The maintenance of the city roads has been a problem, especially because of the instable state the local government. This state is reflected by the short terms that mayors have been in charge over the last 20

years. Without a stable political situation, less attention is paid to long term projects, like infrastructure maintenance. This partly explains the poor maintenance of most roads.

Some examples of capacity decrease in Cartagena are the overtopping of sea water and floodings. Figure 3.18 figures above show examples of how the infrastructure cannot be used to its full extent in case of flooding and overtopping.

Figure 3.19 Geographical chart

Several road types can be distinguished in Cartagena, offering a different capacity amount. In appendix G.5 the speeds, densities and capacities of each road type are presented. The resulting capacities are used as an input for the transport modeling tool OmniTRANS. In Figure 3.19 the major inner-city infrastructure, consisting of 2- and 3-laned connections are marked in yellow.

It can be concluded that the infrastructure capacity of the city of Cartagena is not really well maintained. Besides, it is damaged by overtopping sea water and floodings. Because the priority of the local government is not on long-term issues like infrastructure maintenance, damage to infrastructure is not repaired. All damages lead to lower road capacities than the roads were designed for.

Whether the capacity is sufficient for the demand of traffic, can be quantified by a transport model. Using the transport model, the current state of the road network can be investigated. This is done in paragraph 3.4.4.

3.4.2 Travel demand modeling

To gain insight in the current state of the accessibility of Cartagena and Bocagrande in particular, a transport model will be developed. After briefly discussing the theory of the 4-step model to estimate traffic flows, the modeling decisions that are used to model the Cartagena-situation are explained.

4-step model introduction

Using the 4-step model (see Figure 3.20) is a way to estimate traffic flows, based on aggregate, zonal data. The 4-step model consists of the estimation of 1) *trip production and trip attraction*, 2) *trip distribution and model split*, 3) *period of day* and the 4) *traffic assignment.*

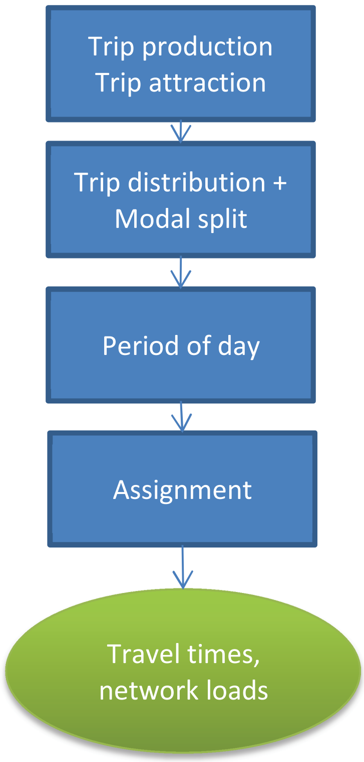


Figure 3.20 4-Step model

The trip attractions and productions can be estimated, using a regression analysis. The zonal data on –in this case– jobs, university places, population, touristic sights, companies etc. is used as an estimator for the amount of attracted or produced trips per zone. Because one regression model per trip purpose is established, also all attractions and productions per zone per purpose need to be known to function as the dependent variables in the regression analyses. Based on the regression analysis, the extent to which several estimators (zonal data) contribute to the generation of traffic flows can be calculated. With those parameters and using the zonal data, the amount of trip attractions and trip productions per zone are calculated.

Once the attractions and productions per zone are known, a distribution model can be used to estimate which origins and destinations are combined to form trips. The distribution model takes the accessibility of different destinations into account to estimate which destination will be chosen for a certain purpose. This accessibility can be measured in distance, travel time or costs. Also, the trip productions and attractions per zone need to be known to determine the potential of a zone to function as an origin or a destination. Since different modalities lead to different transport costs and travel times, the mode choice can be executed in a same way as the destination choice. Therefore, the destination and mode choice are sometimes combined.

Ones the a-priori origin-destination matrix is known, the traffic flows can be assigned to the existing infrastructure. The travel resistances between origins and destinations function as an important input for the assignment. Based on the assignment method some assignment-parameters might be required as well. The easiest way of assigning traffic to the infrastructure is by assuming that all trips follow the shortest path from origin to destination. In that case congestion is not considered. Of course, congestion happens in reality and must be taken into account. Using a value averaging assignment method, all origin-destination pairs with more than one possible connection, will be loaded to such an extent that the travel time of all routes is the same. If a traveler finds a quicker route to its destination than the regular one, he will probably use this route from that moment on. As soon as more travelers find out that a quicker route exists, the quickest route will be used more often until congestion emerges and travel time increases again. In that way, an equilibrium situation is found in which the travel times of all routes are the same.

Once all traffic is assigned to the network, the first model outputs can be analyzed, such as travel times, network loads or total travel time in the network. To check whether your assignment model results in a transport model correspond to the traffic situation in reality, a validity check is needed. Traffic counts can be compared to the model outcome, to see where differences occur. The change of parameters in the different model steps or an adjustment to the origin-destination matrix can lead to a better fit.

Modeling the Cartagena traffic

As shown in the last paragraph, quite some data is needed to succeed every of the 4 steps of the 4-step model in the right way. Unfortunately, that is not all available here in Cartagena. Some zonal data is available, but it has its shortcomings. For example, 60,8% (CENAC, 2011) of all labor in 2008 is informal and therefore not taken into account in official databases. The amount of students per zone is unknown, so the population between 20 to 25 years old is used as an estimator. Also the amount of attractions and productions per zone, functioning as a dependent variable in the trip generation-step, are not defined per travel purpose. That makes it very hard to estimate reliable regression coefficients for the trip generation per purpose.

What is known, thanks to the travel data collected for the Transcaribe-project, is a full origin-destination matrix for public transport travelers. Besides, traffic counts on 40 major cross roads in Cartagena are known, separating the car, bus, motorcycle, truck and bicycle traffic flows. All data is collected in the year 2002.

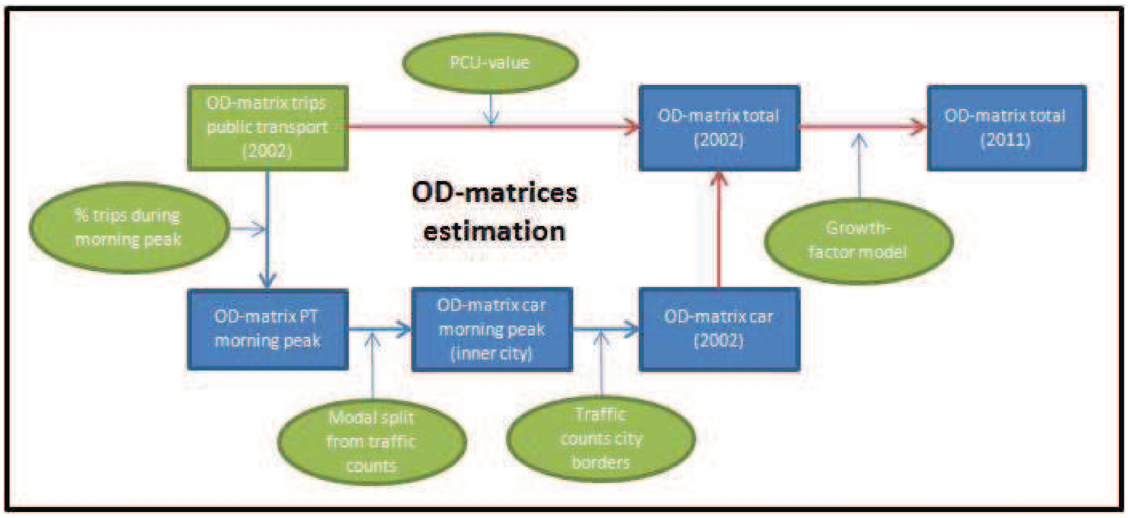


Figure 3.21 OD-matrix

Since the full origin-destination matrix of public transport is known and the modal split can be calculated based on the different traffic counts, this way of estimating an origin-destination matrix for car traffic is possible. In Figure 3.21, the way of estimating the total OD-matrix (car and bus) is explained.

The green figures shown in Figure 3.21 are known, the blue ones are constructed using the information that is available. The squares have to do with matrix estimation, the oval figures represent a piece of data or information that is needed to estimate the next origin-destination matrix. The growth-factor model to translate the base year matrix from 2002 to a 'current' matrix of the year 2011 is based on the population growth, economic growth and the increase of car occupancy per Cartagenean citizen. In appendix G.6 the determination of the growth factor is explained.

Using the public transport matrix as a base to estimate the car origin-destination matrix has some disadvantages:

- It is unknown if the public transport behavior equals the car traffic behavior in terms of productions and attractions, demand and supply.
- By using the third step of the 4-step model as a base for traffic assignment, no insight is gained in the underlying activities and purposes that cause an origin-destination matrix, that are usually dealt with in the first 2 steps.
- Because the underlying estimators for the trips are unknown, it is difficult to execute a future analysis, in which for example the population or the amount of jobs is grown. This future analysis is needed to create a traffic model for the current situation in Cartagena.

Although the disadvantages, it is still possible to gain insight in the current link loads on the infrastructure network of Cartagena. The main bottlenecks in the network can be identified in that way and solutions that do not have to do with one particular modality, like infrastructure expansion can be tested. Because bus and car traffic form about 90% of the traffic load, these are the only modalities that are taken into account when modeling the traffic.

The OD-matrix for the current situation is then assigned to the Cartagena road network using a DUE-assignment method. Figure 3.22 shows that the DUE-assignment method takes congestion effects into account when the traffic is assigned to the network. As a result, traffic will be divided more equally over the network than when only shortest routes are used as assignment criterion. Moreover, the travelers in a DUE-assignment are fully aware of the true travel times. The link travel times are given by the Bureau of Public Roads (BPR)-function: Based on the parameters above and the Method of Successive Averages (MSA, VOLumeAVeraGing in Omnitrans) a user-equilibrium is used. The averaging process stops after 10 iterations or when a relative convergence gap of 0,001 is reached.

BPR-function: $t_a(q_a)=L_a/v_a^{max}*[1+\alpha_a*(q_a/C_a)^\wedge\ \beta_a]$

t_a = travel time on link a (hour)
q_a= flow on link a (vehicle/hour)
L_a = length of link a (km)
v_a^{max}= maximum speed on link a (km/h)
C_a = capacity of link a (vehicle/hour)
α_a = parameter dependent on link type= 0,87

Figure 3.22 DUE-assignment method

3.4.3 Scenarios

To investigate in which cases transport problems exist and if so, in which cases solution will be sufficient, different scenarios will be taken into account in this study. In Figure 3.23 it is shown that the traffic is modeled throughout the whole city of Cartagena (yellow line) and that the focus is on the coastal roads and the access road of Bocagrande (red line).

The regular 4-step model formed the basis for the transport modeling and the outcomes are compared using the criteria traffic intensity, travel time between zones and total travel time. It is expected that major differences in the traffic situation in Cartagena exist throughout the year that are caused by several external factors.

In this study, the external factors *coastal problems* and *tourism* are used to form different scenarios. The tourists, especially arriving in December/January, are expected to have a large impact on the transport demand. The coastal problems have different impact on the accessibility: overtopping waves damage the infrastructure, leading to lower capacity and floodings lead to lower possible speeds, which also diminishes the capacity. In appendix G.7 it is explained how the scenarios are taken into account in the transport model.

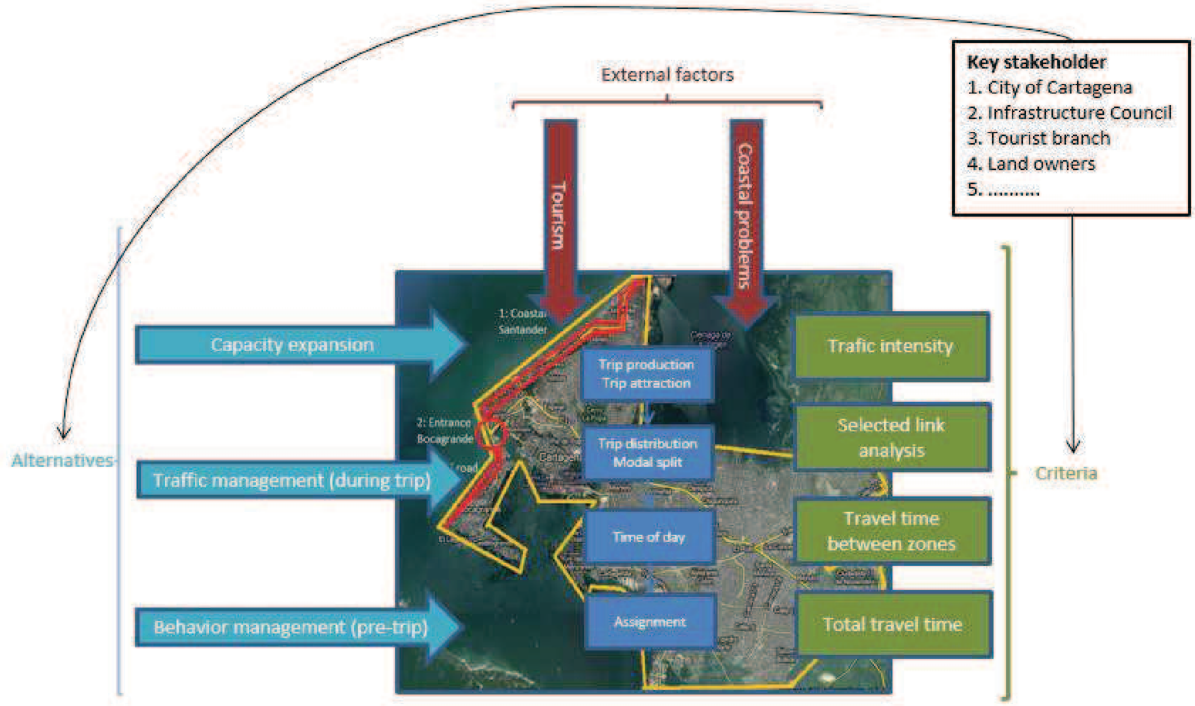


Figure 3.23 System diagram

3.4.4 Problem identification

Using the modeling steps, assumptions and scenarios as described earlier in this chapter, an OmniTRANS transport model is developed to get insight in the traffic flows of cars and buses in Cartagena. In this chapter the results will be analyzed, to identify the major traffic problems in Cartagena. As mentioned during the description of the traffic market in the TRAIL-layer model, this traffic model will also answer the question to what extent the infrastructure network of Cartagena is capable of coping with the travel demand of its people.

First of all, it is important to determine on which criteria the model outputs will be compared. The following criteria will be used:

1. Traffic intensity (visualized with bandwidths on links)
2. Selected link analysis (visualized with bandwidths on links)
3. Accessibility measures
    a. Travel time between zones (table with travel times)
    b. Total travel time between zones (table with total travel times)

Initial situation

In Figure 3.24 the model outcomes of the transport model are shown. The width of the beams along the road represent the traffic intensity, the color represents the relative intensity compared to the capacity of the road (Red is high and green is low). In both the initial (October) and touristic

(December) situation, it is assumed that flooding occurs on Bocagrande and that the coastal road is just partly usable due to the overtopping sea water.

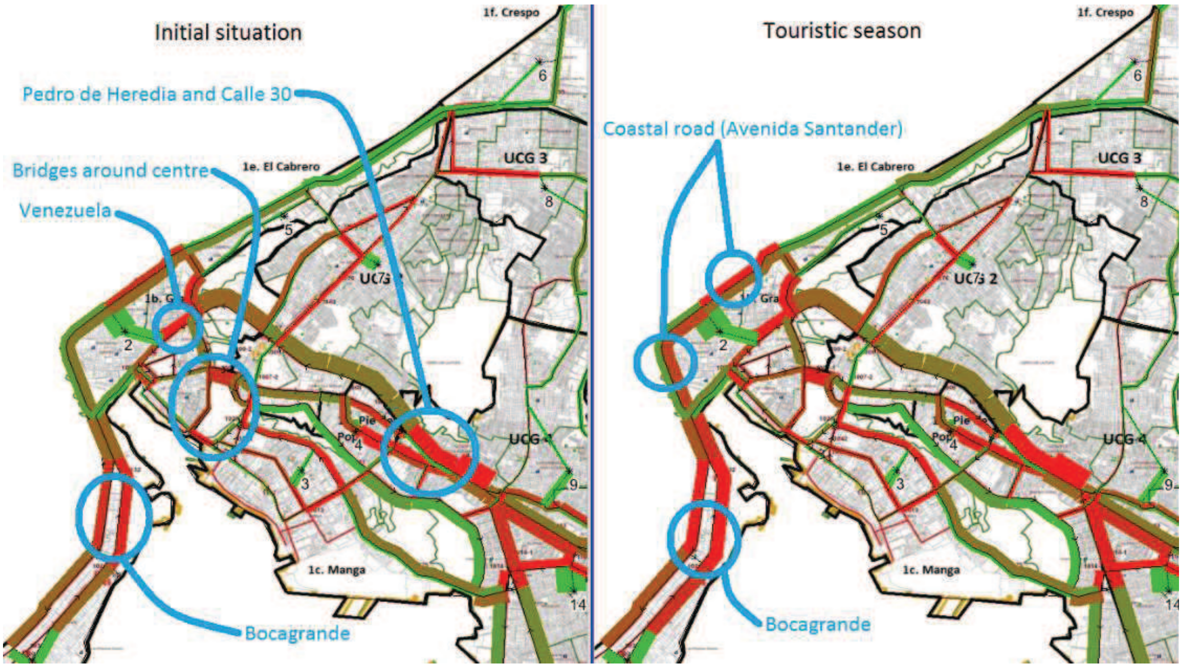


Figure 3.24 Output figure Initial situation & Touristic situation

As can be seen on the left side of Figure 3.24, the available infrastructure in the initial situation already has significant problems with handling the amount of traffic. The biggest problems that can be identified are the Venezuela road, the entrance to Calle 30, the main road Pedro de Heredia, the bridges around the city centre, and the main roads on Bocagrande. Congestion starts occurring when the road intensity has reached about 80% of the total capacity. To illustrate how the road network performs in the initial situation, the intensity/capacity-rates are shown for the problem areas in Table 3.5. It can be seen that in the initial situation the intensity/capacity-rates are still below 1 on the Coastal road and on Bocagrande. As soon as tourism starts occurring, these are the zones that suffer most. The intensity/capacity-rates increase and in case of heavy tourism even a value of 1,32 along the Coastal road is reached. Roads that are not in the area of the coastal road, Centro or Bocagrande are less influenced by the extra tourists, as can be seen from the 'Calle 30 entrance'-example in the table.

Traffic Growth factor 2002-2011 **Tourism**	**80%**
Initial situation	
Intensity/Capacity	
Bocagrande in/out	0,89/0,93
Coastal road north/south	0,78/0,57
Calle 30 entrance	1,23
Tourism (low) 0,80	
Intensity/Capacity	
Bocagrande in/out	1,01/1,16
Coastal road north/south	1,22/0,63
Calle 30 entrance	1,29
Touristic situation 1,00	
Intensity/Capacity	
Bocagrande in/out	1,04/1,21
Coastal road north/south	1,26/0,75
Calle 30 entrance	1,28
Tourism (high) 1,25	
Intensity/Capacity	
Bocagrande in/out	1,06/1,26
Coastal road north/south	1,32/0,74
Calle 30 entrance	1,28

Table 3.5 Intensity/Capacity rate

Touristic season

In the touristic season the traffic demand is increased by tourists. The way that the touristic travel demand is modeled, is explained in appendix G.7. In the figure below can be seen that, besides the problems that were already present in the initial situation bigger problems occur on Bocagrande and along the coastal road (Avenida Santander) in case of high tourism rates. Especially because the areas of Centro and Bocagrande are filled with tourists, more trips are generated around these areas. Also the extra flights that come in from the airport in the north of the city result in higher traffic intensities along the coastal road. It is clearly visible that the places where the road is damaged by overtopping will function as a bottleneck. Based on the ratios of Table 3.6, congestion is expected on the coastal road in touristic seasons.

When the travel times between all zones are compared in the normal and touristic period, major difference can be seen as well, but especially around the Bocagrande and Centro area. In Table 3.6 it is shown that travel times to reach Bocagrande will increase between 24 and 32%, based on the amount of tourists. The travel time to Centro will increase between 12 and 35%. Given the fact that travel times especially increase in the touristic areas, the average travel times in Cartagena only increase by about 3 and 7%.

Table 3.6 Travel time Bocagrande & City centre

	To Bocagrande		From Bocagrande		To Centro		From Centro		Total	
Amount of tourists	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH
Travel time increase	24%	32%	34%	58%	12%	35%	3%	5%	3%	7%
Total travel time increase	34%	55%	76%	136%	35%	77%	14%	22%	9%	19%

When all increased travel times are multiplied by the amount of trips that are made during the morning peak, a value for the total travel time is calculated. As can be seen from Table 3.6 as well, is that more people suffer from the travel time losses, therefore leading to a higher total travel time loss. The total travel time loss from Bocagrande is enormous, because in this region most of the extra travelers arrive, that also experience the longer travel time. The fact that travel time and amount of travelers are increased to such an extent, leads to very high total travel time increases.

3.4.5 Conclusion accessibility

In this section, a problem analysis of the accessibility problems during the morning peak hours of Cartagena is carried out. Only the traffic of cars and buses throughout the city is modeled, about 90% of all traffic intensity. Based on the link load analysis, it can be concluded that in the initial situation traffic problems are already present throughout the city. The effect of the damaged coastal road and flooded streets in Bocagrande is clearly visible. In touristic season the travel demand increases. This mainly results in more traffic around Centro and Bocagrande. The coastal road will have a higher intensity and is expected to be congested in front of the parts of the road that are damaged by overtopping. Travel times towards the city centre will increase with 12-35%, dependent on how severe the touristic peak is.

In Bocagrande, congestion will occur as well, especially for those trying to reach the peninsula in the morning peak. The flooding of the area leads to a lower capacity, which will result in higher congestion than in case of no flooding. Travel times to Bocagrande will increase with 24-32%.

3.5 Causal relationship diagram

The causal relationship diagram is a diagram which gives inside in the causal relationships between the problem areas. Figure 3.25 shows this diagram. The different colors indicate the different kind of factors. The orange color indicates the external factors, which are factors that can influence the system, but cannot be influenced within the system. These external factors will be elaborated in chapter 4. Factors that can be influenced are blue, which are the four issue areas discussed above. The measures will directly affect these four main focus areas, overtopping waves, erosion, flooding and accessibility. Through these factors multiple criteria will be affected. As the figure shows, the issue areas are related with each other, which means for example, that measures on erosion indirectly has an effect on accessibility through the factor flooding. Some of these criteria will be used as design requirements for the construction of the measures, others will be used for the multi criteria analysis to score the measures.

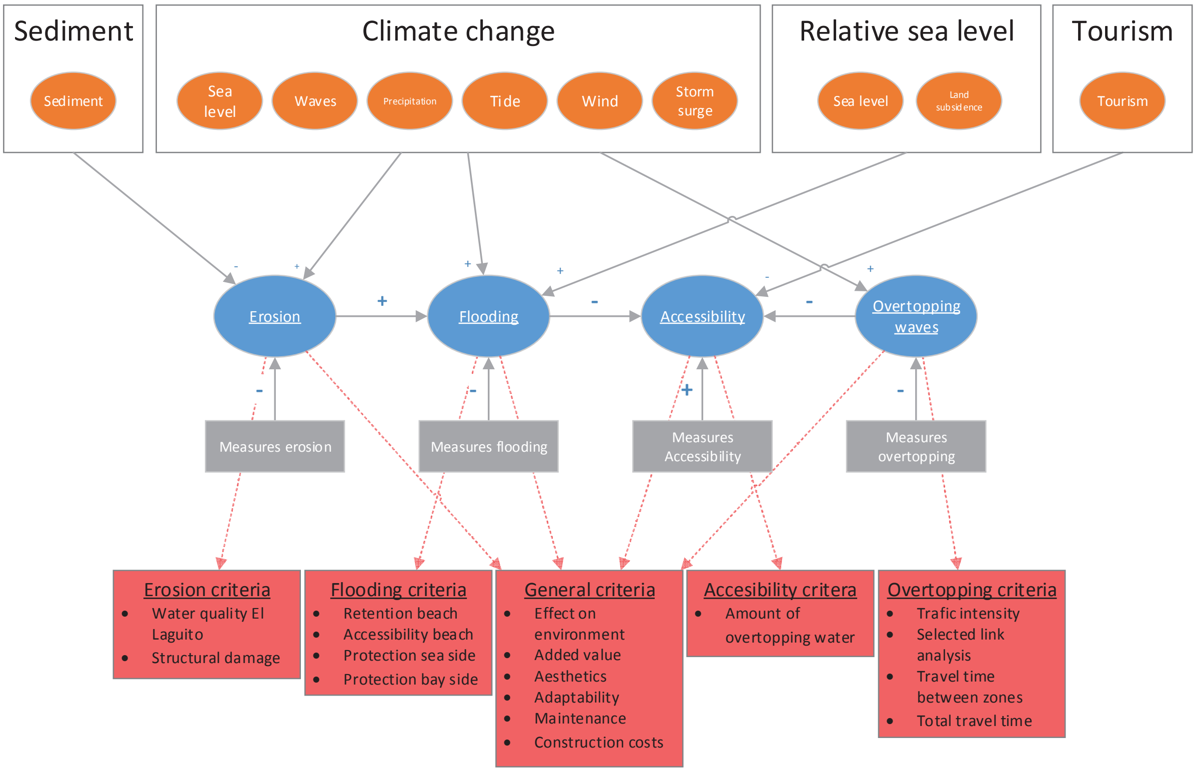


Figure 3.25 Causal relationship diagram

The issues overtopping and flooding negatively influence the accessibility. The infrastructure cannot be used to its full extent due to these issues. Measures for these issues have thus an indirect effect on the factor accessibility. Therefore first the measures for erosion, flooding and overtopping waves will be discussed before looking at the measures for accessibility.

3.6 Conclusion

From the system analysis, it can be concluded that there are several issues which are related with each other and which have different causes and effects. The issues can be grouped in geographic problem areas (see Figure 3.26). In this way, specific solutions per area can be generated, discussed and presented. A research of the history of the coast of Bocagrande shows that the coast line of Bocagrande is stable and there is no structural erosion. However this can change in the future as a result of the structural lack of sediment due to human interference at the mouth of the Magdalena River. The research of the history of the coast reveals two issues, which are also indicated by some actors. Due to erosion of the beach just around the tip of Bocagrande, the beach has disappeared in front of the restaurants and apartments. The second issue is the clogging of El Laguito. Due to its closure it seems the water quality of the lake is deteriorating. These two issues are related to what happened in the past, another issue concerning erosion appears when analyzing what erosion causes today. The beaches are too small and too low to have a buffer for incidental erosion caused by storms or seasonal changes. Therefore the chance of flooding increases which could lead to damage to buildings and infrastructure adjacent to the coast. The analysis of the flooding problem shows that there are two main problem areas concerning flooding. The bay side is flooded at least twice a month due to high tide and no proper sea protection. This causes inaccessibility of the area and damage to property of the residents. The other area, the sea side, has too little protection against stormy weather, especially during the winter months when the beaches are small, there is a chance of flooding on this side. This happens on average once a year. The overtopping of the waves causes damage to the road, which affects the road capacity. Due to holes in the road, traffic will avoid these holes and use 1 lane instead of 2. This decreases the capacity and the velocity of the road. The analysis of the accessibility shows that the previous issues all have an impact on the accessibility. The initial situation already has significant problems with handling the amount of traffic. The biggest problems that can be identified are the Venezuela road, the entrance to Calle 30, the main road Pedro de Heredia, the bridges around the city centre, and the main roads on Bocagrande. As soon as tourism starts occurring, the intensity/capacity rates increases, especially on the roads to and from Bocagrande and the city center. The travel time to the city increases with 4-8% and to Bocagrande with 8-12%.

Figure 3.26 Problem areas

In the following chapter, a future scenario will be given to provide the design requirements for the measures which will be discussed in chapter 5 and 6.

4. Scenario analysis

The system analysis revealed the problem areas, their causes and effects and how they are related to each other. The problems are caused by external factors which cannot be influenced within the system. These factors will be discussed taken the next 50 years into account. Based on the effects the external factors have on the problem areas, system requirements will be formulated which will be taken into account while forming the measures.

The external factors taken into account in this project are:

- Climate (change)
- Relative sea level
- Sediment
- Tourism

For some external factors quantitative information is available, for those without, a qualitative indication will be given.

4.1 Climate

The external factor climate consists of several factors; waves, wind, tide, storm surge and precipitation. These factors are described in appendix E. Some of these factors will change in the upcoming 50 years and will have an impact on the system. Therefore it is important to take the following possible changes into account:

- It's likely that future tropical cyclones (typhoons & hurricanes) will become more intense, with larger peak winds and will occur more often (Karl, et al., 2008). This increase increases the frequency of high waves and the wave heights (between 1,5 – 2,4 m).
- Three mechanism have effect on storm surges; tropical cyclones, cold fronts and local storms. Royal Haskoning calculated a maximum storm surge height of 1m on top of the tide level once in 50 years (Moreno-Egel, Agámez, Castro, & Voulgaris, 2003).
- Heavy rainfall (>350mm per month) will increase. Between 2000 and 2010 4 months where counted with heavy rainfall (>350mm per month). Between 2040 and 2050 36 months of heavy rainfall is expected (Rojas, Wit, & Navarrete, 2012). This will affect the sea level in the bay because of the river mouth of canal del Dique in the bay.

Based on the information above we can conclude that there will be more and heavy rainfall, more frequent high waves and once in 50 years a storm surge. The increase of heavy rainfall effects the sea level in the bay and increases the amount of floodings on the bay side of Bocagrande. The high waves causes more incidental erosion which means smaller beaches, which affects the protection level of the coast line. Higher waves also result in more and heavier overtopping, which affects the road quality and the road capacity.

4.2 Relative sea level

The relative sea level consists of the sea level rise in the Caribbean Sea in combination with the land subsidence. The trend of the last 50 years is approximately 6mm/year sea level rise in Cartagena according to INGEOMINAS (Restrepo & López, 2007), see Figure 4.1.

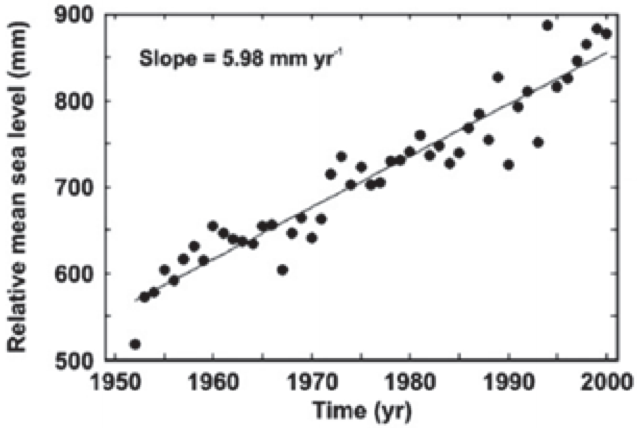


Figure 4.1 Relative sea level rise

It is expected that in the year 2100 the sea level rise is 1m above current mean sea level (Alianze Clima y Desarrollo, 2012). That implies that the rate of sea level rise is expected to increase in the coming years. The increase of relative sea level rise means that large parts of the city will be flooded. On short-term, a larger part of Castillogrande (the bay side) will be flooded not only twice a month, but continuously. According to Bruun's rule for coastline retreat by a raised sea water level, the coasts along Bocagrande will experience a coastline retreat of 0,4m per year (see appendix E). The beaches will slowly disappear and complete flooding of Bocagrande will occur more often during the winter months and in the long-run the whole peninsula will be completely flooded (Rojas, Wit, & Navarrete, 2012). Figure 4.2 shows Bocagrande in 2020 and Figure 4.3 shows Bocagrande in 2040. The blue areas are the flooded areas due to relative sea level rise in combination with heavy precipitation.

Figure 4.2 Flooding of Bocagrande in 2020

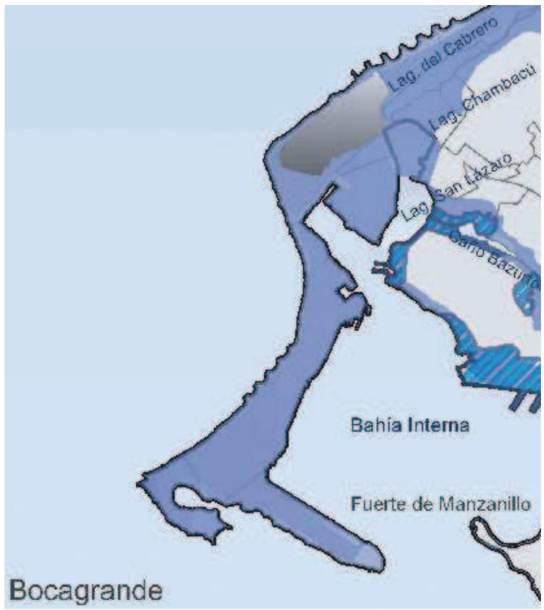


Figure 4.3 Flooding of Bocagrande in 2040

4.3 Sediment

The research of the history of the coast of Bocagrande has shown that the coast line is stable and there is no structural erosion, except for a small part at El Laguito. The beach on the west side of El Laguito is completely eroded and causes a risk of damage to buildings. The sedimentation on the east side of El Laguito caused the closing of the lake. Without interaction with the sea, the lake will deteriorate. For the rest of the coast we assume that the structural sediment supply will stay the same over the next 50 years. However, due to the human interference at the mouth of the Magdalena River it is plausible that sediment supply will change in the future; this should be investigated in further research. The incidental erosion frequency and magnitude will probably increase. As the increasing number and strength of the tropical cyclones is expected, the frequency of high waves coming from another direction than the normal waves rises as well. This will have effect on the protection of the coast.

4.4 Tourism

Cartagena attracts tourism because of its beaches and its cultural value. The beaches around Bocagrande are popular amongst both foreign as domestic tourists. Figure 4.4 shows an increase of tourism and visitors since 2001 (Salazar Fuentes, Resultados Indicadores Turismo 2012, 2013).

Figure 4.4 Tourists &visitors Cartagena

The increase of the amount of tourists and visitors is based on travelers by cruises and planes. However there are tourists and visitors which are inhabitants of Colombia and visit Cartagena by car. Since there is no sufficient data available of these amount of tourists & visitors, they are not taken into account. It is therefore difficult to give an exact indication about the amount of tourists & visitors. The tourists and visitors that arrive by cruises and air transport however give a good insight in the trend over the last 10 years. One can clearly see that since 2006 the amount of tourists & visitors increased significantly. The reason for this increase is not known. The Cartagena tourist organization dedicates this increase to the increase of the number of hotels and apartments. A lot of factors have influence on the amount of tourists and visitors, like the attractiveness of the region and the safety of the country (especially in combination with the FARC). The Cartagena tourist organization and the hotel branch expect the amount of tourists & visitors will grow, since the amount of hotels is continuing to increase.

Right now 9 hotels are under construction, with a total of 1848 rooms (Salazar Fuentes, 2013). Therefore this scenario assumes that the amount of tourists and visitors will increase in the coming years.

4.5 Design requirements

The scenario analysis shows that there are several important external factors which are of great importance to take into account while formulating the measures. All measures will be analyzed on the basis of the criteria formulated in the system analysis. Some of these criteria are so important to meet a certain level that these criteria become design requirements. The design requirements are a set of rules (design conditions) which have to be taken into account while designing the measures. The following system requirements have to be taken into account:

- *Coastal Protection*: the protection of the coast line must defend Bocagrande against a storm that occurs once in 50 years. Currently there is no protection level for the coastal defense, the desired protection level is chosen as 1/50 years. The protection should also be able to deal with a relative sea level rise of 50cm;
- *Accessibility beach:* Access to the beach should be guaranteed
- *Retention beach:* Current beach must be preserved
- *Structural damage:* No structural damage due to erosion around el Laguito
- *Water quality El Laguito:* water quality should be equal to the quality of the bay
- *Amount of overtopping water:* Under normal conditions the amount should be 0, during storm once a year limited overtopping

5. Possible solutions

In this chapter possible solutions to the problem areas previously formulated are presented and tested for their preferability. The preferred solutions will be worked out into conceptual designs in the next chapter. To select a preferred solution per problem area multi criteria analyses are performed using the software Tetra.

The Tetra software is able to analyze different alternatives (possible solutions) on multiple criteria. It uses preference function modeling to do this. The outcome of the analysis will be ranked alternatives according to desirability. The first step is to define the criteria upon which the decision will be based. Subsequently these criteria have to be weighted to determine how important they are in relation to each other. Then the alternatives that are going to be considered in the decision must be formulated. The alternatives will be different for each of the problem areas. To identify several promising alternatives that can be scored, several brainstorm sessions were held. Per problem area ratings can then be given for each of the alternatives with respect to every criterion. The scores of alternatives on the criteria will be on a scale from zero to five. When all this is done Tetra can compute the overall scores and shows a numerical rating of the alternatives.

The criteria and weights will first be elaborated on, these are the same for all the problem areas. For accessibility there will be two extra unique criteria, these will be explained in the paragraph on accessibility further on in the chapter. The rest of the steps necessary for the analysis in Tetra are performed per problem area. This includes the formulation of alternatives, their scores on the criteria, and finally the preferability derived from Tetra.

5.1 Criteria

From the analyses in the previous chapters the following criteria for the ranking of alternatives are derived; construction costs, maintenance, adaptability, aesthetics, added value, and effects on environment. These criteria will now be described.

Construction costs

These are the costs to realize a certain solution. The lower the estimated costs the higher an alternative will score, since less costs is seen as positive.

Maintenance

This criteria is about the amount of maintenance needed and the complexity of the maintenance. In previous analyses it became evident that maintenance can become a problematic issue, due to the fact that maintenance is not common to execute in Colombia. Therefore the less (complex) maintenance needed the higher an alternative scores.

Adaptability

Given that adaptations might be necessary in the future, an alternative scores high when it can easily be adapted or modified. This can give a solution more value because the future might be different than expected.

Aesthetics

Apart from the practical and technical characteristics of solutions the aesthetics will also be assessed. Stakeholders appreciate solutions that are not obnoxious or don't fit the surroundings and are out of context.

Added value

Solutions might have positive effects that add value to the peninsula of Bocagrande. Although dealing with the problems is a primary concern, 'side effects' that have added value, cannot be ignored.

Effects on environment

A solution can have effect on its surrounding environment and third parties. This can be positive or negative, but scores are given relatively between the different alternatives.

5.1.1 Weighted criteria

As mentioned above the criteria will have to be weighted to take into account the relative importance of the different criteria. The weights are interpreted given the information from different stakeholders and performed analyses. The importance of every criteria is also rated on a scale from 0-5. Tetra will automatically compute this to weights expressed in percentages.

- The weight of the construction costs criterion is scored at 4 (25%).
- The weight scores of the maintenance and added value criteria are estimated at 3 (18,75%)
- The Adaptability, aesthetics, and effects on environment criteria are weighted with a score of 2 (12,5%)

The construction costs are of mayor importance in every project, and in this case that is no exception. But in most cases the costs are far more important than other criteria. In this case the criteria maintenance and added value are not far behind. Maintenance is very important because of the analyzed current problems with maintenance (Example of La Bocana in paragraph 2.3.2). Added value is estimated to be equally as important because in the current situation of Bocagrande most of the space that is available is used for buildings and other activities. So a solution that adds value by supplying more opportunities for development of economic activities is very valuable.

Somewhat less important are the adaptability, aesthetics, and the effects on environment. These topics are not mentioned as much as the other criteria by different stakeholders. These seem to be subjects that are found to be of less importance in this situation.

5.2 Overtopping alternatives

From a brainstorm multiple solutions have been found that deal with the overtopping problems. The solutions with their properties are shown in table H.1 in appendix H. A selection of the most effective solutions from this brainstorm is made, and these will now be explained in more detail before they are assessed in Tetra.

5.2.1 Build berm

A good way to dissipate energy is by using a berm in front of the seawall along the entire part where overtopping is a problem. The berm does need a good toe structure in order to be stable.

Figure 5.1 Berm

5.2.2 Raise seawall

A very direct solution to the problem is to heighten the seawall. Off course the seawall does need to be impermeable to make sure the water does not flow through the pores. This solution would probably require a large and high seawall, which can be undesirable close to the historic centre.

Figure 5.2 Raise seawall

5.2.3 Combination of berm and higher seawall

A combination of the previously described alternatives could also be realized. In this case both the berm and the seawall will be needed in a less extreme way because they complement eachother.Since the foreshore differs along this stretch one could vary in the dimensions of the berm and seawall to adapt to the local conditions. This is a great advantage of combining the two methods.

Figure 5.3 Combination of berm and higher seawall

5.2.4 Alternative rating

In Table 5.1 the alternatives are rated on the different criteria on a scale from 0 to 5. This is done in a simple and intuitive manner. The previously explained weight scores are also given in this table.

	weight	Build berm	Combination	Raise seawall
Costs	4	3	5	3
Maintenance	3	3	3	3
Adaptability	2	3.5	3	1
Aesthetics	2	3.5	3	2
Added value	3	2	2	2
Effects on environment	2	3	3	3

Table 5.1 Overtopping alternative scores

In order for tetra to have a scale (0 to 100) on which it can analyze the scores of the alternatives it needs reference alternatives. This can be done by adding 'dummy' alternatives as reference alternatives. This means that a low reference alternative scores 0 on every criteria and a high reference alternative scores 100 on every criteria. The scores of the other alternatives are converted to this new scale of 0-100. Table 5.2 shows the 'indexed' ratings according to this method. This same principle applies for the other problem areas that are analyzed.

	Weight (%)	Reference alternative Low	Build berm	Combination	Raise seawall	Reference alternative High
Costs	25	0	60	100	60	100
Maintenance	18,75	0	60	60	60	100
Adaptability	12,5	0	70	60	20	100
Aesthetics	12,5	0	70	60	40	100
Added value	18,75	0	40	40	40	100
Effects on environment	12,5	0	60	60	60	100

Table 5.2 Overtopping alternative scores for Tetra input

By running the model in Tetra the software computes the scores of each alternative, and the alternatives are ranked on preferability. Figure 5.4 shows the outcome of the model. From this analysis can be concluded that the 'Combination of a berm and raising the seawall' alternative is most preferable. A berm is used as much as possible and raising the seawall is limited to as high as needed in different places. This reasoning is also backed up by the fact that a berm for the complete area is more preferable than a raised seawall for the complete area.

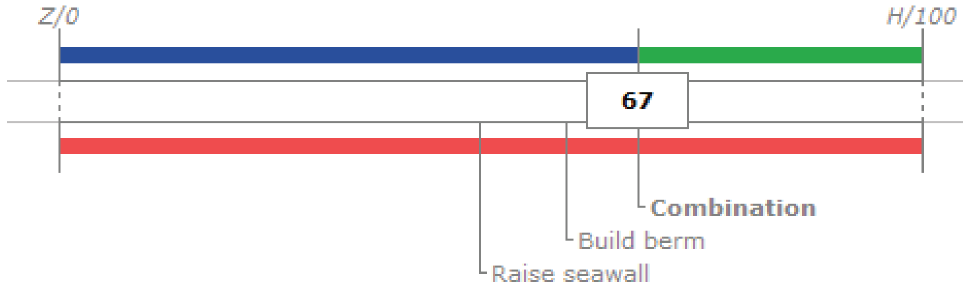


Figure 5.4 Tetra solution overtopping

5.3 Sea side alternatives

A number of solutions that were found during a brainstorm session are presented in table H.2 of appendix H. A short description and pros and cons explain the solutions. A large number of possible solutions have been identified, however not all of the options are as effective as others to solve the problems of erosion and flooding on the sea side of Bocagrande. Some solutions only solve parts of the problem and require a combination of multiple measures. Therefore a selection of the most effective solutions is made, and these will now be explained in more detail before they are assessed in Tetra.

5.3.1 Wall with vegetated dunes

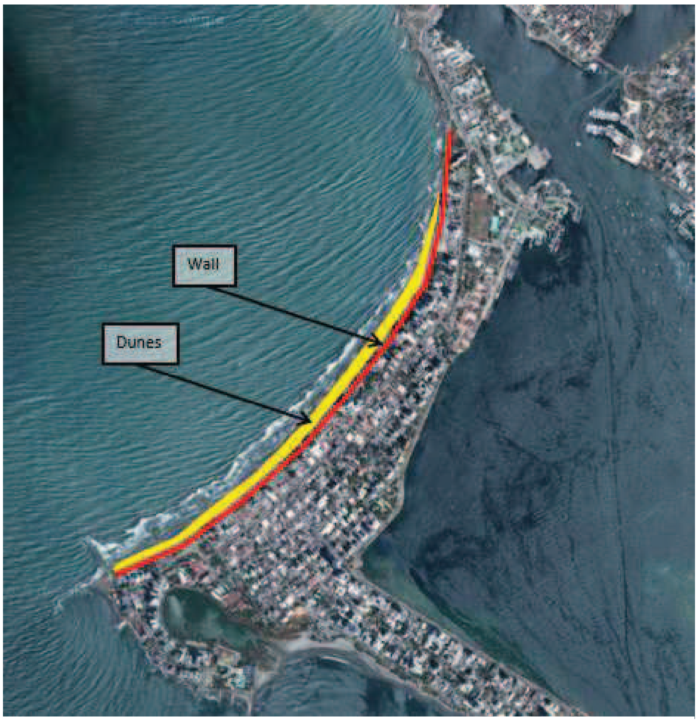


Figure 5.5 Wall with vegetated dunes

This solution combines a wall and the construction of dunes. The wall should be constructed at the landward side, which protects the land behind it against flooding and acts as a limit for the erosion during high wave conditions. On the seaward side of the wall dunes are created, these can build up against the constructed wall. As was observed in the system analysis of erosion, wind induced sediment transport is present along the beaches of Bocagrande. Once the wall is constructed, this sediment can accumulate along the wall and form dunes. Vegetation should provide stability of the sediment against erosion. This solution partly restores the natural situation with dunes and additional value is added if the wall is used for multiple purposes, i.e. a promenade and storage of drained rain water.

5.3.2 Nourishments

Figure 5.6 Nourishments

A relatively simple solution to obtain more beach is to perform nourishments. These nourishments can either be carried out on the beach itself or on the shoreface. To increase the safety against flooding, beach nourishments can be more effective because the beach level can be raised. This solution does need maintenance every 5-10 years depending on the quantity of the nourishments. Larger beaches will add additional value for tourism businesses as well.

5.3.3 T-groynes and nourishments

A combination of T-groynes and nourishments can be used to trap sediment and reduce maintenance nourishments. The T-groynes trap the sediment better than regular groynes and can thereby increase the length of the beaches. The T-groynes also reduce the wave impact on the beaches resulting in less erosion during high wave conditions. The construction of T-groynes does limit the sediment transport along the beach and probably results in downstream erosion. The large structures also have impact on the esthetics of the area, because only a small actual beach remains present.

Figure 5.7 T-groynes and nourishments

5.3.4 Alternative rating

The tables below show the rated alternatives on the different criteria on a scale from 0-5 (Table 5.3) and the indexed ratings (Table 5.4) which are used as input for Tetra. This is done in the same way as described earlier.

	weight	Nourishments	T-groynes and Nourishments	Wall with vegetated dunes
Costs	4	4	2	4
Maintenance	3	1	4	3
Adaptability	2	4	2	3
Aesthetics	2	4	3	5
Added value	3	3	2	4
Effects on environment	2	3	1	5

Table 5.3 Sea side alternative scores

	Weight (%)	Reference alternative Low	Nourishments	T-groynes and Nourishments	Wall with vegetated dunes	Reference alternative High
Costs	25	0	80	40	80	100
Maintenance	18,75	0	20	80	60	100
Adaptability	12,5	0	80	40	60	100
Aesthetics	12,5	0	80	60	100	100
Added value	18,75	0	60	40	80	100
Effects on environment	12,5	0	60	20	100	100

Table 5.4 Sea side indexed scores for Tetra input

Figure 5.8 shows the outcome of the model. From this analysis can be concluded that the 'Wall with vegetated dunes' alternative is most preferable. It scores substantially higher than the other alternatives.

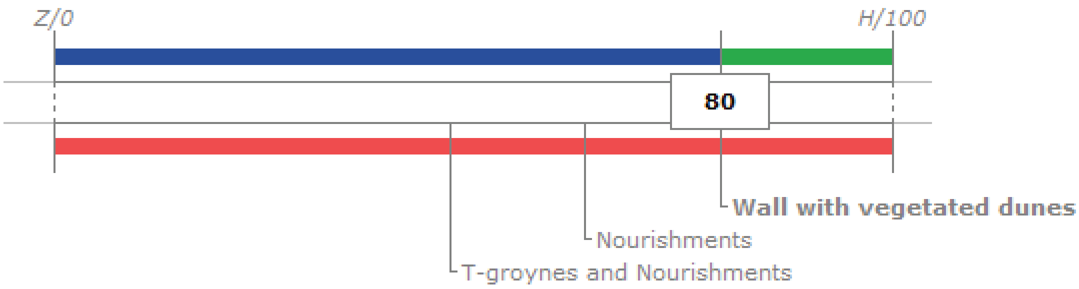


Figure 5.8 Tetra solution sea side

5.4 Erosion El Laguito alternatives

The solutions that were found during a brainstorm session are presented in table H.3 of appendix H. Short description and pros and cons of each solution explain the solutions. By brainstorming a large number of possible solutions have been identified, however not all of the options are as effective as others to solve the erosion problems. Some solutions only solve parts of the problem and require a combination of multiple measures. Therefore a selection of the most effective solutions is made, and these will now be explained in more detail before they are assessed in Tetra.

5.4.1 Seawall

In order to alleviate the damage that can be caused by erosion on El Laguito an effective measure is to use a hard seawall that prevents additional erosion from undermining the existing structures. The area is now partly stabilized with protection against erosion, this protection can be extended to cover the erosion prone area, see Figure 5.9. The seawall does not create any extra value to the area. The existing small restaurants and shops will not be able to continue their business in the future once the beaches are all gone and sea level rise continues.

Figure 5.9 Seawall El Laguito

5.4.2 T-groynes and nourishments

The construction of T-groynes and carrying out sand nourishments will establish beaches and create additional value to the area. The T-groynes are more effective than extending existing groynes because T-groynes trap more sediment in the presence of a large wave angle. Some erosion along Castillogrande could be expected because of reduced sediment transport at the T-groynes area. However, accretion was present in the current situation along Castillogrande and the mouth of Laguito lake, a small reduction in sediment supply will not have a large impact. The soil in the mouth of Laguito lake could be used as a source of sediment for the nourishments.

Figure 5.10 T-groynes and nourishments

5.4.3 Raised Escollera dam and nourishments

A possible solution is to raise the Escollera dam to reduce wave attack on the beaches of El Laguito. In combination with nourishments stable beaches can be established. The dam should have an opening to let boats pass. A possibility is even to make a road on top of the dam with a bridge across the opening, this could increase the interaction with Tierra Bomba. A negative aspect of this option is that the water in the bay has less interaction with the sea, which results in worse water quality inside the bay.

Figure 5.11 Raised escollera

5.4.4 Alternative rating

The tables below show the rated alternatives on the different criteria on a scale from 0-5 (Table 5.5) and the indexed ratings (Table 5.6) which are used as input for Tetra. This is done in the same way as described earlier.

	Weight	Raised Escollera dam and nourishments	Seawall	T-groynes and nourishments
Costs	4	2	4	2
Maintenance	3	4	4	3
Adaptability	2	3	3	3
Aesthetics	2	2	3	3,5
Added value	3	3	0	4
Effects on environment	2	1	3	3

Table 5.5 Erosion El Laguito alternative scores

	Weight (%)	Reference alternative Low	Raised Escollera dam and nourishments	Seawall	T-groynes and nourishments	Reference alternative High
Costs	25	0	40	80	40	100
Maintenance	18,75	0	80	80	60	100
Adaptability	12,5	0	60	60	60	100
Aesthetics	12,5	0	40	60	70	100
Added value	18,75	0	60	0	80	100
Effects on environment	12,5	0	20	60	60	100

Table 5.6 Erosion El Laguito indexed scores for Tetra input

Figure 5.12 shows the outcome of the model. From this analysis can be concluded that the 'T-groynes and nourishments' alternative is most preferable.However, the difference with the seawall alternative is very small. The main reason for this is the low score on added value that compensates the higher score it has on costs. For this problem area the decision on which of the two solutions is best highly depends on the appreciation of this extra value and the extra costs this brings along. Therefore also the seawall will be presented in the next chapter as a low cost, no value adding, alternative.

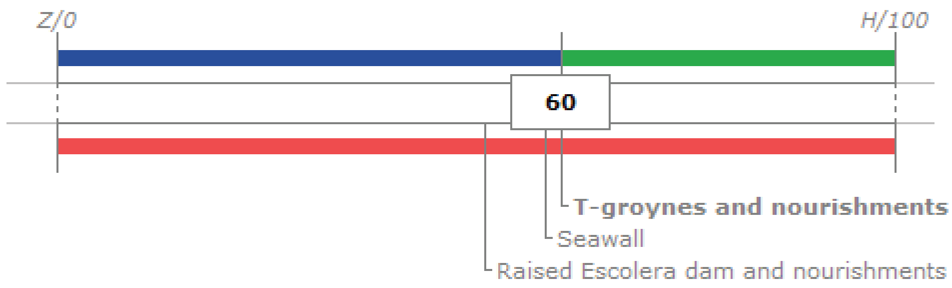


Figure 5.12 Tetra solution erosion El Laguito

5.5 El Laguito lake alternatives

A number of solutions were found for the Laguito lake during a brainstorm session. They are presented in table H.4 of appendix H. A selection of the most effective solutions is made, and these will now be explained in more detail before they are assessed in Tetra.

5.5.1 Fill the lake with soil

In order to get rid of the stagnant water in El Laguito Lake an option is to fill the lake with soil, which creates new land. This option provides new area for project development and thereby adds additional value to the area. However, the lake could be a valuable asset to El Laguito and the hotels and apartments in the neighborhood. But if the city of Cartagena is not able to find a sustainable solution for keeping open the lake, this option is a good alternative. The lake is quite deep because the soil was used for construction of the area. Therefore a significant amount of soil is required to fill the lake.

Figure 5.13 Fill the lake with soil

5.5.2 Dredging, groyne extension and sand trap

To be able to use of the lake in the future, the opening should be dredged or excavated. However, the sedimentation is approximately 25,000 m^3/year so maintenance dredging is required often. A sand trap can be used to trap the sand before it reaches the opening of the lake. The advantage of a sand trap is that the location of the sand trap can be reached more easily than dredging the opening of the lake itself. Also it does not interrupt the ships that use the entrance of the lake. Extension of the largest groyne at the Hilton hotel will reduce sediment transport towards the entrance of the lake. An additional problem for this solution is that less sediment reaches the

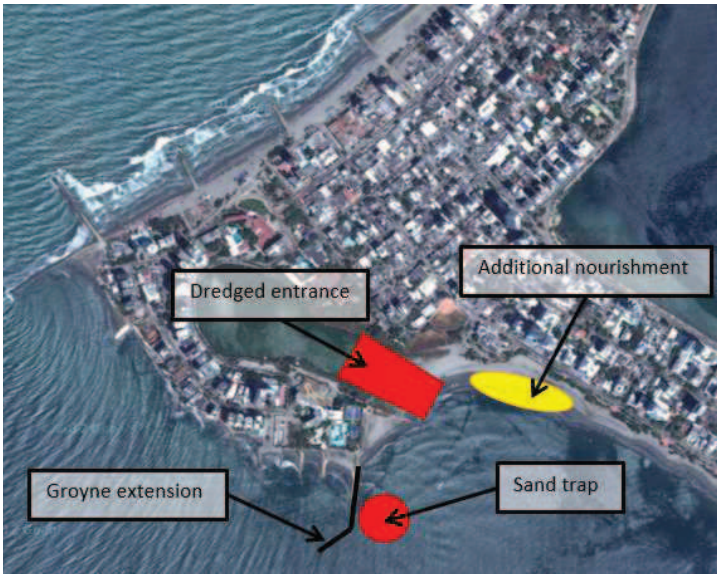


Figure 5.14 Dredging, groyne extension and sand trap

beaches of Castillogrande. Therefore some of the dredged material can be deposited on the beaches of Castillogrande.

5.5.3 Bypass system

A bypass system that continuously dredges the opening of the lake could be used to have a permanent system that keeps the lake open. At the same time it can nourish the beaches in the northern part of El Laguito so that the erosion problems there are mitigated as well. This system is relatively expensive and complex. It also requires significant maintenance.

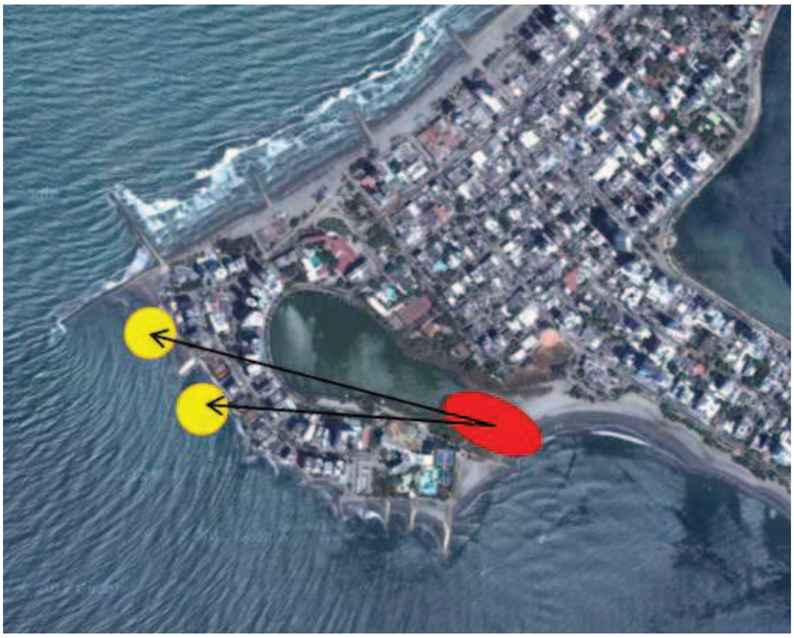


Figure 5.15 Bypass system

5.5.4 Alternative rating

The tables below show the rated alternatives on the different criteria on a scale from 0-5 (Table 5.7) and the indexed ratings (Table 5.8) which are used as input for Tetra. This is done in the same way as described earlier

	Weight	Bypass system	Dredging, groyne extension and sandtrap	Fill the lake with soil
Costs	4	2	3	4
Maintenance	3	4	2	5
Adaptability	2	2	2	1
Aesthetics	2	3	5	1
Added value	3	2	3	4
Effects on environment	2	3	4	2

Table 5.7 El Laguito Lake alternative scores

	Weight (%)	Reference alternative Low	Bypass system	Dredging, groyne extension and sandtrap	Fill the lake with soil	Reference alternative High
Costs	25	0	40	60	80	100
Maintenance	18,75	0	80	40	100	100
Adaptability	12,5	0	40	40	20	100
Aesthetics	12,5	0	60	100	20	100
Added value	18,75	0	40	60	80	100
Effects on environment	12,5	0	60	80	40	100

Table 5.8 El Laguito Lake indexed scores for Tetra input

Figure 5.16 shows the outcome of the model. From this analysis can be concluded that the 'Fill the lake with soil' alternative is most preferable. However the 'dredging, groyne extension and sandtrap' alternative is almost as preferable. Filling the lake is the most straight-forward, cheapest, no maintenance needing alternative. So it scored high on the criteria with the highest weights. But because it also scores very low on the other criteria the choice is made to also present a conceptual design of the 'dredging, groyne extension and sandtrap' alternative in the next chapter. Opening the lake could be something that is very much preferred by a powerful party, although it demands a lot more effort and commitment (maintenance).

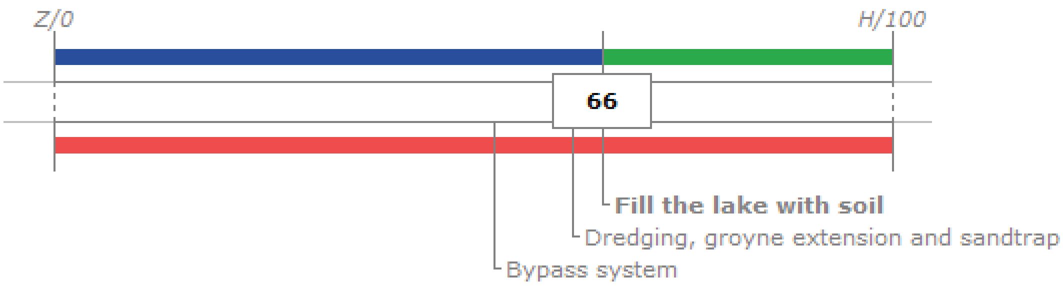


Figure 5.16 Tetra solution lake Laguito

5.6 Bay side alternatives

Through a brainstorm session multiple solutions have been found that alleviate the problems indicated for the bay side of the peninsula. The solutions with their properties are shown in table H.5 in appendix H selection of the most effective solutions is made, and these will now be explained in more detail before they are assessed in Tetra.

5.6.1 Revetment with valves

A solution that is very effective against flooding is to construct a revetment along the shoreline. The height can be chosen that it is high enough to withstand sea level rise in the future. Currently a limited revetment is present along the northern side of Castillogrande with a footpath on top. This revetment can be raised relatively easy in order to have it high enough to prevent floods in the future. Valves should be installed in the drainage pipes to prevent sea water from entering the area. The revetment could also be combined with the drainage system. Water storage could be placed inside the revetment.

Figure 5.17 Revetment with valves

5.6.2 Raise land

A solution that requires the least maintenance and is therefore a durable solution in Cartagena, is to raise the land of the complete peninsula. The elevations of some sections of the peninsula are high enough, but most of the area needs to be raised in order to withstand flooding due to storm surges and sea level rise in the future. An option would be to sacrifice the first floors of buildings to be able to raise the land.

Figure 5.18 Raise land

5.6.3 Alternative rating

The tables below show the rated alternatives on the different criteria on a scale from 0-5 (Table 5.9) and the indexed ratings (Table 5.10) which are used as input for Tetra. This is done in the same way as described earlier.

	weight	Raise land	Revetment with valves
Costs	4	1	5
Maintenance	3	4	2
Adaptability	2	1	5
Aesthetics	2	3	3
Added value	3	2	2
Effects on environment	2	2	3

Table 5.9 Bay side alternative scores

	Weight (%)	Reference alternative Low	Raise land	Revetment with valves	Reference alternative High
Costs	25	0	20	100	100
Maintenance	18,75	0	80	40	100
Adaptability	12,5	0	20	100	100
Aesthetics	12,5	0	60	60	100
Added value	18,75	0	40	40	100
Effects on environment	12,5	0	40	60	100

Table 5.10 Bay side indexed scores for Tetra input

Figure 5.19 shows the outcome of the model. From this analysis can be concluded that the 'Revetment with valves' alternative is most preferable. The difference with the raise land alternative is very clear. The reason for this is that raising the land is a very drastic and expensive solution that will probably gain a lot of resistance as well.

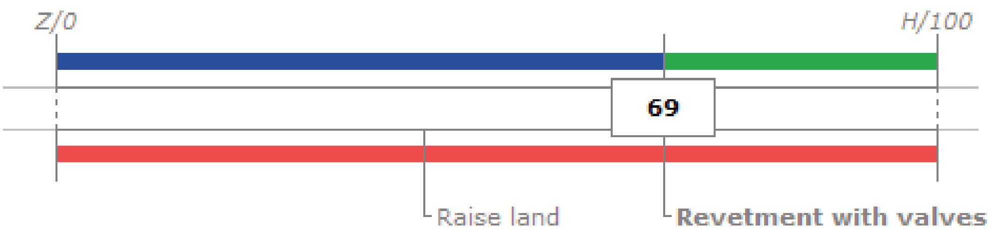


Figure 5.19 Tetra solution bay side

5.7 Accessibility alternatives

For the accessibility a different approach for the assessment of alternatives is in order. Alternatives need to be modelled to be able to assess the criteria that are unique for this problem area; Travel time and link load. An explanation of how these two new criteria will be measured and scored is firstly given.

Travel time

This criterion is measured by the average decrease in travel time to and from Bocagrande. This information will be gained by running the transport model with a possible solution. The output of the model will be a certain average travel time reduction. For the MCA a score between 0 and 5 will be given based on the output of the model. The higher the reduction of travel time, the higher the score.

Link load

This criteria is measured by the link loads of the roads around the connection between Bocagrande and the city centre. From the output of the model the ratio between the capacity and the intensity of these links can be obtained. For the MCA a score between o and 5 will be given based on these calculated ratios. A lower ratio is more positive than a higher one.

An imported aspect of accessibility is that it is negatively influenced by the issues at the other problem areas. So solving these problems will have a positive effect on the accessibility. But how big this effect is, is still unknown. Resolving the flooding and overtopping problems will therefore be analysed as a separate alternative. The other possible solutions will be including this 'base' situation.

5.7.1 Repair roads and no more overtopping and flooding (base solution)

In the model this 'base alternative' entails that the overtopping and flooding problems are resolved and roads are repaired. By doing this existing roads will gain back their full (design) capacity. Along the Avenida Santander both lanes will be fully useable and on Bocagrande the roads will not be flooded anymore, which results in higher possible driving speeds. The results of the model are shown in Figure 5.20.

Figure 5.20 Model outcome 'base alternative'

As presented in Table 5.11 the average travel time for trips to and from Bocagrade will be reduced by 11,3 and 15,1 min. This time reduction is much more than the average travel time reduction per trip in the total model. These values are interpreted into a score of 2/5 for the criteria 'travel time'.

	Time reduction
Average to Bocagrande	11,3 min/vehicle
Average from Bocagrande	15,1 min/vehicle
Average of all trips	1,08 min/vehicle
Total travel time	1941 vehicle * hour

Table 5.11 Travel time reductions base alternative

Concerning the link load Table 5.12 shows that intensities, except for coastal road south, are higher than 1. This is still an undesired link load that leads to congestion. Therefore the score on the link load criteria is interpreted as a 2 out of 5.

	Link load
To Bocagrande	1,04
From Bocagrande	1,21
Coastal road north	1,12
Coastal road south	0,67

Table 5.12 Link loads base alternative

5.7.2 Tunnel and road extension Manga

Figure 5.21 Tunnel and road extension Manga

To take away pressure from the existing Bocagrande-Centro connection, a new tunnel connection between Bocagrande and Manga and a road extension on Manga can be constructed. This is however an expensive solution. The position of the tunnel is chosen to be just north of the naval base. The Naval base limits the possibilities of where a new connection to Manga could be realized on a relatively short term (next 10-15 years). This alternative resembles a great part of a plan that is made by the regional port authority (SPRC), who exploits the port on Manga. Redirecting the main traffic around the northern edge of Manga would reduce the though traffic in Manga and along the port, which has a positive impact on the accessibility of the port. This is seen as a great added value of this possible solution. The results of modelling this alternative are shown in Figure 5.22.

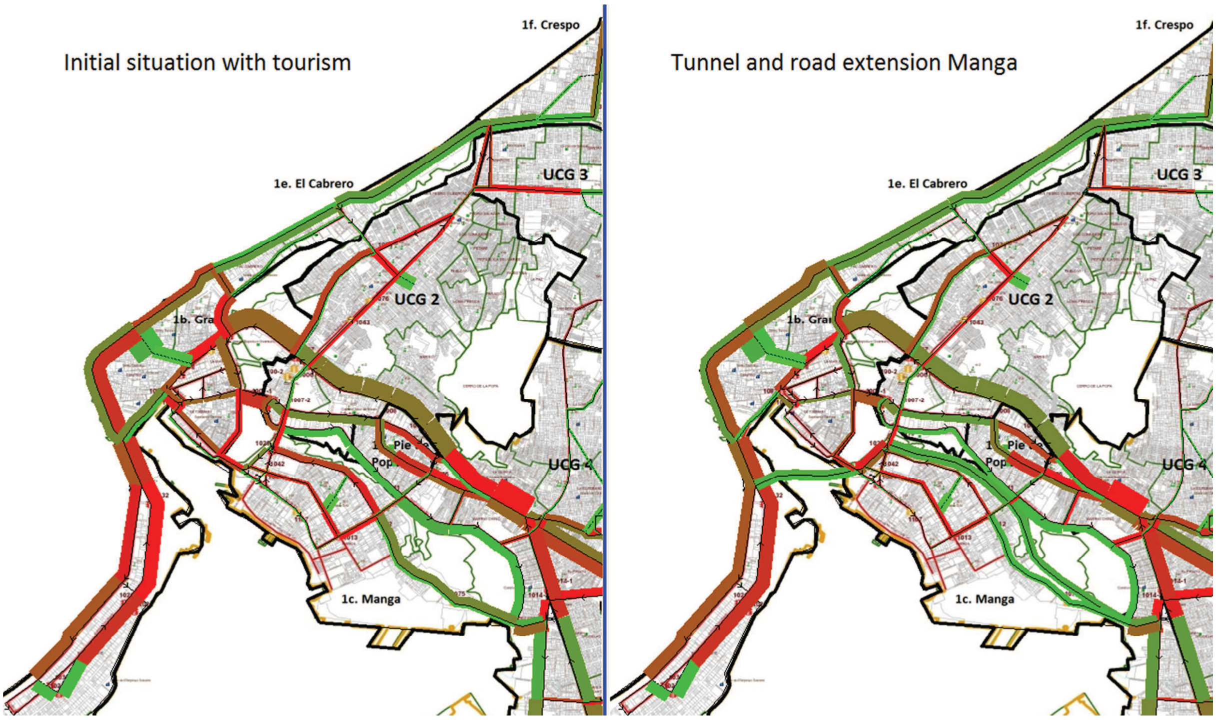


Figure 5.22 Model outcome 'Tunnel and road extension Manga'

As presented in Table 5.13 the average travel time for trips to and from Bocagrade will be reduced by 18,4 and 20,4 min. The average travel time reduction of all the trips is 2,82 min/vehicle. These values are interpreted into a score of 5 out of 5 for the criteria 'travel time'.

	Time reduction
Average to Bocagrande	18,4 min/vehicle
Average from Bocagrande	20,4 min/vehicle
Average of all trips	2,82 min/vehicle
Total travel time	3157 vehicle * hour

Table 5.13 Time reductions tunnel alternative

Although the travel times are greatly reduced with this alternative, the above table shows that intensities going out of Bocagrande are still higher than 1. Therefore the score on the link load criteria is interpreted as a 3 out of 5.

	Link load
To Bocagrande	0,9
From Bocagrande	1,12
Coastal road north	1,01
Coastal road south	0,61

Table 5.14 Link loads tunnel alternative

5.7.3 Widening of existing infrastructure

The capacity of the road between Bocagrande and the centre and along the coast can be increased by adding 2 extra lanes to the existing infrastructure. This means one extra lane for each direction. A difficulty with this alternative is the lack of room for widening the road. It would require the reclamation of land to realize the extra lanes. This will have effect on the designs of solutions for overtopping and the sea side problem areas. This also makes the alternative more expensive. The results of modelling this alternative are shown in Figure 5.24

Figure 5.23 Road widening

Boskalis

Figure 5.24 Model outcome 'Widening of existing infrastructure'

As presented in Table 5.15 the average travel time for trips to and from Bocagrade will be reduced by 11,7 and 16,8 min. The average travel time reduction of all the trips is 1,18 min/vehicle. These values are interpreted into a score of 2,5 out of 5 for the criteria 'travel time'.

	Time reduction
Average to Bocagrande	11,7 min/vehicle
Average from Bocagrande	16,8 min/vehicle
Average of all trips	1,18 min/vehicle
Total travel time	2229 vehicle * hour

Table 5.15 Time reductions widening alternative

Table 5.16 shows that intensities are all acceptable and lower than 1. This solution directly involves the widening of the links between the centre and Bocagrande. The score on the link load criteria is interpreted as a 5 out of 5.

	Link load
To Bocagrande	0,73
From Bocagrande	0,86
Coastal road north	0,79
Coastal road south	0,51

Table 5.16 Link loads widening alternative

5.7.4 Alternative rating

The tables below show the rated alternatives on the different criteria on a scale from 0-5 (Table 5.17) and the indexed ratings (Table 5.18) which are used as input for Tetra. This is done in the same way as described earlier.

	Weight	Repair roads, no overtopping and flooding	Tunnel and road extension Manga	Widening existing infrastructure
Costs	4	5	1	2
Maintenance	3	4	3	3
Adaptability	2	4	2	3
Aesthetics	2	3	3	2,5
Added value	3	2,5	5	3
Effects on environment	2	3	4	3
Travel time	5	2	5	2,5
Link load	3	2	3	5

Table 5.17 Accessibility alternative scores

	Weight (%)	Reference alternative Low	Repair roads, no overtopping and flooding	Tunnel and road extensio n Manga	Widening existing infrastructure	Reference alternative High
Costs	16,7	0	100	20	40	100
Maintenance	12,5	0	80	60	60	100
Adaptability	8,33	0	80	40	60	100
Aesthetics	8,33	0	60	60	50	100
Added value	12,5	0	50	100	60	100
Effects on environment	8,33	0	60	80	60	100
Travel time	20,8	0	40	100	50	100
Link load	12,5	0	40	60	100	100

Table 5.18 Accessibility indexed scores for Tetra input

Figure 5.25 shows the outcome of the model. From this analysis can be concluded that the 'Tunnel and road extension Manga' alternative is most preferable. But the difference with the base solution is relatively small. The main reason for this is the high cost of the tunnel solution. This implicates that the choice whether to implement this solution or not needs careful attention because although the effects on travel time and link load are very positive, especially the costs bring down the preferability to almost the level of the base alternative.

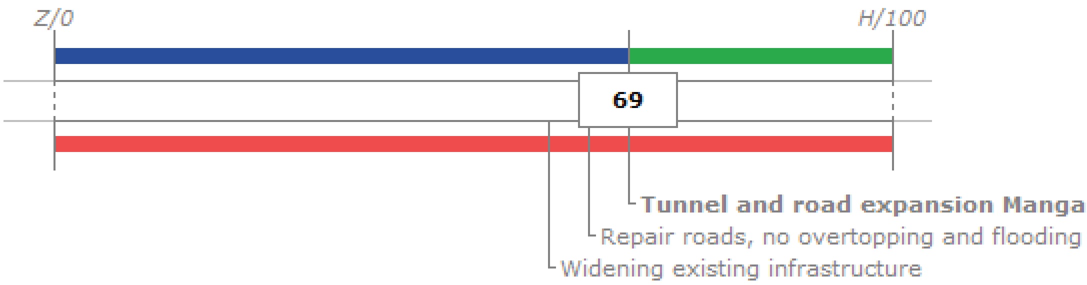


Figure 5.25 Tetra solution accessibility

5.8 Conclusion

For every problem area a most preferable solution, based on the formulated criteria, has now been selected using the multi criteria decision making software Tetra. For the overtopping a 'Combination of berm and higher seawall' is selected. For the sea side the 'Wall with vegetated dunes' is most preferable. 'T-groynes and nourishments' is selected for erosion El Laguito. For El Laguito lake the 'Fill the lake with soil' alternative is selected. For the bay side 'Revetment with valves' is most preferable. And finally for the accessibility the 'Tunnel and road extension Manga' is most preferable.

Conceptual designs of the selected (most preferable) alternatives will be presented in the next chapter. However, for the erosion El Laguito and El Laguito lake problem areas the second best scoring alternative will also be presented because the difference with the most preferable alternative was very small. A slightly different opinion about a weight or a score could easily change which of the two solutions is most preferable.

6. Conceptual design

In this chapter the best scoring solution per problem area from the previous chapter will be elaborated. For each solution the design concept, design requirements, dimensions and the construction costs will be discussed. Subsequently the cost benefit of all the solutions combined will be generated and a final conclusion will be given.

6.1 Solution Overtopping – Berm and raised sea wall

The solution to the overtopping problem is determined by the multi criteria analysis. A combination of raising the existing sea wall and constructing a berm is chosen as the best solution. This chapter discusses the conceptual design of the overtopping solution to protect the road along the old center of Cartagena. The rough design consists of the dimensions of the solution, and how it should fit in the current situation. The dimensions are based on the design requirements and boundary conditions. Also the quantities of required rocks are estimated as well as the execution costs.

6.1.1 Design concept

The current sea wall is not able to prevent overtopping of the road along the coast and severe damage to the infrastructure has taken place. Not only the road is damaged, the sea wall itself has experienced damage as well, which has negatively impacted its function as coastal protection.

Figure 6.1 Sea wall

In order to reduce overtopping of the sea wall, a height increase is very effective. However, the aesthetic value of the area will be vastly reduced if people are not able to look over the sea wall anymore. Therefore another solution other than raising the sea wall is considered. A berm will increase wave energy dissipation so that overtopping over the crest is reduced. The crest should be raised to account for sea level rise and excessive overtopping during storm conditions. The sea wall is considered over a stretch of 2000m, from the first T-groyne north of the old city center to the northern tip of Bocagrande in the south.

The existing seawall has differing dimensions and structural properties over its length. The conceptual design establishes general dimensions for the future seawall, in further research the local conditions and properties should be considered in the design.

6.1.2 Design requirements

- No overtopping under normal conditions: $q_{mean} \approx 0$ $m^3/s/m$;
- Limited overtopping during 1/ year storm conditions: $q_{mean} < 0.01$ $m^3/s/m$, based on table 5.4 (CIRIA, 2007) for safety of vehicles driving at low speed;
- The overtopping quantities should be considered for a sea level rise of 50cm over the next 50 years;
- The seawall slope should be stable for 1/50 year storm conditions;

- The maximum crest height from aesthetic point of view is 1m higher than the current sea wall crest height.

6.1.3 Dimensions

The general dimensions of the sea wall are calculated using overtopping and stability formula thereby applying the design requirements and boundary conditions.

Conditions

The conditions under which the wall has to be able to prevent overtopping are categorized in storm conditions and normal conditions. The water depth limits the maximum wave height, which is set to 2,5m for once a year storm conditions (see appendix E). A spring tidal height of 0,35m is applied to both normal and storm conditions. The 1/50 years storm conditions are used to calculate the stability of the structure, whereas the normal and 1/year conditions are used to calculate overtopping quantities. The following aspects (Table 6.1) with their values are used for the calculation of the sea wall.

	Normal conditions	1/year storm conditions	1/50 year storm conditions
Storm surge	0.2 m	0.5 m	1.0 m
Tide	0.35 m	0.35 m	0.35 m
Wave	1 m	2.5 m	3.0 m

Table 6.1 Conditions

Crest height

The crest height of the current sea wall is estimated to be at MSL + 2m. The maximum crest height from aesthetic point of view is considered to be 1m higher than the current situation. This is a height of MSL + 3m.

Overtopping

The overtopping quantities are calculated using a modified van der Meer formula in order to account for a berm and crest width. Overtopping quantities for the current situation have been calculated in appendix F, which uses this formula as well but without berm factor.

Standard formula: Eq 6.5 (EurOtop, 2007)

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.2 \cdot \exp\left(-2.3 \frac{R_C}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta}\right)$$

Crest width factor: Eq. 6.7 (EurOtop, 2007)

$$C_r = 3.06\exp(-1.5G_c/H_{m0})$$

Boskalis

CB&I

Berm factor: γ_b see appendix F, overtopping calculation (CIRIA, 2007)

Modified formula:

$$q = C_r * \sqrt{g * H_{m0}^3} * \gamma_b * 0{,}2 * exp(-2{,}3 \frac{R_c}{H_{m0} * \gamma_f * \gamma_\beta * \gamma_b})$$

Required dimensions

The dimensions that are required to reduce overtopping enough in order to meet the design requirements are shown in Table 6.2. The mean sea level in the future is adjusted for sea level rise. The maximum crest raise of 1m is applied, therefore overtopping can only be reduced to a limited extend by raising the sea wall. An increased crest width and berm are used in order to obtain additional overtopping reduction.

	Value
Crest height w.r.t. MSL R_c	2.5 m
Crest width G.	6 m
Berm width B_b	5 m

Table 6.2 Required dimensions

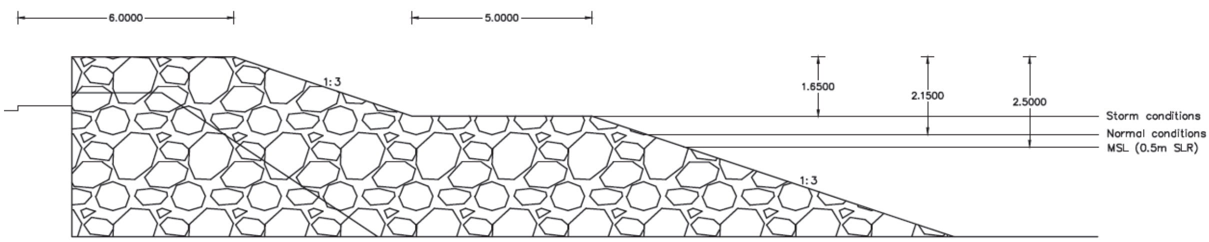


Figure 6.2 Future situation sea wall

	Normal conditions	Storm conditions
Overtopping volume q	$1{,}4*10^{-9}\ m^3/s/m$	$0{,}009\ m^3/s/m$

Table 6.3 overtopping volume

The overtopping discharges meet the design requirements, as $1{,}4*10^{-9}$ is considered to be negligible and $0.009 m^3/s/m < 0.01 m^3/s/m$.

Stone size

The stone size that is required for stability of the sea wall is estimated using the van der Meer formula for shallow water and plunging waves, eq. 5.139 (CIRIA, 2007).

$$\frac{H_s}{\Delta D_{n50}} = c_{pl} P^{0.18} \left(\frac{S_d}{\sqrt{N}}\right)^{0.2} \left(\frac{H_s}{H_{2\%}}\right) \left(\xi_{s-1,0}\right)^{-0.5}$$

The largest stone size that is found at a local quarry is D_{50}=1,2m-1,5m, from a cost point of view the desired required stone size should not be larger than the local available stone size. The required rock size for the breakwater with a slope of 1:3 and the 1/50 years significant wave height of 3m is $\boldsymbol{D_{50} = 1{,}30m}$. See appendix F for the full calculation.

6.1.4 Construction quantities

The new sea wall requires significant more rocks than the current existing sea wall. However, the current seawall rocks can be used as fill material for the new sea wall. The conceptual design only considers the volume of required rock with the required size for stability of the armor layer. In further design stages the core and armour layers can be divided and calculated more accurately.

The current sea wall has a cross sectional area of 22m^2, the future sea wall has an additional cross sectional area of 54,75m^2. The total required volume of rocks is:

$$V_{rocks} = L * A = 2000m * 54{,}75m^2 = \mathbf{1{,}1 * 10^5\ m^3}$$

6.1.5 Cost & benefits

The overtopping of the waves causing damage to the road which reduces the road capacity and causing congestion. The coastal road is one of the main important roads which connects the city centre to Bocagrande. Even during normal weather conditions there is wave overtopping. In stormy weather conditions the road is not accessible at all. The sea wall in its current condition is not sufficient to protect the road and the vehicles on it. During a storm it is possible that stones will get ripped off the sea wall and hit the road or the vehicles on it.

The construction of a berm and raising of the sea wall will decrease the amount of wave overtopping in such a way that there will be no overtopping under normal conditions and that the road is accessible during storm conditions. This will increase the accessibility of Bocagrande and the old city centre. It will also make sure that no stones will hit the road or vehicles on it.

The construction costs of this project is based upon the extension of the sea wall and the stone size.

Construction costs overtopping is estimated around: **$ 23.000.000.000** Pesos

A complete overview of the construction cost and the actual figures are placed in Appendix I

6.1.6 Impression

Below is a sketch of the current situation (Figure 6.3), and sketches of the situations with the wall and berm constructed under normal conditions (Figure 6.4) and storm conditions (Figure 6.5).

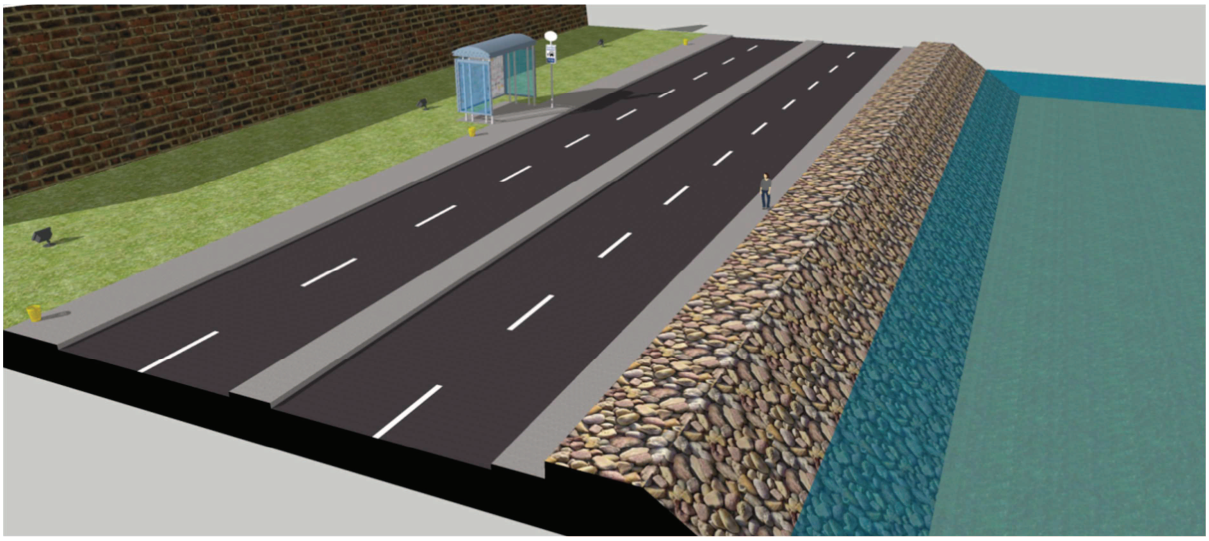


Figure 6.3 Sea wall in the current situation

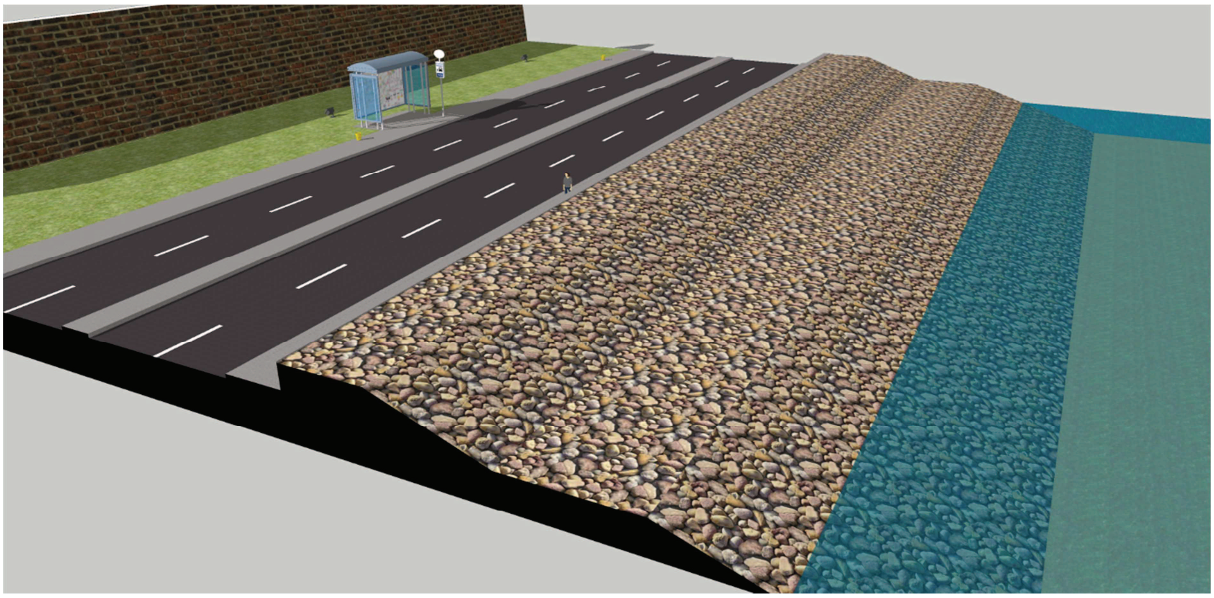


Figure 6.4 Sea wall in future situation under normal conditions

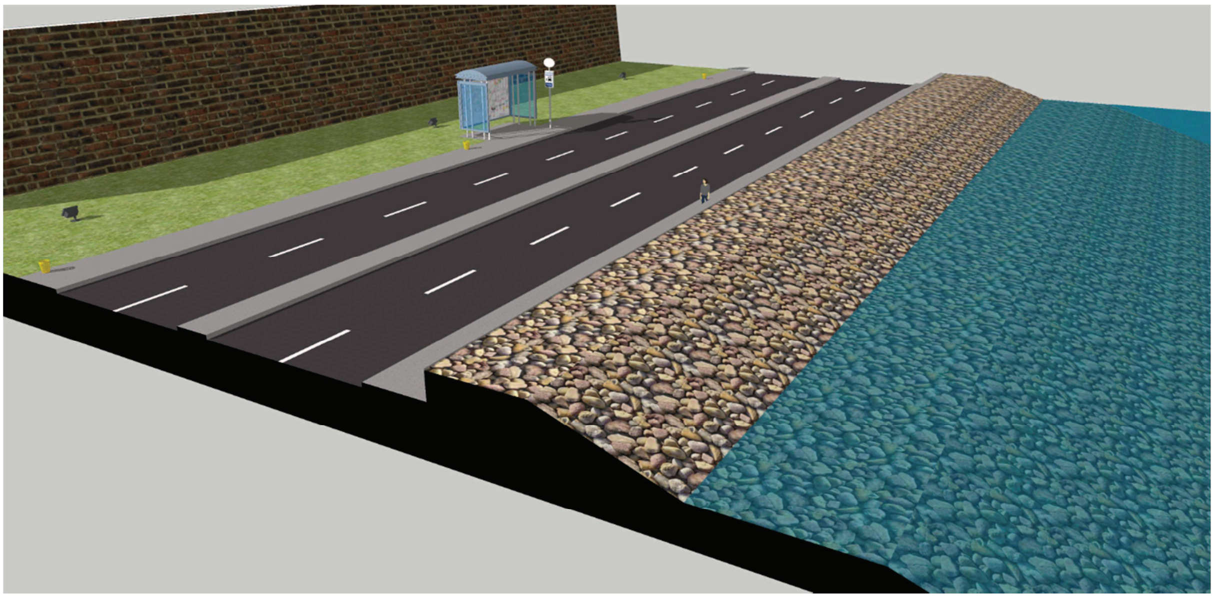


Figure 6.5 Sea wall in future situation under storm conditions

6.2 Solution Seaside – Wall with dunes

In order to solve the seaside problems of incidental erosion and flooding, the best solution according to the multi criteria analysis is to build a wall with dunes in front of it. This chapter presents the conceptual design of the solution on the seaside of Bocagrande.

The rough design consists of the dimensions of the solution, and how it should fit in the current situation. The dimensions are based on the design requirements and boundary conditions. Also the quantities of required nourishments are estimated as well as the execution costs.

6.2.1 Design concept

The solution that consists of a wall with dunes should prevent the seaside area of Bocagrande from flooding and should be able to cope with incidental erosion during the higher wave season. The formation of a storm profile should not threaten the adjacent area and preferably a beach should be present during the higher wave season along the main beaches of Bocagrande.

The wall will be located on the seaside of the road Carrera 1 and will thereby replace the current footpath. The construction of a wall in itself reduces the aesthetic value of the area as it limits the view on the sea, therefore the wall should be combined with measures that increase the value of the area. Therefore on the top of the wall a promenade will be constructed to replace the current footpath and add additional value to the area. This promenade attracts tourists and increases the aesthetic value of the area.

The dunes that are constructed on the seaward side of the wall function as a buffer against incidental erosion and reduce the loss of beach during the higher wave season. Part of the dunes will be created by nourishments. The dunes will accumulate to the wall naturally by wind driven sediment transport. In the current situation the wind induced sediment transport is directed towards the buildings along the shore where the sand is removed by the property owners. The construction of dunes restores the natural situation, see Figure 6.6. Additional vegetation is required to keep the sand of the dunes in place; this can be done by planting bushes or helm grass.

Figure 6.6 Natural dunes (left), wind induced sand transport current situation (right)

The wall will extend north towards the connection of the peninsula to the mainland. The promenade on top of the wall will only be constructed along the main beaches and tourist businesses on Bocagrande. The dunes will only be constructed on existing beaches as well. The stretch of coastline is approximately 2800m long. Over 2000m length the dunes, promenade and wall is constructed and over 800m only the wall is constructed.

6.2.2 Design requirements

The design of the wall and dunes should meet the design requirements in order to guarantee the safety and usability of the solution. The requirements for the wall and dunes are:

- The wall should be able to prevent flooding for 1/50 years conditions, by a combination of storm surge, tide, sea level rise and waves;
- The wall may allow some overtopping due to waves during extreme conditions, the water level should however not overrun the wall;
- Access to the beaches should be guaranteed;
- Current beaches must be preserved

6.2.3 Dimensions

The dimensions of the solution should be such that the design requirements are met and it fits in the current situation. The dimensions of the wall and the dunes are discussed separately.

Wall

The height of the wall is based on the following aspects:

- **Storm surge**
  A 1/50 year storm surge as is described in the boundary conditions (appendix E) has a height of approximately 1m.
- **Sea level rise**
  The relative sea level rise is expected to be 50cm on top the current mean sea level 50 years from now.
- **Tide**
  The probability of an extreme storm surge in combination with the highest tide is very small, therefore an average spring tidal amplitude of 0,35m is added to the wall height.
- **Waves**
  The extra height of the wall to prevent excessive overtopping is determined by the height of the incoming waves. During storm conditions waves can be high, for example the once per year 12 hour storm can create waves up to is 2.5m. However, waves that impact the wall will be of limited height because the waves break before they reach the wall. Because of the storm profile that forms and is provided by the dunes, the dissipation of waves is increased compared to the current situation. Additionally, some overtopping due to waves under extreme conditions is permitted as long as it does not result in full flooding of the area. It is assumed that an additional height of 0,5m is required to account for waves.
- **Freeboard**
  A freeboard of 0,25m is added to the height of the wall. This value is based on the fact that the wall should be as low as possible and that under extreme conditions the promenade will not be used.

The height of the wall with respect to MSL results in:

$$MSL + Storm\,surge + Sea\,level\,rise + Tide + Waves + Freeboard = Wall\,height$$
$$MSL + 1 + 0{,}5 + 0{,}35 + 0{,}5 + 0{,}25 = \boldsymbol{MSL + 2{,}60m}$$

An additional function of the promenade can be to construct a basin for a rain water drainage system underneath. As the wall does not allow water run off to the sea, a drainage system for rain water is required.

The concrete quantities for the wall and promenade are based on the construction of the basin for the water drainage system and the wall reaching to a depth of MSL – 4,5m.

Promenade ≈ 2,5 m^3/m

Wall ≈ 4 m^3/m

$$V_{prom+wall} = (2{,}5 + 4) * 2000 = 13000\ m^3$$
$$V_{wall} = 4 * 800 = 3200\ m^3$$
$$V_{total} = 13000 + 3200 = 16200\ m^3$$

Dunes & beach

The main function of the dunes is to provide a buffer for the higher wave season, thereby preventing damage by erosion due to the formation of a 'winter' profile. The dunes also provide sediment to increase the amount of beach while the 'winter' profile is present. The dunes will be partly nourished and partly develop naturally over time.

The beaches of Bocagrande should be able to deal with erosion due to sea level rise as well. The expected sea level rise over 50 years is 50cm. A coastline retreat of approximately 50m for the expected sea level rise of 50cm will seriously threaten the coast of Bocagrande (See chapter future scenario). If the coastline retreat is of this order of magnitude, most of the coast of Bocagrande is not able to cope with this process and without measures and maintenance significant damage will be done to adjacent structures. This is however a very rough estimate and should not be used for design purposes but only to have an impression of the order of magnitude of the problem. However, it is not necessary to nourish the beaches to an extent so that it can handle a sea level rise of 50cm on a short term. Maintenance nourishments can be carried out every 10 years and adapt the amount of nourished sediment to the actual sea level rise. The current dunes are approximated to reach up to 1m above mean sea level; it is assumed that an additional 1m raise of the dunes should provide an initial situation where the dunes can develop naturally. Vegetation should be planted on the dunes to keep the sand in place; an important practical aspect is that the beach should get specific entrances for people to access the beaches so that the vegetation is not damaged.

In order to construct the dunes additional sand is required. A part of the necessary sand can be obtained from the soil beneath the location where the wall is being built. The other part of the soil needed for constructing the dunes should be obtained by extra nourishments. The difference in sand volume between the current situation and the situation with dunes is approximately $3m^3/m$. The distance of the dune construction is 2000m which results in an initial nourishment of:

$$V = 3 * 2000 = \mathbf{6000m^3}$$

Next to constructing the dunes, beach nourishments should be carried out to account for sea level rise induced erosion. Currently the sea level rise is 6mm/yr, the average sea level rise over the next 50 years is assumed to be 10mm/yr. The difference in the current sea level rise compared to the expected average sea level rise over the next 50 years is $10 - 6 = 4mm/year$. As no structural erosion is observed in the current situation, only the additional 4mm/year sea level rise needs to be accounted for by nourishments, see future scenario. The amount of dredging that is required to compensate for the additional sea level rise of 4mm/year is calculated using equation III-3-19 from the Coastal Engineering Manual (USACE, 2006).

$$W_* = \left(\frac{h_*}{A}\right)^{\frac{3}{2}} \approx 500m$$

$$W_* = Surf\ zone\ width$$
$$h_* = depth\ of\ closure \approx 5m$$
$$A = sediment\ scale\ parameter \approx 0{,}08$$

$$\frac{dV}{dt} = W_* * \frac{dS}{dt} = 500 * 0{,}004 = \mathbf{2{,}0m^3/m/year}$$

If maintenance nourishments are done every 10 years, the amount of sand required for the nourishments along the 2km stretch of coast is:

$V = 2{,}0 * 10 * 2000 = \mathbf{40000\ m^3}$**/10 years**

This means that during construction the first nourishment for the next 10 years should be carried out.

6.2.4 Cost & benefits

In the current situation there is no protection against the sea, only the beach. During a storm the water gets over the beach and floods the main road, calle 1. To protect the people and the property it is necessary to construct something which will withstand a storm occurring once in the 50 years. Dunes are the natural protection of the land and in combination with a wall an ideal solution for the sea side of Bocagrande. The dunes restore the natural situation and will protect against flooding and assure that no sand is lost due to the wind. The road along the coast will be accessible during stormy weather which increases the accessibility of Bocagrande, especially because calle 1 is one of the important access points of Bocagrande.

The construction costs of this project are based upon the construction of the promenade, the wall and the dunes and also include the nourishment of the beach every 10 years.

Construction costs sea side are estimated around: **$ 14.000.000.000** Pesos

A complete overview of the construction cost and the actual figures are placed in appendix I.

6.2.5 Impression

Below is a sketch of the current situation (Figure 6.7) along the coast of Bocagrande and a sketch of the situation with the wall and promenade constructed (Figure 6.8).

Figure 6.7 Seaside of Bocagrande in current situation

Figure 6.8 Seaside of Bocagrande with wall with promenade

6.3 Solution Erosion El Laguito – T-groynes and nourishments

The solution that solves the erosion along the coast of El Laguito the best way according to the multi criteria analysis is the construction of T-groynes in combination with sand nourishments. The conceptual design of the solution is treated in this section. The conceptual design consists of the area layout, dimensions, nourishment quantities and T-groyne stability. The conceptual design is based on the design requirements and boundary conditions.

6.3.1 Design concept

The solution to solve the erosion problems along the coast of El Laguito re-establishes beaches along this section that should be kept in place by hard structures. Because of the large wave angle on the coast of El Laguito this section is very vulnerable to erosion. The sediment that bypasses the Iribarren groyne and the Escollera groyne is less than the sediment transport capacity along the El Laguito coast. Additional measures are required to reduce the threat of damage by erosion to adjacent structures.

The coast of El laguito is divided in four sections of 200m that are enclosed by the T-groynes. T-groynes are effective to trap sand and prevent erosion of the enclosed area. The opening between two T-groynes determines the size of the beach that is formed by incoming waves. A small opening only allows limited incoming waves to enter the enclosed area. The result is also that only a short distance of actual beach-sea interface develops.

Flooding of El Laguito due to high water levels has not been observed. However, with the expected sea level rise of 50cm in the next 50 years the vulnerability of El Laguito to flooding increases. The wall that protects the seaside of Bocagrande should be extended towards the wall that protects Castillogrande. The height of the wall only has to account for water levels being too high because the T-groynes protect the coast against incoming waves.

6.3.2 Design requirements

The design requirements for the solution of the erosion problems around El Laguito are shown below:

- Structural erosion should be prevented, so that structural stability of buildings is guaranteed;
- The solution should be able to cope with a sea level rise of 50cm over the next 50 years;
- The T-groynes should be stable for 1/50 year storm conditions.

6.3.3 Dimensions

The dimensions of the solution should be such that the design requirements are met and it fits in the current situation. The dimensions of the T-groynes and the beach nourishments are discussed separately.

T-groynes

The T-groynes have to protect the beaches from erosion. The coast along El Laguito is divided in four stretches of 200m which are enclosed by the groynes. The T-groynes will extend to 100m offshore to have significant beach. The gaps between the beach parallel sections of the T-groynes should be smaller than the parallel groyne sections in order to avoid erosion of the beach (Bosboom & Stive, 2013). The shore parallel groyne sections will therefore be constructed with a length of 150m with a gap of 50m between the groynes. This should prevent erosion even due to the large wave angle at the considered location (See Figure 6.9).

Figure 6.9 T-groyne design

The total length of groynes that will be present in the future situation is:

$$L = 4 * 100m + 3 * 150m + 2 * 75m = 1000m$$

A number of groynes and a seawall are present currently; these structures should be re-used as much as possible to reduce the amount of rocks that are required for constructing the T-groynes. The current eastern groyne at the Hilton hotel is already of the desired length, therefore only 3 perpendicular groynes need to be constructed. It is assumed that the remaining usable rocks account for one shore perpendicular groyne of 100m. An additional **800m** of groyne will be needed of which 200m is shore perpendicular and 600m is shore parallel.

The height of the groynes is based on the design requirements and boundary conditions. The groynes should prevent erosion of the pocket beaches, but during extreme conditions the groynes may allow for some overtopping and thereby induced erosion. Maintenance nourishments are required after very heavy storm conditions.

The height of the groynes is based on:

- *Storm surge*
  A height of 50cm is added to account for storm surges, as overtopping of the groyne is permitted, it is not necessary to take the highest storm surge for 1/50 years into account. After a very severe storm, maintenance nourishments might be required.
- *Sea level rise*
  The sea level is expected to rise 50cm in the next 50 years. Therefore 50cm is added to the height of the groynes to account for sea level rise.
- *Tide*
  The average spring tidal amplitude is 35cm; this is added to account for the tide
- *Waves*
  An additional height is taken into account to limit wave overtopping; the waves have limited height as Laguito is somewhat sheltered from the open sea. As overtopping is permitted during storm conditions, the additional height that limits severe overtopping is 0,50m.

The height of the groynes with respect to MSL results in:

$$MSL + Storm\,surge + Sea\,level\,rise + Tide + Waves = groyne\,height$$
$$MSL + 0{,}5 + 0{,}5 + 0{,}35 + 0{,}5 = \boldsymbol{MSL + 1{,}85m}$$

The size of the armour stone is roughly estimated using the Hudson formula. This formula has limitations and can only account for normal incident waves. Therefore it is only used as a guideline and to give an estimate of the required stone size and quantity. The groynes should be able to withstand a severe storm in order to protect the beaches from eroding during and after the storm, however, some damage is acceptable as long as the groynes keep functioning. Because the groynes are located in the bay, the maximum wave height is assumed to be 2m, instead of the 1/50 year storm wave height of 2,5m for an open coast.

$$\frac{H_s}{\Delta D_{n50}} = \frac{(K_D \cot\alpha)^{1/3}}{1.27}$$

$$H_s = 2{,}0m$$
$$\Delta = 1{,}65$$
$$\cot(\alpha) = 1{,}5$$
$$K_D = 2{,}0$$
$$D_{n50} = 1{,}07m$$
$$\boldsymbol{D_{50}} = 1{,}07m * \frac{1}{0{,}84} = \boldsymbol{1{,}27m}$$

The volume of the groynes is determined by the length, water depth and crest width. The crest width is chosen as 1,5m and the average water depth at 100m offshore is 2,5m (see appendix E). The shore parallel sections of the groyne have a total of 600m length. These parts of the groynes are located in the deep water of 2,5m. The not yet constructed shore perpendicular sections have a length of 200m with a depth from 0m - 2,5m. On all sections of the groynes the 1,85m above MSL is constructed. The total volume of required stones is approximately:

$$V_{stones} = \mathbf{12000m^3}$$

For the full calculation on the groyne volume see appendix J.

Beaches

The locations of the beaches that will be constructed around Laguito do not have beaches in the current situation. Therefore all sand has to be nourished in order to create new beach surface. A rough estimate on the volume of required sand is given below:

$N = number\ of\ pocket\ beaches = 4$

$L = average\ length\ of\ beach = 100m$

$W = average\ width\ of\ beach = 200m$

$d = average\ depth\ at\ 100m\ offshore = 2{,}5m$

$h_{beach} = additional\ height\ for\ beach = 0{,}5m$

$$V_{sand} = volume\ of\ nourished\ sand = N * (L * W * d * 0{,}5 + L * W * h_{beach}) = \mathbf{140000m^3}$$

Wall

An additional wall is constructed that protects El Laguito for flooding in the future. The wall should connect the seaside protection and the bayside protection. The height of the wall only needs to account for a water level as waves are reduced enough by the T-groynes. The height of the wall is:

- Sea level rise: 0,5m
- Storm surge: 1m
- Tide: 0,35m

The height of the wall with respect to MSL is +1,85m. Some buildings along the coast already have walls protecting them from flooding. Therefore an integrated solution should be made in following design steps. The depth of the wall does not have to be very large because there are beaches protecting for erosion and higher elevations of the adjacent land limits piping. The required volume of concrete for the 'standard' wall is estimated roughly below:

$W = Width = 0{,}50m$

$D = Depth = 2{,}5m$

$L = Length = 1000m$

$$V_{concrete} = W * D * L = 0{,}5 * 2{,}5 * 1000 = \mathbf{1250m^3}$$

6.3.4 Cost & benefits

Constructing T-groynes and re-establish beaches along the coast will add value to the current situation as current restaurants and businesses have suffered by the disappearance of the beaches in the past. Not only will it restore the natural situation and increases the attractiveness of the area, it will also protect against erosion which damage the construction of the buildings.

The construction costs of this project are based upon the construction of the T-groynes, the wall and the nourishment of the beach.

Construction costs erosion El Laguito are estimated around: **$ 5.500.000.000** Pesos

A complete overview of the construction cost and the actual figures are placed in Appendix I

6.3.5 Impression

Below is a sketch of the current situation (Figure 6.10) along the coast of El Laguito and a sketch of the situation with the T-groynes (Figure 6.11).

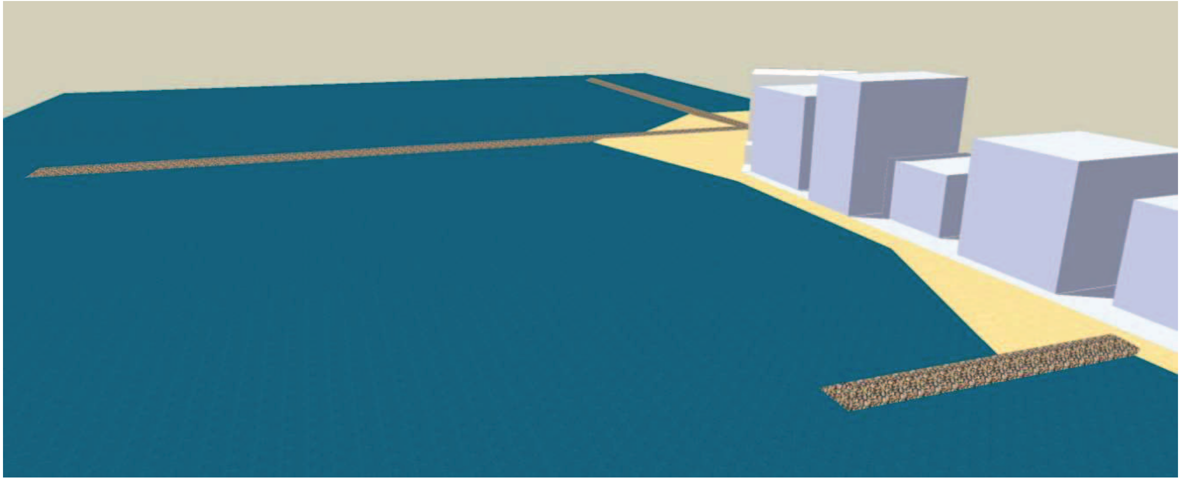


Figure 6.10 El Laguito shoreline current situation

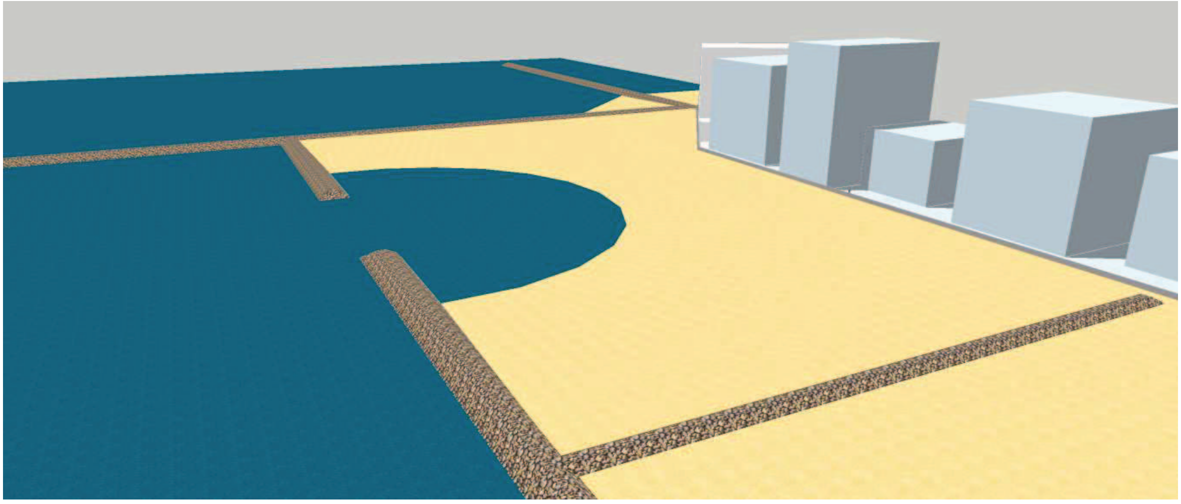


Figure 6.11 El Laguito shoreline future situation

6.4 Solution El Laguito lake – Fill the lake with soil

The result of the MCA show that the best solution is to fill El Laguito. Closing the lake is simple, effective and gains valuable land.

6.4.1 Design concept

The concept is very simple; nourishment should fill the lake with sediment, making it rise above sea water level. Since this is newly formed land it can be nourished high enough to take into account sea level rise.

6.4.2 Design requirements

The solution needs to meet the following requirement:

- The beaches of Castillogrande should not be affected by the measures

6.4.3 Dimensions

In order to gain what is now El Laguito, sand has been dredged from what is currently the lake. The depth after dredging was approximately 14m. However due to the closing of the lake over the years the depth has reduced significantly. The lake is estimated to have, on average, a depth of 4m. When the lake is filled, it is estimated that the new level of the land will be 2,5m above MSL. This takes into account the compaction of sediment and the extra height wanted above sea level.

The surface (**Error! Reference source not found.**) of the lakes measures 62000m^2. This implies a volume of sediment that is needed to create the land of 403000m^3.

Figure 6.12 Surface of the lake of El Laguito

6.4.4 Cost & benefits

Filling up the lake will increase the amount of available land in the area. Since the land is very popular in the region, the value of the land will be high. Which make the land attractive for private investors to build new hotels or apartment buildings on it. It however can also be used as a public park.

The construction costs of this project is based upon the sedimentation of the lake.

Construction costs EL Laguito lake is estimated around: **$ 3.00.000.000** Pesos

A complete overview of the construction cost and the actual figures are placed in Appendix I.

6.5 Solution El Laguito lake – Groyne extension, dredging and sandtrap

This solution opens the lake of El Laguito. This has been done before, without success. In order to make it work in this situation more adjustments have to be made to prevent closure of the lake.

6.5.1 Design concept

The opening of the lake relies on two extra barriers that prevent it from closing. First off, less sediment should reach the opening. This is done by extending the most eastern groyne near the Hilton with such a length that the sediment supply reduces. Secondly a sandtrap is built. This sandtrap will act as a three year buffer accreting for three years and thus preventing the accretion in the mouth. These solutions reduce the amount of dredging that needs to be done in the future. However, dredging still needs to take place to prevent closure of the lake.

6.5.2 Design requirements

The solution needs to meet the following requirements:

- The beaches of Castillogrande should not be affected by the measures
- The opening should at any point during these three year periods be large enough to sustain enough interaction with the ocean such that the water quality of the lake is equal to that of the open bay.

6.5.3 Dimensions

Each of the three parts of the solution are explained separately: groyne extension, dredging and the sandtrap.

Groyne extension

The extension of the groyne is done to reduce sediment transport. In order to reduce the transport the groyne needs to be long enough to ensure it is outside the breaker zone. Waves break when they're about 0.8 times the water depth. Currently the end of the groyne has a depth of -1.75m below MSL (see Figure 6.13). This means that the waves breaking at the tip of the breakwater have a height of 1.4m at mean sea level. During low tide (-0,2m MSL – See appendix E: Boundary conditions) this can even be 1,24m which occurs frequently.

The maximum wave height with an occurrence of once a year is 2.4m at the seaside. Although El Laguito is slightly sheltered from North East, it is not from the North West where storm waves come from (See appendix E). Using 2.4m as a guide to determine the minimum water depth this would mean that a water depth needed for the groyne should be:

$$\frac{2.4}{0.8} = 3m$$

This is however at Mean Sea level. At low tide this would mean that the groyne should be constructed up to a depth of -3.2m MSL. The extension of the groyne is 150m and adds a volume of roughly **5000m^3**.

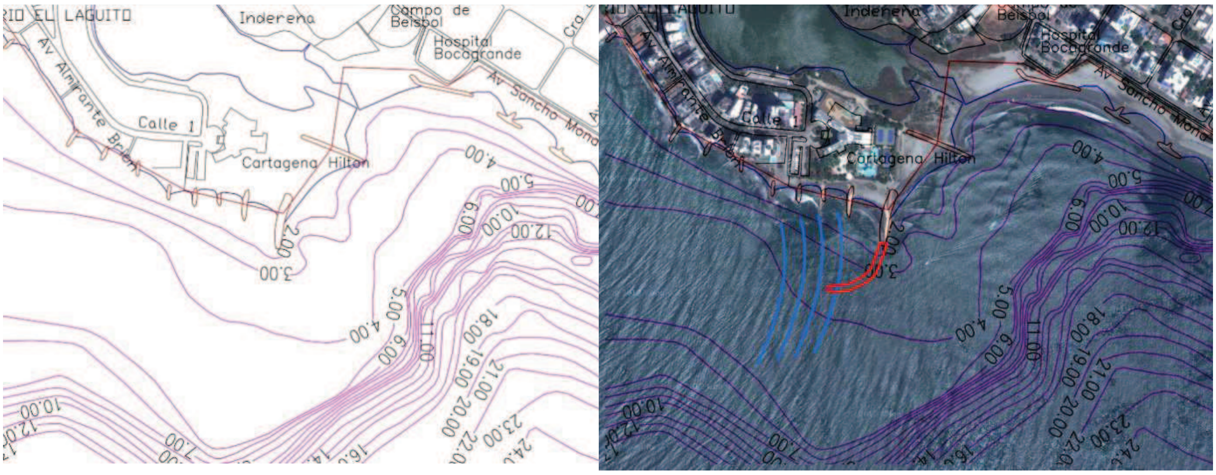


Figure 6.13 Bathymetry map

One could assume that the groyne would block the yearly sediment supply be constructing it to a depth of -3.2m MSL. In reality sand will accrete, some sand will be lost to deeper water but very likely part of the sand will still pass the groyne. It is therefore assumed by constructing the groyne to a depth of 3.5m that the effectiveness is about 60%. 60% of the sediment moves to deeper water and 40% still gets to the entrance of the lake.

When constructing of the groyne is roughly perpendicular to the waves, this means a design that looks as can be seen in **Error! Reference source not found.**. The groyne is also part of the solution to the erosion of the west side of El Laguito (see section 6.3). Further dimensions of the groyne are discussed in that chapter.

Dredging

The dredging part is separated in two parts, the initial dredging of the opening of the mouth of El Laguito and the dredging and maintenance of the sandtrap in front of the mouth. The opening of the mouth is currently closed off by an estimated 0,5m (at MSL) of sand. It is estimated that 2,5m below sea level would be a good depth to flush the lake, add value to the lake by allowing small ships to enter and have a buffer in case more accretion occurs than expected. The surface area that needs to be dredged is roughly 21000m^2. This area is shown in Figure 6.14.

This adds up to a total volume of **63000m³** that needs to be removed initially to open the mouth. Since the mouth can be dredged from land and it is fairly shallow this can be done using an excavator.

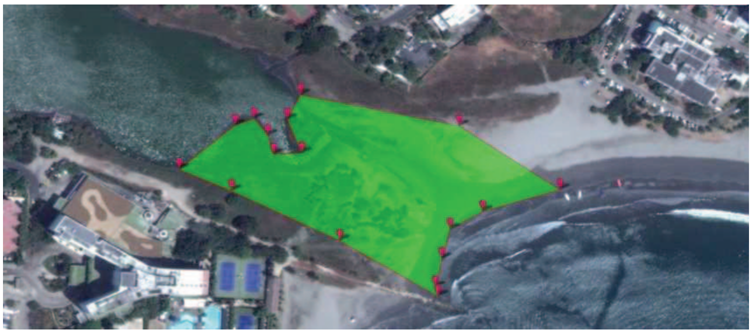


Figure 6.14 Surface area that needs to be dredged to open El Laguito

Little information is known about the amount of sediment transport along the coast. For the sediment accretion at the lake's entrance only the interview with a local engineer is available, therefore we take the amount mentioned in the interview, 25000m³/year, as an estimate (appendix B.6). Due to the construction of the groyne this is reduced to 40%, or 10000m³/year (thus 30000m³ in three years).

The purpose of the sandtrap is to act as a buffer for a three year period. After this period the sandtrap is "emptied" and the process starts again. Coarse sand has an angle of repose of roughly 30˚ (CIRIA; CUR; CETMEF, 2007). The sand near El Laguito is finer therefore a smaller angle of repose of 20˚ is used.

The volume of the sandtrap equals the buffer that needs to be created for once in three years dredging; 30000m³. The trap will have a cone shape.

$$\tan 20^\circ = \frac{height}{radius} \approx \frac{1}{2.75}$$

$$Volume\ cone = V = \frac{1}{3} \times Area\ base \times Height = \frac{1}{3} \times \pi \times r^2 \times h = \frac{1}{3} \times \pi \times (2{,}75 \times h)^2 \times h$$

$$= \frac{1}{3} \times \pi \times 7{,}5625 \times r^3 = 2{,}52 \times \pi \times r^3 = \mathbf{30000m^3}$$

The radius of the cone is 15,6m and the depth is 5,7m. It is placed next to the entrance of the lake on the side of the Hilton. Due to the relatively mild slope and the distance to the groyne of the Hilton it will not destabilize structures.

6.5.4 Cost & benefits

The groyne extension, dredging and the sandtrap are highly maintenance intensive and therefore in this case not preferable. However it will increase the value of the lake a lot. Two important hotels, Hilton and Caribe and a sailing club are located near the lake. For them an open connection to the sea could be very valuable.

The construction costs of this project is based upon the groyne extension, the dredging of the entrance of the lake and the maintenance every three year of the sandtrap.

Construction costs EL Laguito lake is estimated around: **$ 4.500.000.000** Pesos

A complete overview of the construction cost and the actual figures are placed in Appendix I.

6.6 Solution Bayside - Revetment with valves

According to the multi criteria analysis the best solution to solve flooding problems on the bayside is to construct a revetment with valves along the shoreline. A conceptual design of the solution for the bayside of Bocagrande is discussed in this chapter.

6.6.1 Design concept

In the current situation there is a slightly raised sidewalk around most of the bay side. This sidewalk has some small rocks next to it protecting it from the waves. The rocks border with the water in the bay. In the new design the sidewalk involves a wall next to it to prevent water intrusion. This new combination of sidewalk with a wall will be built along the entire bayside. On the western side of Castillogrande where the beach meets the sidewalk the sidewalk will have a similar look as the solution on the seaside of Bocagrande. The new wall and sidewalk will be aesthetically pleasing to increase the value and gain local support for the changes.

On the western side of Castillogrande the relative sea level rise may induce erosion in the future. No differences to the sediment supply, due to the designed solutions for the area, are expected. Since the beach has only grown in the past decade the result of relative sea level rise may not need to be compensated by nourishment. The region should however be monitored in the future to see the results of sea level rise.

6.6.2 Design requirements

The solution needs to meet the following requirements:

- The revetment should be high enough to prevent flooding for a water level that occurs once in 50 years for the next 50 years;
- The groundwater flow underneath the revetment should be small enough in order to be able to drain it with pumps. Piping should also not occur.

6.6.3 Dimensions

The connection of the wall to the pavement does provide stability for the wall. In reality the pavement will be much wider than would be necessary for the stability for aesthetic purposes. In the conceptual design only the height of the wall is further discussed.

Height

The height of the revetment depends on the following factors (appendix E):

- Relative sea level rise: approximately +0,5m in the next 50 years
- Storm surge occurring once in fifty years: +1m above mean sea level
- Wave height on the west side of Castillogrande (and further): assumed approximately 0,5m
- Wave height on the east side of Castillogrande (and further): assumed approximately 0,25m
- Springtide: +0,35m above mean sea level
- Freeboard: 0,25m

Wind setup in the bay is neglected, it is expected to be small and the occurrence of storm surge together with strong winds from the east is very unlikely. Although the chance of storm surge occurring at the same time of springtide is questionable, it is assumed that this is acceptable. This results in a wall height on the east side of 2,35m above MSL and 2,6m above MSL on the west side.

Depth

A wall under the structure needs to prevent piping and reduce the seepage of water through the ground layers. In order to calculate the seepage a model such as *Flownet* can be used, this calculation is recommended for a more detailed design phase but left out in conceptual design.

Piping is calculated with the following formula (Lane & Bligh):

$$\frac{\Delta H}{L} < \frac{1}{C}$$

The height difference of the water is (assuming the road is currently around mean sea level at the lowest points, see appendix E):

$\Delta H = 1 + 0{,}5 + 0{,}35 = 1{,}85m$

$L = \frac{L_h}{3} + L_v \approx \frac{2}{3} + 12 = 12\frac{2}{3}m$ (When using a 6m deep wall)

$C \approx 6$

This can be regarded as safe. However the value for C, which defines the soil type, is an estimate and needs further research.

Length

The total length along which the "bayside" needs a wall is around Castillogrande and on the bay side of Bocagrande. This length is approximately 3900m. The concrete quantities needed for the wall are based on the length and the average surface of the wall (6m^2).

$$V_{wall} = 6 * 3900 = 23400\ m^3$$

6.6.4 Cost & benefits

The construction of the revetment with valves reduces the amount of floodings on the bay side enormously. The streets won't be flooded every month during high tide. Roads can be used to its full extent which will increase the accessibility of some parts of Bocagrande. There will be less damage to the infrastructure and to property of the residents.

The construction costs of this project is based upon the wall construction.

Construction costs Bay side are estimated around: **$ 19.000.000.000** Pesos

A complete overview of the construction cost and the actual figures are placed in Appendix I.

6.6.5 Impression

Below is a picture of the current situation (Figure 6.15) along the bay side of Bocagrande and a sketch of the situation with the wall construction (Figure 6.16).

Figure 6.15 Bayside current situation

Figure 6.16 Bayside protection

6.7 Solution accessibility – Tunnel connection to Manga

From the three alternatives to increase the accessibility of Bocagrande, a new tunnel connection to Manga turned out to be best. This solution is based on a spatial planning study that is executed previously. In this chapter the choices for the modeling will be explained and compared to the results, to come to a more detailed design for the connection. Based on the modeling results, advices will be given on the capacity of the new infrastructure. In the end of this chapter, the benefits of the new tunnel connection are estimated.

As explained in chapter 5, three alternatives have been proposed. The Base Scenario, in which the coastal road that suffers from overtopping is repaired and measures are taken to prevent flooding in Bocagrande, is also included in the other two alternatives. Therefore, first the benefits of only applying the Base Scenario are measured, to be compared with the extra added value of the tunnel connection at the end of this chapter.

6.7.1 Benefits Base Scenario

The benefits of the Base Scenario are measured using the Value of Travel Time (VoTT). This means that only the benefits as a result of travel time reductions are taken into account. Other benefits like lower link loads, emissions or sound levels, are not measured in this study.

In Table 6.4 it can be seen that only updating the infrastructure around the coast to repair the overtopping damage and preventing Bocagrande from flooding saves around $21.000.000.000 pesos per year. This value is based on a Value of Travel Time of $6.720 pesos per hour, as calculated in appendix K. The total cost of the Base Scenario is the sum of the construction costs of the overtopping,

Travel times (average) per vehicle (min)	**Base Scenario**
To Bocagrande	11,3
From Bocagrande	15,1
Average all trips (min)	**1,08**
Total travel time (vehicle*hours)	**1941**
Value of Travel Time (VoTT)	$6.720
Benefit Base Scenario per hour	$13.043.520
Benefit Base Scenario per day (*8)	$104.348.160
Benefit Base Scenario per year (*200)	$20.869.632.000

Table 6.4 Value of Travel Time

seaside and bayside solutions, a total of around $56.000.000.000 pesos. This indicates that more than 1/3 of the investment can be recovered by the Value of Travel Time per year.

This amount of benefits to repair the coastal road and prevent flooding in Bocagrande is compared to the total benefits of the proposed tunnel connection to Manga. In this way, the benefits that are caused by the coastal road update and flood protection measures can be distinguished from the benefits caused by the new connection to Manga and construction of the Manga highway.

6.7.2 Modeling assumptions

In the transportation model to estimate the effect of a new tunnel connection between Bocagrande and Manga, several assumptions are made that influence the model outcome. In this paragraph these assumptions are discussed, to keep in mind when the modeling results are presented.

The amount of traffic that is modeled, is calculated by multiplying the validated traffic flows of the year 2002 by a growth factor 1,8 (see appendix G.6) to come to the traffic flows of the year 2011. On top of that, an amount of touristic traffic is modeled, which is calculated based on the current amount of tourists and the relative attractiveness of several touristic attractions and productions (see appendix G.7). This means that the model output indicates to which extent the infrastructure can cope with current amount of traffic. Since the growth factor of 1,8 and the amount of touristic traffic is already uncertain, no future estimations of traffic flows are done. Though, it should be taken into account that the traffic flows can increase in the future, especially the amount of touristic traffic.

The new tunnel connection has a capacity of 3200 cars per hour in both directions. This can be compared with a two-lane road in both directions. As described in a previous chapter the tunnel will start in between the naval base and the hospital on the north side of Bocagrande, and will run to the first crossing in Manga. This is indicated in Figure 6.17 with a black line.

A new road constructed in Manga intends to relieve Manga from much through traffic. In the traffic model, this road is assumed to have a capacity of 3200 cars per hour as well. The new road can be seen in Figure 6.17.

At the same time, the infrastructure that is currently used in Manga will be downgraded to 600 cars per hour, which can be compared to small local roads. The downgrading of the Manga roads intends to increase the relative attraction of the new road to prevent through traffic in Manga in the future. The downgraded infrastructure is marked red in Figure 6.17.

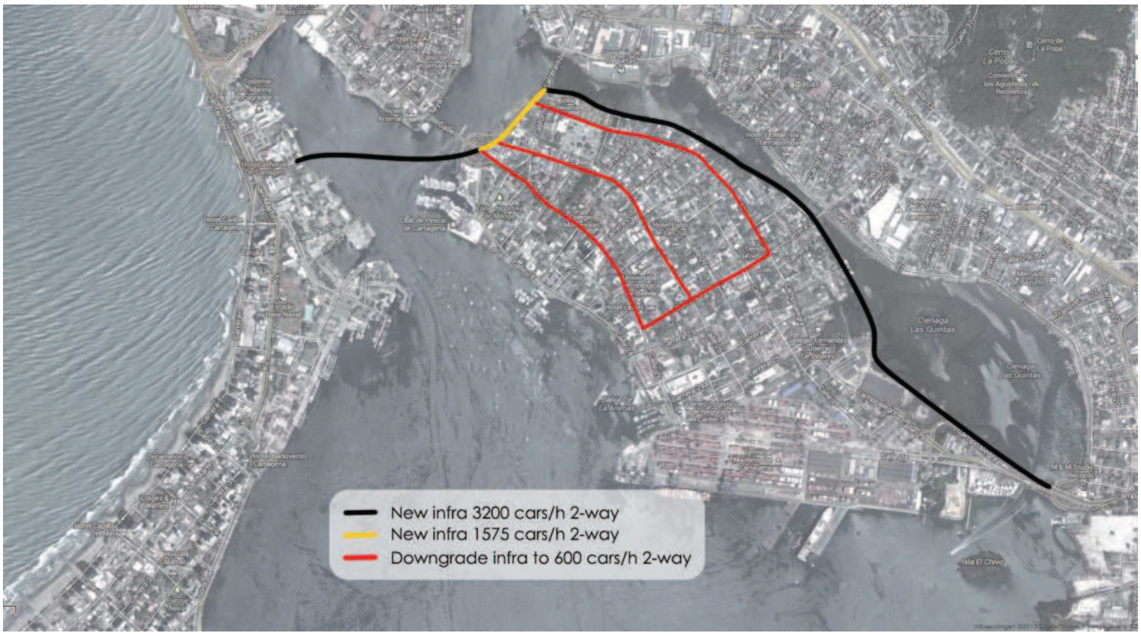


Figure 6.17 Tunnel connection between Bocagrande and Manga

6.7.3 Modeling results

When the current traffic amount, including tourism is loaded on the infrastructure, a transportation model calculates the link loads of all links as shown in Figure 6.18. In this figure, a morning peak during a touristic period is modeled on the left side. As can be seen, the connection between Bocagrande and Centro suffers from high load rates, as well as the coastal road and the connections between Centro and Manga.

As can be seen on the right side of Figure 6.18, adding a tunnel connection to Manga will lead to lower overall travel times and to lower link loads on the bottlenecks. Since this alternative had the best result in the multi-criteria analysis, the effects of this alternative are looked at more closely. Based on that analysis, an advice can be given on several design parameters.

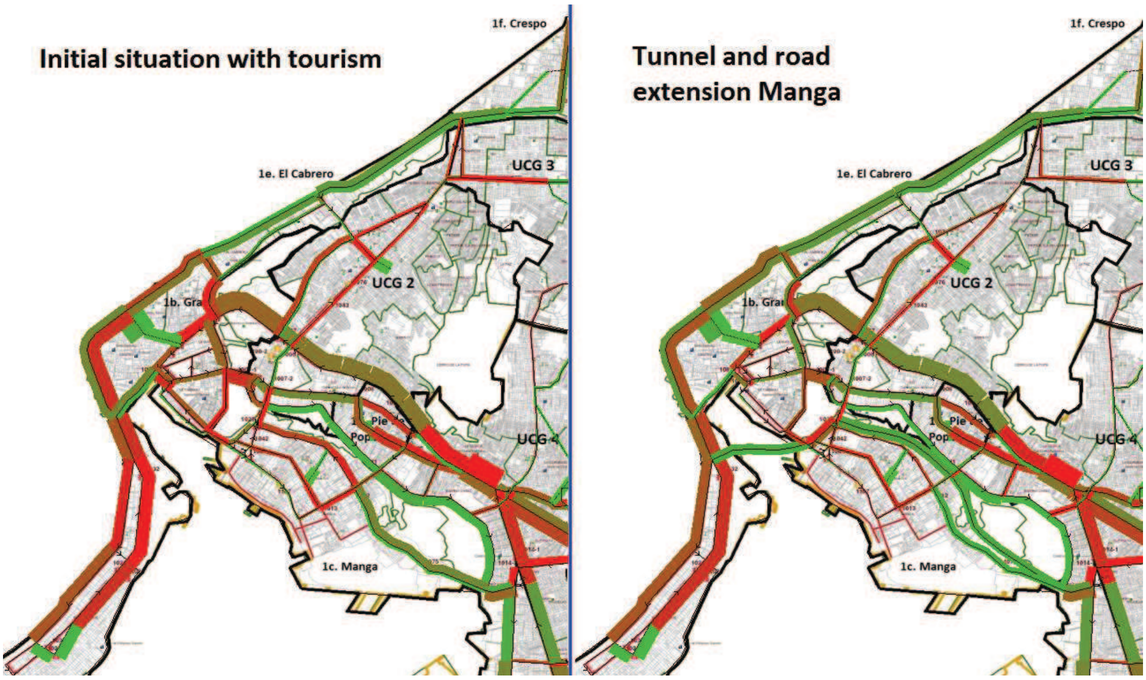


Figure 6.18 Link loads initial and tunnel situation

The following results are expected, based on the modeling study:

Unburden the current Bocagrande – Centro connection

The tunnel connection to Manga eases the load on the current Bocagrande-Centro connection. 1300 cars originating from Bocagrande will use the new tunnel to unburden the current connection, but the 1000 cars that are attracted via the tunnel undo this effect partly. This leads to a net result of about 300 fewer cars per hour (8%) using the current connection to get from Bocagrande to Centro. From all cars using the current Bocagrande-Centro connection, more than 80% has Centro as a destination. This indicates that the connection is not anymore used by much through traffic.

In the other direction, about 680 cars will use the tunnel connection during a peak hour to reach Bocagrande. From Centro, around 170 cars are attracted extra to Bocagrande to use the tunnel connection. This leads to a net result of around 400 (12%) fewer cars using the Centro – Bocagrande connection.

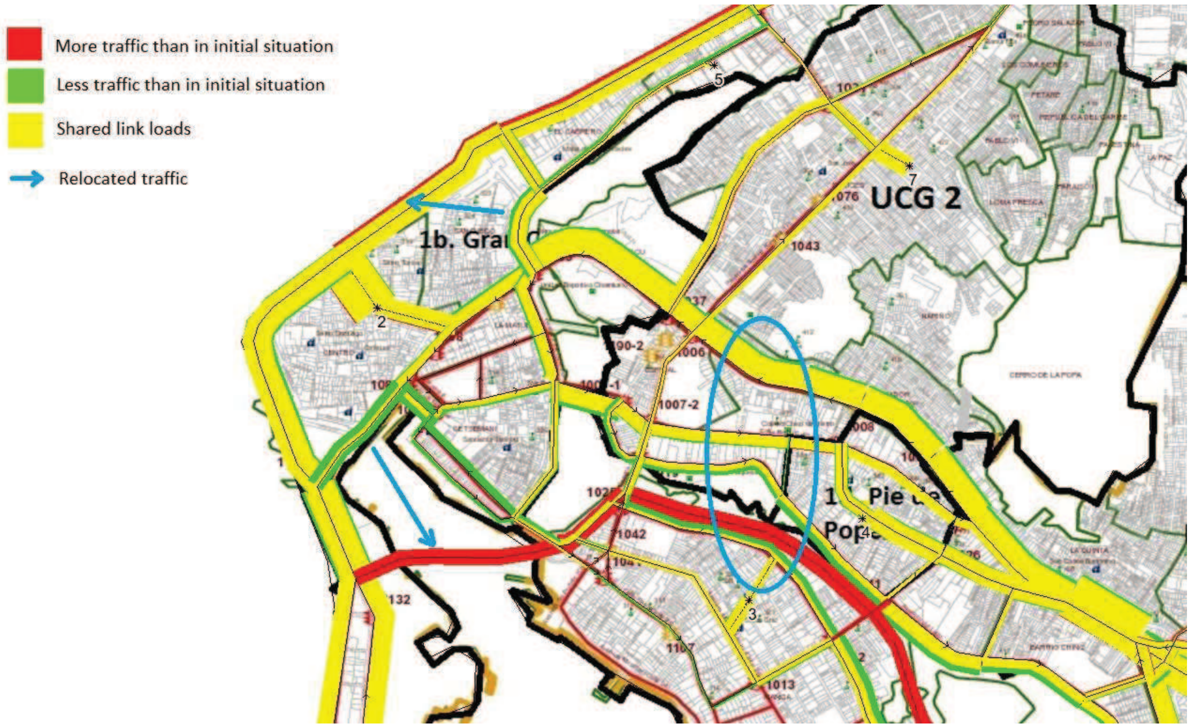


Figure 6.19 Relocation traffic Manga tunnel

Use of the tunnel

To reach Bocagrande as a destination about 20% (680 cars/hour) will use the new tunnel connection. About 2650 cars use the existing Centro – Bocagrande connection.

From all cars using the tunnel in the direction of Manga, more than 50% will use the new constructed road in the north of Manga. This leads to lower link intensities on the west-east connections that currently exist, like the Pedro de Heredia and Calle 30. This can be obtained within the blue circle in Figure 6.19. All links in east-west direction show a lower intensity, which is compensated by the new Manga highway, which has a red color. The intensity on the Calle 30 will be lowered by 30%, the intensity on the Manga – Centro connection in the south of Manga decreases by 45%.

Also, the connection from the Coastal road to the entrance of Calle 30 has a lower intensity of 40%. This is mainly achieved by the improved capacity on the coastal road by preventing overtopping. The higher capacity along the coast attracts more traffic, to relieve the connection between the coastal road and Calle 30. This traffic shift is indicated with a blue arrow in Figure 6.19. Finally, the intensity on the Blas de Lezo drops with more than 70% which is caused by the new alternative route via the Bocagrande-Manga tunnel connection. This is also indicated with a blue arrow in Figure 6.19.

Current loads in the tunnel are around 1670 cars/hour towards Bocagrande and 1470 cars/hour towards Manga. Given the modeled capacity of 3200 cars, this might be a bit too high. A one-way connection could be sufficient as well, as long as the roads are well maintained and strictly managed. It would be wise to first research the traffic growth during the upcoming years, before making a decision on the capacity of the tunnel.

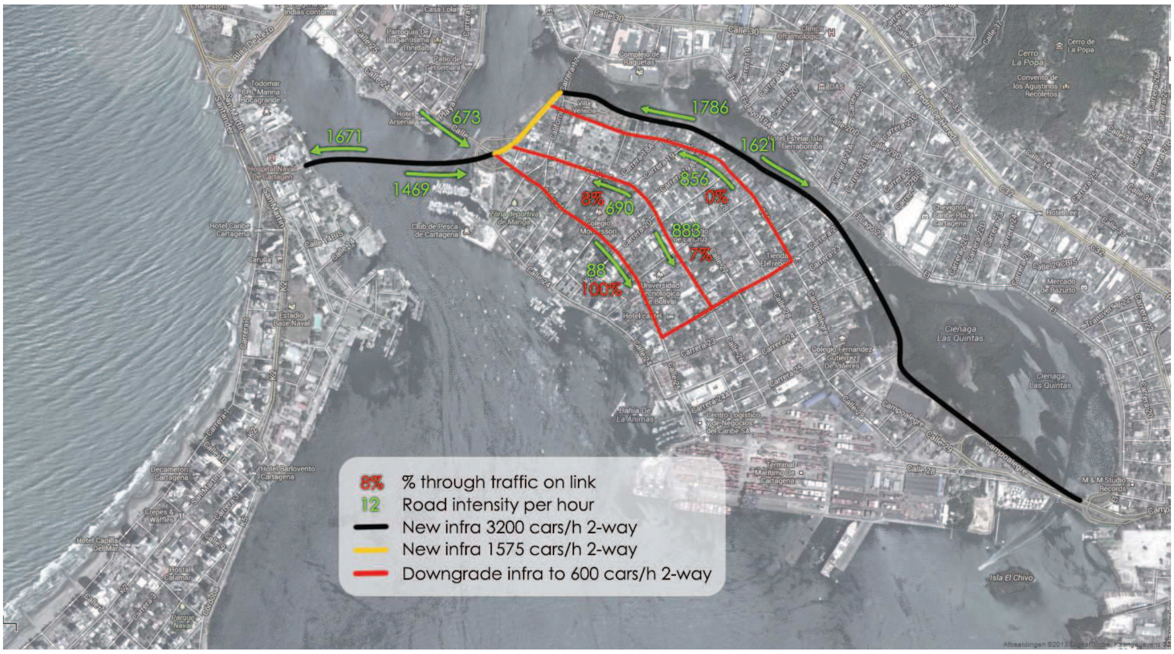


Figure 6.20 Diminishing through traffic Manga

Results in Manga

The expanded infrastructure in the north of Manga and the downgrade of the current roads, leads to different traffic flows through Manga (Figure 6.20).

In the new situation in which the highway around Manga is constructed, more than 90% of all through traffic will use the new highway. Only 3-10% of all through traffic will use the current roads, the rest of the intensity is caused by cars having their origin or destination on Manga itself.

60% of all cars using the new Manga highway in the direction of the city centre use the tunnel to get in the direction of Bocagrande.

From all cars using the Manga highway in the eastern direction, 55% originates from Manga itself, 15% comes from the direction of Centro and 30% from the Bocagrande tunnel.

6.7.4 Design choices

Using the results discussed in this chapter, several design choices are proposed for the implementation of a new tunnel connection between Manga and Bocagrande. Most choices have to do with the minimal road capacity that needs to be chosen for the new parts of the infrastructure.

Tunnel capacity

The capacity of the tunnel is high enough and might even be too high. Around 1500-1600 cars will use the tunnel during a morning peak hour in a touristic season. Given the capacity of 3200 cars per hour, only 50% of the capacity is used. A tunnel with one lane per direction might be sufficient as well, as long as the tunnel is properly designed to reach a capacity of 1800-2000 cars per hour. Considering the growth of the amount of tourists in the next 50 years, the capacity of the tunnel might be used in its full content in the future. However it is still important that further research is done on the future traffic growth to make sure that the tunnel has a capacity that can deal with the future situation.

Bridges around Manga

The bridges that connect Manga to the rest of Cartagena are not upgraded in this alternative. As a result, relative link loads to the capacity become higher than 1. Therefore, it is important to also upgrade the capacity of the bridges around Manga when the plan for a new Manga highway is implemented.

New east-west corridor capacity

The road between the Manga – Centro bridge and the bridge on the north side of Manga has turned into a bidirectional road. The capacity per direction hasn't been increased, resulting in a bottleneck on the new Bocagrande – Manga highway corridor. Therefore, the capacity of all roads that are part of the new east-west connection should be increased to the same level.

6.7.5 Cost and benefits

Because of the limited scope of this research, the exact costs of a new tunnel connection will not be investigated. The absence of the necessary information to make a reliable cost estimation makes it hard to include an estimation in this project as well.

What can be done, is to take a look at the possible benefits of the Bocagrande – Manga connection. In a later stage towards the construction of the tunnel, these benefits can be used to determine the feasibility of a tunnel connection. To see what added value the tunnel connection has, the total benefits of this alternative will be compared with the benefits from the Base Scenario, in which the tunnel connection is not included, but coastal roads are protected and floodings on Bocagrande are prevented.

Travel times (average) per vehicle (min)	Tunnel Manga
To Bocagrande	18,4
From Bocagrande	20,4
Average all trips (min)	**2,82**
Total travel time (vehicle*hours)	**3157**
Value of Travel Time (VoTT)	$6.720
Benefit Base Scenario per hour	$21.215.040
Benefit Base Scenario per day (*8)	$169.720.320
Benefit Base Scenario per year (*200)	**$33.944.064.000**
Benefit Base scenario per year	**$20.869.632.000**
Added value of tunnel connection	**$13.074.432.000**

Table 6.5 Value of tunnel connection

In Table 6.5 the benefits of the tunnel connection are calculated in the same way as the benefits of the Base Scenario were determined earlier this chapter. The Value of Travel Time is discussed in appendix K and the benefits per peak hour are multiplied up to a yearly benefit. As can be seen from Table 6.5, besides the $20.869.632.000 pesos that are earned every year by updating the coastal road and preventing flooding in Bocagrande, another $13.074.432.000 pesos are gained yearly when the connection to Manga is established. This means that 61% of the total revenues are gained by the Base Scenario already, and the other 39% emerge only when the Bocagrande – Manga tunnel connection is constructed.

7. Conclusions and recommendations

To finalize this study the conclusions and recommendations will be presented in this chapter. The goal of this study was to explore the indicated problems, concerning erosion, flooding, overtopping and accessibility around the peninsula of Bocagrande, in order to come up with solutions to the identified problems. The research question formulated with this was: *What is the best integral solution for Bocagrande, concerning the problems of coastal erosion, flood, overtopping waves and accessibility, in order to secure the social and economic value that the peninsula has for the city of Cartagena?*

First the conclusions in regard to the research question will be presented, then the limitations of this study will be discussed, and finally recommendations (for further research) will be given.

7.1 Conclusions

To answer the research question several sub questions were stated and analyses have been carried out. From the analyses it can be concluded that Bocagrande suffers from a number of issues which effect the social and economic value of the peninsula. The stakeholder analysis showed that all direct and indirect stakeholders have the same perception of the issues and they all support the idea of solving the issues. There is however a lack of responsibility among the actors to take action. It is therefore important to involve the actors with decision power by creating sense of urgency, or by bypassing them and making them redundant.

The stakeholder analysis also showed that the lack of accessibility, due to the increase hotels and apartments, is the major problem the direct stakeholders encounter every day. The system analysis showed that the road capacity on Bocagrande is insufficient for the amount of traffic. Some parts of Bocagrande are flooded regularly due to high tide, causing even more road capacity problems and damage to property. Once a year the whole peninsula is flooded due to a combination of heavy precipitation, high tide and stormy weather, closing Bocagrande off from the rest of the city. The only protection Bocagrande has is its beach. However due to incidental erosion, there is no beach to protect the peninsula during storm season, some parts are even completely eroded and cause damage to buildings. Overtopping waves on the Punta Santo Domingo, which is an important connection to the airport, lead to damage to the road and decreases the road capacity. The effect of the damaged coastal road and flooded streets in Bocagrande is clearly visible. During the touristic season the travel demand increases. This mainly results in more traffic around Centro and Bocagrande. The coastal road will have a higher intensity and is expected to be congested in front of the parts of the road that are damaged.

With the climate change, relative sea level rise and the increase of the amount of tourism for the next 50 years in mind, several solutions to solve the technical side of the problems are generated. Based on a multi criteria analysis several solutions are chosen for the integral solution, to limit the effects and to add value to the peninsula.

This integral solution consists of the following parts:

- Construction of a berm and a raise of the seawall near Punta Santo Domingo to reduce overtopping. This will reduce damage to the road and increase accessibility by making both of the two lanes available.
- A wall with vegetated dunes along the seaside coast of Bocagrande will reduce future erosion and prevent flooding. The resulting availability of a beach during touristic season will add value for the hotels, restaurants and the small vendors.
- Construction of T-groynes and nourishment near El Laguito create a beach, preventing flooding and reducing erosion. The beach restores the old situation where restaurants are located. It also protects the buildings from damage due to erosion.
- Filling the lake on El Laguito economically solves the degrading water quality problem and adds valuable land to Bocagrande.
- A wall along the bayside of Bocagrande prevents flooding which reduces the amount of damage to property behind the wall and increases the road capacity.
- The accessibility of Bocagrande increases by the previous solutions. However constructing a tunnel from Bocagrande to Manga increases the accessibility even more. The increasing of the accessibility of Bocagrande, decreases the total travel time.

The integral solution covers all the problem areas indicated by the system analyses and secure the social and economic value of Bocagrande by limiting the effects and adding value where possible.

7.2 Limitations and recommendations

For this study several limitations can be identified that are important when interpreting the conclusions. The most important limitations, which give reason for recommendations, will now be elaborated on. After this recommendations will be stated.

7.2.1 Limitations

Monitoring and data

A lot of time in this study has gone into the collection of data. But a lot of desired data was not available, very old or of bad quality. Therefore many assumptions have been made, which brings along a higher level of uncertainty.

Transport model

Apart from the quality of the data, the transport model that is used can only give a highly simplified reflection of reality. However, the data needed to perform this model already proved to be hard to obtain or not available. Therefore the first two steps of the 4-step model were skipped and no insight is gained in the main estimators of the traffic situation. Next to that, it is not possible to predict a future traffic situation by simply adjusting several estimators to future values, because the relative impact of different estimators is simply not known. Since the latest available traffic data is from 2002, a major gap exists between flows obtained from the data and the traffic flows of the current situation. A growth-factor is used to update the 2002 traffic model, but no current counts are available to validate the growth-factor model.

Qualitative level

The multi criteria analysis is mainly performed on a qualitative level. In a more ideal situation (with more time) the decision between alternatives would be made on a more qualitative level in which the alternatives are investigated in more detail before deciding which is most preferable.

The analysis of the coastal erosion is also purely done in a qualitative way. With the use of a morphologic model, a quantitative analysis could have been carried out. This would have resulted in more accurate results with respect to erosion quantities and the expected future situation. However, before commencing the project it was already decided that the application of a morphological model would take too much time and the availability of required data was questionable (this turned out to be true).

Designs

In this study the chosen solutions are only worked out to conceptual designs. More time and data is needed to define comprehensive designs.

7.2.2 Recommendations

Taking into account the findings and limitations of this study several recommendations can be formulated. Especially the previously described limitations of this study give reason to advice several follow-up studies.

Monitoring and data collection:

Traffic data

Collecting data on traffic would be very valuable for future studies. Traffic counts can be used to validate the transport model of the current situation. When counts are repeated every few years the model can be updated and validated to the new situation.

Inter zonal distances

Since the OD-matrices for traffic estimation were attracted from a public transport study in which all inter zonal travel times were assumed 0, these travel times were used later on in the project as well. Given the fact that the city of Cartagena is divided into only 15 different zones, the inter zonal travel times should be taken into account. For future research is it important that those travel times are estimated to analyze the traffic flows.

Sediment transport along the coast

For the future it is important to monitor the sediment transport along the coast between the mouth of the Magdalena River and Cartagena. This will provide knowledge that can be used to adapt future measures.

Water levels and wind and wave data

Collection of this data is very valuable for designing of coastal protection measures.

Land altitudes

In order to have a good understanding of the relative sea level rise precise monitoring of the land altitudes is important. This should be done using a proper benchmark.

Studies:

Detailed designs of conceptual designs

With more data the given conceptual designs should be evaluated and detailed designs can be produced.

Value of Travel Time

In this study a rough estimation is made of the average value of travel time in Cartagena. An elaborated study is needed to gain a better insight in this value for different groups of people and different trip purposes. This can help with the valuation of benefits of a project to society.

Storm induced erosion

A study on the impact of the storm season (data needed) on the beach profiles would give better insight in the exact effects of the incidental erosions along the coast of Bocagrande.

Economic impact of climate (change) related problems

Insight in the economic damages climate (change) related

Mind-set and institutional:

Maintenance

At this point it seems that doing maintenance is not part of the local mind-set. This is a shame because it can make a great difference when maintenance is considered as a part of projects and budget is therefore reserved for it. There must be private parties willing to take on a maintenance contract.

Knowledge and data sharing

A lot of knowledge and data is available at different institutes and organizations. Sharing this knowledge and data could be of great extra value, providing that it is well organized and easily accessible.

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