Coastal Erosion Mitigation at RN90

Integral approach to Erosion Mitigation along the Caribbean Coast of Colombia

Master of Science Thesis
by S.J.M. Voorend
15th of June 2017

TU Delft Delft University of Technology

Cover image: Critical coastal erosion along the Ruta Nacional 90, Colombia
Source: El Heraldo, 2014

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Abstract

Conflicts arise between the coastal highway 'Ruta Nacional 90' (RN90) and the naturally erosive Caribbean Coast of Colombia between the harbour city Barranquilla and Santa Marta. International sea ports at both the Pacific Ocean and the Caribbean Sea are increasingly important for the export of natural resources, and thereby for the national economy. The growing economic activity in Colombia has led to increased pressure on the natural systems in the coastal zone.

The Barranquilla Bay along the Caribbean Sea is the subject of this study, as this location combines structural erosion with a vulnerable coastal highway (RN90) and an internationally recognized ecological zone. Decades of coastal erosion with rates of up to 9 metres per year have led to severe loss of land. By default the strategy "Accept" was adopted, which was challenged when the coastal highway (RN90) was threatened. The high complexity requires an integral approach for this research, which aims at providing a most promising, long term solution to mitigate the adverse effects of coastal erosion.

Relevant stakeholders were identified by means of a stakeholder analysis, which was based on a site visit, stakeholder research and expert interviews. The resulting stakeholder requirements and their perspectives are used for the evaluation of the alternatives.

The coastal system was characterized to further understand the bay and its development in time. In addition the gathered information is used as input for the coastline modelling.

To predict the coastal development three modelling approaches were applied. For short time scales (<5 years) historic coastline positions were analysed using satellite images. Historic trends were derived, which are extrapolated to the near future. For the longer term, an assessment of the equilibrium bay position was performed using the Parabolic Bay Shape Method. On intermediate time scales (5 -50 years) the coastline model UNIBEST was used. For the process-based model offshore wave climates were transformed towards the coastline using DELFT-3D WAVE. Nine local onshore wave climates were extracted and used to compute the alongshore sediment transport capacity along the 60 kilometre bay. Starting with the coastline position of 2016, the development of the coastline was predicted for up to 50 years ahead. This period is used as it is equal to the expected lifetime of coastal structures and the local highway. The coastline predictions describe a reference scenario, which is expected to take place if no measures would be taken. The results were used to assess the vulnerability of the coastal highway RN90 for damage as a result of the structural erosion, and to identify possible critical locations.

To mitigate the adverse effects of coastal erosion, six alternatives are implemented into the coastline model to assess the impact on the coastline development. The alternatives "Extension", "Revetment", "Breakwater" and "Groin Field" are based on the strategy "Protect". The alternative "Extension" represents the current policy of extending the emergency revetment. The "Nourishment" alternative is based on a maintenance scheme to supply sediment to critical locations. The final alternative "Relocate Road" is based on the strategy "Retreat". The road is build landward of the current position and the erosion is allowed to continue unhindered. The resulting coastline development is evaluated relative to the reference scenario "Do Nothing", together with the stakeholder requirements identified in the stakeholder analysis. For the selection of the most promising alternative a multi-criteria analysis (MCA) is used.

Many stakeholders were identified who have an interest in the project, however it remains unclear which stakeholder is responsible for coastal management. The lack of ownership of the problem has

resulted in a late identification of the problem and the necessity to construct an emergency revetment along the RN90 at KM-19.

Driving forces of coastal erosion along the bay between Barranquilla and Santa Marta are 1) the readjustment of the bay as a result of the natural relocation of the river mouth of the Rio Magdalena, 2) the decreased supply of sediment from the Rio Magdalena since the river mouth is fixated near a deep sea canyon, and 3) the strong gradient in alongshore sediment transport due to the partial sheltering of the bay by the Sierra Nevada de Santa Marta (SNSM) from the dominant north-easterly waves.

The bay is exposed to the north-easterly trade winds and partly sheltered by the Sierra Nevada de Santa Marta. Mainly local generated wind waves turn around the coastal mountain into the bay. As a result alongshore sediment transport is in westerly direction. The transport gradually increases from zero at the rocky section in the east, to a sediment transport capacity of approximately 1 to 1.5 million cubic metres per year near the harbour of Barranquilla. The strong gradient in sediment transport leads to structural erosion along the Salamanca bar with maximum rates of 5 to 9 metres per year.

Two sections along the coastal highway RN90 were identified as critical locations, since the predicted erosion reaches the current highway position. At KM-19 the risk is acute, and already resulted in the construction of the emergency revetment. KM-28 is the second critical location. The erosion is expected to reach the RN90 in 15 years. In addition, KM-40 was identified as a nearly critical location, since the erosion reaches the highway just outside of the evaluation period of 50 years.

The current policy of extending the emergency revetment has a similar impact on the coastline development as the alternative “Revetment”. The only difference is the remaining risk for road collapse with the alternative “Extension”. The alternatives “Revetment”, “Groin Field” and “Breakwater” have a similar effect on the coastline development, as all three alternatives protect the critical section of coastline. However the alternative “Breakwater” is expected to block nearly all alongshore transport, resulting in a strong increase in downstream erosion. The alternative “Nourishment” was identified as the best performing alternative, since the entire bay is stabilized with two nourishments at the critical locations. The conservation of land in the coastal zone however comes with a price, which is relatively high due to a required volume of sand in the order of 650,000 cubic metres per year.

The most cost effective alternative is “Relocate Road”. Here the road is relocated behind a 50-year setback line, allowing the erosion to continue. The combination of unhindered natural processes, safety for road users during storm events and low costs make this alternative the most promising option. It is advised to assign coastal management to an existing or new governmental body, to ensure coastal protection is organized on a nation level. This will not only concentrate coastal knowledge, but will allow for coordination, monitoring and pre-emptive actions as well to avoid the necessity for short-term emergency solutions. As the Barranquilla Bay is identified as a highly dynamic coastal zone, it is advised to avoid the use of hard coastal protection measures. The static structures are expected to provide short term benefits, but become an inconvenience due to expensive scour protection and maintenance.

Since this study was focussed on the coastal aspects of the problems in the area, an additional study is required to select the most suitable highway alignment taking into account the local soil characteristics.

Acknowledgements

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Furthermore, I would like to thank Deltares for providing me with a workplace and software to conduct the coastline modelling. I am especially thankful to Bas Huisman, who helped me a great deal with setting up and calibrating the models. His expert knowledge on modelling coastal processes and detailed feedback has helped me to improve this report.

Additionally I would like to thank Professor Marcel Stive for heading my graduation committee and sharing his experience and knowledge of the coastal system. Your help in taking clear decisions and keeping the overview has been of great value.

Finally, I would like to thank my friends and family for their support during my studies in Delft. I am especially thankful to my girlfriend Frederike for her constant support and for joining me during our site-visit to Colombia.

Bas Voorend

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List of abbreviations

RN90	Ruta Nacional Noventa
MCA	Multi Criteria Analysis
KM-19	Kilometre nineteen
KM-28	Kilometre twenty-eight
KM-40	Kilometre forty
SNSM	Sierra Nevada de Santa Marta
CDD	Colombian Dutch Dialog
NPV	Net Present Value
CAR’s	Corporaciones Autónomas Regionales
MADS	Ministerio de Ambiente y Desarrollo Sostenible
DIMAR	Dirección General Marítima
PNN	Parques Nacionales Naturales de Colombia
MT	Ministerio de Transporte
ANI	Agencia Nacional de Infraestructura
GM	Gobernación de Magdalena
PB	Puerto de Barranquilla
VP	Vicepresidente de Colombia
CORPAMAG	Corporación Autónoma Regional de Magdalena
ANLA	Autoridad Nacional de Licencias Ambientales
CIOH	Centro de Investigaciones Oceanográficas e Hidrográficas del Caribe & Pacífico
INVEMAR	Instituto de Investigaciones Marinas y Costeras
RVO	Rijksdienst voor Ondernemend Nederland
CCO	Comisión Colombiana del Océano
VPIS	Vía Parque Isla de Salamanca
CGSM	Ciénaga Grande de Santa Marta
DNP	Departamento Nacional de Planeación
UNGRD	Unidad Nacional para la Gestión del Riesgo de Desastres

List of Symbols

H_s	Significant wave height
D_{10}	10% grain diameter
D_{50}	Median grain diameter
D_{90}	90% grain diameter
S	Alongshore sediment transport
ϕ	Coastline angle relative to the dominant wave direction
h_d	Depth of closure (relative to MSL)
z_d	Landward height of the active profile (relative to MSL)
Q_s	Alongshore sediment transport
c1	Magnitude coefficient
c2	Curviness coefficient
ϕ_r	Coastline angle relative to the dominant wave direction

1 Introduction

Colombia is one of the upcoming economies worldwide experiencing economic growth and an increase in economic activity (Rijksoverheid, 2012). One of the main contributions to this growth is the mining of natural resources, which are shipped via het major seaports along the Pacific Ocean and Caribbean Sea (Ministerio de Transporte, 2012). With the increase of economic activity and the change in land use in the coastal zone the pressure increases on the natural coastal system since natural coastline variation can lead to conflicts of interest (van Rijn, 2011).

The desire to control and manage the coastal system requires specific knowledge of coastal processes and infrastructural planning for which assistance is provided by the Dutch government. They helped to establish a cooperative relationship between the Colombian government and the Dutch water sector. This resulted in a sector survey in 2012, where opportunities and challenges within the Colombian water sector where presented. Later on a quick scan was performed by Deltares and Invemar, showing critical locations at both the Pacific and Caribbean coast.

The results were used to focus further efforts on areas which required immediate attention. One of the critical locations was the bay between Barranquilla and Santa Marta at the Caribbean coast, where continuous coastal erosion resulted in severe loss of land which threatened the local highway Ruta Nacional Noventa (RN90). To assess the situation and generate solutions a Colombian Dutch Dialog (CDD) was organized. In a joint effort both local and foreign experts visited the site and came up with possible solutions.

This master thesis aims at providing understanding of the physical processes which drive the erosion, identification of stakeholder interests, assess possible ways of solving the problem and present an overview of alternatives with their effects and costs.

1.1 Problem definition

The combination of coastal erosion and sea level rise at the Caribbean Colombian coast has resulted in a regressive coastline for the past decades and resulted in severe loss of land (Correa, Alcántara-Carrió and González, 2005). The erosion has reached a critical point as the RN90 is under threat of collapse (Díaz-Granados, 2014).

The regression of the coastline first led to diminished natural sandy beaches but it now threatens the coastal road RN90 at KM-19. This road connects the port city Barranquilla with the capital Bogota and is the main corridor for goods transport by trucks along the Caribbean Sea. (Ministerio de Transporte, 2012).

Besides coastal erosion other problems were identified and will be taken into account to find an integral solution. The challenge within this master thesis is to come to a good understanding of the relevance of the RN90 and account for three major physical components in the proposed alternative solutions: Coastal erosion, Ecology and Infrastructure.

To prevent immediate failure an emergency measure was taken in 2014 at KM-19 by constructing a local rock revetment. Due to the limited expected lifetime and the local character of this solution a more comprehensive, long term solution is required to deal with the structural coastal erosion (RVO, 2015).

Ecological conditions in the Natural National Parks have deteriorated due to the cut-off of salt water as a result of the construction of the RN90 in 1956 (Kjerfve et al., 2002). Projects have been executed to improve ecological conditions, but the parks have not recovered fully (Botero and Salzwedel, 1999).

The transport capacity of the RN90 is insufficient and should be enhanced to keep up with Colombia's growing economy. For this purpose the existing road will be expanded to two lanes per direction. National Park Isla de Salamanca declared that the expansion is possible within the contours of the park at the existing location (Pérez Díaz, 2015).

1.2 Research objective

The research objective of this research is:

To find the most promising alternative to maintain the availability of the RN90 and mitigate effects of coastal erosion and enhance local ecology using an integral approach.

The sub questions leading to this research objective are:

1. Which stakeholders are involved and what are their interests?
2. What are the characteristics of the natural system?
3. What is the expected coastline development in the future?
4. Which alternative provides the most promising solution?

1.3 Methodology

Even though the focus of this study is on coastal aspects an integrated approach will be used. All relevant stakeholders and their objectives will be taken into consideration to provide the most promising alternative and meanwhile generate support for the proposed solution.

1.3.1 Stakeholder analysis

Stakeholder identification is based on expert interviews and online research. In addition a cultural comparison and a site visit were performed to ensure a good understanding of the local objectives and underlying motives.

After the stakeholder identification, their influence, power and network is studied as well to understand the importance of the different objectives. This allows for the prioritisation of all project requirements, which are later used to evaluate the alternatives.

1.3.2 Natural system development

An analysis of the historic development of the Barranquilla Bay is done using satellite images dating back to 1970. In addition literature is used to assess the historic development of the Rio Magdalena delta on larger time scales.

A priori, it is expected that longitudinal transport processes will dominate the coastline development of the Barranquilla Bay, which is why the one-line coastline model UNIBEST will be used. Offshore wave data, local bathymetry and sediment characteristics will be the main input.

The stability of the Barranquilla Bay is evaluated using MEPBAY, which is based on the equilibrium bay shape method. This will provide insight in the period before the bay reaches an equilibrium position.

Expert knowledge will be used throughout this part of the study to improve modelling results.

1.3.3 Evaluation of alternatives

The evaluation of alternatives will be based on the criteria identified during the stakeholder analysis. They are translated to measureable physical, social and financial quantities. On the basis of this set of criteria, six typical alternatives will be evaluated on the basis of the following aspects:

The coastline development will be based on the outcome of coastline model computations. Sensitivity to input parameters will also be part of the study, because the reliability of the model approach and the measure itself are important factors to consider.

The ecological development will be based on expert opinion to get a first impression into the expected consequences. This will result in a lower reliability and degree of detail as a consequence of the fact that this Master Thesis is focussed on coastal processes.

Costs are also an important characteristic of the measures, and will be presented as Net Present Value (NPV) over time. The expenses will be based on bulk figures which lack a high level of detail. However for comparative purposes it is expected to provide of sufficient information to correctly estimate the relative cost differences.

A scorecard will be presented summarizing the characteristics and performance of each alternative to allow for an easy comparison. The scorecard will be presented from different stakeholder viewpoints to emphasize the different perspectives. The selection of the most promising alternative will be made using MCA combining all discussed aspects of the alternatives.

2 Stakeholder analysis

2.1 Introduction

Coastal erosion is taking place on a large scale along the Caribbean coast of Colombia and therefor has an effect on people, businesses and institutions throughout the country. To provide a suitable solution to the problem of local erosion along the RN90 between Barranquilla and Santa Marta the proposed measure or strategy should match the interests and values of stakeholders involved. A suitable solution will need support on both local and governmental level to make it a successful solution for both the short and long term.

Technical measures can be characterised by a number of qualities it possesses. To what extend a quality is regarded as a benefit depends on your perspective. Therefor comparison of measures can't be done impartial, but is always based on a perspective corresponding to the position relative to a situation.

Figure 1 illustrates this idea by showing a stranded man on an island who is happy to see a boat on the horizon, while the man in the boat is happy to see land on the horizon.

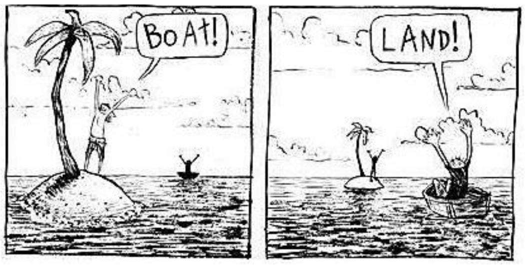


Figure 1: Illustration on the relevance of perspective

The stakeholder analysis will be used to identify the perspective of local stakeholders towards the project and the differences among them. Awareness of this phenomenon will help to take all stakeholders into account and follow an integrated approach for this project. The perspective of stakeholders will also be used to evaluate the alternatives in a later stage. Alongside stakeholder perspective, this chapter will elaborate on the involvement of stakeholders in the project. A suggestion will be presented how stakeholders could participate in the project to include local knowledge and generate support for the project .

2.2 Approach

Identification of stakeholders and their values and interests is the first step providing the basis for this chapter. Based on the question: *"Who is affected?"* a list of stakeholders is made and their perspectives on the project are identified. The identification will be separated into categories based on role groups. The two main role groups for this project are end-users and governmental institutions. After selection the most relevant stakeholders are described with more detail in the rest of the chapter.

To specify the role of each stakeholder, their interest for the project and power over the project will be assessed. This will help identify the differences between stakeholders. The information will be used for both the participation planning and the organisation of the project requirements. The method of participation planning is adapted from the International Association for Public Participation (IAP^2,2007) and is applied to this project based on expert interviews resulting in a suggestion for the involvement of relevant stakeholders.

The summary will give an overview of the most relevant requirements and will provide criteria for the evaluation of alternatives.

2.3 Stakeholder identification

Stakeholders from different role groups are identified in different ways, end-users are located geographically based on land use while governmental stakeholders are identified using the governmental hierarchy.

2.3.1 Land use

Ownership of land is a complex matter in Colombia, where the recent past was full of conflict. As a result Colombia has the highest number of internally displaced persons in the world. (Data.worldbank.org, 2017) Therefore land use based on satellite images and the site visit is used to identify local stakeholders.

Figure 2 shows the location and area of major stakeholders. The Rio Magdalena is indicated in blue, flowing from the south towards the Caribbean Sea. Some 20 kilometres from the sea the port of Barranquilla is located, which is indicated in black. Urban areas are displayed in red, with the city of Barranquilla to the west of the Rio Magdalena. Santa Marta is located to the east, with the town of Ciénaga in the middle. In yellow the road network is displayed, connecting port of Barranquilla with the hinterland. The RN90 connects Santa Marta to Barranquilla, allowing commuters and all sorts of transportation to reach the harbour city. For a complete overview of all stakeholders, see Appendix A.

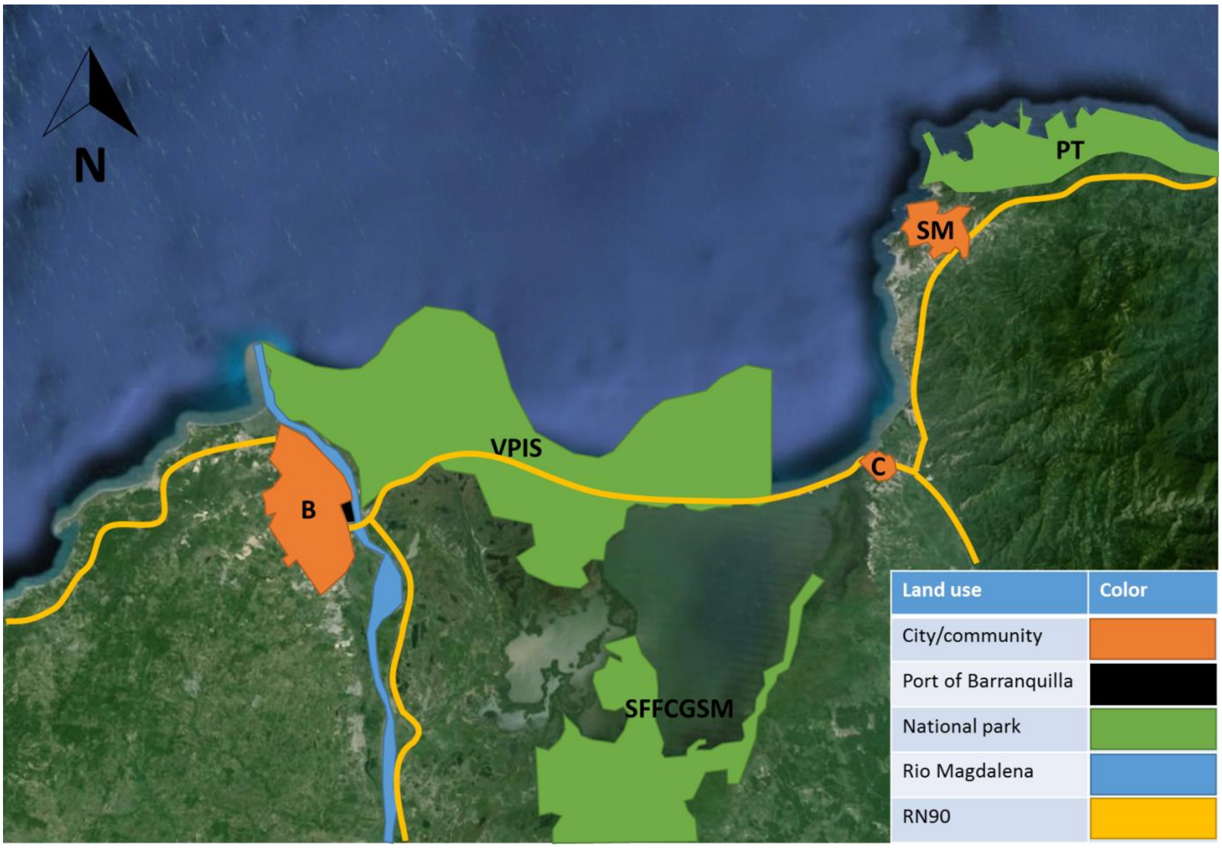


Figure 2: Stakeholder identification based on land use

2.3.2 Governmental institutions

The executive branch of the government is headed by the President of Colombia, who is assisted by the Vice President, ministries and departments.

The ministries make and execute policy on national level based on their particular specialisation. The country is also divided into departments which work on a provincial level. Within departments several municipalities are located who are responsible for execution on a local level. According to consecution the governmental bodies are subordinate to policies made by a higher policy maker.

To focus on environmental issues, special organisations where established, called 'Corporaciones Autónomas Regionales' (CAR's). They act on a regional level, between the departments and municipalities, and are formed based on geographic locations of ecosystems. They have legal and financial independence and are responsible for the environment and renewable natural resources. They are placed under the 'Ministerio de Ambiente y Desarrollo Sostenible' (MADS) since they take part in the board of directors.

Some governmental organisations such as MADS and 'Dirección General Marítima' (DIMAR) are involved with relevant research institutes which are incorporated in this paragraph since they could play a useful role within the project.

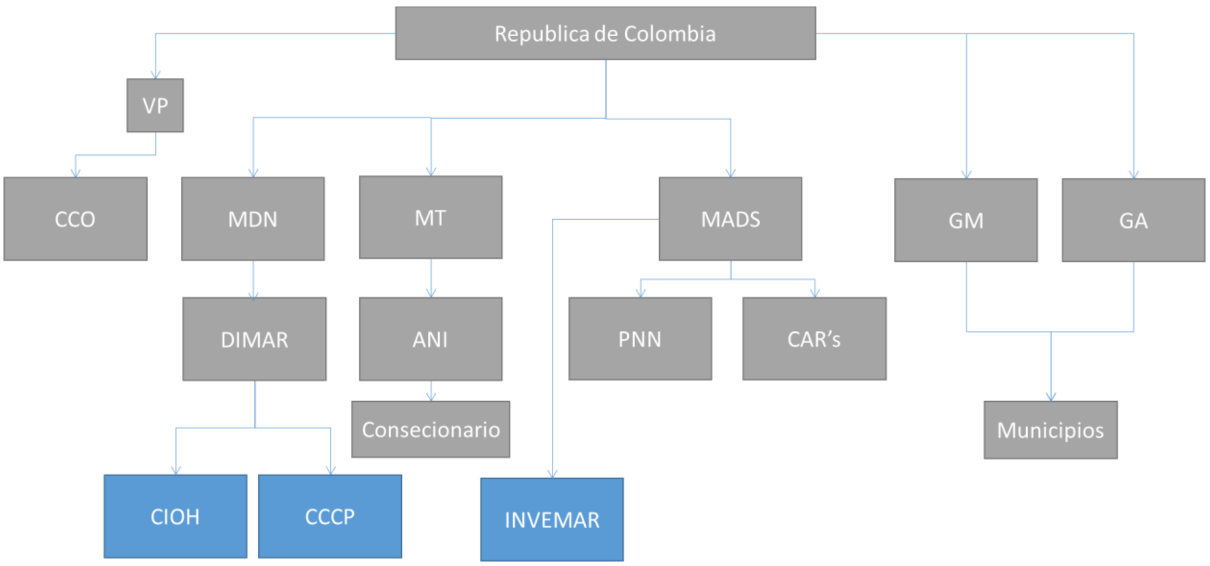


Figure 3: Stakeholder identification based on governmental hierarchy

2.3.3 Selection

Relevant stakeholders are presented in Table 1, where the role-group, name and acronym of the stakeholders are presented. General information on all relevant stakeholders is presented in paragraph 2.3.4. The selection of stakeholders is based on relevance to the project; stakeholders with a mutual goal and perspective are grouped together for the purpose of clarity.

Relevant governmental organisations are present at different management levels and should all be included in the early stages of the project. For simplicity it is assumed that most contact will be with both MADS and 'Parques Nacionales Naturales de Colombia' (PNN) who will represent the interest of the national parks and environmental groups as shown in Figure 4. Similar for the infrastructural aspects it is assumed that both 'Ministerio de Transporte' (MT) and 'Agencia Nacional de Infraestructura' (ANI) act as representatives for all parties involved in the full "column".

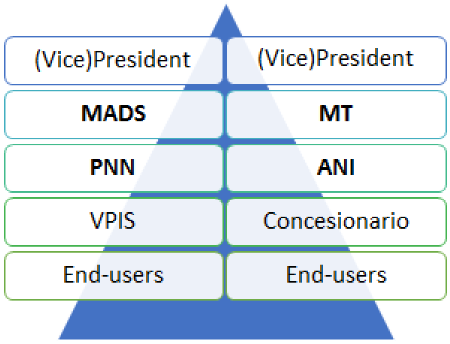


Figure 4: Selection of relevant stakeholder in the 'management column'

As can be seen from Table 1 most end-users are not part of the list of relevant stakeholders. This does not mean their interests are neglected during this study. It is assumed that the 'Gobernación de Magdalena' (GM) acts as a representative for these stakeholders when the importance of infrastructure is seen on a regional scale. Housing and safety of residents of the Salamanca bar is also considered to be part of the perspective of GM.

An important aspect of this study is the local character of this specific case, while structural erosion along Colombia's beaches is of national importance. This results in a smaller interest from bigger, national stakeholders while maintaining a high power since national policy has to be followed by the lower governmental institutions. Although the importance of a national approach is recognized, it is outside of the scope of this study. It is part of a study performed by ARCADIS 'Master plan Coastal Protection Colombia'.

Table 1: Relevant stakeholders for the project

Role-group	Name	Acronym
End-users	Puerto de Barranquilla	PB
Government	Vicepresidente de Colombia	VP
Government	Ministerio de Transporte	MT
Government	Ministerio de Ambiente y Desarrollo Sostenible	MADS
Government	Gobernación del Magdalena (representing local end-users)	GM
Government	Corporación Autónoma Regional del Magdalena	CORPAMAG
Government	Parques Nacionales Naturales de Colombia	PNN
Government	Agencia Nacional de Infraestructura	ANI
Government	Autoridad Nacional de Licencias Ambientales	ANLA
Research	Centro de Investigaciones Oceanográficas e Hidrográficas del Caribe & Pacífico	CIOH
Research	Instituto de Investigaciones Marinas y Costeras	INVEMAR
Financier	Rijksdienst voor Ondernemend Nederland	RVO

2.3.4 Relevant stakeholders

Port of Barranquilla (PB)
The port of Barranquilla is located just upstream of the mouth of the Rio Magdalena. Connecting marine, riverine and land-based transport chains the harbour is used for transport and trade and plays a major role for the Colombian economy.

Both the city and the port of Barranquilla are relying on a good connection with the rest of the country by road. The RN90 is a major part of this connection since transport towards the capital Bogota and other parts of the country make use of this road. A reliable connection via the road and limited inconvenience during construction are therefore important aspects for the harbour. Besides the connectivity on land measures for the RN90 could influence coastal processes near the harbour and have an effect on sedimentation in the harbour basin as well as the approach channel. Additional maintenance costs as a consequence of measures for the RN90 should therefore be avoided.

The interests of the harbour of Barranquilla are attended by the harbour master. Due to important local connections with the city as well as the 'Gobernación de Atlantico' (GA) as well as the importance of the harbour for the national economy there will be a lot of shared interests with other stakeholders.

Vicepresidente (VP)
The Vice President of Colombia is elected together with President and is entrusted with the promotion of interagency and inter-sectorial coordination. Therefor this stakeholder doesn't have a personal agenda or preference. Considering the stakeholders involved and the different perspectives the Vice President is important for the project to consider all aspects and make a final political decision.

Comisión Colombiana del Océano (CCO)
The CCO is a national inter-sectorial advisory body to the government on issues which relate to the sustainable development of Colombia's seas and their resources. They are related to the project, since it problems in the coastal zone are addressed. Structural coastal erosion is a problem of a national scale, and therefore requires cooperation on a national level.

CCO is headed by the Vice-president and has a similar aim to assure cooperation at a national level for sustainable national development and welfare for Colombians.

Ministerio de Transporte (MT)
The ministry of Transport aims at developing and improving the transport system that allows the integration of regions, economic growth and social development. The RN90 is under their direct jurisdiction and a road expansion will be executed to provide extra capacity with a second lane for both directions. Their relation to the project is to keep the existing road and future investments safe and provide a long term solution to maintain and improve connectivity along the Caribbean Coast of Colombia.

Since the ministry is also responsible for other modes of transport they are closely connected to the port of Barranquilla.

Agencia Nacional de Infraestructura (ANI)
As part of the ministry of transport ANI is responsible for the concessions for the design, construction and operation of infrastructure. The RN90 is under concession by concesionaro "Ruta del Sol". The

erosion is now directly threatening the road and action is required to protect the road and keep a connection by road available between Barranquilla and Santa Marta. This problem initiated the project making ANI an important stakeholder.

ANI, the ministry of transport and the Port of Barranquilla have similar interests making this a strong group of stakeholders.

Ministerio de Ambiente y Desarrollo Sostenible (MADS)
The ministry of Environment and Sustainable Development is a public entity responsible for defining the National Environmental Policy and promote recovery, conservation, protection, planning, management, use and exploitation of renewable natural resources to ensure sustainable development and guarantee the right of all citizens to enjoy and inherit a healthy environment.

Nature is managed as developing in time, so natural changes are a characteristic of the National Parks as long as the high biodiversity can be maintained. Changes as a consequence of human actions are to be avoided.

Through the care for the environment MADS is connected to the PNN and CORPAMAG, providing support on a local level.

Parques Nacionales Naturales de Colombia (PNN)
The mission statement of the PNN is: Preserve in situ biodiversity and ecosystem representative of the country, provide and maintain environmental goods and services, protect the cultural heritage and natural habitat where traditional cultures as part of the National Heritage develop and contribute to sustainable human development.

National Parks are present in our area; the 'Vía Parque Isla de Salamanca' (VPIS) is directly affected by the on-going erosion and local measures for the RN90 could have a big impact on the erosion at the park. 'Ciénaga Grande de Santa Marta' (CGSM) is located behind the sand bar and is very dependent on the inflow of both salt water from the Caribbean Sea and fresh water from the Rio Magdalena. Failure of the sand bar as a whole would change the ecological conditions completely.

The Rio Magdalena delta with the characteristic shallow lagoon and mangrove forest provides a number of natural resources and should be handled with care. Fishery in the Caribbean Sea is directly related since the Ciénaga Grande is considered a nursing ground for many fish species.

PNN operates on a national level with parks throughout the whole country. It is directly related to MADS.

Corporación Autónoma Regional del Magdalena (CORPAMAG)
CORPAMAG is a corporate body of public nature responsible for managing the environment and promoting sustainable development of Magdalena. It has administrative and financial autonomy and its own assets and legal status. The main function is to implement policies, plans and programs on environmental issues defined by the 'Departamento Nacional de Planeación' (DNP) and the Ministry of Environment.

Environmental problems at the Salamanca bar and CGSM are within the jurisdiction of CORPAMAG and they are the local authority responsible.

Gobernación de Magdalena (GM)
Mission statement: GM must execute the powers of planning, coordination and mediation between the national, regional and local levels to improve the quality of life for its residents.

Magdalena residents at Santa Marta, Ciénaga and the Salamanca bar are represented by GM, which leads to a stakeholder with local support. Availability of transportation and safe housing are the main interests.

Within Magdalena many stakeholder are active and leading to an important mediating role for GM.

Autoridad Nacional de Licencias Ambientales (ANLA)
ANLA is a governmental organisation responsible for evaluation, monitoring and control of projects, works or activities subject to licensing, permits or environmental procedures to contribute to the balance between environmental protection and development of the country for the benefit of society.

No direct interest from this stakeholder is expected, but measures taken in the project have to be in accordance with existing laws and regulations. ANLA is part of MADS.

Centro de Investigaciones Oceanográficas e Hidrográficas Caribe y Pacifico (CIOH)
The CIOH is a research institute established to support DIMAR with applied research in the various disciplines of oceanography and hydrography and use of natural resources.

Specifically for Integrated Coastal Zone Management CIOH has objective to:

“Generate knowledge for the identification and characterization of islands, coastal areas and rivers under the jurisdiction of the DIMAR, in order to provide scientific and technical support in the decision making of the DIMAR and other entities, authorities and people involved in coastal management, for an appropriate integrated management of these areas, the technical determination of public goods and prevention and mitigation of disasters.”

CIOH could play a role within the RN90 project since local knowledge and measurement data is expected here.

Dirección General Marítima (DIMAR)
DIMAR is a research institute, advising the government on maritime activities. They are responsible for the installation and maintenance of navigational aids, hydrographical surveys and nautical cartography. Together with the navy they coordinate the control of maritime traffic.

Since the project is located along the Caribbean Sea, DIMAR is related to the project. They are directly under the Colombian navy.

Instituto de Investigaciones Marinas y Costeras (INVEMAR)
INVEMAR was founded in 1963 by three German professors from the University of Giessen as a tropical research centre to observe and systematically describe climate, geology, flora and fauna of the region, centred mainly in the Sierra Nevada. Knowledge with regard to ecosystems and the impact of proposed measures is necessary to complete the impact considerations of measures and the evaluation of alternatives.

Linked to MADS it has been active in environmental research for both coastal and marine ecosystems.

Unidad Nacional para la Gestión del Riesgo de Desastres (UNGRD)
Objective of the UNGRD is to direct the implementation of disaster risk management, addressing the sustainable development policies and coordinate the operation and continued development of the national system for attention and prevention of disasters.

The emergency measure taken at KM-19 was funded by the UNGRD.

Rijksdienst voor Ondernemend Nederland (RVO)
RVO is a Dutch organisation promoting the cooperation between the Dutch Water Sector and the Colombian government. Through the Colombian Dutch Dialog in 2014 the RVO was actively involved and acts as co-financier of the project.

Stakeholder representing coastal zone
After introducing all relevant stakeholders for the project it is clear that a number of agencies are related to the national coastline (MADS, CAR's, CCO, DIMAR, etc.). However coastal management is currently not part of the jurisdiction of any ministry or governmental organisation.

The lack of ownership of the problem is an important factor if we consider why it has taken so long before a response to the regressive coastline was formulated.

Due to the lack of a general governmental vision and approach for coastal problems the solution to current problems are locally generated and only apply for each individual case. To organize a more systematic approach ownership of the problem should be placed on a higher governmental level to centralize knowledge and experience and to increase effectiveness in reacting to coastal issues nationwide. How this should be organized is beyond the scope of this project, and is part of a study by Arcadis regarding a Masterplan for the Colombian Coast.

2.4 Project requirements

With the stakeholder identification their position to the project is also described. Based on their interests, project requirements are formulated for the evaluation of alternatives in a later stage of this study. Table 2 presents all requirements following the order in which the stakeholders were described.

Table 2: Project requirements

Project requirements	Stakeholder(s)
Provide reliable, safe way to connect (the port of) Barranquilla with the existing road network	PB
Minimize impact on harbour maintenance	PB
Minimize hindrance of ships approaching Barranquilla	PB
Limit inconvenience for transport by road during construction	PB
Integral approach to the project with efficient solutions	VP
Provide a long term solution to maintain and improve connectivity in the Caribbean region	MT
Recovery of CGSM should be improved by project measures	MADS
Existing ecological values should be conserved	MADS
Protective measures for RN90 should not aggravate erosion at VPIS	PNN
Salamanca sand bar should be maintained to protect CGSM	PNN
Salt water supply from Caribbean Sea to CGSM should be improved	PNN
Fresh water supply from Rio Magdalena should be improved	PNN
Keep local communities connected via the road network	GM
Protect villages an Salamanca bar from eroding away	GM
Provide safe conditions for people to live on the Salamanca bar	GM
Provide safe conditions for existing infrastructure	ANI
Measures should be in accordance to existing laws and regulations	ANLA
Cost effectiveness of measure	VP/RVO

2.5 Interest versus Power

Using a power versus interest grid the different roles for stakeholders within a project can be identified. On the vertical axis a stakeholder's interest is shown, describing to what extent a stakeholder is interested or involved in the project. The horizontal axis covers whether the stakeholder is able to influence the results, known as power.

Based on the position within the grid stakeholders can be divided into four major groups: **"Players"** have both interest and power and are therefore very important to the project. **"Subjects"** have limited power but high interest, resulting in a dependent role on other stakeholders. **"Context Setters"** do have power but limited interest, making them less involved but their requirements are still to be taken into account. At last we have the **"Crowd"** who have limited power and minor interest for the project.

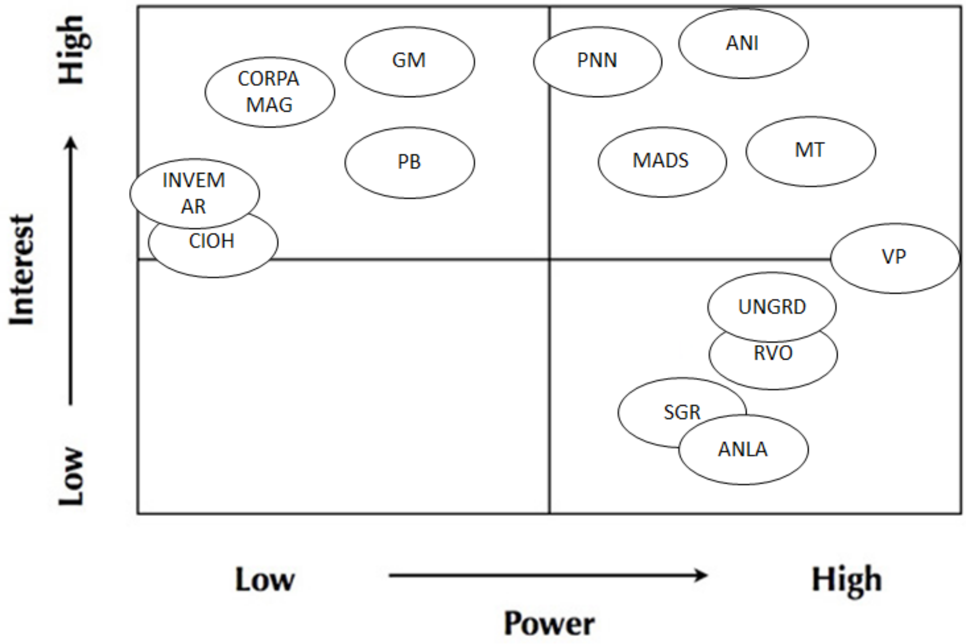


Figure 5: Interest vs. Power grid

As a result of the power versus interest grid we can divide our stakeholders into groups and use this information for the ranking of requirements as well as the participation planning later on.

- **"Players"**, as defined in the beginning of the paragraph, are MT, MADS, PNN and ANI. Their requirements make the framework of the project and they should be actively involved in the project.
- **"Context Setters"** are ANLA and DIMAR, who provide the general boundaries between which the project needs to be realised.
- **"Subjects"** are CORPAMAG, GM and both cities Barranquilla and Santa Marta, whose requirements can be seen as desires, and will be taken into account if it does not conflict with other requirements.
- No stakeholders are identified as **"Crowd"**, since they are not part of the stakeholder selection.
- The Vice president plays a dual role as both **"Player"** and **"Context Setter"** as he has decisive power over the project but does not add to the project requirements besides enhancing the cooperation between the stakeholders.

2.6 Intermezzo: Culture only exists by comparison

As this study takes place in another country and even on another continent it is of interest to all parties involved to learn and be aware of possible cultural differences. This can improve the cooperation between nations, organisations and individuals.

To compare the Colombian and Dutch culture the 6-D Model© by Geert Hofstede is used (Hofstede et al., 2014). For an elaboration on the model, see Appendix B.

In summary Figure 6 presents the scores of both cultures on the six cultural dimensions. The following can be mentioned as a practical advice for Dutch Engineers:

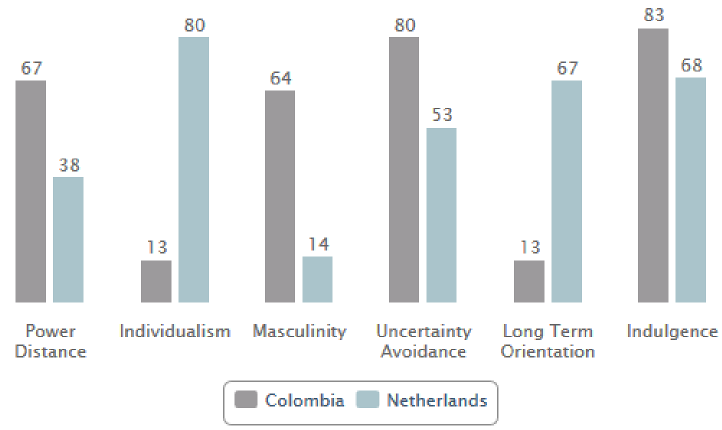


Figure 6: Comparison between Colombia and the Netherlands on Cultural Dimension

- Based on the Power Distance, hierarchy is very important in the Colombian culture. It is therefore very important to present a clear project leader who has the authority to make decisions. When working with local people a leading role is expected, a consultation with subordinates is unusual and should be organised with care and after coordination with the superior in charge.
- The masculine society of Colombia is not suitable for the Dutch approach of discussions and reaching consensus. The collective character of the Colombian culture indicates that the most effective way to convince a group is through the leader, the high Power Distance confirms this since not all stakeholders have the same influence and power.
- The importance of personal relations should not be underestimated. Having a consistent project team is very important since replacement of a member would require establishing a new relation taking time and hindering efficiency.
- To prevent being seen as an ‘outsider’ within the collective Colombian culture, you should work closely with local contacts to introduce yourself to new contacts. Here to, do not underestimate the required time to build a relation and necessity for it within the Colombian culture.
- Expect nepotism due to the strong sense of taking care of each other and the fact that you will stay an outsider to a certain degree.
- Uncertainty avoidance results in using ‘proven’ technologies which have been applied with success in the past. Very little room is available for innovation and processes are strictly guided by conservative rules and laws.
- The lack of long term orientation can become a problem since all processes in the coastal region are long term compared to election cycles. Quick results are hard to achieve and do not necessarily correspond to preferred long term solutions.
- Any proposed organisations or institutes should be positioned within an existing group to guarantee local support and establish a clear position within existing hierarchy.

2.7 Participation Planning

Stakeholders identified earlier in this chapter should have a say in the development of a solution for the situation. Using the method of Participation Planning based on (Bryson, 2004) and the Interest vs. Power grid presented in paragraph 1.4 the level of participation is determined for each stakeholder. Table 3 shows the different levels of participation with the corresponding promise to the stakeholder in the second column and the goal for the project in the third column.

Table 3: Explanation of terms

Level of participation	Promise to stakeholder	Participation Goal
Inform	We will keep you informed.	To provide balanced and objective information to assist in understanding the problem, alternatives, opportunities and/or solutions.
Consult	We will keep you informed, listen to you and provide feedback on how your input influenced the decisions.	To obtain public feedback on analysis, alternatives and/or decisions.
Involve	We will work with you to ensure your concerns are considered and reflected in the alternatives considered, and provide feedback on how your input influenced the decision.	To work together throughout the process to ensure concerns and aspirations are consistently understood and considered.
Collaborate	We will incorporate your advice and recommendations to the maximum extent possible.	To partner up in each aspect of the decision including the development of alternatives and the identification of the preferred solution.
Empower	We will implement what you decide.	To place final decision-making power.

Table 4: Level of participation per stakeholder

Stakeholder	Level of Participation
Vicepresidente de Colombia	Empower
Ministerio de Ambiente y Desarrollo Sostenible	Collaborate
Ministerio de Transporte	Collaborate
Parques Nacionales Naturales de Colombia	Collaborate
Agencia Nacional de Infraestructura	Collaborate
Unidad Nacional para la Gestión del Riesgo de Desastres	Involve
Gobernación del Magdalena	Involve
Instituto de Investigaciones Marinas y Costeras	Consult
Centro de Investigaciones Oceanográficas e Hidrográficas del Caribe & Pacífico	Consult
Rijksdienst voor Ondernemend Nederland	Inform
Corporación Autónoma Regional del Magdalena	Inform
Puerto de Barranquilla	Inform
Autoridad Nacional de Licencias Ambientales	Inform

The stakeholders initiating the project are the two ministries, MADS and MT. They are expected to take a leading role and activate other stakeholders. Together with the more directly involved PNN and ANI close cooperation is required to make sure both the interest for infrastructure and ecology are represented in the project.

The 'Gobernacion de Magdalena' is actively involved in the project since they represent a large group of stakeholders living in the region. Safety for both housing and infrastructure is important and should be implemented within the solution. Both financiers are involved as well since the project is dependent on their financial aid and should therefore match their requirements.

Stakeholders such as Puerto de Barranquilla, CORPAMAG, RVO and ANLA are informed on the project results and progress during execution.

The 'Vicepresidente' is also taken an active role in the project, as he is empowered to make the final decision. With many stakeholders involved and conflicting interests a third parties is required to make a decision in the best interest of Colombia and its people.

2.8 Stakeholder summary

To provide a clear overview of the stakeholder analysis, all results are presented in Table 5 below. The stakeholders are ordered based on participation, in the far right column. A high level of participation is advised for the stakeholders mentioned in the top of the table.

Table 5: Stakeholder summary

Role-group	Name	Acronym	Perspective	I vs. P	Participation
Government	Vicepresidente de Colombia	VP	Encourage inter-governmental cooperation	Player	Empower
Government	Ministerio de Ambiente y Desarrollo Sostenible	MADS	Protect natural system within protected area's for future generations	Player	Collaborate
Government	Ministerio de Transporte	MT	Improve road network to facilitate economic growth	Player	Collaborate
Government	Parques Nacionales Naturales de Colombia	PNN	Preserve dynamic natural processes characterizing	Player	Collaborate
Government	Agencia Nacional de Infraestructura	ANI	Protect connection by road currently provided by RN90	Player	Collaborate
Financier	Unidad Nacional para la Gestión del Riesgo de Desastres	UNGRD	Provide assistance against natural disasters	Context Setter	Involve
Government	Gobernación de Magdalena	GM	Improve quality of life for all residents	Subject	Involve
Research	Instituto de Investigaciones Marinas y Costeras	INVEMAR	Provide scientific and technical support on marine and coastal issues	Subject	Consult
Research	Centro de Investigaciones Oceanográficas e Hidrográficas del Caribe & Pacífico	CIOH	Generate knowledge and support decision making related to coastal management	Subject	Consult
Financier	Rijksdienst voor Ondernemend Nederland	RVO	Encourage cooperation between Colombia and Dutch water sector	Context Setter	Inform
Government	Corporación Autónoma Regional del Magdalena	CORPAMAG	Prevent mismanagement of natural resources	Subject	Inform
End-users	Puerto de Barranquilla	PB	Minimize negative effects on harbour operations and maintenance	Player	Inform
Government	Autoridad Nacional de Licencias Ambientales	ANLA	Ensure relevant laws and regulations are adhered to	Context Setter	Inform

3 Natural System Description

3.1 Introduction

This chapter introduces the project location and gives the geographic frame of reference. Sequentially, the following topics are discussed:

- Study area
- Geology
- Rio Magdalena
- Ciénaga Grande de Santa Marta
- Ocean currents
- Tide
- Wind climate conditions
- Wave climate conditions
- Bathymetry
- Sediment
- Human interventions

3.2 Study Area

The study area is located in the northern part of South-America, at the interface between the Caribbean Sea and Colombia, in the river delta of the Rio Magdalena.

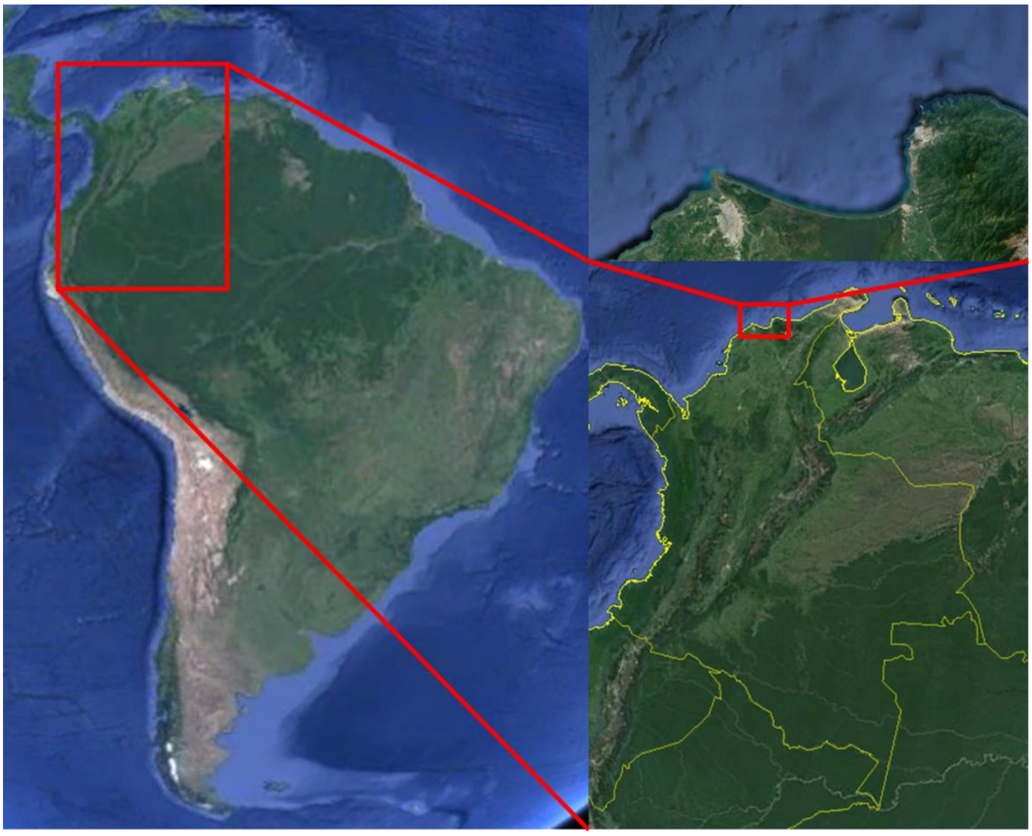


Figure 7: a)South America b) Colombia c) Bay between Barranquilla and Santa Marta (Google Earth, 2016)

3.3 Geology

As can be seen in Figure 8, the Caribbean coast of Colombia is located in a tectonically active area. between Nazca, the Caribbean and the South American plates. The area is subject to high geologic variety with both low relief planes and high relief rocky massifs. The area has been classified as an intermediate seismic risk zone. (USGS, 2016)

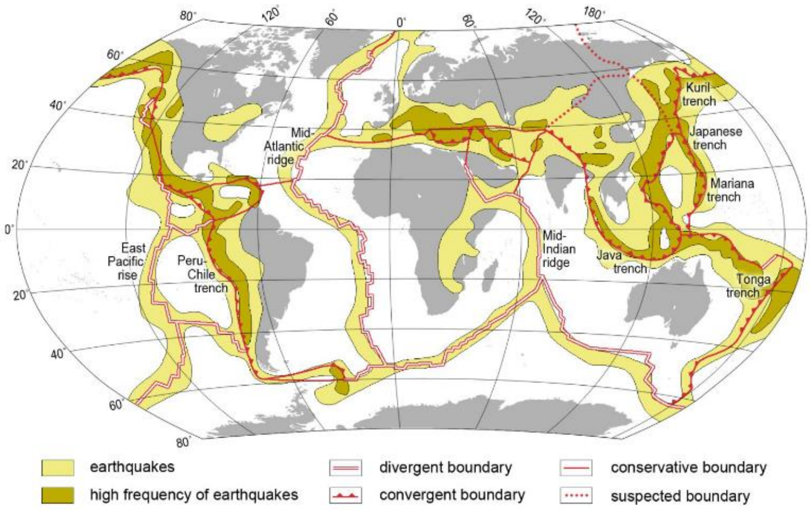


Figure 8: Global distribution of earthquake occurrences (Bosboom and Stive, 2015)

The continental shelf is very narrow as can be seen in Figure 9; especially at the mouth of the Rio Magdalena, where the shelf is non-existing due to the presence of the several canyons. The deep sea canyons (4000m) hinder the sediment supply from the Rio Magdalena to the Caribbean Coast of Colombia. (Estrada, 2006)

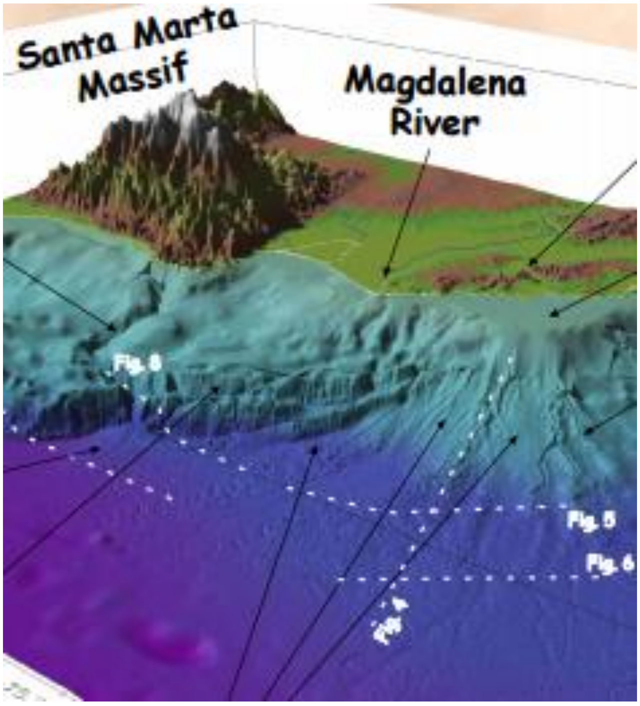


Figure 9: 3D composition of bathymetry (Estrada, 2006)

Colombia is located on the northern side of the Andes Mountains, which is the source of the Rio Magdalena. The river flow is directing by the Sierra Nevada de Santa Marta massif, which is the highest coastal mountain in the world, reaching 5800m at Pico Bolívar, 60 km from the coastline (Correa and Morton, 2010). The mountain ridge provides sheltering from incoming waves, therefore creating the local wave climate which shapes the bay between Barranquilla and Santa Marta.

3.4 Rio Magdalena

The Rio Magdalena is of major influence for the development of the Caribbean Coast of Colombia. The river has formed six different deltas at sea since the Pleistocene ranging from Cartagena to Riohacha as can be seen in Figure 10. It is estimated that the change from Cartagena to GCSM occurred 700,000 years.

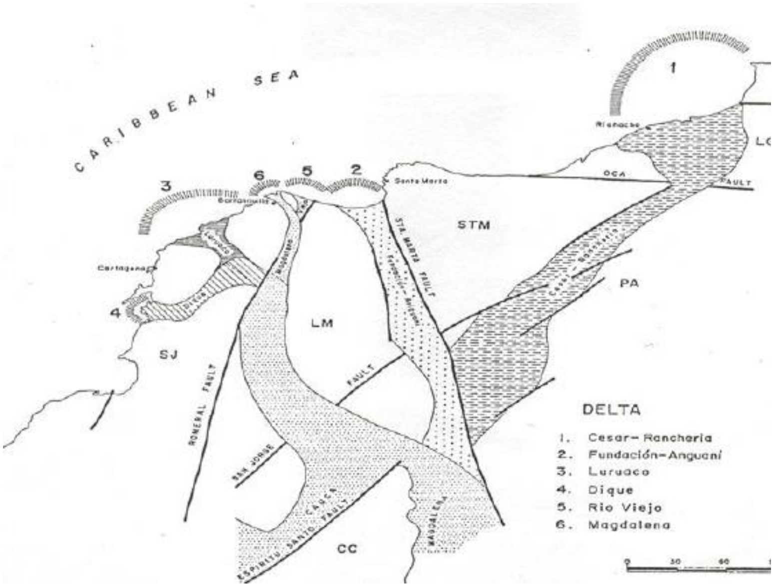


Figure 10: Historic positions of the Rio Magdalena (Alvarado Ortega, 2008)

The final position where the Rio Magdalena flows in the Caribbean Sea at Barranquilla is referred to as 'Bocas de Ceniza'. The name literally translates to 'ash mouth', which refers to the big colour difference between the sediment rich river water and the clear blue water of the Caribbean Sea.

The latest relocation of the river mouth is of great importance for the area of interest, since the bay is continuously readjusting to the new situation. Combined with the reduced sediment supply this is the primary cause for the structural coastline regression (Von Erffa, 1973).

Measurements downstream at Calamar show an annual discharge of 7232 m^3s^{-1} and a sediment load of $144*10^6$ ton/year. This sediment supply has major consequences for the entire Caribbean coast of Colombia. Sediment from river was filling the continental plate, with a progressive coast as a consequence. To the west of Barranquilla the supply of sediment led to the formation of numerous spits and bars while to the east the Salamanca bar was formed providing shelter for the lagoon in the hinterland.

The Magdalena River is the largest river of Colombia stretching 1612 km from Magdalena's Lake at 3685 metres above sea level in the Andes to Barranquilla at the shore of the Caribbean Sea. The river drains 257.438 km^2, and many major cities such as Bogotá, Medellín, Cali, Burcaramanga and Barranquilla are located within the watershed of the Magdalena River. In total 79% of the population of Colombia lives within the watershed. Characteristic for the basin is high tectonic activity, steeps hillslopes, landslides, steep gradients, high relief tributary basins (Restrepo et al., 2006).

Figure 11: Rio Magdalena and its catchment area.

3.5 Ciénaga Grande de Santa Marta

Within the Rio Magdalena delta a lagoon developed, confined by the Salamanca bar. The bar stretches for 65km and forms the coastline of the eastern Magdalena delta. With a height of 2 metres above sea level the bar has been subject to overwash events. Only one connection between the sea and the lagoon remained at Tasajeras mouth.

During high water periods in the Rio Magdalena the river banks flooded and an impulse of fresh water and sediment flowed through the lagoon. Likewise during storm events the sea would wash over or even penetrate the Salamanca bar and a permanent connection with the Caribbean Sea was established at the Tasajeras mouth. The dynamic brackish condition provided unique conditions for the formation of a diverse mangrove forest and marsh known as Ciénaga Grande de Santa Marta (CGSM).

The lagoon is the largest estuarine complex of Colombia and it is located in a very arid zone were evaporation exceeds precipitation. With water deficit of 1031 mm/year the Ciénaga is very dependent on inflow of fresh water from the Rio Magdalena and exchange with the Caribbean Sea (Cardona and Botero, 1998). The mangrove forest and shallow lagoon is the main source of fish and shellfish for the north coast of Colombia. Oyster beds, prop root, small creeks and lagoons served as breeding, nursing and feeding grounds for a lot of commercial species or take part of the food web (Botero and Salzwedel, 1999).

3.6 Ocean currents

The North Equatorial Current enters the Caribbean Sea from the East, and is thereafter called southern Caribbean Current and flows along South America in Westerly direction. This current continues into the Gulf of Mexico, but also feeds the Panama-Colombia gyre and the Caribbean Coastal Undercurrent, which is a semi-continuous eastward directed coastal subsurface flow at a depth of 100 to 200m associated with offshore cyclonic eddies(Andrade and Barton, 2000). A velocity estimate for the southern Caribbean Current at 30 km depth is in the order of 0.1 m/s near the Colombian coastline (Jouanno et al., 2008).

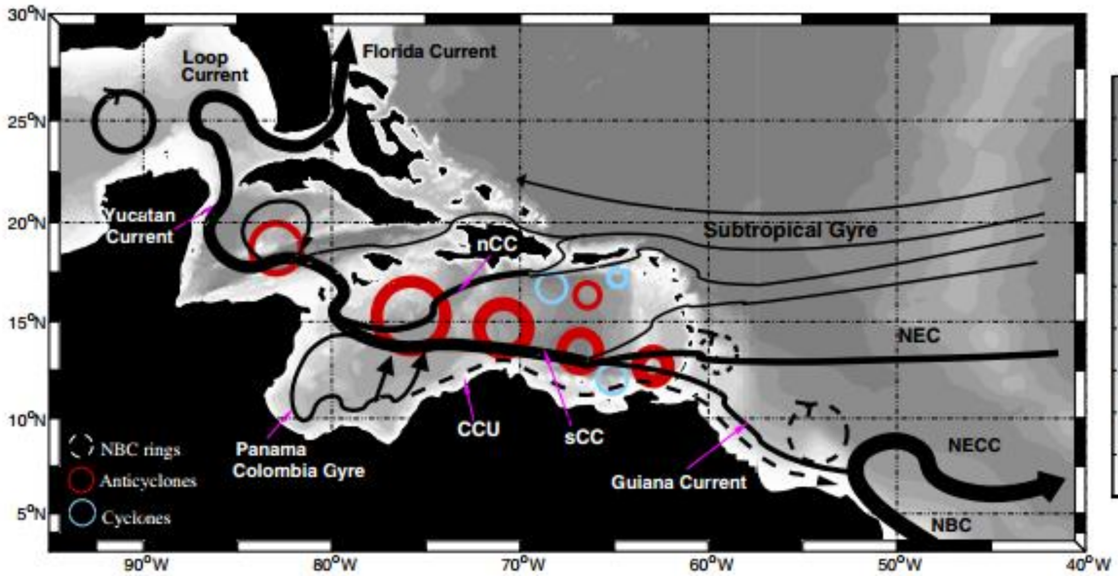


Figure 12: Current paths in- and outside Caribbean Sea (Jouanno et al., 2008).

3.7 Tide

The Caribbean Sea has a micro tidal climate, with a mean tidal range of 20 cm at the Caribbean coast of Colombia. Based on tidal data from Cartagena a form number of 1.68 has been calculated, characterising the tidal type as mixed primarily diurnal (Kjerfve, 1981).

Figure 13 shows the tidal chart of Barranquilla for the start of May 2016. The largest known tidal range at Barranquilla is 0.42 metre and 0.60 metre at Santa Marta relative to Mean Lower Low Water.

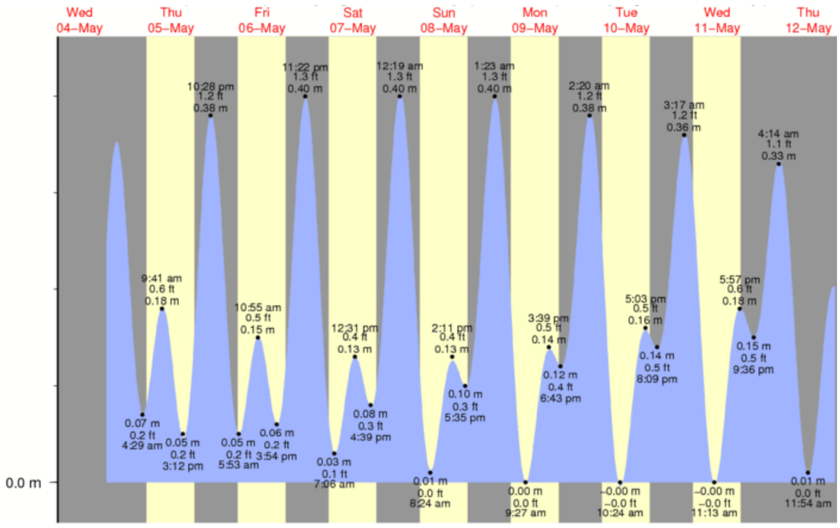


Figure 13: Tidal Chart Barranquilla

3.8 Wind system

With is geographical position close to the equation the wind system of the Caribbean Sea is dominated by the north-easterly trade winds (Figure 14). The red circle indicates the location of Colombia on the globe. The wind direction is therefore focussed around 65 degrees, with a wind speed ranging up to 18.6 m/s. Seasonal influences are limited, from January to July a strong wind from the east-northeast (ENE) is present, while lower wind speeds and more northerly orientated winds are observed in the second half year. More detailed information is presented in Appendix D.

The Caribbean is known for the presence of hurricanes; however hurricanes only occasionally reach Barranquilla. The influence of hurricanes is therefore only observed as storm events (Ortiz Royero, 2011).

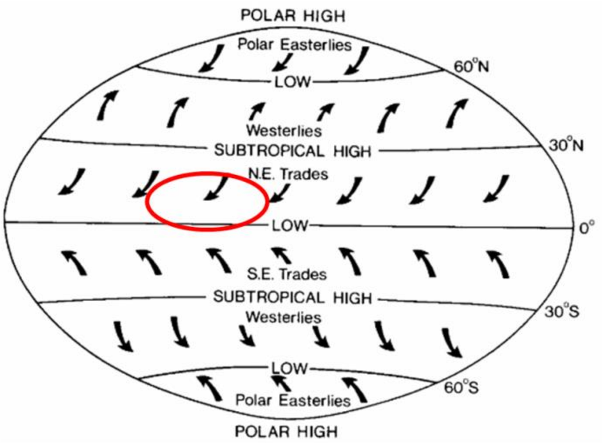


Figure 14: Global wind systems (Bosboom and Stive, 2015)

3.9 Wave climate

Waves are strongly influenced by the north easterly trade winds, as is described in Section 3.8. As a result waves from the northeast (65°) are dominant. The significant wave height varies between 1 and approximately 4.5 metres. The year starts with waves ranging from 2 to 4 metres. Wave heights reduce in the second half and fluctuations in wave heights are observed. More detailed information on the wave climate can be found in Appendix D.

Figure 15 shows the wind rose for swell waves, as well as for waves generated by local winds. From the figure it is clear that only small swell waves are present, while the major waves are related to local winds. This was expected, since the Caribbean Sea is a sheltered sea where externally generated swell has a small influence on the wave conditions.

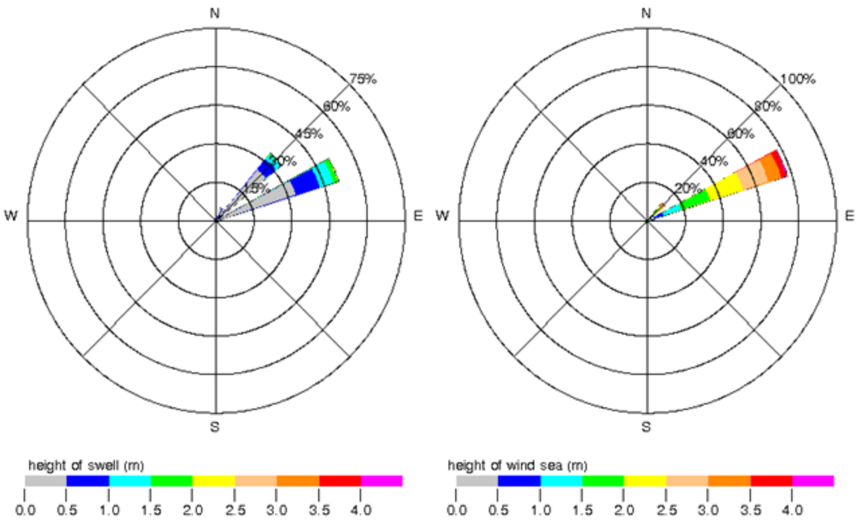


Figure 15: Swell wave rose and wind wave rose

3.10 Bathymetry

The impact of the Rio Magdalena on the bay between Barranquilla and Santa Marta is shown in Figure 16, where the old underwater deltas are still visible in the bathymetry. The old deltas have been eroding since the relocation of the river mouth of the Rio Magdalena in 1924. As a result of the change in sediment supply the coastline development is effected in the long term.

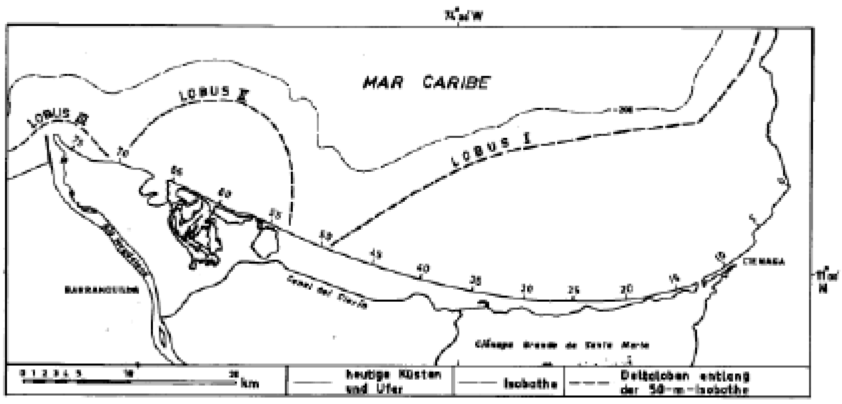


Figure 16: Under water delta's of Rio Magdalena, (Von Erffa, 1973)

Bathymetry data based on CIOH Admiralty charts from 2006 and 2007 yield the results shown in Figure 17. The former river deltas are less explicit but their influence on the bathymetry of today is clearly visible as they extend 5 to 10 metres seaward from the surrounding coast at MSC -20 metres and deeper. The former river deltas can be considered as plateaus at a depth of 5 to 20 metres.

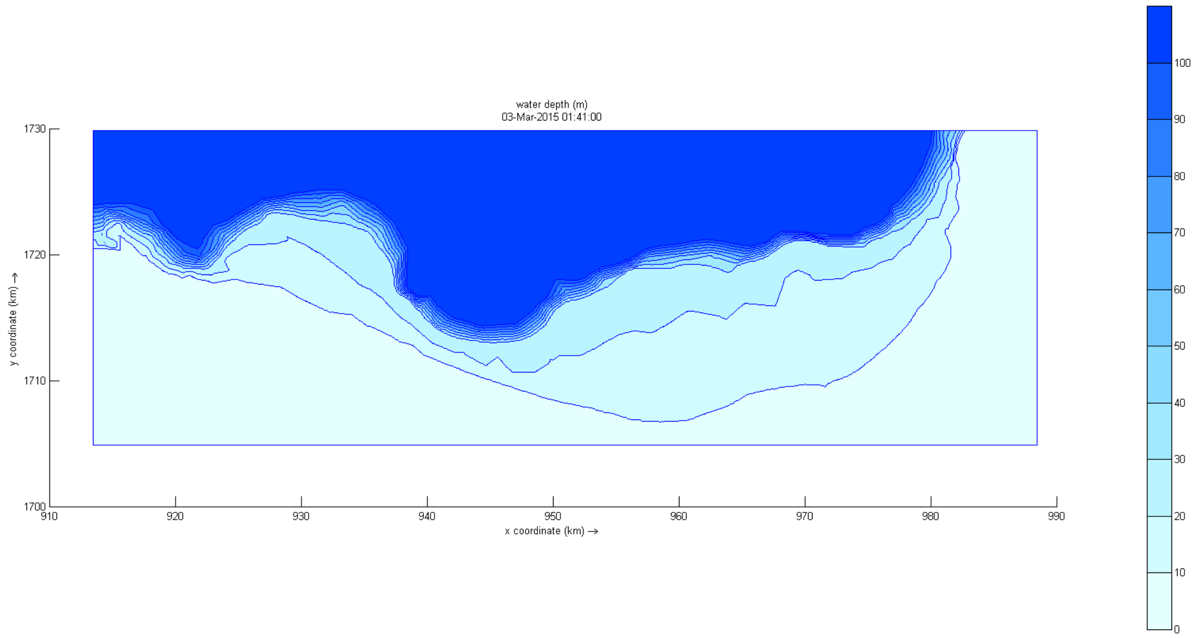


Figure 17: Bathymetry of the Barranquilla Bay

3.11 Sediment

Since the Rio Magdalena is transporting a lot of sediment towards the Caribbean Sea it is likely the sediment in the entire delta has similar characteristics. Samples from 'playa de Miramar' to the west of the river mouth and 'Costa Verde' to the east of the town of Ciénaga were collected and the results are shown in Table 6 below.

Table 6: Sediment Characteristics at the Rio Magdalena delta

	Rio Magdalena delta							K2-000		
		Mira seca	Mira linea	Mira sub	Costa Verde	km 55 m4	km 55 m5	playa	orilla	sub
D_{10}	[µm]	180	190	-	170	156	130	180	150	150
D_{50}	[µm]	300	430	76	300	302	252	300	300	290
D_{90}	[µm]	430	1000	210	420	604	471	400	410	400
Gravel	[%]	0.17	0.16	0	0	0.1	0.2	0	0	0
Sand	[%]	98.61	99.16	50.72	99.66	99.9	99.8	98.89	99.49	98.89
Clay/Silt	[%]	1.22	0.68	49.28	0.34	0	0	1.11	0.51	0.94

Comparing the samples in black (taken from coastline) we see that the sediment consists largely out of sand. The grain diameters are very similar with the largest variations at location playa de Miramar with more coarse sediment. In general a D_{10} of 160 µm, D_{50} of 320 µm and a D_{90} of 600 µm is representable for the sediment present in the Rio Magdalena delta (Sisco Ingeniería, 2015).

3.12 Human interventions

The first known settlement near the Rio Magdalena mouth dates back over 2000 years and served as a place of exchange between indigenous groups because it was easily reachable from the river and the creeks in the delta. The settlement continued to develop and Barranquilla obtained the legal status of town in 1813 during the Spanish occupation and the status of city in 1819. In 1908 the naturally dynamic river mouth relocated from Boca del Rio Viejo to the current position at Boca de Ceniza.

The natural dynamic river behaviour of flooding and river relocation was not beneficial to the development of transport and trade and was therefore controlled by river training and structures for the stabilisation of the river mouth. A sea port was built from 1922 to 1930.

To improve connections with the hinterland several roads were built starting with the highway RN90 on the Salamanca bar in 1956 and later followed by a road on the eastern bank of the Rio Magdalena in the 1970s.

Consequences of these projects were severe since the dynamic conditions on which the ecology of the CGSM developed were influenced. The roads led to major decrease in water exchange between the Rio Magdalena and the CGSM, as well as with the Caribbean Sea. The lack of a fresh water supply and the high evaporation led to hyper salinization. These conditions were not suitable for the mangrove trees and a major part of the mangrove forest withered away. In 1995 the PRO-CIÉNAGA project was started to recover the natural values in the region and restore the mangrove forest.

The stabilisation of the river mouth at 'Boca de Ceniza' in 1924 resulted in the loss of river sediment since it is positioned directly in from of a deep sea canyon (5000 metres). The sediment is lost from the coastal system and the lack of sediment supply has major effects on the coastal development.

Due to the fixture of the river mouth at the submarine canyon the dynamic littoral transport is substantially changed. Destabilisation of numerous spits to the west of the river mouth was the result; especially the 'Puerto Colombia' spit and the 'Galerazamba spit' were severely influenced (Martinez, Pilkey and Neal, 1990). The lack of sediment supply to the east is leading to the erosion of the Salamanca bar.

First actions were taken in 2011 at KM-19 along the RN90. To protect the road against erosion an underwater seawall was constructed and small nourishments were executed. In addition to the measures taken in 2011 the construction of a 300 metre long emergency revetment designed by SISCO started in the beginning of 2014. This was intended as a temporary structure with a limited expected lifetime. See Appendix C for more detailed information on the structures at KM-19.

In the same year the Colombian Dutch Dialog (CDD) was organized where Colombian and Dutch coastal experts visited affected areas, identified critical locations and discussed possible solutions.

Developments in the near future are the expansion of the RN90 from a single lane road to double lanes and the construction of a new bridge over the Rio Magdalena at Barranquilla. These developments should be taken into account when developing an integral a solution.

4 Coastline development

4.1 Introduction

The natural morphological development of the bay between Barranquilla and Santa Marta is discussed in this chapter with the aim of finding the natural development at short to long time scales. The predicted natural coastline development provides a reference for the evaluation of alternatives in Chapter 5. Key questions are related to the 'magnitude of the shoreline changes' and the 'persistence of the erosion' (i.e. how long it will last). The coastline development is predicted on short (<5 year), intermediate (5 to 50 year) and equilibrium time scales. For each time scale a different method is used, as is shown in Figure 18.

Along the horizontal axis time is plotted in years, the vertical axis shows the coastline regression relative to the coastline position of 2016. Cumulative erosion is defined as the total experienced erosion per year, starting from 2016. The erosion rate, (rate of change) is represented by the slope of the blue line. This rate of changes is expected to decrease in time, as an equilibrium position is reached.

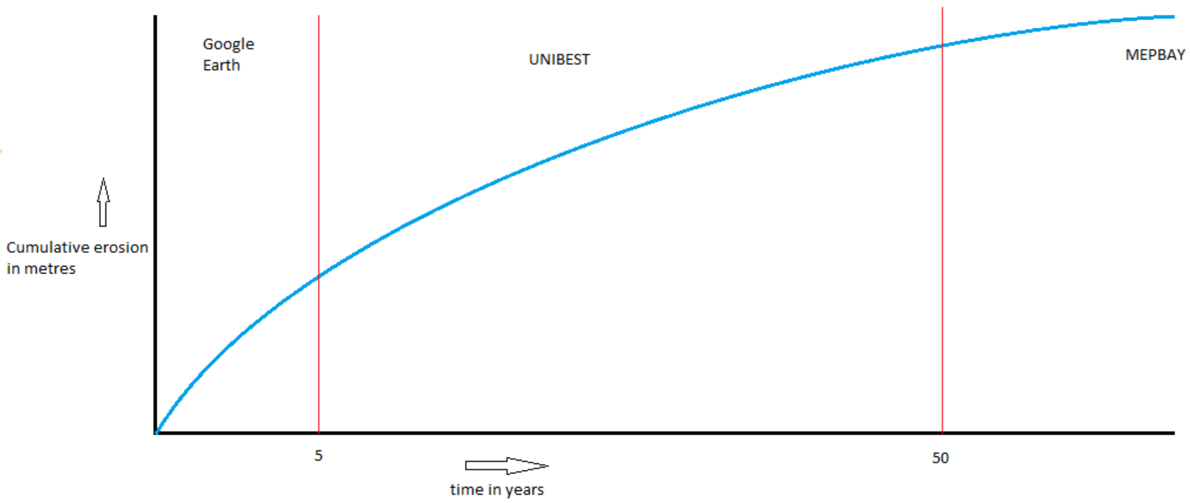


Figure 18: Theoretical example of expected erosion in time combined with a suitable prediction method per time scale

This chapter starts with the short time scale (1-5 years) prediction of the coastline changes on the basis of historic coastline positions (Section 4.2). Coastal changes at intermediate (engineering) time scales (5-50 years) are discussed in Section 4.3, for which the UNIBEST coastline model is used. The model allows for changes in coastline orientation, as the predicted sediment transport is adjusted accordingly. Structures can also be implemented, which will be used in Chapter 5 to assess the impact of alternatives on the coastline development. The long term development of the bay shape of the coastline between Barranquilla and Santa Marta was investigated with the MEPBAY equilibrium bay shape model (Section 4.4). This method is based on the process of diffraction and uses 1) a representative wave direction, 2) one diffraction point and 3) a down coast control point to determine an equilibrium position.

The main focus of the study will be on the intermediate time scale, because the expected lifetime of the coastal highway is estimated at 50 years.

4.2 Short term: Historic coastline development

4.2.1 Introduction

For better understanding of the system, information about the historic coastline development is necessary. By presenting the historic coastal development we can put the current situation in a perspective as well as recognize a possible linear trend which could be extrapolated towards the future. For short term estimates this simple method is suitable.

4.2.2 Literature

The natural development of the bay (with a shift in the course of the Rio Magdalena) and human interventions have led to the present situation, where erosion is dominant for almost the entire Caribbean coast of Colombia. With exception of a few local sedimentation zones near river mouths, the entire coast is eroding in a fast pace (Correa, 2005). The figure below, adapted from (Overeem et al., 2014) shows an active coastal zone with high erosion rates.

Figure 19: Indication of current sediment transport (Overeem et al., 2014)

4.2.3 Satellite images

Historic coastline positions were derived from satellite images, which were available through Google Earth. Since the collection of images was based on availability of the data, the time steps between subsequent images is varying in time. The limited availability of images resulted in few images with full bay coverage at one specific moment. Therefore both a qualitative and a quantitative method were used to analyse the coastline development. A qualitative approach was applied using the few images of the complete bay at a specific moment in time. This resulted in an overview of the bay and provides insight into the question whether the erosion and accretion is uniform along the bay. This was combined with a quantitative approach; all available images for one location were used to collect data points of the local coastline development in time. The results provide a local, detailed representation of the historic coastline regression.

Figure 20 shows where six cross-sections have been defined along the bay. Five locations are spread evenly along the bay; additionally one cross-section was added at KM-19 along the RN90 since this location is of special interest. At these locations the coastline changes were measured.

Figure 20: Location of used cross-sections along the bay

It is noted that some interpretation is needed to acquire the position of the coastline from the satellite images, since no clear separation between land and water is visible. The observed waterline is dependent on the sea level (subject to tide, wind setup and the breaking of waves) and may not always coincide with the MSL shoreline position. The coastline was therefore chosen between the lighter sand on the dry parts of the beach and the white crests of the last breaking waves. As a result of this definition the accuracy range is expected to be in the order of 10 metres.

4.2.4 Results

A qualitative evaluation of the coastline changes was made by means of a visual comparison of satellite images with a reference coastline (Figure 21). The satellite image is shown jointly with the coastline of 1970 (i.e. white line), giving an impression of the historic coastline changes. Three details are added to provide more detailed information of relevant locations.

The figure shows the highest coastline deformation near the breakwaters at the port of Barranquilla in detail A. Strong sedimentation led to a seaward migration of the coastline of 400 metres in approximately 45 years. Most erosion occurred around KM-19 with over 200 metres of erosion, which is shown in detail B. Detail C shows the coastline at cross-section E, which is stationary since the deviation is within the accuracy range of the coastline position determination.

The data shows a slow increase of erosion from a stable coastline in the east to severe erosion at KM-19. Along the Salamanca bar the coastline changes are growing in size from 60 metres of erosion at cross-section D up to 130 metres at cross-section C in a period of 45 years. The coastline changes decrease from KM-19 towards Barranquilla, with 180 metres of erosion at cross-section B. The changes decrease towards the west and change abruptly to sedimentation close to the breakwaters of the port of Barranquilla.

Figure 21: Coastline position of 2016 (photo) combined with the reference coastline of 1970 (white). Subplots show respectively the details of the coastline change at locations at the western end of the Barranquilla Bay, at KM-19 and at the most eastern side.

A quantitative analysis of the changes in coastline position for KM-19 is shown in Figure 22, which gives an impression of the coastline development in time. Along the horizontal axis the time in years in plotted, while the vertical axis contains the coastline regression relative to the coastline of 2016.

The uneven spread of available satellite images through time is clear since no data is present between the first available coastline (1970) and the image taken in 2003. For the last 15 years however multiple images were available resulting in a detailed insight into the coastline development in the recent history. Because of the data gap two trendlines were fitted; the first with the early coastline of 1970 included (red), for the second trendline (blue) the focus is on the recent past.

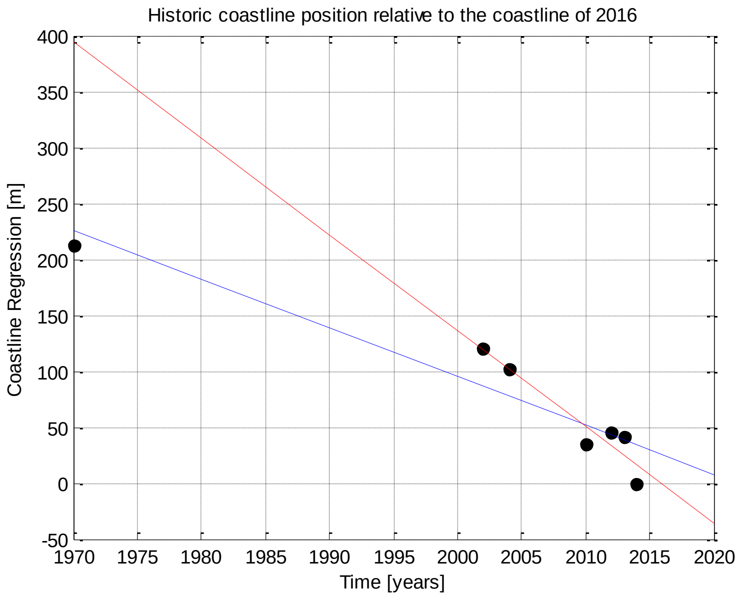


Figure 22: Historic coastline development since 1970

For all cross-sections the two trendlines were fitted, and the obtained results are shown Table 7. When the coastline of 1970 is included the trendline is less steep, compared to the trendline fitted to the data of the last 15 years. An erosional trend was observed for most of the cross-sections (B to D) with retreat rates of 1.4 to 9 m/yr. The coast at location E (in the East) was rather stable, while considerable accretion was observed at A. The trend of rapid accretion at location A is not expected to continue in the future. Dynamic behaviour at this boundary is caused by influences of the Rio Magdalena and various harbour structures.

Table 7: Historic erosion rates per cross-section [m/yr.]

	trendline 45	trendline 15
A	*15.8*	*61.2*
B	-4.0	-4.7
KM-19	-4.7	-9.1
C	-2.9	-3.7
D	-1.4	-2.2
E	0.1	0.4

The difference between the two trendlines at one cross-section seems to indicate an increase of the erosion in time since the erosion rates increase when recent data is given a higher importance. Additional data from the period between 1970 and 2000 is required to confirm the development of the erosion rates in time. Possible causes for the change in erosion rates vary from diminished sediment supply from the Rio Magdalena, to tectonic activity or Sea Level Rise. Additional research is required to demonstrate a clear correlation between the erosion rates and any one of the possible causes.

To conclude; the two obtained historic trends (i.e. 45 years and 15 years) are considered to cover the range of expected short-term coastline changes at the considered locations. The more recent data is considered to be more reliable and relevant; therefore the trend based on the last 15 years will be used to provide an historic reference. Figure 23 shows the spatial distribution of the erosion rates along the bay in the upper figure. The erosion rates are combined with the approximate alongshore sediment transport in the lower section.

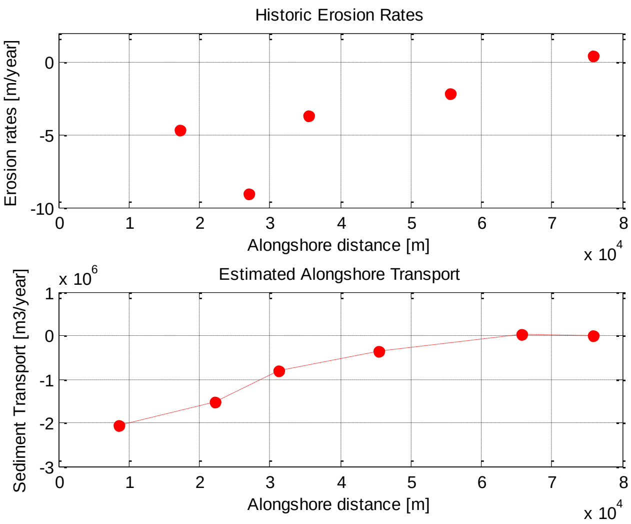


Figure 23: upper) Historic Erosion rates along the bay; lower) Sediment Transport along the bay rates

4.3 Intermediate time scale: Coastline modelling

4.3.1 Introduction

This section aims at obtaining insight in the expected shoreline changes at the Barranquilla Bay (especially at KM-19) at the time scale of the life time of the coastal highway. For this purpose, the coastline model UNIBEST (Deltares, 2011) will be used to predict the potential shoreline retreat. The modelling process as presented in this paragraph is divided into four main processes:

- Offshore climate schematisation
- Onshore climate translation
- Sediment Transport calculation
- Coastline development

Figure 24 shows these processes in the middle column, with their input to the left and output to the right. The processes are in succeeding order since the input for each step is formulated in the previous step.

First the offshore wind and wave data are reduced to an offshore climate, which can then be used as input for the wave transformation model DELFT3D – WAVE (Booij et al, 1999). The wave transformation was calculated with additional bathymetric information and onshore wave climates were extracted. The sediment transport was determined using UNIBEST-LT, which combined local wave climates with the beach profile, coastline orientation and sediment characteristics,

This model calculates local S-ϕ curves, describing the relation between the coastline orientation and the expected sediment transport capacity. Finally the coastline orientation and the S-ϕ curves are combined in UNIBEST- CL. This model is used to predict the coastline changes over time as a result of the wave impact schematized in the previous steps.

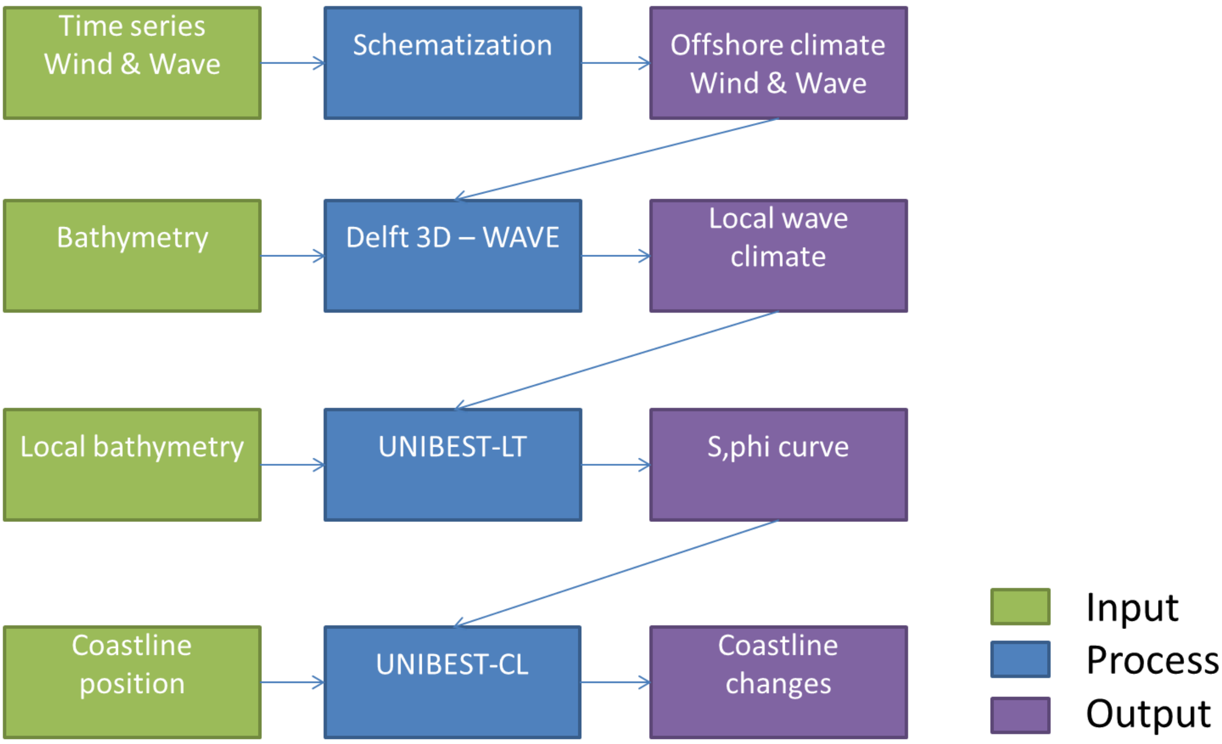


Figure 24: Modelling process schematized

4.3.2 Offshore climate schematization

Offshore wave data were derived from the ERA-Interim database (Dee et al, 2011) and the Wavewatch III model hindcasts (Tolman, 2009). Both data sets were used to classify an offshore wave climate for the wave model, since it is unclear which data-set better represents the wind and wave conditions. Coastline predictions were also made for both offshore wave climates to provide a range of possible values. It is not intended to provide upper and lower limits of the expected coastal evolution; however it does give an impression of the uncertainty that governs coastal engineering predictions.

A representative wave climate was generated from the datasets, using the closest grid point to our project location, which was at 12° north and 75° west, as can be seen in Figure 29. The schematisation of the wave climate was made for 20 wave height classes, 36 wave direction classes and 36 wind direction classes. Other parameters such as wave period and wind speed were schematized jointly with the wave height, wave direction and wind direction, as they are assumed to be correlated to the schematized parameters. The schematisation resulted in 101 climate conditions for ERA-interim data and 76 for the Wavewatch III data.

For further reference the schematized climate based on the ERA-Interim data is referred to as climate 1, or the lower estimate. The climate derived from Wavewatch III data is called climate 2, or the upper estimate. The offshore climate can be characterized by:

- Mean wave & wind direction of 65 degrees.
- Maximum wave height of 4 metres, with a wave period of 8.5 seconds.
- Wave climate mainly consists of sea waves.
- Wave direction is correlated to the wind direction. Especially for the dominant direction of 65 degrees. Additional figures on the wave climate comparison are presented in Appendix D.

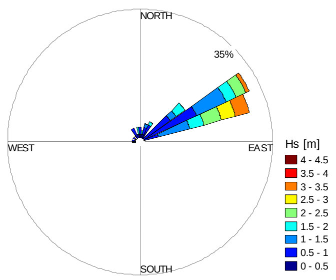


Figure 25: Wave rose of Offshore climate 1 (ERA)

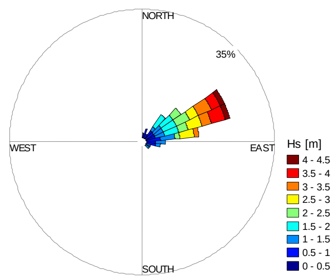


Figure 26: Wave rose of Offshore climate 2 (WWIII)

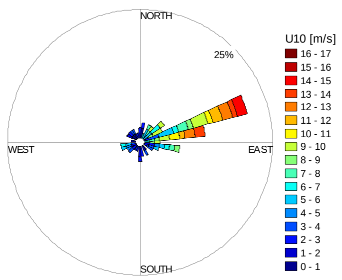


Figure 27: Wind rose of Offshore climate 1(ERA)

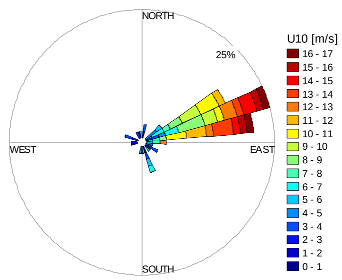


Figure 28: Wind rose of Offshore climate 2 (WWIII)

A comparison between the two offshore climates in Appendix D yields:

- Climate 2 contains higher waves (max 4.1 metres) compared to Climate 1 (max 3.5 metres).
- Both climate 1 and 2 have a dominant wave direction of 65 degrees.
- Climate 2 is closely and more symmetrically spread around the dominant wave direction.
- Climate 1 is spread wider and unevenly, with more waves from north and north-western direction, with an abrupt end after the dominant wave direction.
- Limit of 'wave steepness' is the same for both climates.
- Both climates consist mainly of sea waves.
- Longer wave periods are observed in climate 2, indicating the presence of swell waves.
- Significantly higher wind speeds with Climate 2.
- Less variation in wind direction for Climate 1.
- Wave and wind direction are correlated, especially at the dominant direction of around 60/65 degrees.
- Less spreading in wave direction compared to wind direction.

It is noted that the duration of the considered offshore time series is of influence on the characteristics of the wave climate. This could be a partial explanation for the differences. The wave conditions from climate 1 are based on a time series for the year 2013, while climate 2 is based on a time series from 1992 until 2014. When a longer period is considered, the time series is likely to contain more extreme conditions. The resulting climate is therefore expected to contain more energy. On average the 2013 climate is, however, much more quiet than the long-term average climate conditions. This could be an indication of the temporal variations in the wave climate conditions.

4.3.3 Onshore climate translation

Nearshore wave boundary conditions were derived from a DELFT-3D-wave model at nine locations along the Barranquilla Bay for the computation of sediment transport (with UNIBEST-LT). The DELFT-3D-wave model was used to compute the offshore to nearshore transformation of the two considered offshore climates (i.e. ERA-interim and Wavewatch III). Figure 29 shows the output location from the offshore data-sets with a red dot. The nine green dots represent the onshore output locations where the local wave climates were extracted after the wave transformation.

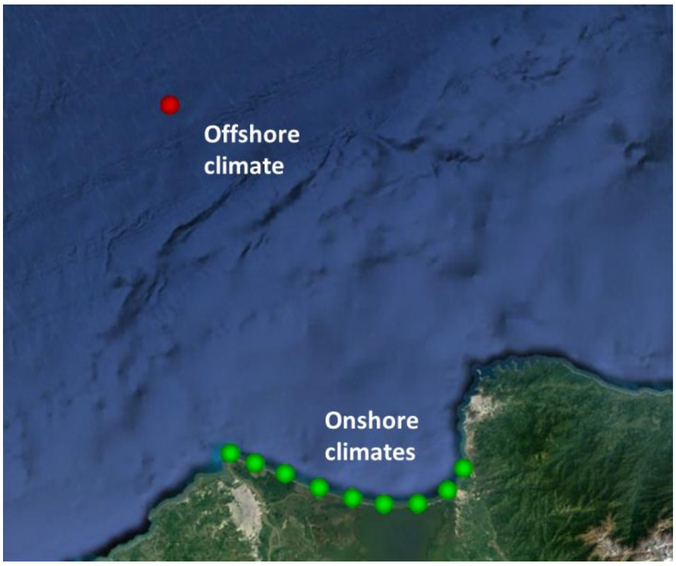


Figure 29: Offshore climate location (red) and nine offshore climate locations (green)

Two nested rectangular grids were used in the DELFT-3D-wave model. The mash size of the main grid was 500x500 metres, while the more detailed grid was 100x100 metres. The accuracy was set to 99.5% of wet grid points with relative change of 1% for both the wave height and period, with a maximum of 25 iterations. More detailed model specifications are presented in Appendix E.

Figure 30 shows the bathymetry used in the model, which was derived from Admiralty Charts (Chartworx, 2016). The dark green area represents land, while the dark blue area represents the deeper offshore areas. At the seaward boundary the depth is over 2000 metres. This boundary was located here to match the output location, as was shown in Figure 29. To limit the disturbance of possible boundary effects the eastern and western grid boundary is located away from the area of interest. The east and west grid boundaries are relocated further away from the area of interest to minimize the impact of possible numerical boundary effects. Due to the limited availability of bathymetrical data the coastline is schematized as a straight line with an uniform profile. The simplification of the bathymetry far away from the area of interest does not affect the local wave climate at the area of interest.

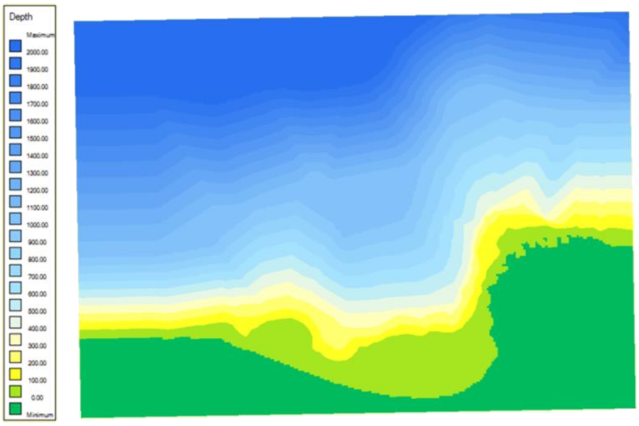


Figure 30: Used bathymetry in DELFT3D

The wave transformation was calculated for all schematized conditions of both data-sets. Figure 31 shows a representative condition to give an impression of the wave transformation. The offshore mean wave direction was 68.1 degrees relative to the north and the wave height was 0.67 metres for this condition.

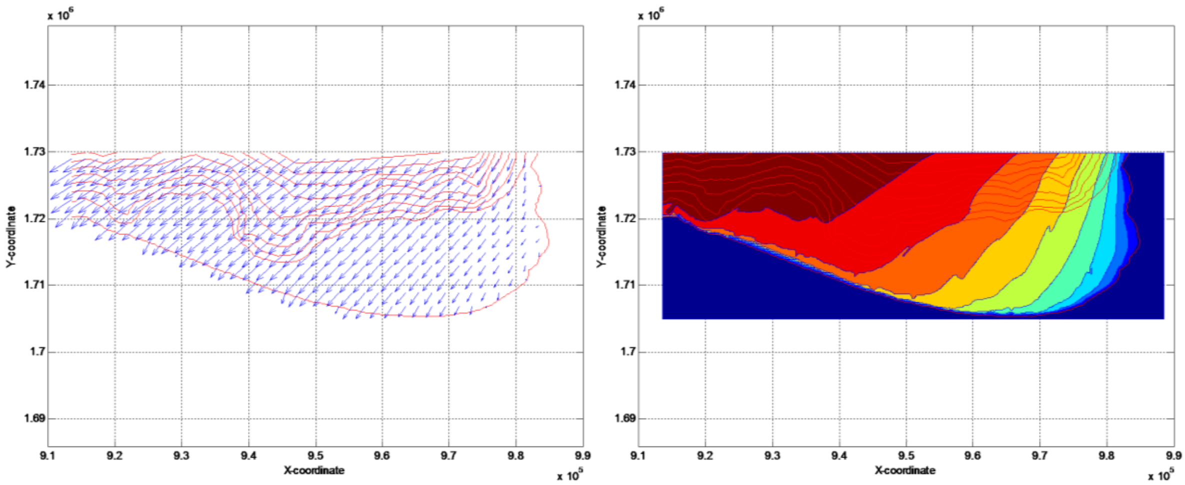


Figure 31: Wave transformation of wave condition with Hs = 2.47m and direction from 70.03 degrees North; a) Mean wave direction b) Significant wave height

Nine onshore climates were extracted after transformation of all conditions. The climates are shown in Figure 32, and can be characterized by:

- Partial sheltering from north-eastern waves by the Sierra Nevada de Santa Marta
- Gradient in wave height along the bay, the maximum significant wave height is ranging from over 3 metres at the western boundary to only 1 metre at the eastern boundary.
- Wave direction is dominated by north-eastern waves, for all onshore climates.
- Increasing northward orientation of wave direction towards the east.
- Shift in wave direction at location 2 is the result of refraction over the former river delta. (See Figure 30)

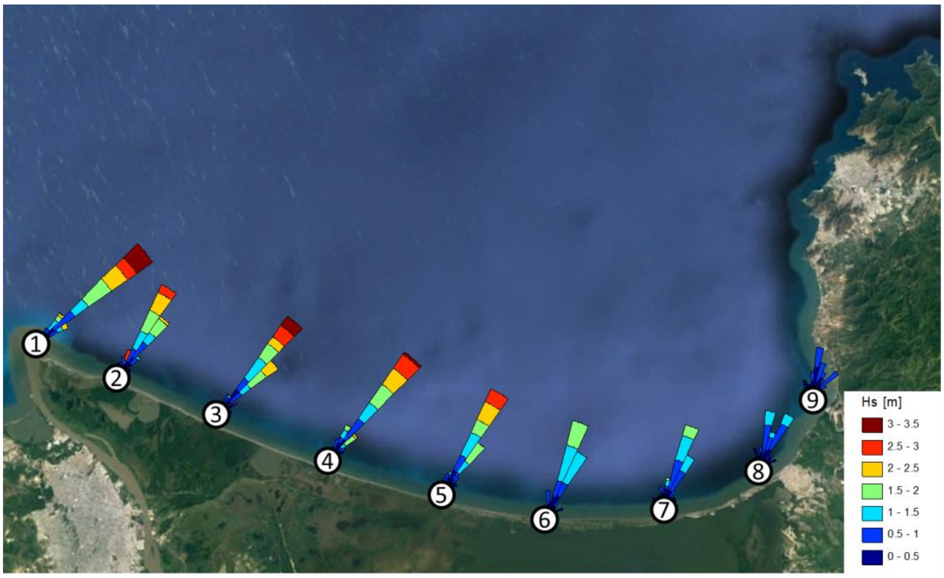


Figure 32: Onshore wave climates, based on offshore climate 2

4.3.4 Alongshore Transport Model

The alongshore sediment transport was computed for nine cross-shore profiles along the bay between Barranquilla and Santa Marta, which is considered sufficient to represent the large scale coastline behaviour. The profile locations correspond to the onshore climate locations in Figure 29, which are evenly distributed along the bay. Using UNIBEST-LT the S-phi curves were calculated at these locations based on the nearshore wave climate, local bathymetry and sediment characteristics.

Cross-shore profile

Cross-shore profiles were derived from the used bathymetry (Figure 30). Figure 33 gives an impression of the used profile at cross-section 4, which corresponds to the critical location at KM-19 along the RN90. The horizontal axis represents the cross-shore distance from the shoreline, which is located at the right side of the figure. The depth of the profile is defined relative to MSL, which is equal to zero in the figure. We see a gentle slope of approximately 1:100 along the profile, with a decrease in steepness at the top.

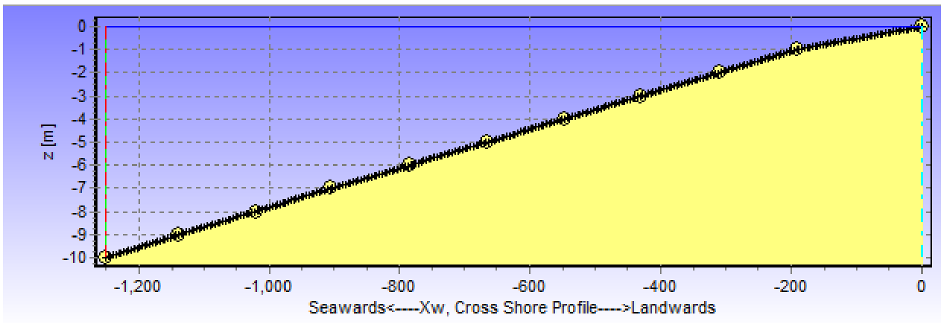


Figure 33: Cross-shore profile TR4, at KM-19

The profiles extend from MSL to MSL -10m. The offshore location of the cross-shore profile corresponds with the output location of the schematized wave climate of DELFT3D. The location of the offshore boundary is related to the limit of the morphological activity, which will be further elaborated on when the active height is discussed. In addition the boundary is the transition from the bathymetry data of DELFT3D-WAVE to the bathymetry based on profiles and the assumption of parallel depth contours in UNIBEST-LT. Figure 34 shows the depth contour lines up to a depth of 10 metres for the entire bay. We can see the contours lines follow the coastline, which corresponds to the assumption of alongshore uniform depth contours within UNIBEST-LT.

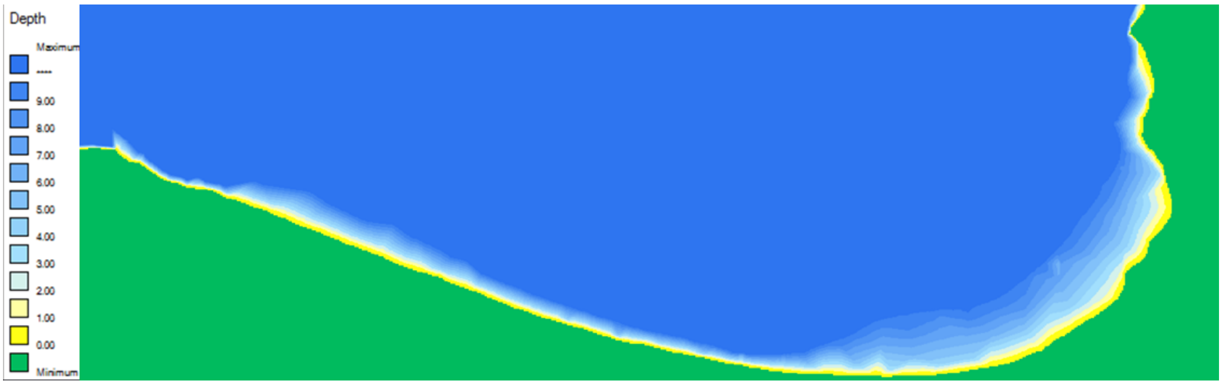


Figure 34: Depth profile up to 10 metres along the bay

The active height used in this modelling approach consists of two components, being the depth of closure (h_d) and the height of the land (z_d), both relative to mean sea level. Figure 35 shows a sketch of a typical cross-section with the two components of the active profile. Three additional profiles are drawn to indicate the development of the profile over time.

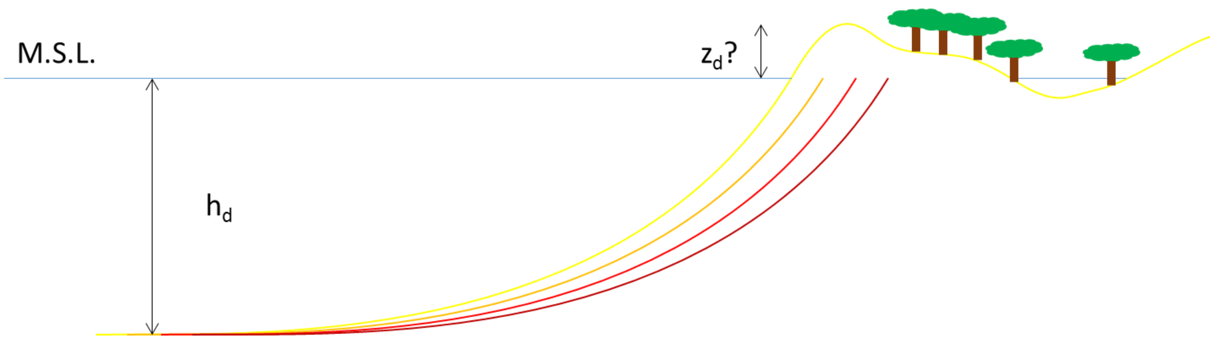


Figure 35: Active Profile Height, indicated by the depth of closure (h_d) and the height of land (z_d)

The depth of closure can be determined using the theory of Hallermeier, using the extreme 1/1 year wave height. The depth of closure can also be based on the cross-shore distribution of sediment transport.

A depth of closure of 7.1 metres is determined, using the method of Hallermeier. This corresponds with the cross-shore distribution profile in Figure 37, where we see the majority of sediment transport occur in the upper part of the profile, above 7.1 metres for both climates.

The depth of closure is determined using the highest expected wave for the considered period. If a shorter period is evaluated, the probability of experiencing an extreme wave is lower. As a result a smaller depth of closure is acquired. The choice for the considered period therefore has a direct influence on the active height.

The height of the landward boundary was estimated based on the height of the hinterland that is expected to erode. The presence of several lagoons and vegetation are incorporated into this estimation to account for their influence on the erosion speed. When lagoons are present in the hinterland, sediment is replaced by water, and a negative land height is used since sediment is only available below Mean Sea Level. If mangrove forests are present, the sediment is retained by the roots and erosion rates are expected to be reduced. This effect is taken into account by increasing the height of the land, resulting in a similar decrease in erosion speeds. Additional information on lagoons and vegetation is presented in Appendix F.

The specific spatial distribution of land height, lagoon presence and vegetation is not taken into account, since the goal of this modelling approach is to correctly represent the development of the bay. As a consequence detailed, local conditions are not required and are summarized by and average height of 1.5 metres above Mean Sea Level. Combined with the depth of closure this leads to a total height of 8.6 metres for the active profile.

For the calculation of the alongshore sediment transport the formula TRANSPOR2004 (van Rijn, 2007) was used. The sediment is characterized by a D50 of 320 µm and a D90 of 600 µm as is described in paragraph 3.11. More detailed model specifications are presented in Appendix E.

Results

Figure 36 shows the S- ϕ curves for both climates at cross-section 4 (KM-19). The vertical green line indicates the current coastline angle (20°). The vertical orange and light blue lines indicate the equilibrium angle at 38.5° and 43.7° for climate 1 and 2 respectively. The difference between the equilibrium angle and the current coastline angle shows the required reorientation of the coastline before an equilibrium is established. The amplitude of the curves shows the sensitivity of the transport capacity to changes in coastline orientation. Together they describe the relation between the coastline orientation and the expected sediment transport. The S- ϕ curve is constructed using three parameters, magnitude (c1), curviness (c2) and relative coastline angle (θ_r). With these parameters the transport is calculated using the formula below:

$$Q_s = c_1 * \theta_r e^{-(c_2 * \theta_r)^2}$$

The yearly transport at location 4 is approximated at 950,000 m^3/yr and 2,750,000 m^3/yr for Climate 1 and 2 respectively in 2016. The deviation of the average wave angle from the current coastline orientations was 23.7° and 18.5° for Climate 1 and 2 respectively at location 4. As the bay reshapes towards the equilibrium orientation, the coastline orientation shifts towards the right in Figure 36. As we can see a corresponding decrease in sediment transport is expected.

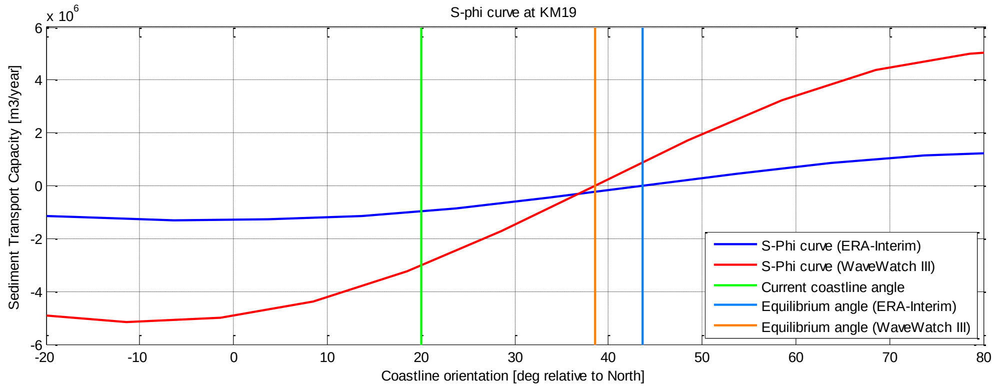


Figure 36: S-phi curve at KM-19 for both datasets

The alongshore transport capacity at cross-section 4 is based on the local nearshore wave conditions. UNIBEST-LT is used to compute the alongshore transport over the cross-shore profile for each of the nearshore wave conditions. The contributions of all conditions are summed to a net yearly transport, which is shown in Figure 37. The figure shows the cross-shore profile shape (upper panel) and the cross-shore distribution of the alongshore sediment transport at KM-19 (lower panel). The distributions for both climates are presented, as two climates were used from different wave data-sets. In blue we see the Climate 1, and the red line represents Climate 2. The wave height from Climate 1 is smaller compared to the wave height of Climate 2. Since the sediment transport is approximately proportional to the wave height by a power of 2.5, the transport capacities deviates correspondingly.

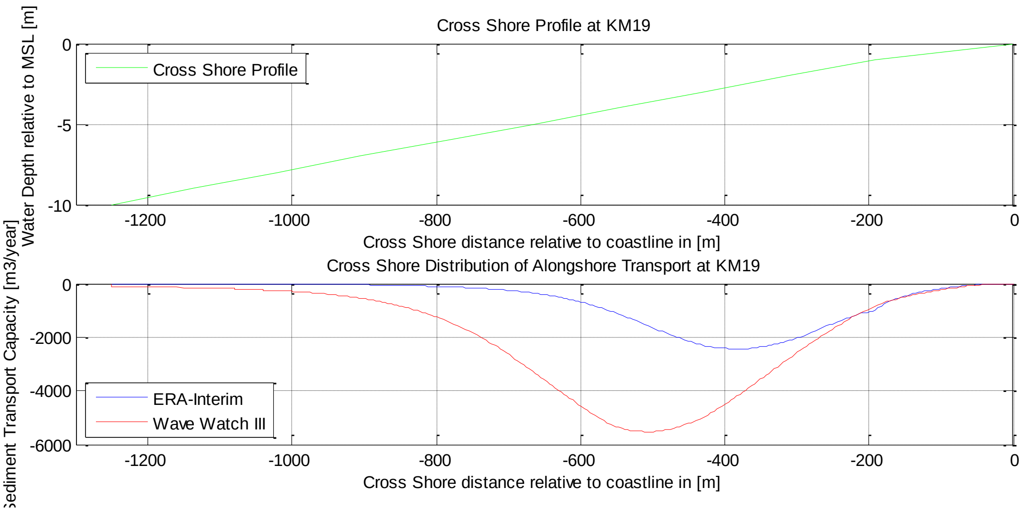


Figure 37: Alongshore Sediment Transport Capacity Distribution over the Cross Shore Profile

An overview of the uncalibrated transport rates along the coast is shown in Figure 38 for both climates for a coastline position after 50 years. In blue we see the uncalibrated output using climate 1, and in red the uncalibrated output of climate 2. The black dots represent the calculated sediment transport using the available satellite data from the past 15 years. This excludes the coastline position of 1970, as defined in section 4.2.4. Both calculations start at the eastward end with zero transport as this is the boundary condition. From there we see a gradual increase of transport capacity towards the boundary at the west. The qualitative prediction of both calculations is similar, while they show a large quantitative difference, up to a factor two at the eastward boundary.

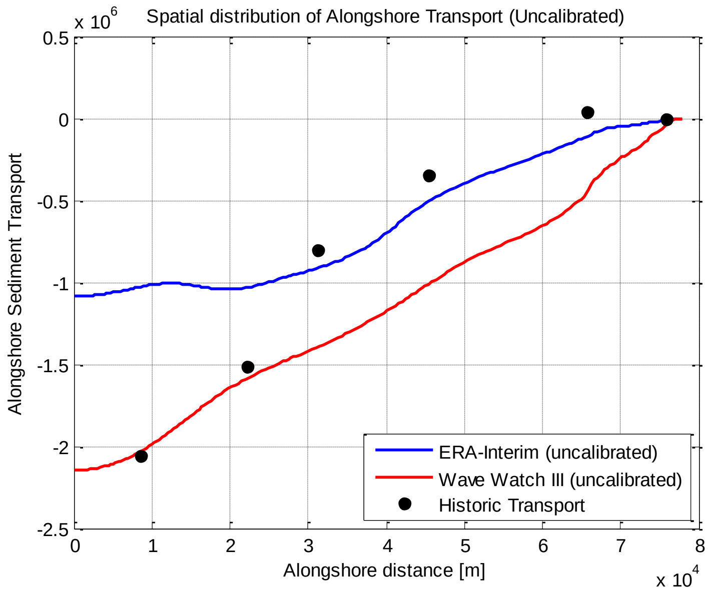


Figure 38: Uncalibrated model results

Comparing the results of both climates with the historic reference, it was found that a discrepancy is present in the computed transport rates (along the coast) and the sediment transport that is derived from observed short-term coastline changes. A possible hypothesis is that the western wave component is underrepresented in the offshore wave climate. This is the result of parameterized wave conditions (Hs, Tp and Hdir) which are used for the wave transformation. Waves with a north-easterly origin are always dominant in the parameterized offshore wave directions, as a result of the north-easterly trade winds. A small north-western component may in reality be present, but is not included in the wave parameters. Waves from this direction become relevant when sheltering from north-easterly waves takes place.

The trends from observed coastline changes are therefore considered to be more reliable, and consequently calibration of the model is necessary. The onshore wave climates are used as the basis, and adapted to reproduce the observed trends in coastline development. The calibration consisted of 1) smoothening of the c1 parameter along the bay and 2) adjustment of the equilibrium angle to match local transport and erosion rates.

The calibration also accounts for the decrease of sediment transport at approximately 20 kilometres from the westward boundary. This is not in accordance with the historic observations and is therefore addressed in the calibration process. Furthermore, the model output does not fully represent the coastline changes as observed in the satellite data near the Barranquilla harbour. This can be explained by the local effect of the breakwaters and the outflowing Rio Magdalena. Since this region is not at the heart of our area of interest deviations from the actual coastline development are accepted at this location.

Climate 2 (WaveWatch III) is selected to be used for further modelling steps, since this climate represents the observed historic trends more closely. The results of climate 1 (ERA-Interim) are however used in later stages as an indication of the uncertainty that governs coastal engineering predictions. Figure 39 presents the computed transport based on climate 2, after calibration of the model. The model output is better matched with the historic observations, and the local steepness matches the erosion rates found in the historic data.

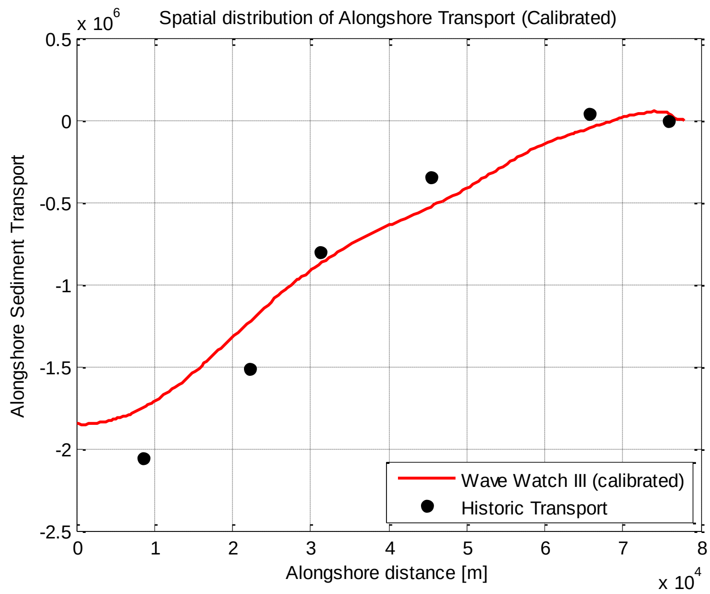


Figure 39: Calibrated model results

Figure 40 shows the cumulative erosion over time at KM-19, combined with the historic data in black. The model predictions are reasonably aligned with the extended trends found in the satellite data, although a somewhat slower response is computed with the UNIBEST-CL+ model, compared to the trends found in the historic data. This may relate to the adjustment of local coastline undulations to the climate conditions. The limited number of onshore climates enforces a relatively large number of coastline points. As a result local variations in the coastline position are smoothened out during an initial adaptation time.

The predicted absolute coastline position includes the behaviour of adaptation period. This should be considered during the interpretation of the results. However if the changes in coastline development are considered relative to a reference scenario, the initial discrepancies are expected to cancel each other out. In principle the coastline model is most suitable to be used for a relative comparison of coastline changes with respect to the reference scenario. To account for this the qualitative scoring of alternatives in Chapter 5 will be done relative to the reference scenario “Do Nothing”, as is presented in the next paragraph.

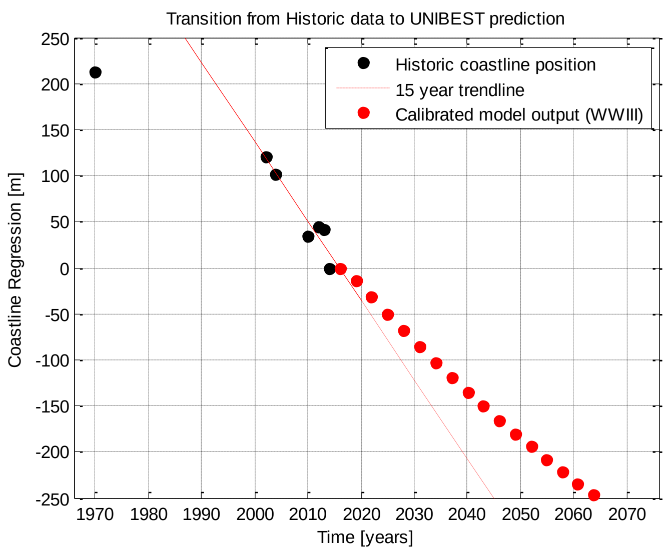


Figure 40: Coastline regression in time at KM-19

4.3.5 Coastline Model

The coastline evolution in time is computed on the basis of the relations between coastline orientation and sediment transport (S-ϕ curves) using The UNIBEST-CL coastline model. The S-ϕ curves were computed for the nine alongshore locations with UNIBEST-LT. The initial coastline orientation is used by the model to compute the initial sediment transport (Figure 41). With the alongshore sediment transport the alongshore gradient can be determined, leading to local erosion or sedimentation. The local changes in the coastline effect the orientation, and a new sediment transport can be calculated based on the adjusted coastline orientation.

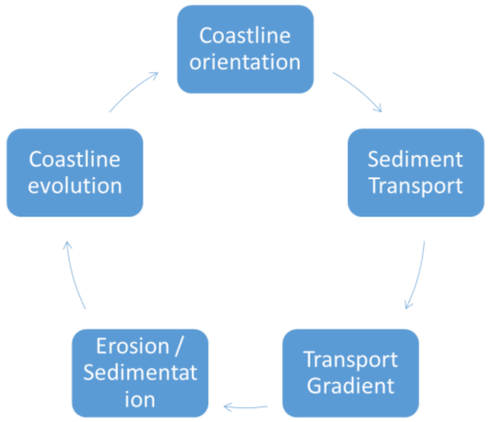


Figure 41: Process of UNIBEST-CL

Initial Coastline

A model domain was used which covers the full Barranquilla bay. The model grid has a resolution of 350 metres. The modelling domain for UNIBEST-CL is smaller compared to that of DELFT-3D since the wave climate is now schematized and only the development of the relevant coastline is calculated. The calculated coastline development assumes availability of sediment, so parts of the bay where this assumption is not met are excluded from the domain. The eastern boundary of the domain is therefore chosen as such that the rocky coastline around Santa Marta is not part of the domain. Transport is set to zero at this boundary, while a fixed coastline location is assumed at the western boundary.

4.3.6 Results

The expected coastline changes for the reference scenario “Do Nothing” is visualized in the top left of Figure 42 for the considered period of fifty year. The coloured lines represent the coastline at a specific moment in time. The thick yellow line is located along the RN90, to show the expected damages to the highway. Globally the changes of the bay shape are relatively small over a period of 50 years. However, the erosion is expected to threaten the coastal highway at the critical locations, which are shown in the detailed figures.

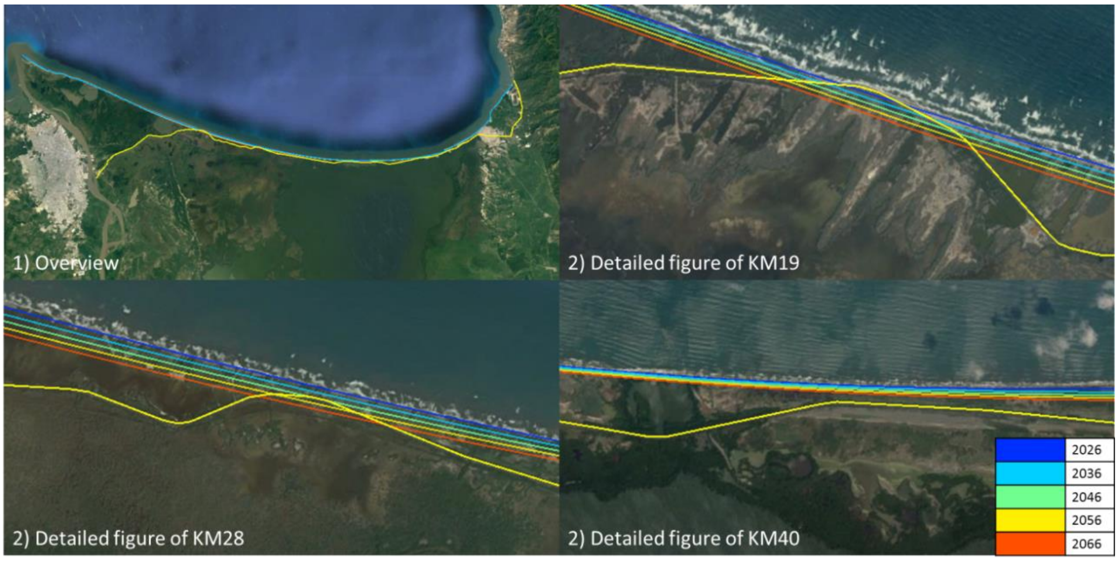


Figure 42: Coastline evolution over time

Along the bay two critical locations were identified. KM-19 is the first critical location, since measures are already taken here. The emergency measure is not included in this model run, to provide a clear reference scenario for the evaluation of the alternatives in a later stage. The emergency measure is included in the alternatives. Without the emergency revetment, erosion rates of 9 m/year would be expected, leading to immediate damage to the highway.

The second critical location is identified at KM-28, where erosion rates of 6 m/year are expected. Consequently the position of the highway is expected to be reached by erosion in 12 to 15 years. Despite the fact that the problem here is not as acute as at KM-19 the erosion should be addressed as an integral problem and the measures should be coordinated since the problems are not two independent incidents.

The third location (KM-40) does not become critical within the considered 50 years. However the highway is closely approached by the eroding shoreline with 3 m/year. This location deserves attention, however since it does not become critical in 50 years it falls outside the scope of this study.

4.4 Long term: Equilibrium bay shape

4.4.1 Introduction

The equilibrium position of the Barranquilla bay was calculated based on the Parabolic Bay Shape Method (da Fontoura Klein et al., 2003), to provide insight into the duration and extend of the structural erosion. For this method, the parabolic formula is fitted along the bay, based on the following input:

- Representative Wave Direction
- Diffraction Point
- Downcoast Control Point

Furthermore a sandy coastline (and a closed coastal cell) is assumed to allow for complete adaptation of the bay shape to the wave conditions. The input is elaborated on in section 4.4.2 and in section 4.4 the resulting equilibrium position is presented in combination with UNIBEST predictions and an historic reference. For more detailed information about the Parabolic bay Shape Method, see Appendix E.3.

4.4.2 Input

The bay between Barranquilla and Santa Marta experiences wave sheltering due to the presence of the Sierra Nevada de Santa Marta Mountain at the Eastern side of the Bay. The dominant wave direction is NE.

The incoming wave directions for both swell and sea waves are focussed around 45° and 67.5° with a small directional spread. The higher sea waves are expected to dominate the sediment transport, so a wave direction of 67.5° is chosen to represent the wave climate for this analysis.

Small changes in the input can lead to large deviations in the output, with the wave direction as the most important input parameter since the diffraction point is chosen based on the wave direction. With changing wave directions the diffraction point might be changing locations as well. This has a major influence on the predicted equilibrium coastline.

Sheltering against wave energy begins at the most protruding point along the coastline. From this point onward sheltering causes wave energy to be transported along the wave crests resulting in a decrease of wave energy per meter of coastline. The diffraction point is chosen at the most protruding island to the north of Santa Marta.

Based on images from Google Earth the down coast control point is chosen at the tip of the breakwater at Bocas de Ceniza. This is a fixed point and the straightest part of the coastline is located here.

At the downcoast control point the coastline does not seem to be parallel to the wave crests of incoming waves. This suggests that the coastline at this point will be in equilibrium with a wave oriented more northerly, indicating an influence of the Sierra Nevada de Santa Marta on the wave climate at this location.

The downcoast control point was selected at the tip of the Barranquilla breakwaters where is can be observed from the results that the coastline is not parallel to the crests of incoming waves, contradicting the definition of the downcoast control point. This indicates an incomplete bayshape, since an unaffected stretch of coast from the wave sheltering can’t be found. The applicability of this method is therefore uncertain. More detailed information is presented in Appendix E.3.

4.4.3 Results

The green line in Figure 43 is the result of the predicted equilibrium position of the coastline. The static equilibrium coastline is landward of the existing coastline. This indicates an unstable bay and suggests coastline regression to continue until the coastline reaches the static equilibrium since there is no sediment input into the system.

Figure 43: Expected coastline development combined with static equilibrium of coastline (green)

The coastline changes in Figure 40 were extrapolated towards the long-term expected equilibrium coastline position, which is shown in Figure 44. The expected equilibrium coastline is indicated by a horizontal green dashed line. The three methods are combined in this figure to put the relevant time and spatial scales into perspective. Since the UNIBEST results do not include the equilibrium coastline position a transition area is indicated in grey. The lower limit is provided by a linear approximation, where the transport rates are assumed to be constant. To determine the required period before the equilibrium position is reached, the excess volume of land (Figure 43) is divided by the transport rate at the western boundary. This simplified calculation yields an order of magnitude of 1000 years before an equilibrium will be reached. The estimated time scale should serve as a lower limit, since the static equilibrium will be reached like an asymptote. This behaviour is caused by the fact that transport rates will decrease as the coastline orientation approaches the equilibrium orientation (Figure 36).

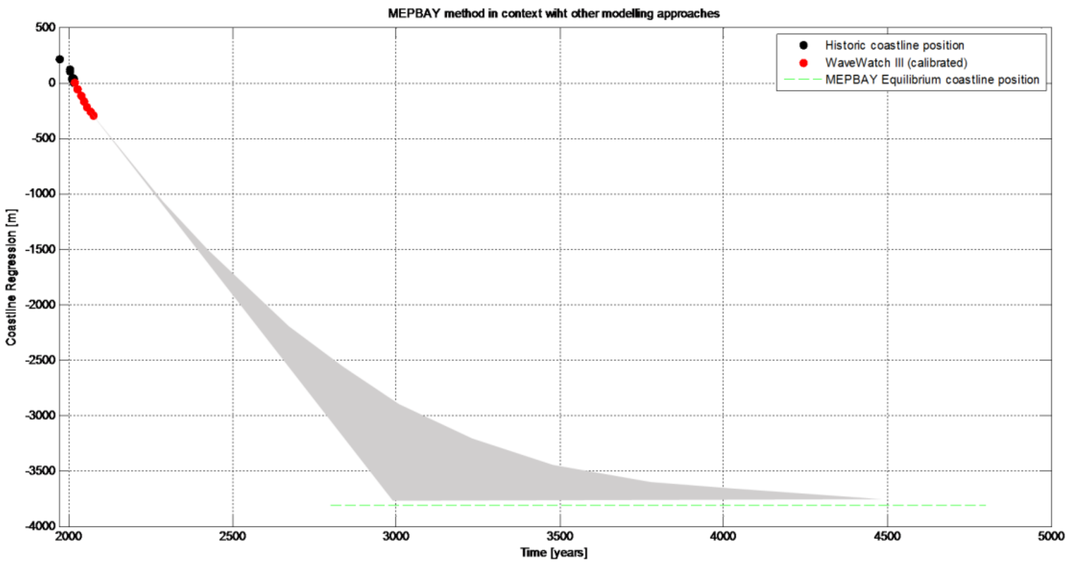


Figure 44: Coastline regression from all modelling approaches combined

Summarizing, the results show a much more curved coastline compared to the current situation. High erosion rates are expected in the central section of the Barranquilla bay on the long term, which can amount to coastline regression of over 3.5 kilometres.

The computed equilibrium shoreline should be interpreted with a considerable margin, since the input is overly simplified and wave refraction and transport processes also affect the bay development, which are not taken into account. However, the overall tendency of the model to create a more curved coastline is considered realistic. The bay is not expected to reach an equilibrium position in the near future. Consequently, continuous, structural (long-term) erosion should be anticipated at the middle sections of the bay.

4.5 Conclusions Coastal development

The natural coastline development can be characterized by:

- A stable, rocky eastern boundary and a western boundary with highly dynamic behaviour at the jetties of the port of Barranquilla;
- A sandy coastline along the Salamanca bar with towards the west decreasing shelter from incoming north-easterly waves;
- Increasing alongshore transport in westward direction, with transport rates up to 1.5 to 2 million cubic metres per year at the westward end;
- Erosion along the bay, with maximum rates of 5 to 9 metres per year as a result of the strong gradient in sediment transport;
- Two main critical locations are identified at KM-19 and KM-28, where the coastal highway RN90 is in danger within the considered lifetime of 50 years;
- Immediate action is required at KM-19. For the short term an emergency revetment has been built, but a solution for the long term is still required;
- The situation at KM-28 will become critical within a period of 15 years, requiring mitigation measures as well;
- In addition, KM-40 is identified as a location requiring attention, since in 50 years the coastline is closely located near the highway;
- Structural erosion is expected to continue on the long term (more than a thousand years), as the expected equilibrium bay position is several kilometres landward of the current coastline position.

5 Alternatives for Coastal Erosion Mitigation

5.1 Introduction

This chapter focuses on the evaluation of alternatives based on requirements formulated in Chapter 2. First the main strategies for coastal zone management are discussed, leading to the presentation of the alternatives. The impact of the alternatives on the coastal development of the Barranquilla bay is predicted for a period of 50 years using the model as presented in Chapter 4.

Technical results are discussed directly after description and schematisation of each alternative. Related stakeholder values such as enhanced downstream erosion, nuisance during storm events and long term application of the alternatives are discussed together with the coastline development.

In the next paragraph the impact of the alternatives on the stakeholder requirements is further elaborated on to emphasize the influence of stakeholder perspective on the evaluation. The benefits and drawbacks of the alternatives are presented in the scorecard. Besides the personal perspective as is used in the scorecard, other stakeholder perspectives are evaluated to see the comparison of alternatives in a broader view. To complete the chapter a most promising alternative is selected.

5.2 Strategies

The strategies to respond to structural coastal erosion vary, as can be seen in Figure 45.

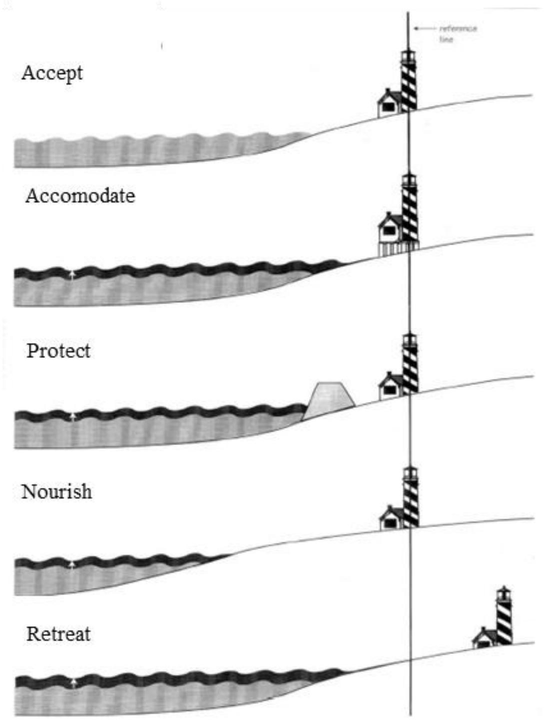


Figure 45: Alternatives for shore protection (U.S.A. C.E., 2006)

Accept
In the absence of human intervention, acceptance of the natural coastal development can be considered to be the 'default' strategy. Only when a conflict of interest arises, action is required. With regard to the considerable costs for interventions in the coastal system acceptance could be the preferred approach on economic grounds.

Accommodate
Accommodation of land use to a (slowly) changing coastal system is a natural response. Small changes spread over time result in slow shift of the coastal zone inland corresponding to the on-going erosion rate.

Protect
Protection of the coastline becomes relevant when it becomes economic viable to intervene in the natural system. Due to the high costs for building coastal protection works, it is important to carefully select locations worth protecting. An impact on the coastal processes is intended, but secondary effects at transition areas and starvation of the downstream sediment supply should be taken into consideration as well.

Nourish
Sediment from a borrow site can be supplied to the coastal system to manipulate the sediment balance at a specific location and hold off erosion. The natural transport processes remain active and lead to transportation of sediment along the bay. This results in a repetitive character for the measure with an interval dependant on transport rates and the nourishment volume.

Retreat
The strategy "Retreat" can be less expensive compared to building protection works, if land use is not flexible and hard to accommodate within the coastal zone. A new location can be found for buildings using set-back lines. Set-back lines combine the expected lifetime of structures with the expected erosion in this period. This is used to determine a distance landward from the existing coastline. Behind the set-back line the building is safe from erosion during the expected lifetime.

5.3 Overview of alternative solutions

Alternatives are generated in line with the discussed strategies, as is shown in Figure 46.

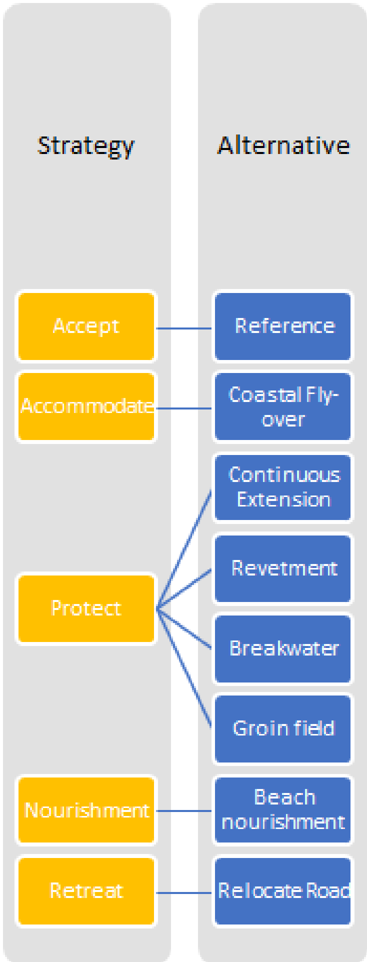


Figure 46: Relations between Alternatives and Strategies

The first alternative based on the strategy 'Accept' is unhindered development of the coastal system. This alternative will not be elaborated on in this chapter since it is presented in detail in Chapter 4. It is however used as reference to illustrate the impact of the other alternatives.

For the strategy 'Accommodate' a coastal fly-over was considered. The feasibility of this alternative was considered low due to the expected high costs, in the order of 50 M USD per kilometre of highway. In addition the preferred alignment for the "Coastal Fly-over" corresponds to the new location of the highway RN90 after road relocation. This is due to the curved alignment at both of the critical locations. Considerations for the impact on the coastal zone are similar for the two alternatives "Coastal Fly-over" and "Relocate Road" (Section 0) since the coastline can develop unhindered. The alternative is excluded from the selection of alternatives due to its high costs.

The strategy 'Protect' is evaluated based on the continuation of the current policy and additional, other measures such as the construction of a revetment, a breakwater, a groin field and a nourishment. The nourishment will be applied on the beach as this is expected to be most cost-effective.

The final alternative is to retreat the land-use in the coastal zone behind setback lines. This will be performed by relocating the RN90. The position is determined based on the expected erosion for the coming 50 years.

Preliminary, basic designs were used to compare the impact of the alternatives, leading to a comparison between working principles instead of detailed designs. This approach is chosen to allow for a broad comparison within the limits of time constraints. To make sure equivalent cases are compared all alternatives start with the coastline of 2016, with existing structures as described in Chapter 4.

5.4 Alternative 1: Continuous Extension

With each alternative a simple, illustrative sketch will be presented, similar to Figure 47. The green, solid line represents the initial coastline. The green, dotted line is the expected coastline position after 50 years. The yellow line represents the RN90. The structure is shown in grey.

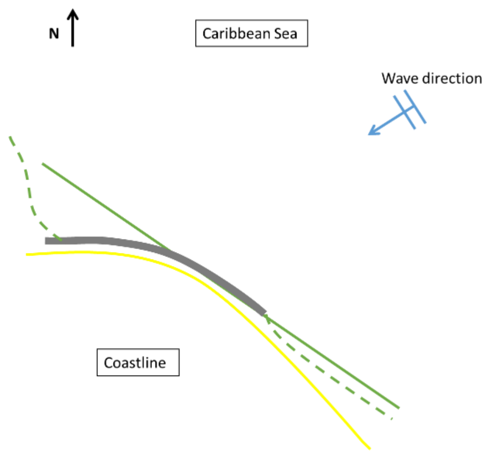


Figure 47: Simplified sketch of alternative "Extension"

This sketch shows the current policy, where an emergency revetment is extended along the RN90 following the on-going erosion to the west. The principle of this approach is to prevent damage to the RN90 by periodic extension of the emergency revetment along the RN90.

As increased erosion is expected downstream of the emergency revetment, a new section of the RN90 will become under threat and is expected to require protection. As the erosion continues, the emergency revetment is periodically extended towards the west.

Besides the alongshore shift of erosion, scour will take place in front of the revetment. This can be explained if we consider the cross-section. Erosion will be enhanced in deeper parts of the cross-shore profile since the upper part is protected by the revetment. To avoid collapse of the revetment, scour protection in deeper areas is required. Dumped rock fill can stabilize the deeper parts of the profile. This can be combined with the maintenance or it can be placed at the moment of construction in the form of a falling apron.

The risk of collapse of the RN90 remains, since a single storm event can have a significant impact on the coastline position. This approach therefore heavily depends on the ability to provide accurate predictions of the short term coastline development. In addition continuous, detailed monitoring is required to adequately maintain the emergency measure. This comes with high maintenance costs, but also brings the benefit of optimizing the maintenance scheme in accordance with monitoring results.

5.4.1 Schematisation

The schematisation of a revetment within UNIBEST-CL+ means that the transport at the downdrift side of a structure on an eroding coast is set at the same value as the updrift sediment transport (Deltares, 2011). This results in the elimination of the gradient in the sediment transport, preventing any erosion for the length of the revetment. The model assumes that the whole active profile is protected with the revetment. The settings for the climate and active height are similar to the reference scenario of Chapter 4.

In Figure 48 we see the schematization in the model interface, which shows the RN90 in green. The revetments at KM-19 and KM-28 are shown as the thick red dotted lines. To imitate a periodically extended revetment, the structure is partially schematized on land (i.e. landward of the blue dotted line). This means the western section of the schematized revetment is initially covered by sediment. The revetment does not have any effect of the coastline development, as long as it is located behind the coastline. The revetment will be exposed in subsequent phases, as the coastline in front of the schematized revetment continues to erode. Drawback of this method is that we assume a constant process of extending the revetment, while in reality it is executed in advance in yearly phases.

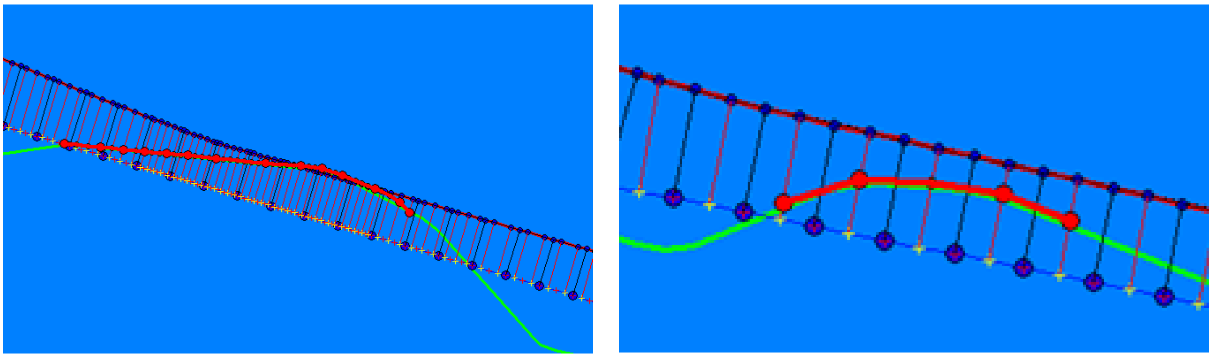


Figure 48: Schematization of the alternative "Extension" at critical cross-sections. Panel a) KM-19 and b) KM-28.

The revetments schematized in Figure 48 are positioned along the RN90, since the revetment follows the erosion towards the west while keeping the highway safe. The emergency revetment will be extended in accordance with the design of Sisco (Sisco Ingeniería, 2015), as shown in Chapter 3 and Appendix C.

Similar to the structure at KM-19 an emergency revetment will be built at KM-28 after 15 years. Here the revetment follows the RN90 as well, providing protection to a minimal amount of land. A cross-section similar to the cross-section built at KM-19 will be applied here.

5.4.2 Results

Figure 49 shows the coastline development at KM 19 during the considered period of 50 years. In the background we see a satellite image of the existing coastline in 2016. The coloured lines represent the various predicted coastline positions through time.

Figure 49: Coastline development over time with the alternative "Extension" at the critical locations

The coastline development indicates increased erosion downstream of both revetments compared to the reference scenario (Figure 42). The transition from the natural coastline to the downstream end of the structure is very smooth, since the revetment follows the RN90, which is located more landward here. The enhanced erosion decreases with distance from the structure, and is negligible after approximately 15 kilometres. In upstream direction the revetment has a stabilizing effect, as the upstream boundary of the revetment is a fixed coastline position. This decreases the erosion rates in the upstream area, until the influence of the structure at KM-28 is felt. This revetment has a downstream area of its own, with similar behaviour.

Initially scour will take place in front of the revetment, leading to a slight increase of sediment transport along the revetment, and consequently a decrease of downstream erosion. However the deeper parts are expected to stabilize over time either naturally or as a result of scour protection. After this period the assumed constant sediment transport along the revetment will correspond to the expected reality. This effect is expected to have a minor effect on the predicted erosion, since the scour volume is small compared to the predicted erosion over a period of 50 years.

The model results provide an estimate for the required revetment length of 1,800 metres during the considered period of 50 years to keep the RN90 safe from erosion at KM-19. An additional structure of 1,000 metres is required at KM-28. Since no land is protected, the expected downstream erosion is minor compared to the other alternatives. The comparison will be presented in the following paragraphs. With this alternative the road is directly located along the revetment and the Caribbean Sea, which could limit the road availability during storm events.

After 50 years this alternative will be a protrusion from the coastline. Adaptation of the local bathymetry is expected to lead to a focus of wave energy at this location. The structure will therefore require additional maintenance and scour protection on the longer term.

5.5 Alternative 2: Revetment

Figure 50 shows a simplified sketch of the alternative “Revetment”, where we see a revetment along the existing coastline in front of the critical location.

The general objective for the ‘Revetment’ alternative is to directly protect the sediment at the critical locations. To eliminate the repetitive character of extending a revetment, the entire required length is constructed at the start of the project. The revetment is positioned along the existing coastline, which is parallel to the emergency revetment. This is chosen to eliminate the threat of unexpected collapse during the considered lifetime.

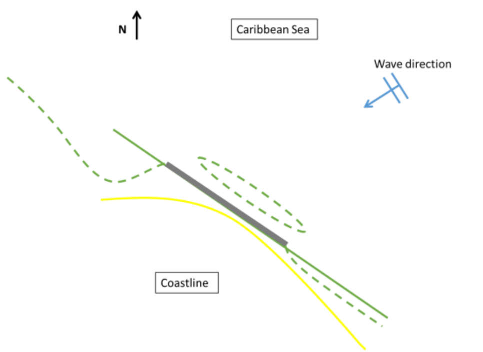


Figure 50: Simplified sketch the alternative “Revetment”

A revetment protects the sediment with an armour layer which can withstand the energy of the breaking waves during a storm event. The wave energy is partly dissipated when the waves break over the armour layer and the energy decreases while it penetrates the structure. Filter layers are constructed underneath the armour layer to prevent the finer material to be moved or wash out. The required rock size decreases in accordance with the decrease of energy to keep the structure stable.

Secondary effects are expected at both sides of the structure. Since erosion was taking place before construction of the revetment a gradient in sediment transport is present at this location. After construction of the revetment, sediment is no longer available along the structure. Therefore the sediment transport increases, while the amount of transported sediment is limited by the amount of sediment entering from the upstream side. Therefore a deficit will build up along the full length of the revetment. At the downstream boundary of the revetment sediment becomes available again. Therefore the sediment starvation is replenished here, leading to enhanced erosion at the downstream side of the revetment (left in Figure 50).

The revetment acts as a fixed coastline, while the upstream area (right in Figure 50) continues to experience erosion. The local coastline directly upstream of the revetment will reorientate. The resulting transport capacity is lower, as we have seen in the S-ϕ curve (Figure 36) in Chapter 4. Consequently the local upstream erosion will decrease, since the gradient in sediment transport has decreased. The revetment is partially 'blocking' the upstream sediment transport, leading to lower erosion rates directly upstream of the revetment. This process also affects the downstream area, since less sediment will pass the revetment. The sediment which is withheld in the upstream area will be eroded in the downstream area. The difference between the revetment and the upstream coastline will continue to increase as a result of the on-going erosion. Therefore both the upstream and downstream impact of this process will increase over time.

Scour is expected at the toe of the revetment. Sediment in the upper part of the profile is retained by the revetment, leaving the deeper sections of the profile vulnerable to erosion. The interaction between waves and the revetment will add to this effect as the increased turbulence leads to more movement of sediment. The design of an adequate toe is therefore critical for this alternative.

5.5.1 Schematisation

With this alternative the entire revetment will be built in one phase along the initial coastline of 2016. After 15 years a similar structure will be built at KM-28.

Figure 51 shows the schematization of the alternative 'Revetment' in the coastline model. The thick red line indicates the position of the extended revetment at KM-19. The additional required length of revetment is 2000 metres.

A smaller revetment of 1200 metres is required at KM-28 (Figure 51) since the problems are less severe at this location. Because the situation at KM-28 is less time-critical this structure is included in the model from 2031 and onwards.

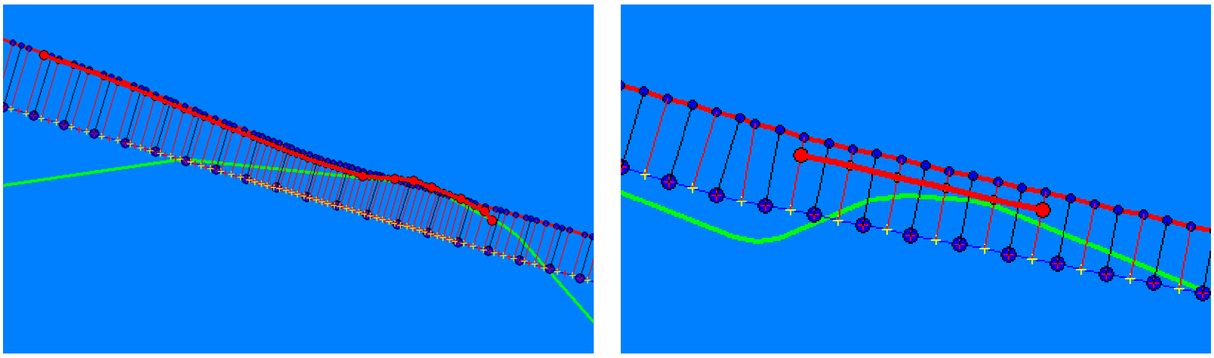


Figure 51: a) Schematization of the alternative "Revetment" at critical cross-sections. Panel a) KM-19 and b) KM-28.

5.5.2 Results

Figure 52 shows the coastline development at KM 19 during the considered period of 50 years for alternative "Revetment". In the background we see a satellite image of the existing coastline in 2016. The coloured lines represent the various expected coastline positions through time.

Figure 52: Coastline development over time with the alternative "Revetment" at the critical locations

Similar downstream erosion is observed as with the alternative “Extension” with the only difference that this alternative shows an abrupt transition at the downstream structure boundary. This can be explained by the fact that the downstream boundary is fixed during the entire period of 50 years. The expected coastline position is different from the model predictions in Figure 52 due to the effect of diffraction at the west side of the revetment. This will lead to the development of a curved, smooth transition between the structure and the natural coastline. The expected curved transition close to the structure is seaward of the predicted coastline by the model. The coastline position as shown in Figure 52 can therefore be considered as a conservative coastline position.

The upstream effect of the alternative “Revetment” is very similar to the alternative “Extension” as both alternatives have an upstream boundary at the same position. A slightly higher increase in erosion rates can be observed when we compare the results with the results of the alternative “Extension”. The initial revetment protects a longer stretch of coastline starting directly after the initial building phase, while this is spread over time with the alternative “Extension”. The impact of wave overtopping is limited, since the Caribbean Sea and the RN90 are not only separated by the revetment, but a section of land as well. Beyond the period of 50 years new locations downstream of KM-19 will become critical. Additional measures are required at those specific locations and moments in time.

5.6 Alternative 3: Breakwater

In Figure 53 we see the “Breakwater” alternative, where a long dam is constructed perpendicular to the coastline. In time sedimentation is expected at the upstream side, while enhanced erosion takes place in the downstream area. Aim of the “Breakwater” alternative is to prevent erosion at the critical locations by blocking the outgoing sediment transport.

The long breakwater of 800 metres crosses the entire breaking zone, blocking all alongshore transport. Sediment is deposited at the upstream side of the breakwater, and the area will fill both towards the tip of the breakwater and in the upstream direction.

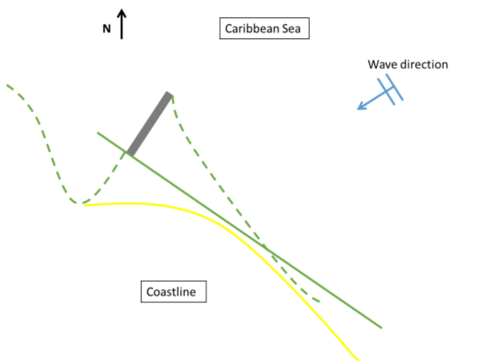


Figure 53: Simplified sketch of the alternative “Breakwater”

Increased erosion occurs at the downstream area, as the sediment transport picks up. The blocked volume of sediment which is removed from the alongshore sediment transport is replenished here.

Erosion at the base of the "Breakwater" alternative is expected to be limited, since the breakwater provides shelter from incoming easterly waves to the directly downstream area. Therefore a landward extension of 150 metres is expected to be sufficient.

Sedimentation reaches the tip of the breakwater over time, and bypassing will start to occur. A dynamic equilibrium will establish where the coastline orientation is determined by the sediment transport from the west and the orientation of the incoming waves.

The position of the breakwater is depending on the combination of the upstream protection of the critical locations and acceptable erosion at the downstream side. As a result the revetment is located downstream of the critical locations. The length of the breakwater is based on the required blocking percentage and the desired upstream reach. The combination of position and length determine the experienced delay before the sedimentation reaches the vulnerable locations. The behaviour on the short term requires further research to optimize the structure and assess the need for additional temporary measures.

5.6.1 Schematisation

For the alternative "Breakwater" a coastal structure is made perpendicular to the coastline. The breakwater is schematized in UNIBEST-CL by defining an X-coordinate along the coastline and a breakwater length. The length is defined as the distance from the tip of the breakwater to the initial coastline of 2016. In addition the blocking percentage of the breakwater is specified, which is used to determine the sediment bypassing.

Figure 54 illustrates how the blocking percentage is defined. We see a sketch of the cross-shore distribution of the alongshore sediment transport, similar to Figure 37 in Chapter 4. The length of the schematized breakwater determines the blocked part of the alongshore sediment transport. Since the breakwater is not permeable, a percentage of 100% is assumed. Over time accretion is expected at the upstream side of the structure. This will reduce the effective length of the breakwater, as is shown in the figure. This is why the modelled volume of sediment that passes the breakwater is expected to increase over time.

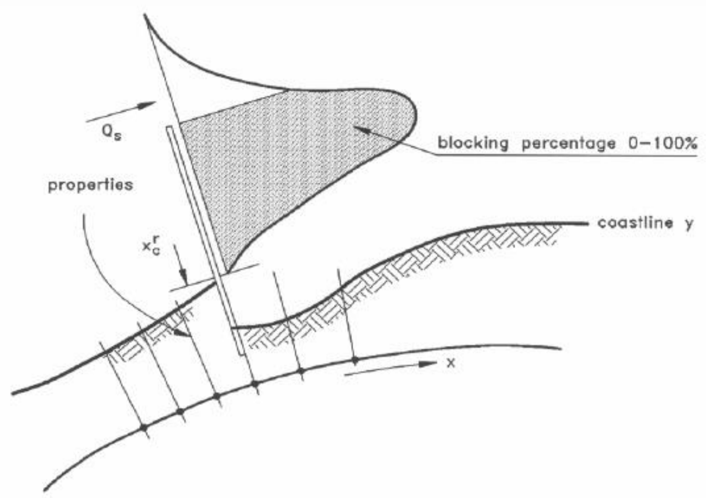


Figure 54: Definition of blocking percentage (Deltares, 2011)

The length and position of the breakwater are the result of a local optimization sequence. Initially the breakwater was located directly downstream of the critical sections and a length of 200 metres was sufficient to protect the coastal highway. However the development of a new critical section in the downstream area should be avoided. Since the road is located further away from the coastline to the west, the breakwater is shifted westward until the predicted erosion does not cause any problems. Located further away from the vulnerable section of highway, the breakwater should be extended to assure the safety of the highway at KM-19. The longer breakwater now blocks a larger part of the alongshore sediment transport, leading to an increase of downstream erosion. This iterative process led to the final position 3500 metres westward of KM-19, with a length of 800 metres (Figure 55a). The alignment of the coastal highway is therefore critical for the design of the alternative “Breakwater”.

The breakwater does not only affect the coastline development by partially blocking alongshore transport, but also by the changes in local climates around the structure. Therefore additional local wave climates are schematized using adjusted RAY-files to account for sheltering, refraction and diffraction at both sides of the breakwater. Undisturbed climates are added as well to restrict the influence of the local climates to the area close to the structure.

Figure 55b shows the breakwater at KM-28, which has a length of 200 metres. The breakwater is schematized in the same way as at KM-19 with local climates at both sides. A shorter length is sufficient at this location since the erosion is less severe and the road alignment does not cause a problem in the downstream area. The structure will be realized in 2031, since the highway becomes critical in a later stage at KM-28.

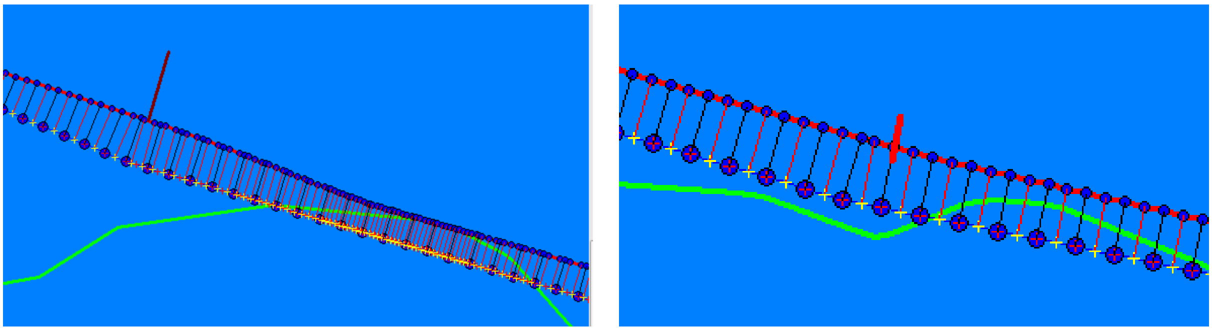


Figure 55: a) Schematization of the alternative “Breakwater” at critical cross-sections. Panel a) KM-19 and b) KM-28.

5.6.2 Results

Figure 56 shows the coastline development at KM-19 during the considered period of 50 years for alternative “Breakwater”. In the background we see a satellite image of the existing coastline in 2016. The coloured lines represent the various expected coastline positions through time.

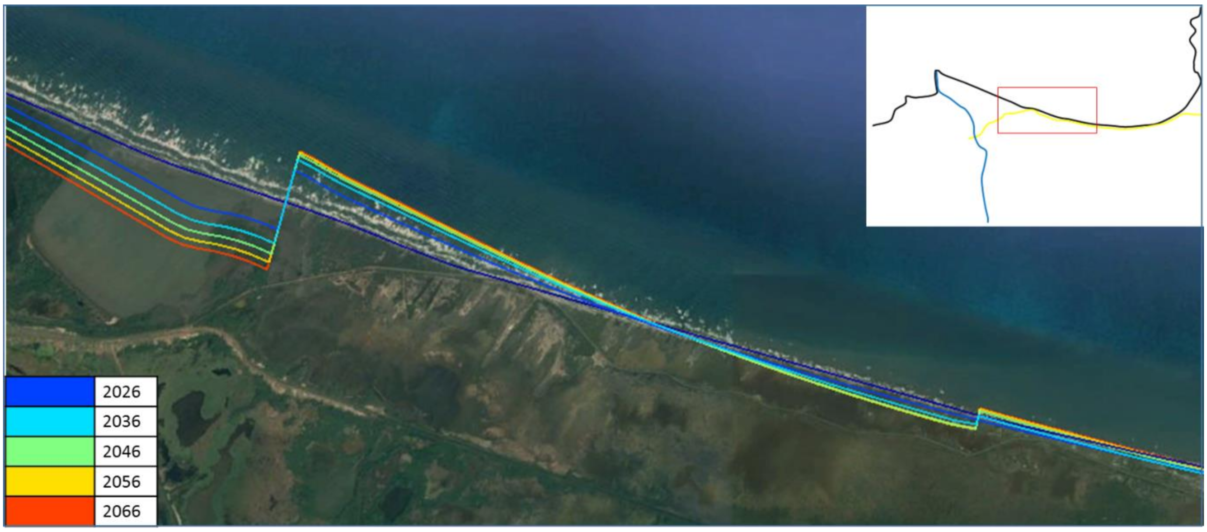


Figure 56: Coastline development over time with the alternative "Breakwater" at the critical locations

The construction of the long breakwater at KM-19 has a major impact on the coastline development. The full blockage of the active zone leads to high erosion rates of 20 metres per year directly downstream of the structure in the first year. The corresponding sedimentation is 15 metres per year, which takes place directly upstream. With the alternative “Breakwater” most interaction between the two locations is observed, as erosion in the downstream area of KM-28 slows down on the longer term.

Since almost the total alongshore transport is blocked by the breakwater, this alternative results in the strongest increase of erosion in the downstream area. Due to the sedimentation in front of the critical locations wave overtopping is not expected to become a problem with this alternative. Similar to the alternative “Revetment” this alternative will require additional protection at new critical locations downstream of KM-19.

5.7 Alternative 4: Groin field

Figure 57 shows a simplistic overview of the alternative “Groin field” which consists of several short groins in front of the critical locations.

The groin field aims at stabilizing the coastline by creating small, partially closed coastal cells.

The alongshore sediment transport is partially blocked, by constructing small groins in the breaker zone. The blocked sediment will accumulate to the right of each groin, while erosion takes place to the left of each small groin. In between the groins a small coastal cell will establish. Here the coastline will re-orientate based on the sediment input and the incoming waves.

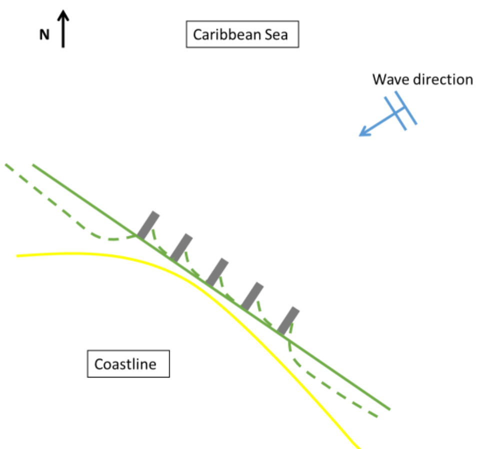


Figure 57: Simplified sketch of the alternative “Groin field”

In time a dynamic equilibrium will be reached between the groins in which the coastline orientation is readjusted to the local climate and the incoming sediment. A small shift in coastline orientation in the cells has limited consequences, due to the small width in between the groins and because the tip of the right groin provides a fixed point for the coastline. At this point sediment can bypass the groin field, leading to lower downstream erosion rates compared to the initial situation.

Like the revetment, severe erosion near the western boundary is expected. But due to the small length of the groins only a small percentage of the total alongshore transport will be blocked, therefore reducing the downstream erosion rates in comparison to the single breakwater where full blockage is expected.

The distance between two consecutive groins is of great influence on the landward erosion, since larger cells will allow erosion to go further inland. Optimisation is possible here.

Compared to a revetment this alternative does not protect the coast against cross-shore transportation processes. Additional loss of sediment is therefore expected after a storm event, but the high alongshore transport rates are expected to provide sufficient sediment to resupply the area in a short time period.

The downstream groin has to be protected against scour, since the down-drift erosion is expected to follow the breakwater closely. An extension of 200 metres landward is therefore included with this alternative. The coastline regression is expected to go beyond the first 200 metres, but further landward local effects such as sheltering, diffraction and refraction are expected to be dominant. The local processes are expected to shape the downstream area similar as a partially sheltered bay with a headland.

5.7.1 Schematisation

Similar to the alternative “Breakwater”, the groins along the coastline must be schematized. With the alternative “Groin Field” however, eleven structures are schematized along the coastline at KM-19. The spacing of between two successive groins is approximately 250 metres, within the model the spacing is could not be exactly reproduced, since groins can only be schematized at an X-coordinate of the coastline. The spacing between coastline coordinates is not uniform, resulting in a slight variation in spacing between two successive groins.

Figure 58a shows the schematized structures for the alternative “Groin field”. Similar as with the alternative “Breakwater” and “Revetment” the downstream boundary is located westward to prevent problematic erosion in the downstream area. Upstream of the eastward groin sedimentation will occur, and the critical location is protect from further erosion. Over time the emergency revetment is expected to be covered in sand.

Figure 58b shows the schematized groins at KM-28. The spacing is increased to 500 metres between successive groins, and the length of the groins is 200 metres. Similar to the other alternatives, the structures at this location are implemented after a period of 15 years.

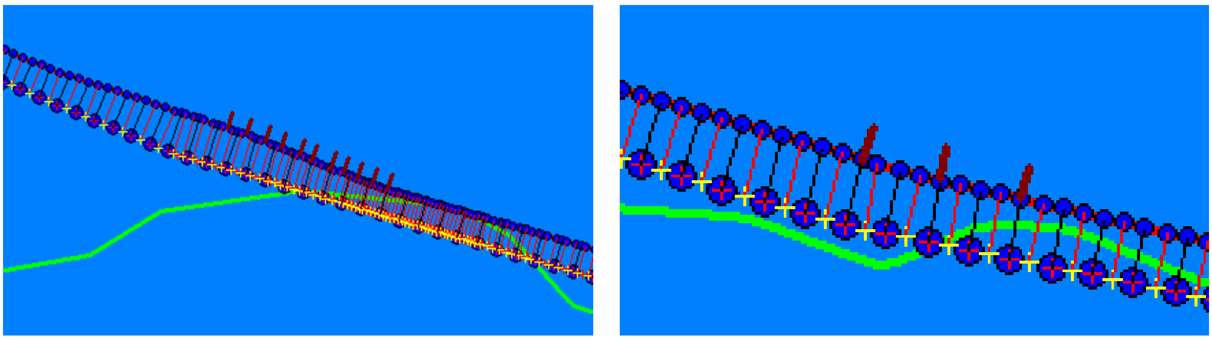


Figure 58: a) Schematization of the alternative “Groin field” at critical cross-sections. Panel a) KM-19 and b) KM-28.

During the design of this alternative the length of the groins was varied, to assess the impact on the coastline development. Very short groins (50 metres) resulted in a similar coastline development as with groins of 200 metres, which are used for this alternative. It is however expected that the very short groins only have a minor influence on the alongshore sediment transport and are not expected to change the development of the cross-shore profile.

The effect can be explained by the initial model assumption of parallel depth contours in UNIBEST. When a small change is made at the coastline, the cross-shore profile is expected to follow. This assumption holds for sandy coastlines, but not around structures. Therefore a realistic length of the groins should be used, with sufficient impact on the alongshore transport and thereby the development of the cross-shore profile. With the cross-shore distribution of alongshore transport from Chapter 4 (Figure 37) in mind, a length of 200 metres is assumed to be sufficient. However erosion in deeper parts of the profile is still expected, since the structures are built in a strongly erosive coastal zone. As with the other alternatives, significant scour protection will be required over time to protect the structures from undermining as a result of scour in the deeper parts of the profile.

5.7.2 Results

Figure 59 shows the coastline development at KM 19 during the considered period of 50 years for alternative “Groin Field”. In the background we see a satellite image of the existing coastline in 2016. The coloured lines represent the various expected coastline positions through time.

Figure 59: Coastline development over time with the alternative "Groin Field" at the critical locations

The alternative “Groin field” acts as the middle ground between the alternatives “Revetment” and “Breakwater”. The upstream effect is comparable to the alternative “Revetment” as the tip of the last groin acts as a fixed coastline point similar to the upstream end of the revetment. As a result the interaction between the two locations is also similar to the alternatives “Revetment” and “Extension”.

The downstream erosion is slightly stronger compared to alternative “Revetment”, but significantly less compared to the alternative “Breakwater”. Wave overtopping is expected to be a problem, since the groins are only constructed perpendicular to the beach. The blocking of incoming waves is therefore limited, and run-up along the beaches could reach the RN90. Similar to the alternatives “Revetment” and “Breakwater” this alternative will require additional protection at new critical locations downstream of KM-19.

5.8 Alternative 5: Nourishment

In Figure 60 a sketch of the "Nourishment" alternative is shown. The nourished volume of sand is depicted with the grey area.

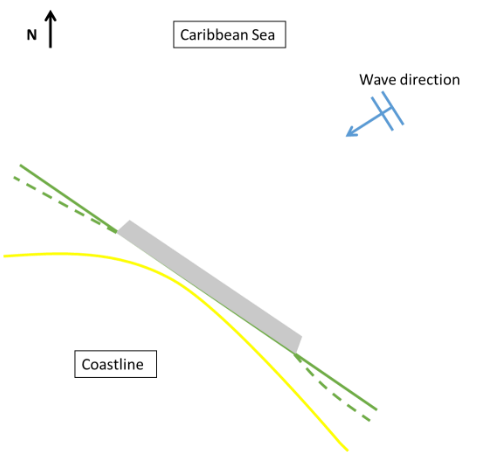


Figure 60: Simplified sketch of the alternative "Nourishment"

With a beach nourishment additional sediment is supplied to vulnerable locations. By direct intervention in the local sediment balance the coastline position can be controlled. A limited amount of regression can be allowed, or to the current coastline position is fixated entirely.

The natural processes responsible for the sediment transport are not interrupted and the sediment will in time move to the west as a result of the incoming waves, similar to the current situation.

Secondary effects as described with the 'hard' solutions above are not expected. By adding sediment to the system the erosion is not tackled by replacing it. Due to the movement of the sediment in time the downstream area will receive additional sediment, reducing the erosion rates there as well.

The nourishment will have an upstream impact as well, similar to the upstream effect of a revetment (Section 5.5). Erosion is reduced at the nourishment location, while the original erosion takes place upstream. The difference in erosion rates will lead to a reorientation of the coastline in the transition area. The new orientation is closer to the equilibrium orientation, so less transport takes place. Over time this effect will migrate upstream as the difference between the eroding upstream area and the maintained nourishment location grows.

A repetitive approach is required because of the fact that the sediment is moved away in time. With a cycle time of one year the predicted erosion for the upcoming year will be added to the existing coastline. The sediment transport can continue, but does not lead to erosion and conflicts with the local highway or any other form of land use.

Availability of sediment with the correct diameter and distance to the borrow location is crucial for this alternative since these factors determine the costs for this approach. Optional borrow locations are 1) the former under water river deltas directly offshore of the nourishment location 2) maintenance dredging operations at the Rio Magdalena or Port of Barranquilla 3) the CGSM as sand mining location 4) the shoreface directly eastward of the Rio Magdalena river mouth. Beside economic considerations, the grain diameter of 320 µm (Section 3.11) should be taken into account in the selection of the borrow location to assure compatibility.

5.8.1 Schematisation

The schematization of a nourishment in UNIBEST-CL can be done by adding a source. A source is defined by a location along the coastline, and the volume of supplied material which will be distributed over the active height of the profile. The sediment supply can be defined as a function of time, allowing for the schematisation of various nourishment schedules. Both a yearly and a 5-yearly nourishment frequency are applied for this alternative.

At KM-19 (Figure 61a) the nourishment is schematized along a stretch of 3 kilometres, requiring 50 sources which supply the coastline. The required nourishment volume is determined based on the observed erosion rate of 9 metres/ year (Table 7). For a coastline section of 3000 metres with an active height of 8.6 metres (Section 4.3.4), the eroded volume is approximately 232,000 m^3/year. After several model runs the required nourishment volumes were determined as presented in Table 8. For KM-19 the required nourishment volume to maintain the coast at KM-19 ranges from 240,000 to 384,000 m^3/ year (depending on the severity of the climate conditions).

The difference between the nourishment volume estimated on the basis of historic retreat and the required volumes for maintenance of the considered critical sections is considerable. This can be explained by the coastal extension that will develop over a period of 50 years at KM-19 and KM-28 relative to the reference scenario. In addition the upstream sediment transport will decrease over time as a result of the upstream impact of the nourishment. Since the downstream sediment transport remains more or less constant, the nourishment volume is increased to maintain the coastline position.

The nourishment at KM-28 (Figure 61b) starts after 2031. Here an area of 2 kilometres is supplied with sediment using 10 sources. The required nourishment volume is estimated at 216,000 to 432,000 m^3/year (depending on the severity of the climate conditions).

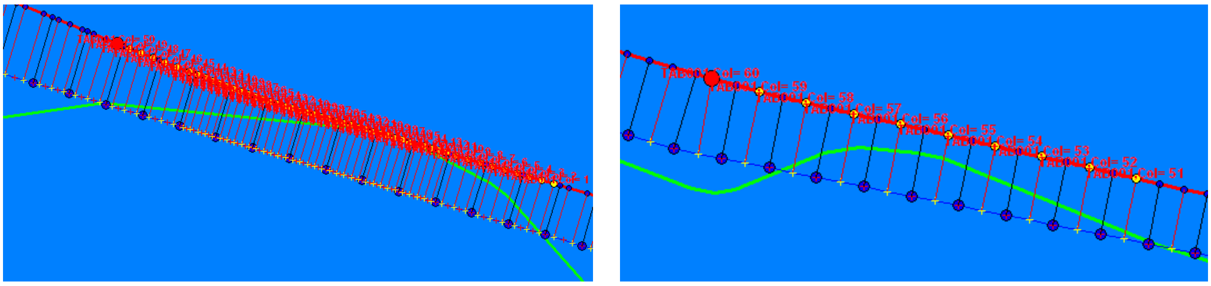


Figure 61: a) Schematization of the alternative "Nourishment" at critical cross-sections. Panel a) KM-19 and b) KM-28.

As can be seen in Table 8, the required volume for a nourishment scheme with a 5 yearly frequency requires slightly more sediment in total. This could be explained by the fact that the bigger nourishment causes a stronger decrease in upstream erosion. The shown volumes are the average over the considered period of 50 years.

Table 8: Nourishment details

Climate	Frequency	Location	Volume per cycle	Nourishment volume per m beach width	Nourishment type
[-]	[-]	[-]	[m3/cycle]	m3/m	[-]
ERA	Yearly	KM-19	240,000	80	Beach
		KM-28	216,000	108	Beach
WWIII	Yearly	KM-19	384,000	128	Beach
		KM-28	432,000	216	Beach
ERA	5-yearly	KM-19	1,248,000	416	Foreshore
		KM-28	1,296,000	648	Foreshore
WWIII	5-yearly	KM-19	1,996,800	665.6	Foreshore
		KM-28	2,592,000	1296	Foreshore

5.8.2 Results

Figure 62 shows the coastline development at KM 19 during the considered period of 50 years for alternative "Nourishment". In the background we see a satellite image of the existing coastline in 2016. The coloured lines represent the various expected coastline positions through time.

Figure 62: Coastline development over time for the alternative "Nourishment" at the critical locations

Limited changes in coastline position are observed for this alternative. With a nourishment frequency of one year, the fluctuation in coastline position is very limited. When a 5 year frequency is applied, the range of the coastline fluctuation would be larger and more seaward. The stabilisation of the entire bay is the main results of alternative “Nourishment”, independent from the chosen nourishment scheme.

The erosion downstream of KM-19 is slowed down or even stopped with this alternative. Wave overtopping is expected to be limited, since the RN90 is only exposed to the Caribbean Sea along the existing emergency revetment. On the longer term no new critical locations are expected to develop, as long as the yearly nourishments take place.

5.9 Alternative 6: Relocate Road

Figure 63 shows the option of road relocation, where we see the new road position as a yellow dashed line, behind the expected coastline of 2066.

The objective of this alternative is to prevent conflict by adapting land use to the on-going erosion.

With this alternative the erosion will be accepted, and the position of the road will be adapted to the expected coastline development (Figure 64). With an expected lifetime of 50 years a bypass with a length of 5 kilometres is required at KM-19 and a new road of 2.5 kilometres at KM-28.

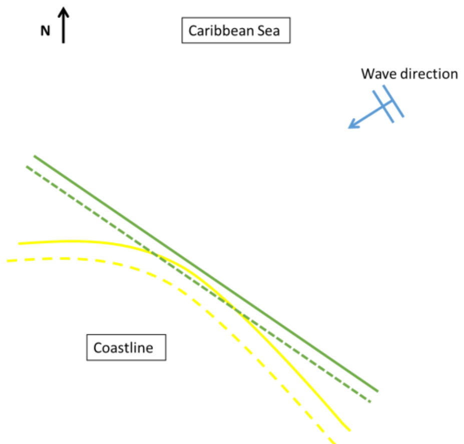


Figure 63: Simplified sketch of the alternative “Relocate Road”

Since acting processes are not stopped the erosion is expected to continue without reaching an equilibrium in the foreseeable future, see CH4. After the period of 50 years the existing issues will again be critical, but for a longer stretch of road since the coastline develops more parallel to the coastline, compared to the current situation.

Figure 64: Location of suggested new road

With this measure it is required to protect the current situation during the design, preparation and execution of the alternative highway. Only after completion the existing highway can be decommissioned and removed along with the temporary protections. A short term strategy to protect the existing highway for an additional 5 years should therefore be part of this alternative.

The emergency measures taken at KM-19 have a negative effect on the required set-back of the road since erosion is focussed on the westward boundary. The timely demolition of the revetment is therefore a vital part of this alternative.

Since road expansion plans are already made, the construction of new road sections can be combined with the additional lanes between Barranquilla and Santa Marta. Management and maintenance costs are not included for this alternative since the total length of road will decrease and therefore no additional expenses are required.

5.9.1 Schematisation

Similar to the Do Nothing scenario only the existing structures are schematized as described in Chapter 4. After a period of 5 years the emergency revetment will be removed to prevent the focussing of the erosion.

5.9.2 Results

Figure 65 shows the coastline development at KM 19 during the considered period of 50 years for alternative “Nourishment”. In the background we see a satellite image of the existing coastline in 2016. The coloured lines represent the various expected coastline positions through time.

Figure 65: Coastline development over time with the alternative "Relocate Road" at the critical locations

The coastline development is very similar to the reference scenario. After 5 years the temporary structure is removed and the minor differences are rapidly reduced. No difference can be observed after 50 years.

The erosion is enhanced on the short term, but later no change is observed. Initially the new road position will be sufficiently far inland to prevent hindrance from wave overtopping, but as the set-back period is approached the distance between the Caribbean Sea and RN90 becomes smaller. However, since a buffer area is incorporated between the set-back line and the new road position, no negative effects are expected. Please note that the alternative “Relocate Road” is less suitable as a long-term strategy, since the relocation has to be repeated after the chosen period of 50 years, and a larger stretch of road will have to be relocated.

6 Evaluation of alternatives

6.1 Introduction

In this chapter the impact of the different alternatives is evaluated using a Multi Criteria Analysis. The criteria are defined as stakeholder requirements, which were identified in Chapter 2. The expected impact of the alternatives on the stakeholder requirements is based on the predicted coastline development (Chapter 4) and personal estimates. The level of detail varies per criterion, as the focus of this study is on Coastal Engineering.

The impact of the alternatives is considered relative to the "Do Nothing" reference scenario. As a result of the relative scoring the focus of the comparison is on the differences in impact among the alternatives. The scorecard presents the six alternatives and their rated impact on all relevant criteria. The impact on the stakeholder criteria is discussed per theme: Infrastructure, Coastal System, Ecology, Organization and Costs.

The infrastructural aspects are strongly related to the national economy. Both road safety and nuisance for road uses were identified as important criteria. Enhanced erosion is an undesired side-effect of most alternatives, and is therefore an important criterion for the Coastal System. In addition, the interaction with the harbour of Barranquilla is addressed. The behaviour during storm events was also identified as an important criterion. The suitability for extending the chosen approach beyond the period of 50 years is also evaluated here. Ecological aspects are discussed only briefly, because they are not the focus of this research. A quick scan is performed on aspects where the alternatives are influential, such as the water exchange between the Caribbean Sea and the Ciénaga Grande de Santa Marta, as well as the surface of mangrove forest near the coastline. Both the organisational criteria and costs are relevant for the national stakeholders, responsible for the organisation and financing of the final solution.

In section 6.3 the importance of perspective is elaborated on. The impact of the alternatives is evaluated from different perspectives, showing the sensitivity of the 'Total Qualitative Score' to the chosen perspective (represented by the weight factors).

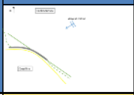
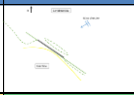
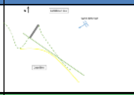
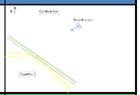
To conclude this chapter the argumentation for the selection of the Most Promising Alternative is presented.

6.2 Impact on stakeholder criteria

6.2.1 Scorecard

The Scorecard is presented in Table 9 to provide an overview of all relevant characteristics of the alternatives. The rows contain the relevant criteria, which followed from the stakeholder analysis in Chapter 2. Each column describes the impact of an alternative, which is shown in the sketch at the top of the column. The impact of the alternatives on the criteria, relative to the "Do Nothing" reference scenario, is shown using a colour scale. A negative impact is indicated in red, while a positive impact is indicated in green. At the lower end of the table the 'Total Qualitative Score' and the 'Net Present Value' of the alternatives are shown, to present two important performance indicators per alternative.

Table 9: Scorecard of evaluated alternatives

Scorecard		Extension	Revetment	Breakwater	Groin field	Nourishment	Relocate Road
							
Infrastructural	Safety of RN90 against coastal erosion during a lifetime of 50 years	Yellow	Green	Green	Green	Green	Green
	Nuisance for road-users during construction	Red	Yellow	Yellow	Yellow	Green	Green
Coastal	Men induced enhanced erosion/impact on coastal system	Yellow	Yellow	Red	Red	Yellow	Green
	Suitability for longer term application (>50 years)	Red	Yellow	Yellow	Yellow	Green	Red
	Impact on harbour operations and sedimentation	Green	Green	Green	Green	Yellow	Yellow
	Risk of wave overtopping during storm events	Red	Yellow	Yellow	Red	Green	Green
Ecological	Impact on water exchange between CGSM and Caribbean Sea	Green	Green	Red	Yellow	Red	Green
	Surface of mangrove forest	Red	Red	Red	Red	Green	Yellow
Organisational	Designs in compliance with laws and regulations	Yellow	Green	Green	Green	Green	Green
	Project complexity and stakeholder involvement	Green	Yellow	Yellow	Yellow	Red	Green
	Provide integral solution	Yellow	Green	Green	Green	Green	Yellow
Total Qualitative Score		Red	Yellow	Yellow	Yellow	Green	Green
Net Present Value		**$29 M**	**$35 M**	**$8 M**	**$35 M**	**$213 M**	**$6 M**

6.2.2 Infrastructure

Most residents are depending on the highway RN90, as it is the primary means of transportation between Barranquilla and Santa Marta. As the main connection between the port of Barranquilla and the hinterland, the road is also of vital importance to the national economy. All alternatives are therefore designed to protect the RN90 against erosion, as this was the primary motivation to undertake this study. However, the structural and operational safety of the highway varies among the alternatives. With the current policy of continuous extension, a risk of unexpected collapse remains, since erosion close to the road is allowed. As a result, the safety provided by the alternative “Extension” is relatively low (yellow in Table 9). Both alternatives “Revetment” and “Groin field” score high (green in Table 9) since they include a structure directly in front of the vulnerable locations. Both alternatives “Relocate Road” and “Breakwater” require additional structures to temporarily protect the critical locations. For the relocation of the road, a period is required to design and build the new road. For the alternative “Breakwater” the upstream area has to be filled with sediment. With the alternative “Nourishment” the coastline is allowed to approach the highway periodically. However, the safety is guaranteed by means of monitoring and the possibility to make changes to the maintenance scheme.

Nuisance for transport and commuting along the RN90 is expected to be highest when yearly construction works are required close to the road, as is the case for the alternative “Extension”. Relocation of the road could be done with little to no hinder, as the new road can be built parallel to the existing section of highway. The alternative “Nourishment” is also expected to have little impact on road-users as it will mainly be executed from the sea, and to a lesser extend from land. The three coastal structures “Revetment”, “Breakwater” and “Groin Field” are built close to the road, but the nuisance will be limited to the initial construction phase.

6.2.3 Coastal system

The erosion downstream of the measures at KM-19 is compared in Figure 66. The expected coastline position for all alternatives is presented after 50 years, for the ease of comparison. The use of colours in this figure does not refer to the coastline development in time, but helps to distinguish the different alternatives. The alternative “Breakwater” has the most extreme impact on the coastline west of KM-19. As the entire active zone is blocked by the breakwater, the erosion is strongly enhanced at the down-drift side of the breakwater.

All other hard measures show a similar behaviour, since the erosion is enhanced at the down-drift side. Only "Relocate Road" has limited effect on the current erosion, since the coastal processes are only disturbed during the temporary protection phase. This has no lasting effect on the longer term. The alternative "Nourishment" slows down the erosion. The 'gained' land, relative to the reference location, is not appreciated and therefore leads to a lower score.

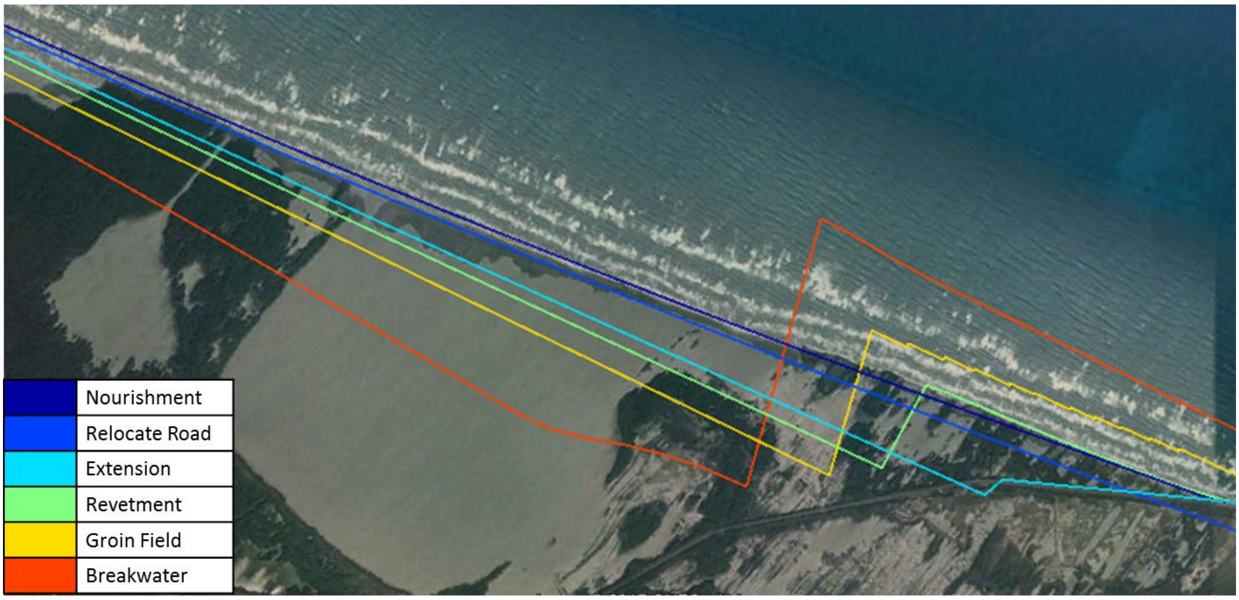


Figure 66: Impact of all measures downstream of KM-19 after 50 years

Looking beyond the evaluated period of 50 years, not every measure is suitable to be continued on the longer term. "Relocate Road" scores poorly on this aspect, since the required efforts are expected to increase over time. After 50 years a longer section of the RN90 becomes vulnerable, and the current efforts to relocate the road no longer hold any value. Both alternatives "Nourishment" and "Extension" can simply continue as they have a repetitive character. The required length of the revetment extensions is however expected to increase. Long-term problems are expected to arise in the down-drift area of the hard measures "Revetment", "Breakwater" and "Groin Field" since the erosion is focussed there. Additional structures or a nourishment are required to mitigate the effects.

Storm events can have a significant impact on the road usage. When the coastline is close to the road, wave overtopping can cause hazardous situations. After relocation of the road this effect is expected to be minimal, since the road is furthest away from the coastline of all alternatives. With both "Breakwater" and "Nourishment" the coastline is separated from the sea. This will however have a periodic character for the "Nourishment" alternative. Both "Revetment" and "Groin field" have a similar section of road close to the sea, while the section length of the alternative "Extension" increases over time.

6.2.4 Ecology

Several national parks are close to the area of interest, leading to the incorporation of ecological values into the list of criteria. Since this study focusses on the RN90 and the Caribbean coastline, the impact of the alternatives on the ecological conditions are expected to be limited. The main impact is on water exchange and surface of the mangrove forest.

The water exchange between the Caribbean Sea and the Ciénaga is expected to improve after relocation of the road since the erosion is allowed to continue. The road construction allows for the implementation of additional culvert along the critical locations, leading to improved water exchange for the alternative “Relocate Road”. All hard measures lead to a reduction of the barrier width, this effect is strongly focussed on the downstream side of the structures. The focus of the erosion is not expected to have a big impact on the ecological conditions of the Ciénaga Grande de Santa Marta. The alternative “Nourishment” is expected to perform worst on this aspect, since the added sand might clog the culverts which are already present along the RN90.

The surface of mangrove area in Via Parque Isla de Salamanca is directly influenced, since the park is located around the RN90 and along the Caribbean Sea. Enhanced erosion will lead to the speeding up of deforestation as a result of the erosion. The highest impact is expected with “Breakwater”, followed by the other hard solutions. Only “Relocate Road” allows the natural erosion to continue, and the corresponding limited collapse of trees along the coastline. The alternative “Nourishment” maintains the current coastline and prevents further loss of mangroves along the coastline.

6.2.5 Organisation

With the current policy of extending the revetment, an acute problem can arise as a result of unexpected storms. An immediate response would be required, such as the immediate dumping of additional rick fill which does not comply with laws and regulations. All other alternatives allow for a design period in advance, so they can be adapted to the laws and regulations.

Low complexity and involvement of local stakeholders is desired to develop local support for the measure. This is best achieved with the alternatives “Extension” and “Relocate Road”, as these alternatives are executed with local equipment and materials. The alternatives “Revetment”, “Breakwater” and “Groin Field” are more complex as a result of the extensive scour protection, and require sea-going equipment during the construction phase. The alternative “Nourishment” can only be executed with specialist equipment, as a result local stakeholders are less involved.

Not all alternatives are equally suited to provide an integrated answer to the different problems of coastal erosion, limited road capacity and preservation of ecological values. The alternative “Extension” only addresses the coastal erosion, and is difficult to combine with the other problems. The nourishment scheme provides many secondary benefits, including the preservation of ecological values. The other hard solutions can be combined with water exchange improvements.

6.2.6 Cost Estimation

Costs are relevant to the governmental agencies who will finance the construction and maintenance of the final solution.

To account for the different moments in time when investments are required the Net Present Value will be used to compare the costs of each alternative. With this method future costs will be translated to their current value using a discount rate. This allows for a clear comparison between the required investments at the start of the project for each alternative.

The applied discount rate is an important parameter. A high rate results in a preference for alternatives with low initial investments and higher investments in later stages. With this in mind the results for multiple rates will be presented to show the impact of the chosen rate.

The cost estimation was performed in a rather rough way, as in this phase of the study an elaborated design of each alternative is not required. The costs are estimated making used of both coastal and infrastructural reference projects. The costs of reference projects were transformed in unit prices and applied to the alternatives. This is documented in more detail in Appendix G.

Using the dimensions of the alternatives as presented earlier in this chapter the Net Present Value of the alternatives were calculated with different discount rates. As we see Table 10, all measures have a negative value because no revenue is considered for any of the options. The impact of using the Net Present Value is best seen for the 'Nourishment' since the decrease in Net Present Value is most extreme compared to the other alternatives. This can be explained by the even spreading of expenses over the considered period of 50 years, which is higher appreciated when higher discount rates are used.

Table 10: Net Present Value for varying discount rates in M USD

Discount rate [%]	0	2	4	5
Extension	-65.7	-41.6	-28.7	-24.5
Revetment	-53.7	-41.6	-34.7	-32.3
Breakwater	-10.4	-8.6	-7.5	-7.2
Groin field	-50.2	-40.4	-35.0	-33.2
Nourishment	-462.5	-300.3	-212.5	-183.8
Relocate Road	-7.3	-6.6	-6.1	-5.9

As we compare the NPV as presented in Table 10, we see that the costs for the alternatives "Extension", "Revetment" and "Groin field" are rather similar. This is because these three alternatives require a similar volume of rock. The costs of the alternative "Extension" are spread over time, resulting in a slightly lower NPV.

Despite the benefit of spreading the costs over time the alternative 'Nourishment' is by far the most expensive option. The alternatives "Breakwater" and "Relocate Road" both require limited investments. The alternative "Breakwater" requires fewest rocks among the hard solutions, leading to low costs. The "Relocate Road" alternative is the most cost effective alternative since the road construction can be combined with the planned highway expansion.

6.3 Stakeholder Perspective

At the bottom of the table a summarizing ‘Total Qualitative Score’ is presented, which combines the impact of the alternatives for all criteria. Since not all criteria are equally important, weight factors are introduced. The result is a weighted ‘Total Qualitative Score’, to indicate the qualitative performance of the alternatives.

The weight factors which are used in the actual decision-making process of this complex, integrated project are the result of local politics and an interactive process involving all relevant stakeholders. For reasons of practicality this was not part of this study, and a personal assumption was made to define a set of weight factors. This is done with the intention to provide a workable assumption to allow for the evaluation of the alternatives, not to imitate or represent any political decision.

The weight factors which are used for the study are based on a presumed consensus between the economical and the ecological perspective. Both perspectives are presented in Table 11, together with the assumed weight factors.

The table presents an ecological and an economical perspective (second and third column), and a compromise (fourth column). A total of 10 points is divided among the themes according to the importance of the criteria. From an ecological point of view, the highest weight factor (5) is given to Ecological criteria, Coastal and Organisational criteria are less important (2), while the Infrastructural criteria are least appreciated (1). For a strictly economic approach the weights are divided in a similar way, in this case with preference for the Infrastructural criteria (5) over Ecology (1). Coastal and Organisation criteria are equally important (2). The scorecard as presented in Table 9 is not based on one of these perspectives, but on an assumed set of weight factors. The highest importance is given to Infrastructural criteria (4), since the erosion close to the RN90 has initiated the project. Coastal criteria (3) and Ecological criteria (2) are expected to be less important, with the Organisational criteria (1) as least important theme.

Table 11: Relevance of theme's based on stakeholder perspective

	Ecological perspective	Economical perspective	Assumed weight factors
Infrastructural	1	5	4
Coastal	2	2	3
Ecological	5	1	2
Organisational	2	2	1

6.3.1 Sensitivity

The ‘Total Qualitative Score’ is strongly dependant on the chosen weight factors. To address the importance of the stakeholder perspectives, the ‘Total Qualitative Scores’ are presented for the three perspectives, as presented in Table 11.

In Figure 67 the ‘Total Qualitative Score’ is shown along the vertical axis for all six alternatives. The height of the columns indicates the qualitative score of the various alternatives. For ease of comparison the three perspectives are combined into one figure. Note that the costs are excluded to allow for a comparison based on the qualities of the alternatives.

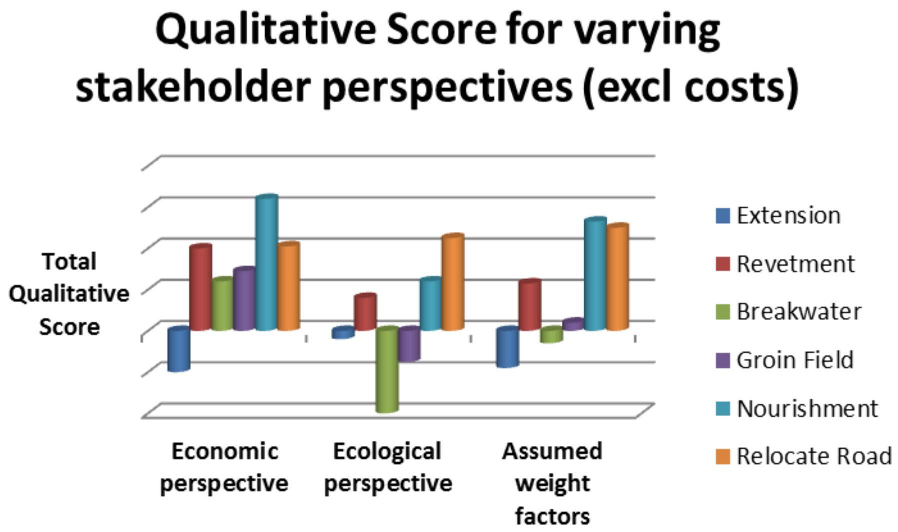


Figure 67: Qualitative score for varying perspectives

From an economic perspective, secondary effects like enhanced downstream erosion are less relevant, leading to an overall higher score of the alternatives. “Extension” is a less preferred alternative, since the risk of collapse remains at a higher level compared to the other alternatives. “Nourishment” has the highest qualitative score due to the long-term suitability of this solution, followed by the alternative “Relocate Road”.

From an ecological point of view “Breakwater” is the least performing alternative, since this solution is accompanied by the most extreme erosion in the downstream area. The preferred solution is “Relocate Road”, which scores significantly higher since the coastal processes are undisturbed and the water exchange can be improved.

The result of the suggested compromise is a clear mix of both Ecology and Economy, as “Nourishment” and “Relocate Road” both have a good performance. For both “Breakwater” and “Groin Field” the negative ecological impact is compensated by the positive economic aspects. “Extension” is the worst performing alternative, since it does not perform well on infrastructural and ecological aspects.

6.4 Selection

When costs are excluded, “Nourishment” is the best performing alternative from both the “Economic” and the “Compromise” perspective. The erosion is countered by the supply of sediment, instead of passing the erosion on to downstream areas, as is the case with coastal structures. The solution is very suitable for longer term application, and the nuisance for road users is limited. The existing mangrove forest is protected, since the coastline is stable. In addition this solution opens the possibility for further collaboration between the Colombian and Dutch water sector.

Moreover, the nourishment has a large influence in both downstream and upstream directions, leading to a bay-wide stabilization of the coastline. The nourishment provides more protection in addition to the required local intervention at critical locations, as was identified in Chapter 4. The conservation of land in the coastal zone comes with a price, since vast amounts of sand are required on a yearly basis. In fact, it seems that the role of sediment supplier, previously served by the Rio Magdalena, is fully taken over by this alternative. “Nourishment” is therefore considered to be an effective and environmental friendly solution, but with high costs.

The coastal structures all have a similar impact, especially “Extension”, “Revetment” and “Groin Field” as they retain a similar stretch of coastline with different rocky structures. The upstream erosion is slowed down, while downstream erosion is enhanced to compensate for the blocked transport. The blockage of nearly all transport by the alternative “Breakwater” results in the most extreme erosion, followed by “Groin Field”, “Revetment” and “Extension” in ascending order of transport blockage and enhancement of erosion. The static coastal structures are suitable for a selective impact at critical locations. However, the application of static, rocky structures within a highly dynamic coastal zone is not suitable for long term application. Scour is expected in deeper parts of the profile, resulting in high costs for construction and maintenance.

The selection of the most promising alternative is not expected to be influenced by the chosen wave climate. The differences in wave climate are expected to lead to different absolute coastline changes. However, since relative coastline changes are considered, the resulting, relative differences between the wave climates are expected to be minimal. For an analysis of the longer term behaviour, the orientation of the wave climates becomes relevant, however this is outside of the scope when a period of 50 years is considered.

The alternatives “Extension”, “Revetment” and “Groin Field” are in the same price range, as all three alternatives require a similar amount of rock for the structure and scour protection. The alternative “Breakwater” requires less material, resulting in lower costs. “Nourishment” results in the highest costs, as the volumes of supplied sediment are high. The road relocation is a relatively cheap solution. The new road sections will be constructed with double lanes, leading to savings for the already planned road expansion project (‘doble calzada’). Further integration of the road expansion and the road relocation could enhance the financial benefits.

The relocation of the road is expected to have a short-term impact on the ecology of Vía Parque Isla de Salamanca, but this will be limited to the construction phase. The loss of park area is compensated since the current road position will become vacant. The coastal highway RN90 was accepted within the park boundaries since the establishment of the park. As long as the processes are driven by natural causes, erosion is accepted. Therefore active protection of the parks is not desired.

The alternative “Relocate Road” is the most cost effective, since the qualitative score is of the same range as “Nourishment” but with lower costs. The main benefits of this alternative are:

- Safety for RN90 is provided, however the considered lifetime of 50 years should be optimized;
- Low nuisance is expected since the construction of the new road sections can be executed parallel to the existing road;
- Road construction can be integrated with the already planned road expansion project (‘doble calzada’).
- No disturbance of the natural erosion processes;
- Additional culverts can be realized along the new road section to improve the water exchange between the Caribbean Sea and the CGSM;
- The ecological impact will be limited since the old road location becomes available again;
- Lowest costs.

7 Final Conclusions

The most relevant stakeholders are identified as:

- The ‘Vicepresidente’ as entity to encourage inter-sectorial collaboration for projects involving coastal engineering and as the decision maker;
- The ‘Ministerio de Transporte’ and ANI as representatives of the coastal highway RN90 and the related economic development on a national level;
- MADS and PNN as representatives of the ecological values and the National Parks and the ecological values;
- CCO as inter-sectorial advisory body for issues relating oceans and coastal areas;
- ‘Gobernación de Magdalena’ as representative of the local population;
- INVEMAR and CIOH as research institutes with relevant knowhow;
- UNGRD as (partial) financier of the emergency measure and possible solutions.

Coastal management is not part of the jurisdiction of any ministry or governmental organisation. Consequences are:

- Lack of (long term) vision;
- Slow, local responses to problems in the coastal zone;
- No monitoring of coastline behaviour;
- No gathering and concentration of knowledge.

Driving forces of coastal erosion are:

- Readjustment of the Barranquilla Bay after the relocation of the Rio Magdalena. The former river deltas are slowly removed, leaving the shoreline more exposed to incoming waves;
- Lack of sediment supply to the coastal system as the river mouth is located down-drift of a deep sea canyon;
- Strong gradient in alongshore transport due to partial sheltering by the Sierra Nevada de Santa Marta from north-easterly waves.

The natural coastline development can be characterized by:

- A stable, rocky eastern boundary and a western boundary with highly dynamic behaviour at the jetties of the port of Barranquilla;
- A sandy coastline along the Salamanca bar with towards the west decreasing shelter from incoming north-easterly waves;
- Increasing alongshore transport in westward direction, with transport rates up to 1.5 to 2 million cubic metres per year at the westward end;
- Erosion along the bay, with maximum rates of 5 to 9 metres per year as a result of the strong gradient in sediment transport;
- Two main critical locations are identified at KM-19 and KM-28, where the coastal highway RN90 is in danger within the considered lifetime of 50 years;

- Immediate action is required at KM-19. For the short term an emergency revetment has been built, but a solution for the long term is still required;
- The situation at KM-28 will become critical within a period of 15 years, requiring mitigation measures as well;
- In addition, KM-40 is identified as a location requiring attention, since in 50 years the coastline is closely located near the highway;
- Structural erosion is expected to continue on the long term (more than a thousand years), as the expected equilibrium bay position is several kilometres landward of the current coastline position.

Considering the alternatives for mitigation of erosion:

- A nourishment scheme is the best alternative if only qualities are considered and costs are excluded. A nourishment stabilizes the coastline, conserving the status-quo. The benefits are accompanied by high expenses, as very large volumes of sand are required to nourish the coastline on a regular basis;
- Coastal structures in a highly dynamic coastal zone require a large volume of rock to protect against severe scour;
- Erosion in the downstream area of the coastal structures is not appreciated, as it disturbs the natural erosive processes.
- The decrease in erosion as a result of the alternative “Nourishment” is considered to be a disturbance of the natural processes as well.
- The alternative “Relocate Road” has no long-term impact on the coastal processes and is therefore preferred;
- When costs are taken into consideration the most promising alternative is “Relocate Road”. The natural erosion will be allowed to continue with this alternative and the road is relocated landward of the predicted coastline position. An additional benefit is caused by the planned highway expansion. Building a new section of road can be integrated with the construction of additional lanes along the RN90 between Barranquilla and Santa Marta.

This leads to the final conclusion that the Most Promising Alternative to mitigate the coastal erosion is the alternative “Relocate Road”. Measures to (locally) stabilise the coastline result in higher costs and disturb the natural coastal processes. The highly dynamic coastal zone is not expected to reach an equilibrium position in the near future.

8 Recommendations

- Assign coastal management to an existing or new governmental body, so knowledge, monitoring and maintenance efforts are centralized on a national level;
- Apply spectral analysis to the currently available climate data to improve the offshore wave schematisation;
- Improve wave climate data using long term wave buoy measurements. A combination of one offshore and at least one onshore location is advised to calibrate the wave transformation;
- Avoid the use of short term, rocky measures as they are not a suitable approach in a highly dynamic coastal zone. Necessity of the emergency measure at KM-19 can be prevented when coastal monitoring is implemented;
- Optimisation of the set-back period beyond the considered 50 years is advised. Locating the road further landward and thereby increasing the lifetime is expected to require limited extra efforts;
- Include a monitoring plan to evaluate and improve model predictions;
- An additional study is required to select the most suitable alignment of the new section of highway taking into account the local soil conditions and impact on the ecological values.

Appendices

A: Stakeholder information

This appendix provides additional information for the stakeholder analysis. Table 12 shows all stakeholders involved in the project, organized by role group. Acronyms are added for ease of reference throughout the report and the selection of stakeholders is indicated in the last column.

In Table 13 background information for the selected stakeholders can be found. This information is used to determine the perspective and project requirements for each of the stakeholders.

Table 12: Stakeholder overview

Role group	Name	Acronym	Selection
End-users	Cuidad de Barranquilla	CB	0
End-users	Puerto de Barranquilla	PB	1
End-users	Via Parque Isla de Salamanca	VPIS	0
End-users	Ruta Nacional 90	RN90	0
End-users	Rio Magdalena	RM	0
End-users	Mar Caribe	MC	0
End-users	Tasajeras	T	0
End-users	Puebloviejo	P	0
End-users	Ciénaga	C	0
End-users	Cuidad Santa Marta	CSM	0
End-users	Sierra Nevada de Santa Marta	SNSM	0
End-users	Parque Tayrona	PT	0
End-users	Santuario de Flora y Fauna Ciénaga Grande de Santa Marta	SFFCGSM	0
End-users	Pole villagers Ciénaga Grande de Santa Marta	PVCGSM	0
End-users	Farmers on eastern bank of Rio Magdalena	FRM	0
Government	Republica de Colombia	RC	0
Government	Vicepresidente de Colombia	VP	1
Government	Ministerio de Transporte	MT	1
Government	Ministerio de Ambiente y Desarrollo Sostenible	MADS	1
Government	Ministerio de Comercio, Industria y Turismo	MCIT	0
Government	Gobernación del Atlántico	GA	0
Government	Gobernación del Magdalena	GM	1
Government	Corporación Autónoma Regional del Rio Grande de la Magdalena	CORMAGDALENA	0
Government	Corporación Autónoma Regional del Atlántico	CRA	0
Government	Corporación Autónoma Regional del Magdalena	CORPAMAG	1
Government	Parques Nacionales Naturales de Colombia	PNN	1
Government	Dirección General Marítima	DIMAR	1
Government	Comisión Colombiana del Océano	CCO	1
Government	Agencia Nacional de Infraestructura	ANI	1
Government	Instituto Nacional de Vias	INVIAS	0
Government	Autoridad Nacional de Licencias Ambientales	ANLA	1
Research	Centro de Investigaciones Oceanográficas e Hidrográficas del Caribe & Pacífico	CIOH	1
Research	Instituto de Investigaciones Marinas y Costeras	INVEMAR	1

Research	**Universidad del Norte**	**UNINORTE**	**0**
Research	**SISCO**	**SISCO**	**0**
Research	**Arcadis**	**ARCADIS**	**0**
Financier	**Unidad Nacional para la Gestión del Riesgo de Desastres**	**UNGRD**	**1**
Financier	**Departamento Nacional de Planeación**	**DNP**	**0**
Financier	**Sistema General de Regalías**	**SGR**	**0**
Financier	**Rijksdienst voor Ondernemend Nederland**	**RVO**	**1**

Table 13: Background information on selected stakeholders

Stakeholder	Objective	Vision	Mission	Source
Vice Presidente	The Vice President shall be elected by popular vote the same day and in the same formula with the President of the Republic. The Vice President shall have the same period as the President and replace him in his temporary or permanent faults, even if they arise before his inauguration. The President of the Republic may entrust the Vice missions or special assignments and designate it in any position of the executive branch.	[no information available]	1. Commit to Vice President missions, interagency and intersectoral coordination that contributes to the development of projects that are related to housing, infrastructure and special urban renewal projects. He also coordinates special attention to certain regions of the country. 2. To exercise the Presidency of the Intersectoral Ocean Commission directly or through his representative.	http://www.vicepresidencia.gov.co/vicepresidencia/Paginas/funciones.aspx
Ministerio de Ambiente y Desarrollo Sostenible	The Ministry of Environment, Housing and Territorial Development is the lead management of the environment and renewable natural resources, responsible for guiding and regulating the environmental planning and defining policies and regulations to which the recovery, conservation, protection shall be subject , organization, management, use and sustainable use of renewable natural resources and environment of the nation, to ensure sustainable development, without prejudice to the functions assigned to other sectors.	In 2020 the Ministry of Environment, Housing and Territorial Development will promote the sustainable development of the country, through the consolidation of a policy framework and governance for integrated land management, climate change, conservation and sustainable use of natural, marine and mainland capital and improving environmental quality by strengthening the environmental performance of the productive sectors.	Being a public entity responsible for defining the National Environmental Policy and promote recovery, conservation, protection, planning, management, use and exploitation of renewable natural resources to ensure sustainable development and guarantee the right of all citizens to enjoy and inherit a healthy environment.	https://www.minambiente.gov.co/index.php/ministerio/mision-y-vision

Ministerio de Transporte	The Ministry of Transport has as its primary objective the formulation and adoption of policies, plans, programs, projects and economic regulation in transportation, transit and infrastructure modes road, sea, river, rail and air transport and technical regulation on transport and transit of road, sea, river and railway.	The Ministry of Transport guarantee to Colombian society, a transport system that allows the integration of regions, economic growth and social development.	Ensure the development and improvement of transport, transit and infrastructure, in a comprehensive, competitive and secure way.	https://www.mintransporte.gov.co/publicaciones.php?id=33
Parques Nationcales Naturales de Colombia	1: Administer and manage National Parks System and regulate the use and operation of the areas that make it. 2: Propose and implement policies and regulations related to the National Parks System. 3: Formulate planning tools, programs and projects related to the National Parks System.	Being a public entity positioned at the national level, with international recognition and social legitimacy, with technical capacity, an effective organizational scheme, political impact and financial strength; who serves as environmental authority in the areas of the National Parks System, leads process conservation, management and coordination of protected areas, contributing to the environmental management of the country.	Managing National Parks and coordinate the National System of Protected Areas under the environmental planning, in order to preserve in situ biodiversity and ecosystem representative of the country, provide and maintain environmental goods and services, protect the cultural heritage and natural habitat where traditional cultures as part of the National Heritage develop and contribute to sustainable human development; under the principles of transparency, solidarity, equity, participation and respect for cultural diversity.	http://www.parquesnacionales.gov.co/portal/es/organizacion/#
Agencia Nacional de Infraestructura	The National Infrastructure Agency will aim to plan, coordinate, structure, contract, implement, manage and evaluate projects concessions and other forms of Public Private Partnership - PPP for the design, construction, maintenance, operation,	2021 national transport infrastructure will be among the best in Latin America and the ANI will be recognized worldwide as a model entity in structuring and project management.	We develop infrastructure through Public Private Partnerships to generate connectivity, quality services and sustainable development. Our management is based on teamwork and personal and professional growth of our human talent.	http://ani.gov.co/quienes-somos/mision-y-vision

	management and / or operation of public transport infrastructure in all modes and associated or related services and project development of public-private partnership to other public infrastructure when specifically determined by the National Government on infrastructure such those set out in this article, in compliance with the rules governing the distribution of tasks and responsibilities and their allocation.			
Unidad Nacional para la Gestión del Riesgo de Desastres	The National Unit for Disaster Risk Management directs the implementation of disaster risk management, addressing the sustainable development policies and coordinates the operation and continued development of the national system for attention and prevention of disasters	By 2017 the Unit will have achieved empower national and international authorities, public or private entities and society in general about their responsibility for managing disaster risk is concerned, promoting social participation in monitoring institutional performance, promoting optimal use of technology in the field and significantly reducing risk conditions, loss of lives and costs associated with disasters.	We are the unit that directs, guides and coordinates Risk Management Disaster in Colombia, strengthening the capacities of public, private, community organizations and society in general, with the explicit purpose of contributing to improving the quality of life of people and sustainable development through knowledge risk reduction and management of disasters associated with natural phenomena, socio-natural, technological and human unintentional.	http://portal.gestiondelriesgo.gov.co/Paginas/Objetivos.aspx

Gobernacion de Magdalena	1: Increase access of people, especially the vulnerable, to social services, programs and measures to improve quality of life, with differential focus and rights 2: Promote better organization of space and urban-rural and regional functionality of the territory of the department of Magdalena 3: Strengthen the main productive bets for competitiveness related to services and infrastructure.	In 2020, the resident community in Magdalena enjoys an atmosphere of peace and harmonious coexistence, where respect for the law, the republican democratic institutions, human rights and environmental sustainability are the current expressions of our way of living life, with eternal Caribbean joy that characterizes us, a fair, high standard of living, including products from a highly competitive territory.	The Central Administration Department of Magdalena must run the powers of planning, coordination and mediation between the national, regional and local levels, ensuring competitive conditions conducive to sustainable growth in economic and social Department, within a legal, democratic and participatory framework .	http://www.magdalena.gov.co/quienes_somos.shtml
Instituto de Investigaciones Marinas y Costeras	• provide scientific and technical support to the National Environmental System (SINA), on the competition aspects of INVEMAR. • Conduct basic and applied research of renewable natural resources, the environment and coastal and ocean ecosystems, with emphasis on research systems with greater diversity and productivity as coastal lagoons, mangroves, seagrass beds, coral reefs and rocky, upwelling zones and sedimentary funds. • Issue technical concepts on the conservation and sustainable use of marine and coastal resource.	A scientific institution of excellence, recognized nationally and internationally for its high quality and leadership in its activities in basic and applied research and its commitment to sustainable use of marine and coastal resources. INVEMAR to be comprised of a dedicated, highly qualified group with ethical values that contribute to improving the quality of life of Colombians.	Perform basic and applied research of renewable natural resources and the environment in coastal and marine ecosystems and ocean national interest in order to provide the necessary scientific knowledge to policy, decision-making and the development of plans and projects leading to the development of these, toward the sustainable management of resources, the recovery of the marine and coastal environment and improving the quality of life of Colombians, through the rational use of the scientific capacity of the Institute and its articulation with other public and private entities.	http://www.invemar.org.co/web/guest/50-mar

Centro de Investigaciones Oceanográficas e Hidrográficas CIOH (ICZM)	Generate knowledge for the identification and characterization of coastal and island areas and rivers under the jurisdiction of the Directorate General Maritime, in order to provide scientific and technical support in the decision making of the National Maritime Authority and other entities, authorities and people involved in coastal management, for an appropriate integrated management of these areas, the technical determination of public goods and prevention and mitigation of disasters.	AMIZC projects in the short and medium term as the element of support and technical and scientific support of the DIMAR in the Colombian Caribbean, for making decisions with regard to natural or man-made damages on the coastal zone; the administration, control and management of coastal property for public use and characterization and evaluation of the physical processes that act on them. It is also projected as a generator of knowledge for regional, national and international integrated coastal zone management in the Colombian Caribbean programs.	The area of integrated coastal zone CIOH is addressed to the generation of scientific knowledge aimed at the protection, restoration and responsible development of the coastal resources of the Nation. In addition, it focuses on the generation of products that establish criteria for the proper management and control of the coastal Colombian Caribbean, its property for public use partners for the support of programs and plans of Integrated Coastal Zone Management (ICZM) to national and regional level.	http://www.cioh.org.co/index.php/zona-costera http://www.cioh.org.co/index.php/mision-y-vision
Dirección General Marítima	Advise the Government on the adoption of policies and programs related to maritime activities and execute them within the limits of their jurisdiction programs. 1. Manage, regulate, control and promote the development of the Merchant Marine, marine scientific research and the exploitation of marine resources. 2. Coordinate with the Navy the control of maritime traffic. 3. Install and maintain the service navigation aids, making hydrographic surveys and produce national nautical cartography.	By 2030, to be the axis that consolidates the sea, river and coastal country, contributing to the positioning of Colombia as a regional power.	Manage space, sea, river and coastal activities with comprehensive security and service vocation to contribute to the development of sea and river interests.	https://www.dimar.mil.co/content/mision-vision

Comisión Colombiana del Océano	The Colombian Ocean Commission is an inter-sectorial advisory body, consulting, planning and coordination of the National Government's National Policy of the Ocean and Coastal Areas and its various related, strategic, scientific, technological, economic and environmental issues related to sustainable development of the Colombian seas and their resources.	By 2035, the Colombian Ocean Commission incorporates the countries oceans for efficient and sustainable national development and welfare of Colombians.	Advise the Government on marine and coastal issues and on issues related to the National Policy of the Ocean and Coastal Zones - PNOEC, planned and coordinated with various agencies and institutions of the State; in order to raise awareness and maritime culture in Colombian and help the recognition of our oceans as a sustainable resource use for socio-economic development of the nation.	http://www.cco.gov.co/mision_y_vision.html
Corporación Autónoma Regional del Magdalena	- 50% increase in revenue for environmental management department based on projected for the term Corporate Environmental Action Plan 2012-2015 income. Reduce the time of procedures by 5%, for the evaluation of environmental licenses, permits and authorizations granted by the Corporation. - Exercise monitoring and environmental control of 80% annually during the specified time period.	[no information available]	- Implement policies, plans and programs on environmental issues defined by the law approving the National Development Plan and the National Investment Plan or the Ministry of Environment as well as the regional order that have been entrusted under the law within the scope of its jurisdiction; - Exercise the function of maximum environmental authority in the area of your jurisdiction, according to the rules of superior character and in accordance with the criteria and guidelines set by the Ministry of the Environment;	http://www.corpamag.gov.co/index.php/es/quienes-somos/obj-func-deber

Comisión Colombiana del Océano	The Colombian Ocean Commission is an inter-sectorial advisory body, consulting, planning and coordination of the Government's National Policy of the Ocean and Coastal Areas and its various related, strategic, scientific, technological, economic and environmental issues related to sustainable development of the Colombian seas and their resources.	By 2035, the Colombian Ocean Commission incorporates the countries oceans for efficient and sustainable national development and welfare of Colombians.	Advise the Government on marine and coastal issues and on issues related to the National Policy of the Ocean and Coastal Zones - PNOEC, planned and coordinated with various agencies and institutions of the State; in order to raise awareness and maritime culture in Colombian and help the recognition of our oceans as a sustainable resource use for socio-economic development of the nation.	http://www.cco.gov.co/mision_y_vision.html
Puerto de Barranquilla	We are the leading multipurpose port in the Colombian Caribbean. We transport all types of cargo such as containers, solid and liquid bulk, general cargo and coal.	[no information available]	[no information available]	http://www.puertodebarranquilla.com/index.php/quienes-somos/
ANLA	ANLA strengthen the organizational culture committed to responsible stewardship of natural resources and economic development. Develop and implement technical and technological mission tools to optimize processes to respond in a timely manner the requirements of users.	A 2025 be a national and international reference as Environmental Authority for quality assessment, monitoring and control licenses, permits and formalities within its competence as well as the design and implementation of technical tools that allow us to be guarantors of sustainable development for the benefit of present and future generations, counting with qualified human talent and committed	Ensure that evaluation, monitoring and control of projects, works or activities subject to licensing, permits or environmental procedures of our competition is conducted in a transparent, objective and timely manner, with high standards of technical and legal quality to contribute to the balance between environmental protection and development of the country for the benefit of society.	http://www.anla.gov.co/mision-y-vision

B: Cultural dimensions theory

This appendix provides background information about the cultural model in paragraph B1 as well as an elaboration on the cultural comparison between Colombia and the Netherlands in paragraph B2.

B.1 Dimensions of National Culture

Professor Geert Hofstede conducted one of the most comprehensive studies of how values in the workplace are influenced by culture. He analysed a large database of employee value scores collected within IBM between 1967 and 1973. The data covered more than 70 countries, from which Hofstede first used the 40 countries with the largest groups of respondents and afterwards extended the analysis to 50 countries and 3 regions. Subsequent studies validating the earlier results include such respondent groups as commercial airline pilots and students in 23 countries, civil service managers in 14 counties, 'up-market' consumers in 15 countries and 'elites' in 19 countries.

In the 2010 edition of the book Cultures and Organizations: Software of the Mind, scores on the dimensions are listed for 76 countries, partly based on replications and extensions of the IBM study on different international populations and by different scholars.

B.1.1 Definitions of Cultural Dimensions

Hofstede uses six dimensions to compare different cultures. They are statistically independent and the definitions are elaborated on in this paragraph.

Power Distance has been defined as the extent to which the less powerful members of organizations and institutions (like the family) accept and expect that power is distributed unequally. This represents inequality (more versus less), but defined from below, not from above. It suggests that a society's level of inequality is endorsed by the followers as much as by the leaders. Power and inequality, of course, are extremely fundamental facts of any society. All societies are unequal, but some are more unequal than others.

Individualism on the one side versus its opposite, Collectivism, as a societal, not an individual characteristic, is the degree to which people in a society are integrated into groups. On the individualist side we find cultures in which the ties between individuals are loose: everyone is expected to look after him/herself and his/her immediate family. On the collectivist side we find cultures in which people from birth onwards are integrated into strong, cohesive in-groups, often extended families (with uncles, aunts and grandparents) that continue protecting them in exchange for unquestioning loyalty, and oppose other in-groups. Again, the issue addressed by this dimension is an extremely fundamental one, regarding all societies in the world.

Masculinity versus its opposite, Femininity, again as a societal, not as an individual characteristic, refers to the distribution of values between the genders which is another fundamental issue for any society, to which a range of solutions can be found. The IBM studies revealed that (a) women's values differ less among societies than men's values; (b) men's values from one country to another contain a dimension from very assertive and competitive and maximally different from women's values on the one side, to modest and caring and similar to women's values on the other. The assertive pole has been called
'masculine' and the modest, caring pole 'feminine'. The women in feminine countries have the same modest, caring values as the men; in the masculine countries they are somewhat assertive and competitive, but not as much as the men, so that these countries show a gap between men's values and women's values.

Uncertainty Avoidance is not the same as risk avoidance; it deals with a society's tolerance for ambiguity. It indicates to what extent a culture programs its members to feel either uncomfortable or comfortable in unstructured situations. Unstructured situations are novel, unknown, surprising, and different from usual. Uncertainty avoiding cultures try to minimize the possibility of such situations by strict behavioral codes, laws and rules, disapproval of deviant opinions, and a belief in absolute Truth; 'there can only be one Truth and we have it'.

Values related to a **Long Term Orientation** are perseverance, thrift, ordering relationships by status, and having a sense of shame; values at the opposite, short term pole were reciprocating social obligations, respect for tradition, protecting one's 'face', and personal steadiness and stability.

Indulgence stands for a society that allows relatively free gratification of basic and natural human desires related to enjoying life and having fun. Restraint stands for a society that controls gratification of needs and regulates it by means of strict social norms. Scores on this dimension are also available for 93 countries and regions. Table 6 lists a selection of differences between societies that validation research showed to be associated with this dimension.
Indulgence tends to prevail in South and North America, in Western Europe and in parts of Sub-Sahara Africa. Restraint prevails in Eastern Europe, in Asia and in the Muslim world. Mediterranean Europe takes a middle position on this dimension.

B.2 Elaboration on Colombian and Dutch cultural scores

For each dimension a short elaboration on the national score is given starting with Colombia followed by the Dutch score.

B.2.1 Power Distance

At 67 Colombia scores high on the scale of the PDI, so it is a society that believes that inequalities amongst people are simply a fact of life. This inequality is accepted in all layers of society, so a union leader will have a lot of concentrated power compared to his union management team, and they in turn will have more power than other union members. A similar phenomenon will be observed among business leaders and among the highest positions in government.

The Netherlands scores low on this dimension (score of 38) which means that the following characterises the Dutch style: Being independent, hierarchy for convenience only, equal rights, superiors accessible, coaching leader, management facilitates and empowers. Power is decentralized and managers count on the experience of their team members. Employees expect to be consulted. Control is disliked and attitude towards managers are informal and on first name basis. Communication is direct and participative.

B.2.2 Individualism

At a score of 13 Colombia is amongst the lowest Individualist scores; in other words, it lies amongst the most collectivistic cultures in the world, beaten only by Ecuador, Panama and Guatemala.

Since the Colombians are a highly collectivistic people, belonging to an in-group and aligning yourself with that group’s opinion is very important. Combined with the high scores in PDI, this means that groups often have their strong identities tied to class distinctions. Loyalty to such groups is paramount and often it is through “corporative” groups that people obtain privileges and benefits which are not to be found in other cultures. At the same time, conflict is avoided, in order to maintain group harmony and to save face.

Relationships are more important than attending to the task at hand, and when a group of people holds an opinion on an issue, they will be joined by all who feel part of that group. Colombians will often go out of their way to help you if they feel there is enough attention given to developing a relationship, or if they perceive an “in-group” connection of some sort, however thin. However, those perceived as “outsiders” can easily be excluded or considered as “enemies”. The preferred communication style is context-rich, so public speeches and written documents are usually extensive and elaborate.

The Netherlands, with the very high score of 80 is an Individualist society. This means there is a high preference for a loosely-knit social framework in which individuals are expected to take care of themselves and their immediate families only. In Individualist societies offence causes guilt and a loss of self-esteem, the employer/employee relationship is a contract based on mutual advantage, hiring and promotion decisions are supposed to be based on merit only, management is the management of individuals.

B.2.3 Masculinity

At 64 Colombia is a Masculine society – highly success oriented and driven. Colombians are competitive and status-oriented, yet collectivistic rather than Individualist. This means that competition is directed towards members of other groups (or social classes), not towards those who are perceived as members of your own in-group.
People seek membership in groups which give them status and rewards linked to performance, but they often sacrifice leisure against work, as long as this is supported by group membership and by power holders.

The Netherlands scores 14 on this dimension and is therefore a Feminine society. In Feminine countries it is important to keep the life/work balance and you make sure that all are included. An effective manager is supportive to his/her people, and decision making is achieved through involvement. Managers strive for consensus and people value equality, solidarity and quality in their working lives. Conflicts are resolved by compromise and negotiation and Dutch are known for their long discussions until consensus has been reached.

B.2.4 Uncertainty Avoidance

At 80 Colombia has a high score on Uncertainty Avoidance which means that as a nation they are seeking mechanisms to avoid ambiguity. Emotions are openly expressed; there are (extensive) rules for everything and social conservatism enjoys quite a following. This is also reflected in religion, which is respected, followed by many and conservative. Rules are not necessarily followed, however: this depends on the in-group’s opinion, on whether the group feels the rules are applicable to their members and it depends, ultimately, on the decision of power holders, who make their own rules. In work terms this results in detailed planning that may not necessarily be followed in practice.

The combination of high UAI with the scores on the previous dimensions means that it is difficult to change the status quo, unless a figure of authority is able to amass a large group of people and lead them towards change.

The Netherlands scores 53 on this dimension and thus exhibits a slight preference for avoiding uncertainty. Countries exhibiting high Uncertainty Avoidance maintain rigid codes of belief and behaviour and are intolerant of unorthodox behaviour and ideas. In these cultures there is an emotional need for rules (even if the rules never seem to work) time is money, people have an inner urge to be busy and work hard, precision and punctuality are the norm, innovation may be resisted, security is an important element in individual motivation.

B.2.5 Long Term Orientation

With a low score of 13, Colombian culture is classified as normative. People in such societies have a strong concern with establishing the absolute Truth; they are normative in their thinking. They exhibit great respect for traditions, a relatively small propensity to save for the future, and a focus on achieving quick results.

The Netherlands receives a high score of 67 in this dimension, which means that it has a pragmatic nature. In societies with a pragmatic orientation, people believe that truth depends very much on the situation, context and time. They show an ability to easily adapt traditions to changed conditions, a strong propensity to save and invest, thriftiness and perseverance in achieving results.

B.2.6 Indulgence

Scoring a very high 83 in this dimension, Colombia is shown to be an Indulgent country. People in societies classified by a high score in Indulgence generally exhibit a willingness to realise their impulses and desires with regard to enjoying life and having fun. They possess a positive attitude and have a tendency towards optimism. In addition, they place a higher degree of importance on leisure time, act as they please and spend money as they wish.

With a high score of 68, the culture of the Netherlands is clearly one of Indulgence. People in societies classified by a high score in Indulgence generally exhibit a willingness to realise their impulses and desires with regard to enjoying life and having fun. They possess a positive attitude and have a tendency towards optimism. In addition, they place a higher degree of importance on leisure time, act as they please and spend money as they wish.

C: History of structures at KM-19

This appendix provides a timeline of structures which were built at KM-19. Technical (SISCO, 2015) are added to the timeline if available.

- 1956
  Construction of the coastal highway RN90 along the Caribbean Sea. Wide sandy beach is assumed to separate the highway from the coastline at that time. Satellite images dating back to 1970 show a distance of 250 metres between coastline and road.
- February 2011
  Construction of a submerged concrete barrier (see Figure 68 and Figure 69) with a length of 1,004 metres alongshore located 100 metres from the coastline combined with sandbags for local scour protection. The barrier was locally complimented with a 150,000 m3 beach suppletion.

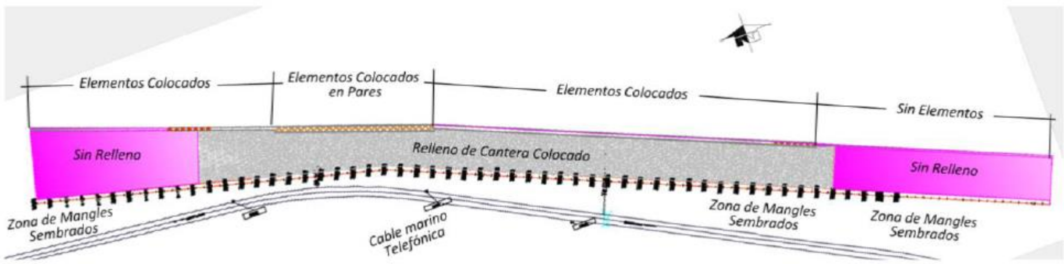


Figure 68: Plan view design February 2011 (SISCO, 2015)

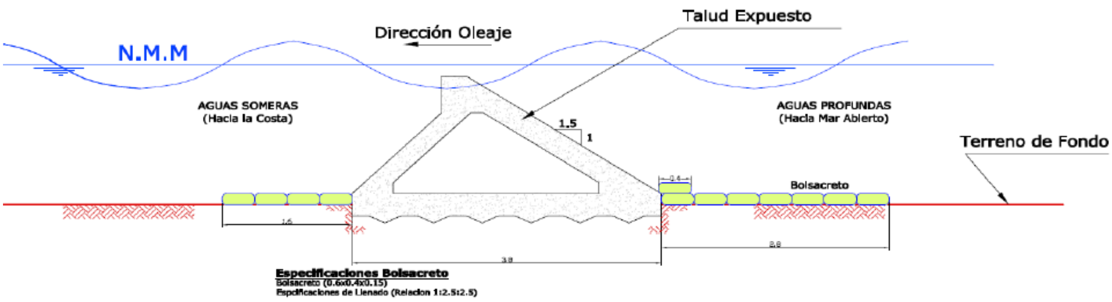


Figure 69: Cross section design February 2011 (Sisco Ingeniería, 2015)

- August 2013
  Foundation of a former electric tower becomes visible.
- June 2014
  Section of 300 metres is protected with big bags filled with sand, combined with perpendicular retaining structures, indicated with black circles in Figure 70. Figure 71 gives an impression of the construction phase.

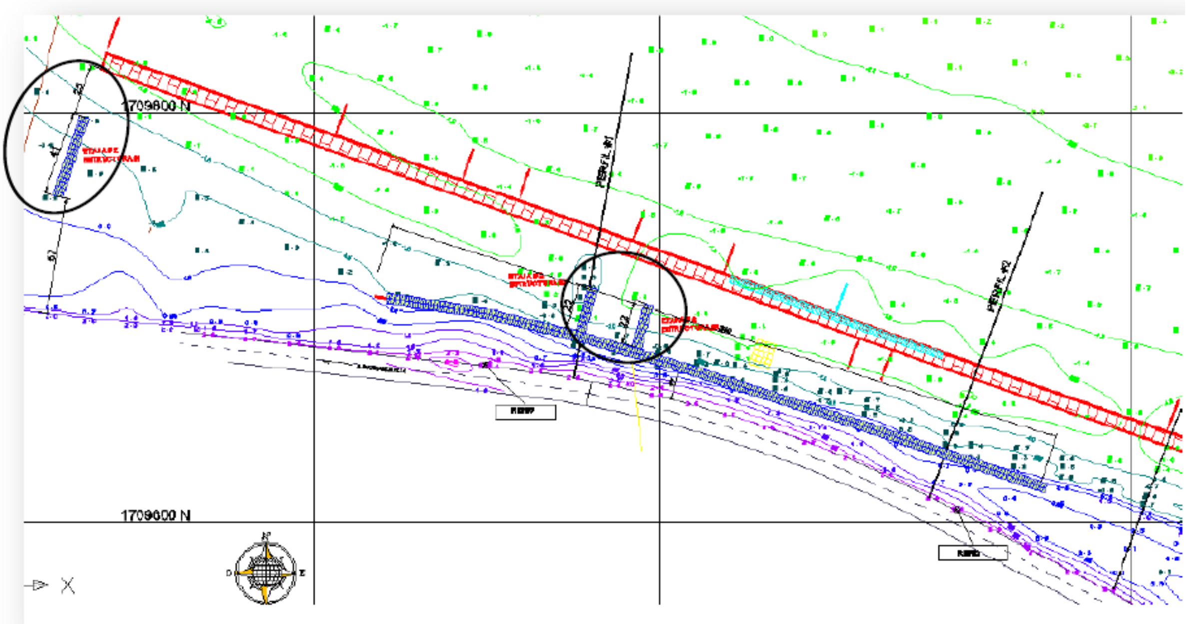


Figure 70: Plan view design June 2014 (Sisco Ingeniería, 2015)

Figure 71: Photograph during construction (Sisco Ingeniería, 2015)

- October – December 2014
  A rock revetment is constructed along 330 metres to provide additional protection against the erosion. The big bags from the former design are re-used as impermeable core of the revetment, indicated in blue in Figure 72.

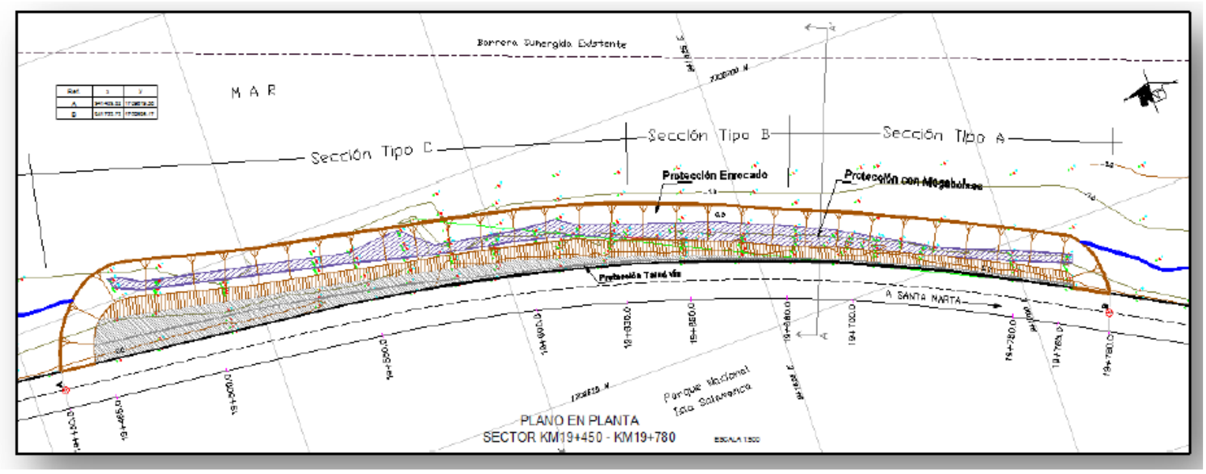


Figure 72: Plan view design October 2014 (Sisco Sisco Ingeniería, 2015)

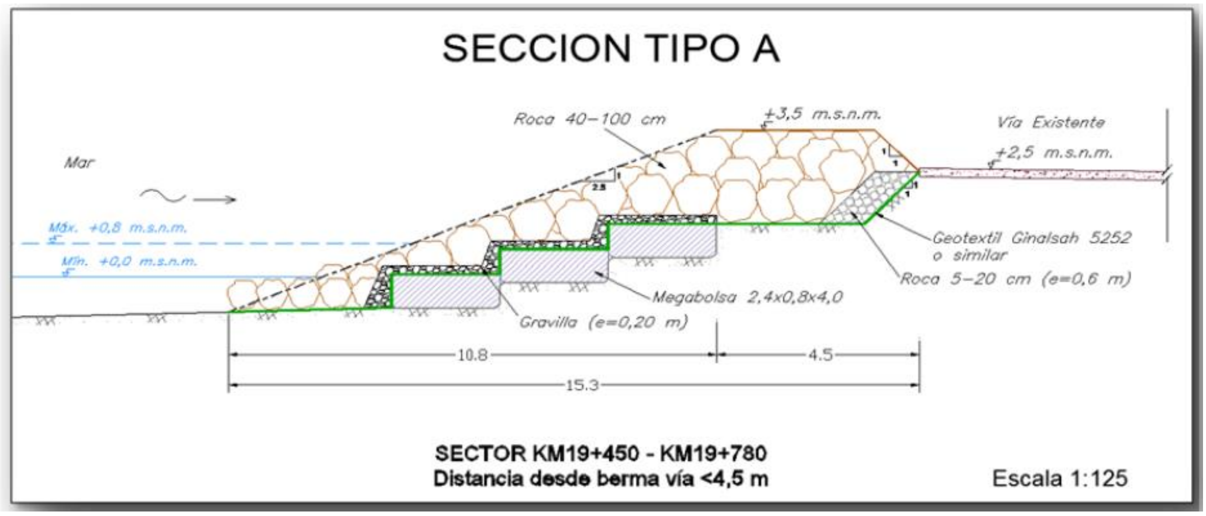


Figure 73: Cross section type A; design October 2014 (Sisco Ingeniería, 2015)

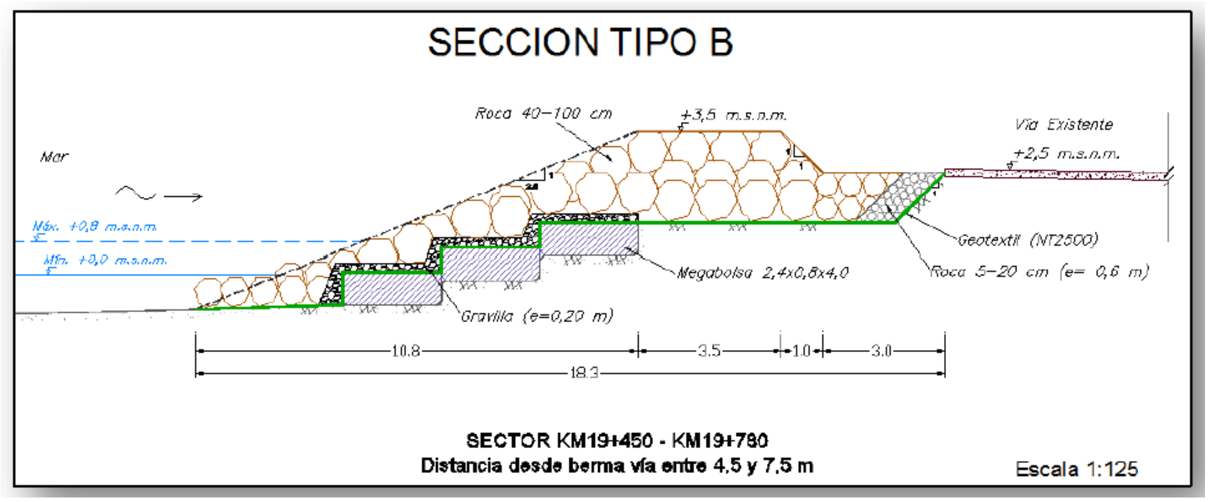


Figure 74: Cross section type B; design October 2014 (Sisco Ingeniería, 2015).

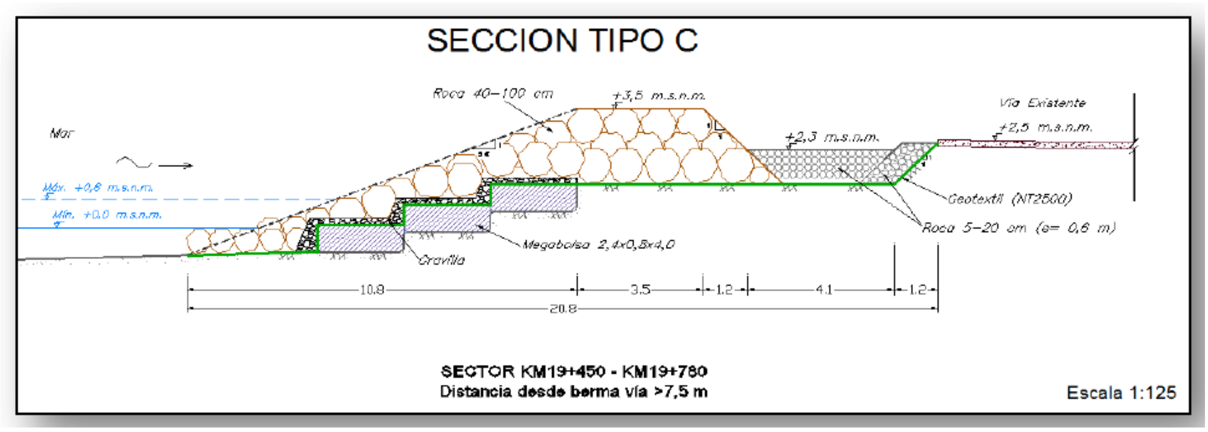


Figure 75: Cross section type C; Design October 2014 (Sisco Ingeniería, 2015).

D: Wind & Wave Climate

This appendix provides additional information on the characterisation of the wind and wave climate in Section 3.8 and 3.9. Wave data from the Wave Watch III global hindcast model at 12°N 75°W for the period 1992 till 2014 was used for this purpose.

Furthermore, the WaveWatch III climate is compared to the wave data from ERA-Interim of for the year 2013.

D.1 Climate Characterisation (WWIII)

North easterly trade winds from a direction of approximately 65 degrees north are dominant throughout the year (see Figure 76). From August to December we see larger deviations from the mean wind direction due to waves from the north. The wind speed varies between 0 and 18.6 m/s, as can be seen in Figure 77. Consistent, strong winds of approximately 13 m/s are present from January to July. From August to December a stronger fluctuation in wind speed can be observed. The first half of the year we see a wind with constant speed and direction. Figure 78 we conclude that during this period a more northerly directed wind component is followed by an easterly. The remaining year consists of a fluctuating signal with smaller wind speeds and a larger spread in wind direction. The extreme values from Figure 76 in the second half of the year are not recognisable in the wind roses of Figure 78.

The wave direction in Figure 79 is more constant compared to the wind direction with an approximate direction of 65 degrees. We see some peaks in the second half of the year corresponding to the fluctuations in wind direction in the same period.

In Figure 80 we see that the significant wave height follows the wind speed and ranges between 0.97 and 4.42 metres. The year starts with waves ranging from 2 to 4 metres. Wave heights reduce in the second half but strong fluctuations are present.

The general shapes of Figure 76 and Figure 79 are similar as well as Figure 77 and Figure 80, suggesting dominance of wind waves over swell.

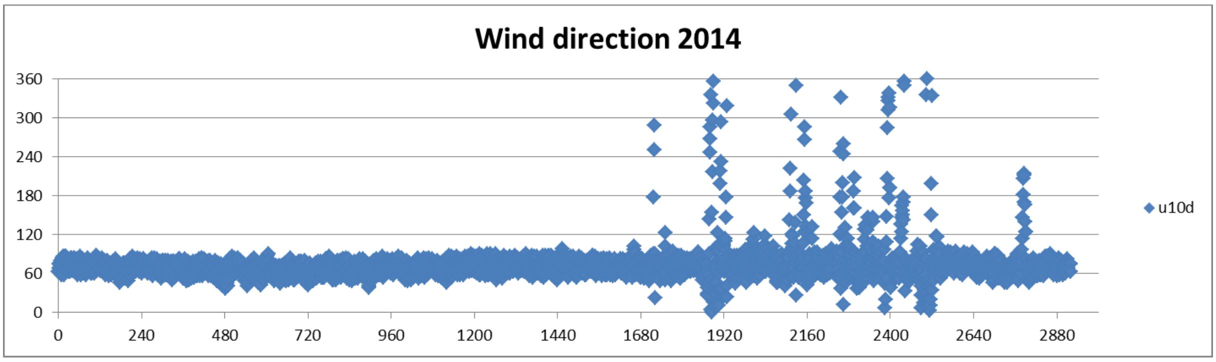


Figure 76: Wind direction from time series 2014

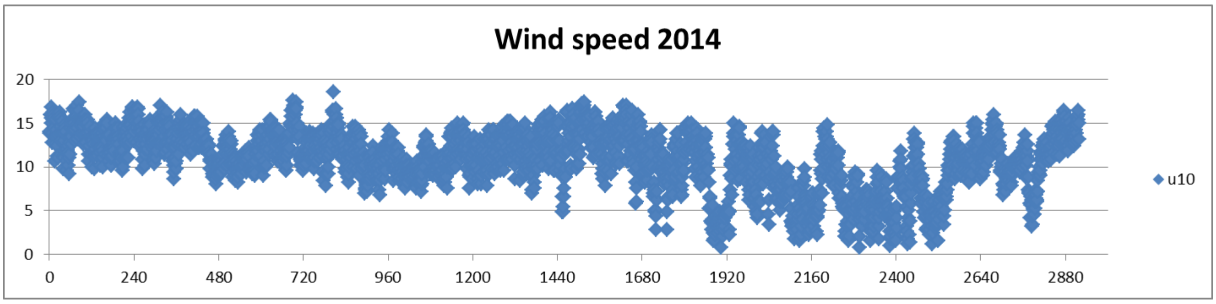


Figure 77: Wind speed from time series 2014

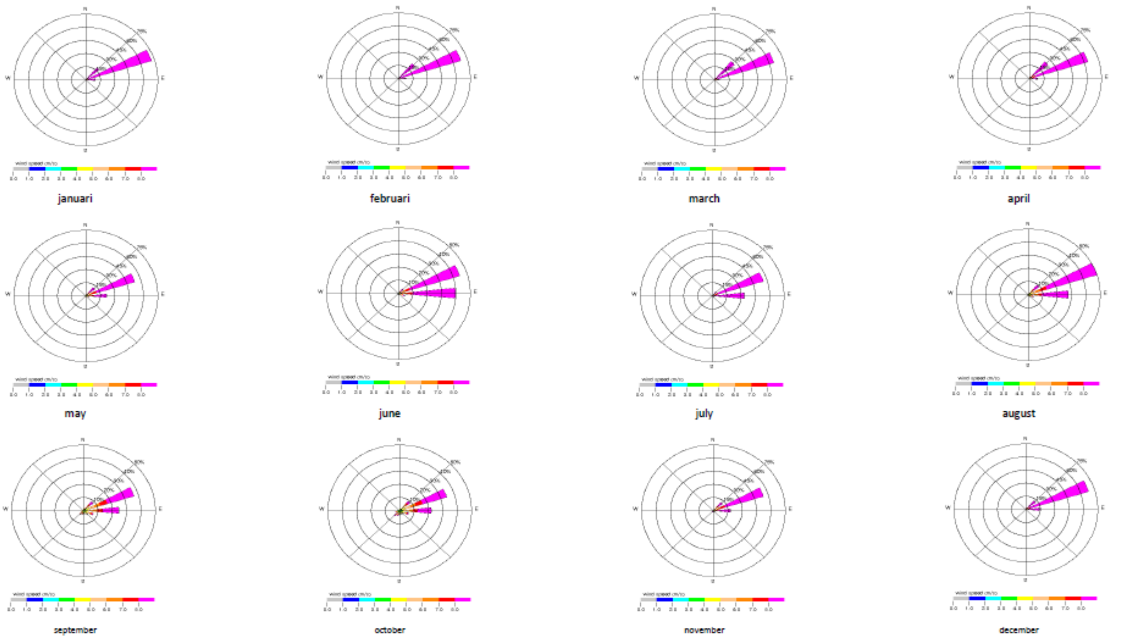


Figure 78: Wind rose per month based on data from 1992 to 2014

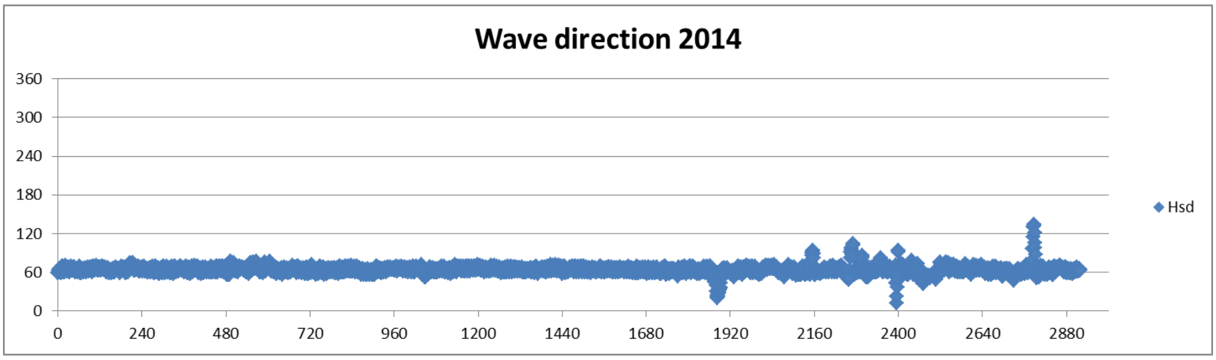


Figure 79: Wave direction from time series 2014

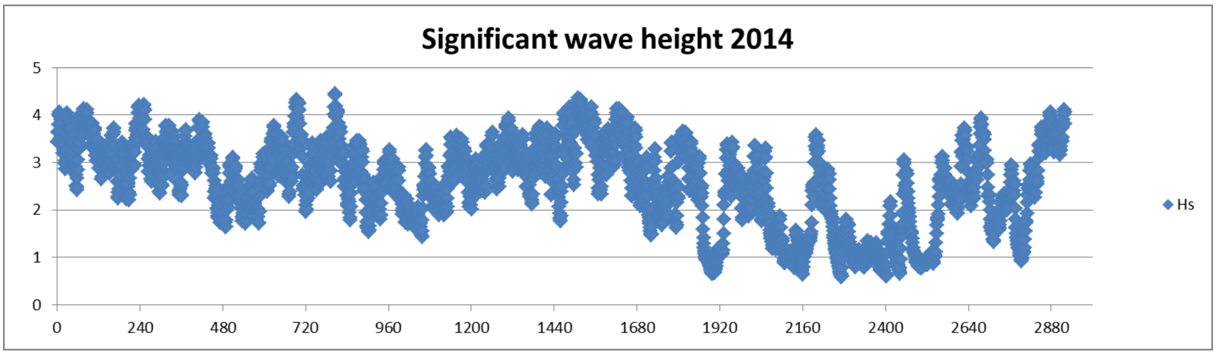


Figure 80: Significant wave height from time series 2014

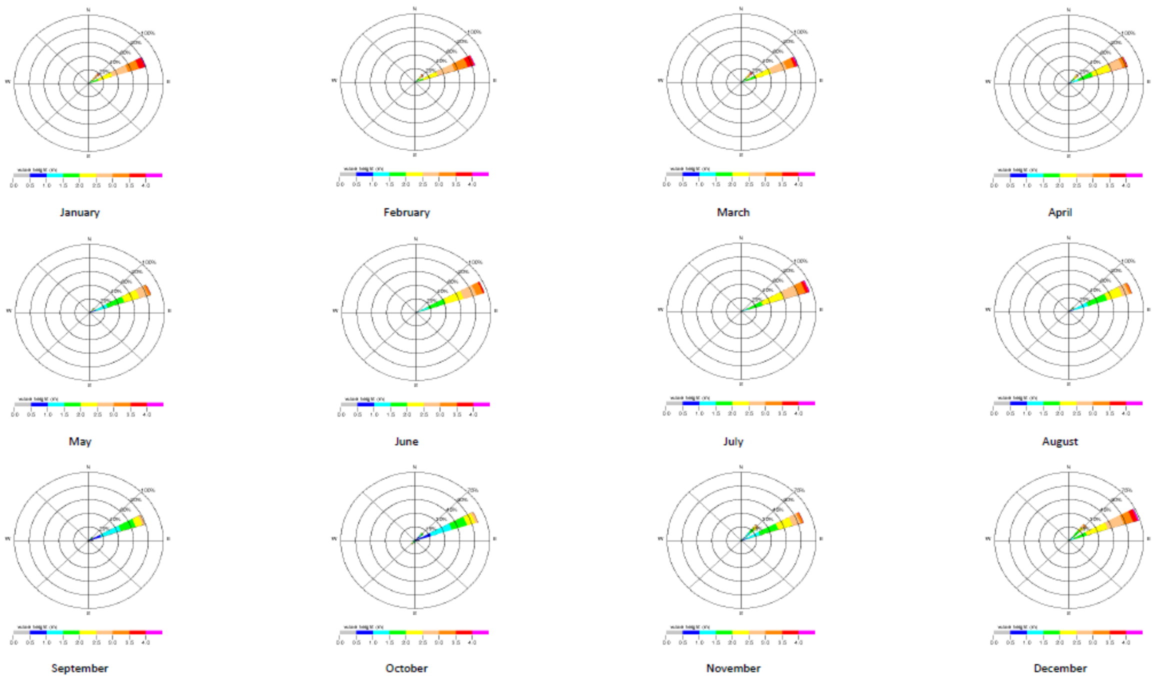


Figure 81: Wave rose per month based on data from 1992 to 2014

D.2 Climate Comparison

In this appendix additional figures are presented for the comparison of offshore climates in Section 4.3.2. The comparison yields:

- Climate 2 contains higher waves (max 4.1 metres) compared to Climate 1 (max 3.5 metres).
- Both climate 1 and 2 have a dominant wave direction of 65 degrees.
- Climate 2 is closely and more symmetrically spread around the dominant wave direction.
- Climate 1 is spread wider and unevenly, with more waves from north and north-western direction, with an abrupt end after the dominant wave direction.
- Limit of 'wave steepness' is the same for both climates.
- Both climates consist mainly of sea waves.
- Longer wave periods are observed in climate 2, indicating the presence of swell waves.
- Significantly higher wind speeds with Climate 2.
- Less variation in wind direction for Climate 1.
- Wave and wind direction are correlated, especially at the dominant direction of around 60/65 degrees.
- Less spreading in wave direction compared to wind direction.

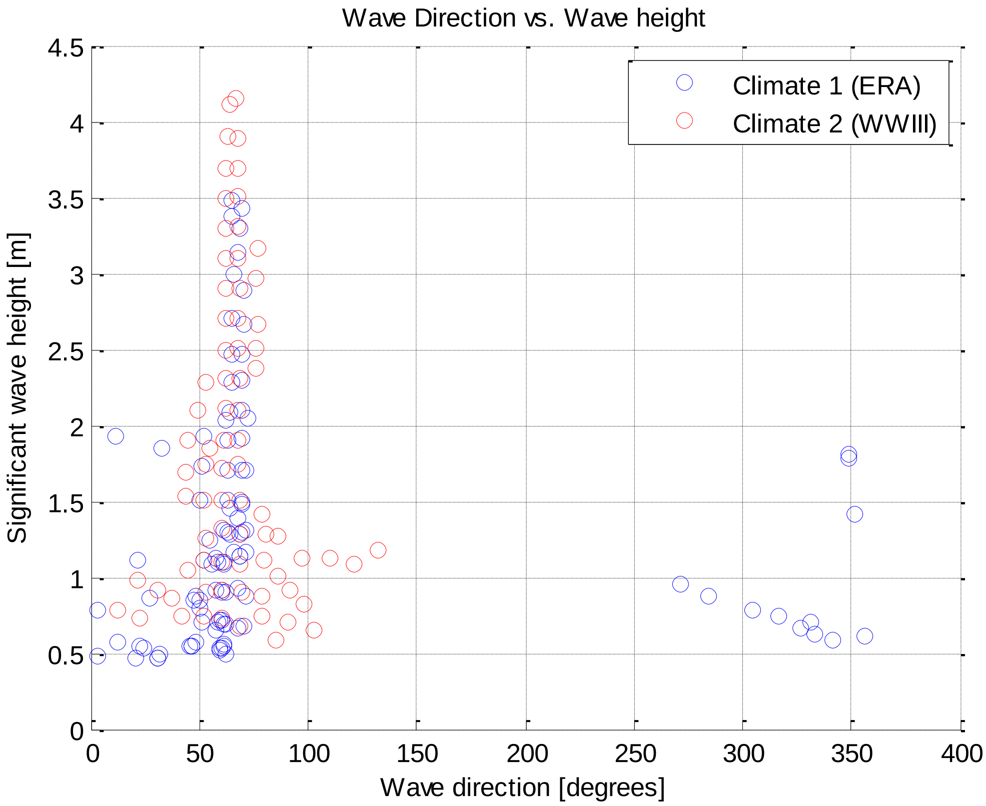


Figure 82: Wave direction vs. Wave height for both ERA-Interim and Wave Watch III climates

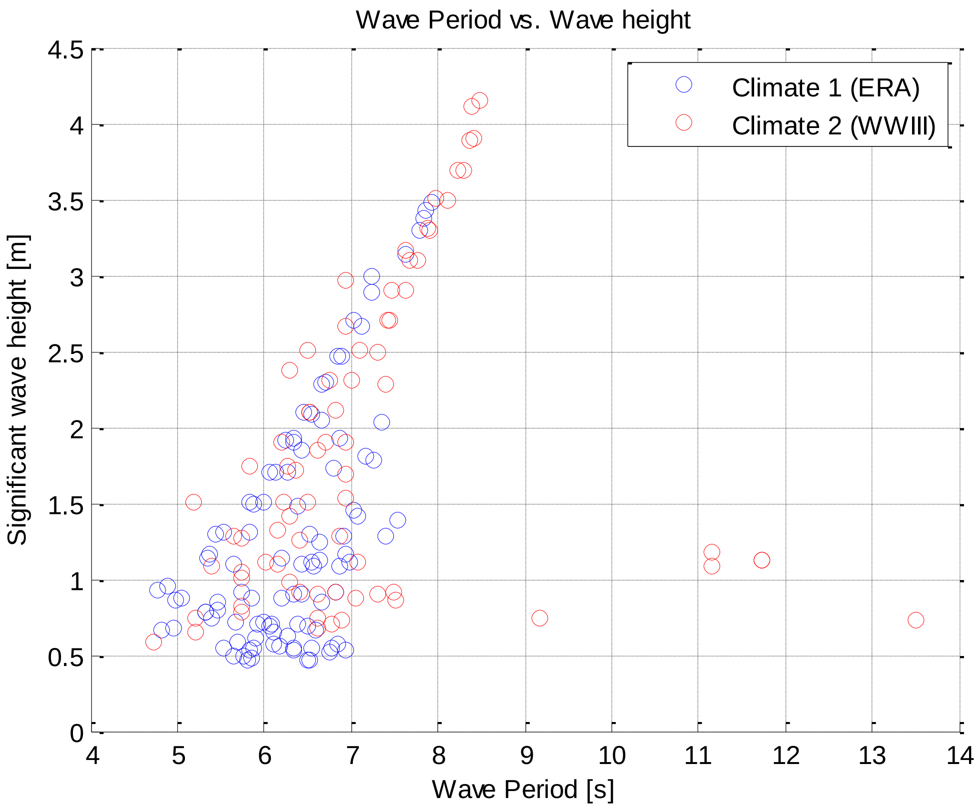


Figure 83: Wave Period vs. Wave height for both ERA-Interim and Wave Watch III climates

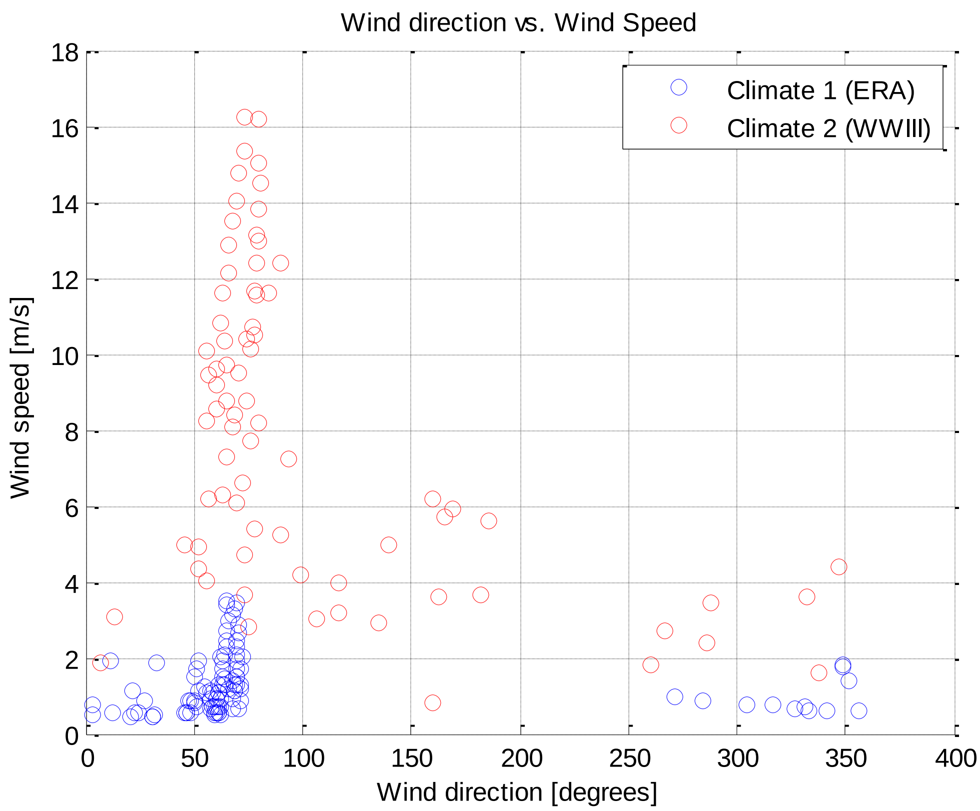


Figure 84: Wind direction vs. Wind Speed for both ERA-Interim and Wave Watch III climates

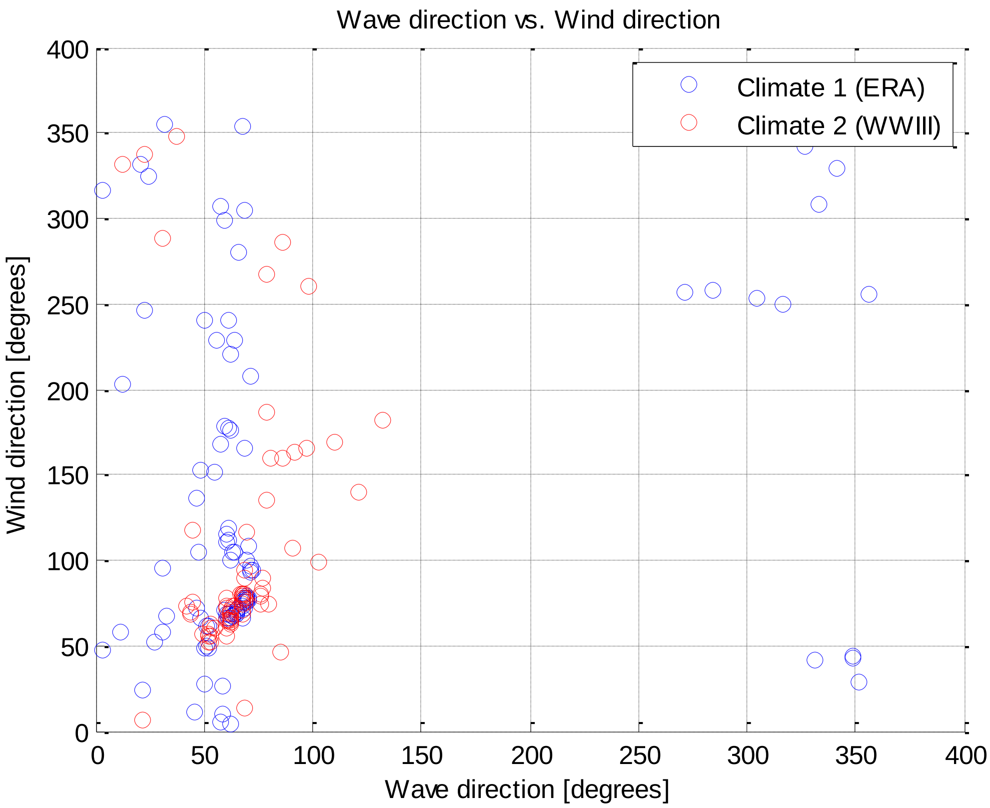


Figure 85: Wave direction vs. Wind direction for both ERA-Interim and Wave Watch III climates

E: Modelling specifications

This appendix contains a detailed description of the model used for the intermediate time scale predictions. First Delft3D – WAVE is elaborated on in paragraph E.1, followed by UNIBEST in paragraph E.2.

E.1 Delft3D – WAVE

Grid setup

The settings of the model grid of the three Delft3D-wave nest models are presented in Table E1.

Table 14: Model grid settings

		Coarse_200x300:	Medium_750x250:
M	[cells]	300	750
N	[cells]	200	250
Delta x	[m]	500	100
Delta y	[m]	500	100
Origin N	[°]	10.5	Irrelevant
Origin W	[°]	-74.5	Irrelevant
Origin x	[m]	953750	913480
Origin y	[m]	1653000	1704900
Rotation	[°]	45	0

Using nesting to improve the level of detail at the headland has proven to be useless since the grids are calculated in sequence of nesting. The bigger grids are calculated first and provide boundary conditions for the smaller grids. The extra information gained by using a more detailed grid is thus neglected for the transformation of waves towards the shoreline.

As an alternative to nesting local refinement is used to provide the level of detail required and be able to use the additional information to calculate the nearshore wave climate. The location of the medium2_150x100 grid corresponds to the location of the local refinement. To smoothen the transition between the cell sizes the operation 'line smooth' is used for both the M and N direction of the grid to improve the quality of the grid.

Depth generation

The bathymetry is acquired from several Admiralty charts shown in the table below.

Table 15: Nautical charts used to acquire bathymetry data

Chart title	Source Code	Source Producing Agency	Issue Date	Update Date
BARRANQUILLA A RIOHACHA	41	Ministerio de Defensa	24-09-05	24-12-06
ISLA FUERTE A BARRANQUILLA	42	Ministerio de Defensa	24-09-05	14-01-07
PUERTO COLOMBIA A SANTA MARTA	407	Ministerio de Defensa	12-09-03	24-12-06
BAHIA DE TAGANGA PUNTA BARRO BLANCO	unknown	Ministerio de Defensa	24-09-03	01-09-06

To digitize the information a program called 'DigitizeIT' was used. With the program a reference frame was added to all chart images based on the geographic coordinates. By clicking in the image the location was calculated and a depth value could be added to the position.

Since the model is made in a local x,y coordinate system (MAGNA SIRGAS) the coordinates where then converted to this reference frame and the depth samples could be uploaded to the model. The samples from large scale maps where used to identify the contours in the deep sea and towards the shoreline more detailed information replaced the general information from the large scale maps. With this method the level of detail increased towards the shoreline, corresponding to the relevance of the parameter water depth for wave transformation.

For calculations it is required to know the depth as each grid point, so the operation 'triangular interpolation' was used to convert depth information from the samples into depth information at all grid points. This information can then be exported as a .dep-file and be used as input file for DELFT3D - WAVE

Parameter settings

Two different model runs were made (BAR and CAR). The BAR run was made for the WaveWatch III climate which was derived for Baranquilla (for the period 1992 till 2014), while the CAR run was made with the ERA-interim wave data for 2013 for the Cartagena climate. An overview of the settings is shown in Table 16.

Table 16: Parameter settings of the wave models

	BAR	CAR
Latitude [°]	12°N	12°N
Longitude [°]	75°W	75°W
Period	1992-2014	2013
Location	...\BAR\BAR2.mdw	...\ERA3\car1_sep.mdw
Grids	Coarse & Medium	Coarse & Medium
Spectral resolution	Circle with 36 segments 0.05 Hz – 1Hz, 24 bins	Circle with 72 segments 0.05 Hz – 1Hz, 24 bins
Nesting	Medium (nested in coarse)	Medium (nested in coarse)
Hydrodynamics	No data from FLOW model	No data from FLOW model
Mode	Stationary	Stationary
Boundaries	76 wave conditions in md_vwac file	101 wave conditions in md_vwac file
Obstacles	No	No
Wave setup	No	No
Breaking coeff	γ=0.73, α=1	γ=0.73, α=1
Triads	Off	Off
Bottom friction	JONSWAP (=0.067)	JONSWAP (=0.067)
Diffraction	No	No
Processes	Wind growth White capping (Komen et al) Refraction Frequency shift	Wind growth White capping (Komen et al) Refraction Frequency shift
Numerical	CDD=0.5, CSS=0.5 ΔH_s-T_m = 0.01, at 99% points Max iterations=25	CDD=0.5, CSS=0.5 ΔH_s-T_m = 0.01, at 99% points Max iterations=25
Output	At model grids	At model grids

E.2 UNIBEST Model Setup

Modelling domain

The modelling domain for UNIBEST is smaller compared to that of DELFT-3D since the wave climate is now schematized and only the development of relevant coastline is calculated. The calculated coastline development assumes availability of sediment so parts of the bay where this assumption is not met will be excluded from the domain. The eastern boundary of the domain is therefore chosen as such that the rocky coastline around Santa Marta is not part of the domain.

Table 17: UNIBEST-LT Modelling domain

To represent the alongshore variation in depth 9 profiles are used perpendicular to the current coastline. The profiles are evenly spread within the domain.

The deepest point of the profile should correspond to the output location of the schematized wave climate from DELFT3D. A depth of 10 metres is chosen because it is expected that the morphological active zone ends here and the depth contours can be represented by parallel depth contour lines from this point landward. Using Quickin the cross shore profiles are measured from the Medium grid.

Alongshore transport computations at cross-shore profiles

The settings of the UNIBEST sediment transport computations (LT-module) at Barranquilla – Santa Marta are presented in Table 18 and

Default settings are used for general parameters such as Criterion deep water Hsig/h. The wave-current interaction was assumed to be linear, which is expected to have only a small impact on the outcomes of the modelling.

Table 19.

Default settings are used for general parameters such as criterion deep water Hs/h. The wave-current interaction was assumed to be linear, which is expected to have only a small impact on the outcomes of the modelling. The formula of Bijker is used to calculate the sediment transport, taking both bed and suspended load into account. The sediment properties are based on Section 3.11 (Sisco Ingeniería, 2015).

Table 18: Used transport parameters

Parameter	Quantity	Unit
D_{10}, 10% grain diameter	120	µm
D_{50}, median grain diameter	200	µm
D_{90}, 90% grain diameter	300	µm
D_{SS}, 50% grain diameter of suspended	160	µm

sediment		
Sediment density	2650	kg/m^3
Seawater density	1025	kg/m^3
Porosity	0.4	-
Temperature	15	° Celsius
Salinity	30	Ppm
Current-related suspended transport factor	1	-
Current related bedload transport factor	1	-
Wave-related suspended transport factor	1	-
Wave-related bedload transport factor	1	-

Default settings are used for general parameters such as Criterion deep water H_{sig}/h. The wave-current interaction was assumed to be linear, which is expected to have only a small impact on the outcomes of the modelling.

Table 19: Used wave parameters

Parameter	Quantity	Unit
Coefficient for wave breaking (gamma)	0.8	-
Coefficient for wave breaking (alfa)	1	-
Coefficient for bottom friction	1	-
Bottom roughness (kb)	0.1	m

Coastline model

The settings of the UNIBEST coastline development computations (CL-module) at Barranquilla – Santa Marta are presented in Table 20 to Table 22. The coastal structures which included in the reference scenario are presented in Table 23 and Table 24.

Table 20: Numerical model settings

Parameter	Quantity	Unit
Run Input		
Time steps per year	200	Steps/year
Number of Phases	1	[-]
Number of Cycli	1	[-]
Start time (t0)	2016	Year
From	0	Years
To	60	Years
Run Output		
Fist time step	0	Xxx
Step period	200	xxx
Max number of steps	1000	xxx

Table 21: Coastline schematization

Coastline schematization	
Coastline rays	370
Coastline cells	369
Average cell width	200

Table 22: Onshore climate locations

	Climate 1	Climate 2	Climate 3	Climate 4	Climate 5	Climate 6	Climate 7	Climate 8	Climate 9
Xw	916765	923706	932483	942018	951424	960304	969883	978148	982531
Yw	1720603	1717885	1715466	1711155	1708180	1706220	1706539	1710354	1716534
.RAY-file	'TR1_CAL'	'TR2_CAL'	'TR3'	'TR4'	'TR5'	'TR6'	'TR7'	'TR8_CAL'	'TR9'

Table 23: Schematized revetment sections

Revetment section 1			Revetment section 2			Revetment section 3		
Xw	Yw	Top	Xw	Yw	Top	Xw	Yw	Top
923152.8	1717032	-69.5	979336.7	1708832	-88.79	981839.7	1711364	-1.14
923339.1	1717032	-8.85	979547.5	1709057	13.1	981832.3	1711932	77.88
923644.6	1716984	18.01	979942	1709350	-1.83	981946.4	1712181	-32.65
923858.9	1716934	0.78	980522.5	1709861	-1.55	981951.4	1712181	-36.65
924015.4	1716853	-37.03	981559.4	1710809	1.65			
Revetment section 4			**Revetment section 5**					
Xw	Yw	Top	Xw	Yw	Top			
982371.8	1712763	5.89	983644.6	1714362	3.43			
983227.6	1713622	-38.29	984649.1	1715523	-14.42			

Table 24: Schematized Groins

	Groin 1	Groin 2	Groin 3	Groin 4	Groin 5	Groin 6	Groin 7	Groin 8
Xw	975390	919830	921644.4	920416.5	921221.3	981552	981948.9	983253.7
Yw	1706900	1718200	1717223	1717802	1717788	1711146	1712451	1714034
TOP	200	50	10	50.16	50	160.89	139.44	136.78
Block (%)	100	100	100	100	100	100	100	100
Key_ar	0	0	0	0	0	0	0	0

E.3 Parabolic Bay Shape Method

An equation to describe the shape of a bay in static equilibrium is proposed in Hsu and Evans, 1989:

$$\frac{R_n}{R_\beta} = C_o + C_1 \frac{\beta}{\theta_n} + C_1 \frac{\beta}{\theta_n}^2$$

The equation describes the relation between the length-ratio and the angle ratio. Both β and R_β are predetermined and represent the location of a chosen downstream control point relative to the upstream diffraction point. The three C coefficients where determined by regression analysis to fit 27 prototype beaches in static equilibrium.

MEPBAY

A software package based on this method has been developed called MEPBAY. The application of the PBSM will be done using the following procedure:

1) Choose a control point on a straight section of the coastline.
2) Choose a diffraction point at the upstream side of your study area
3) Connect both points with a straight line, called control line (R_β)
4) Determine the predominant wave direction
5) Draw a line perpendicular to the wave crests starting at the diffraction point
6) Determine the angle (β) between the wave crest line and the control line
7) Calculate rays from the diffraction point to the beach. With a given angle (θ) the ray length can be calculated using the theory of Hsu and Evans.

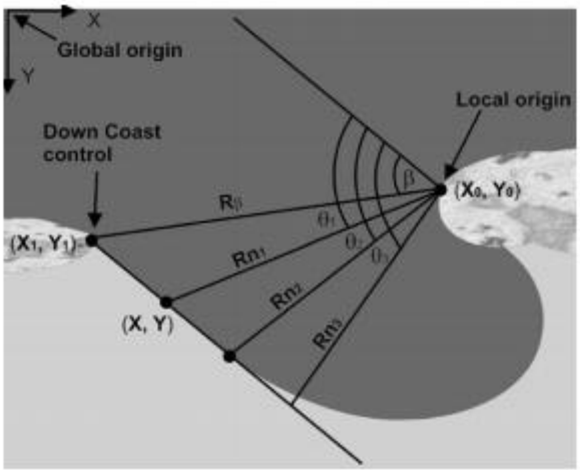


Figure 86: Definition sketch from Klein et al, 2003

8) Sketch the static equilibrium coastline based on the coastline coordinates (R_n, θ_n)
9) Compare the existing coastline to the static equilibrium coastline to determine the state of the beach.
    a. Coastlines coincide -> static equilibrium
    b. Existing landward of predicted -> dynamic equilibrium

Interpretation of results

Figure 87: Static equilibrium of coastline (green) over the current coastline of 2016

The position of the static equilibrium coastline is dependent on the exact location of both the diffraction and the control point. The position of these points is arbitrary, and therefore the results are accompanied by a large uncertainty. The following aspects should be taken into account during the interpretation of the results:

- The wave direction is the most important input parameter, since the both the diffraction point and the downcoast control point are depending on the wave direction. Furthermore the orientation of the bay is very sensitive by changes in wave direction, as can be seen in Figure 88.
- Offshore wave data was used for this assessment, while the local climate near the diffraction point could differ significantly.
- The Control point should be outside of the influence of the diffraction. This location does not exist, since the wave climate at the harbour jetties of Barranquilla are also influenced by the Sierra Nevada de Santa Marta. The bay is considered to be ‘incomplete’, and a virtual control point can be used. This definition of the location however remains unclear.
- Additionally coastal structures are present in the bay, leading to a local stabilization of the coastline. This conflicts with the assumption of a sandy bay. By relocating the control point towards the east, the structures can be excluded from the predicted bay shape (Figure 89)
- The exact location of the diffraction point is chosen at the edge of the island but this point could also be located further offshore based on detailed local bathymetry. If information is available the position could be further specified.
- Within the first parabolic bay shape there are other diffraction points which have influence on the static equilibrium position of the bay. To take this effect into account the local wave climate should be calculated and additional plots can be made. Unclear is how the interaction can be taken into account and how the plots should be combined.

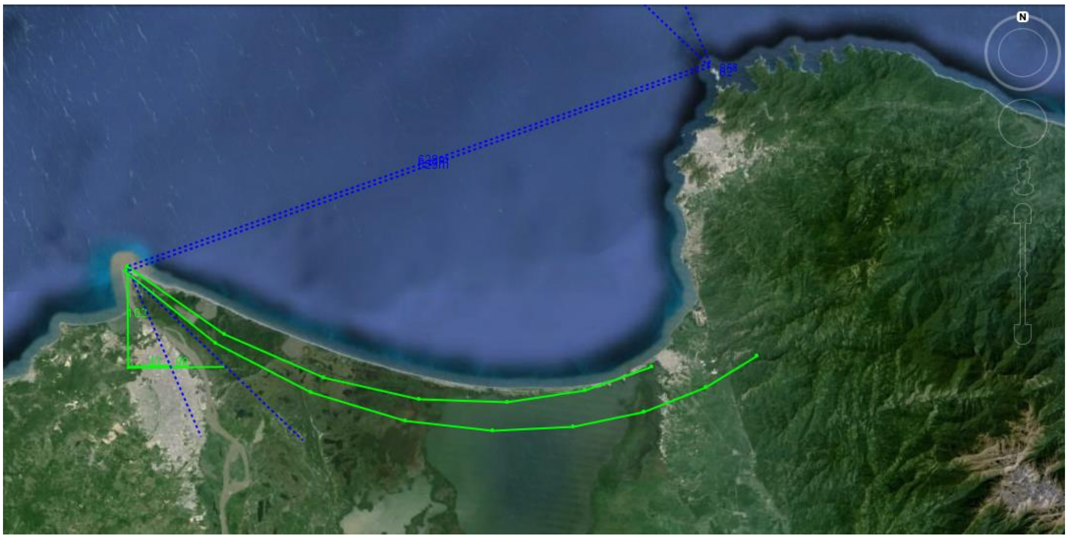


Figure 88: Sensitivity to changes in wave direction

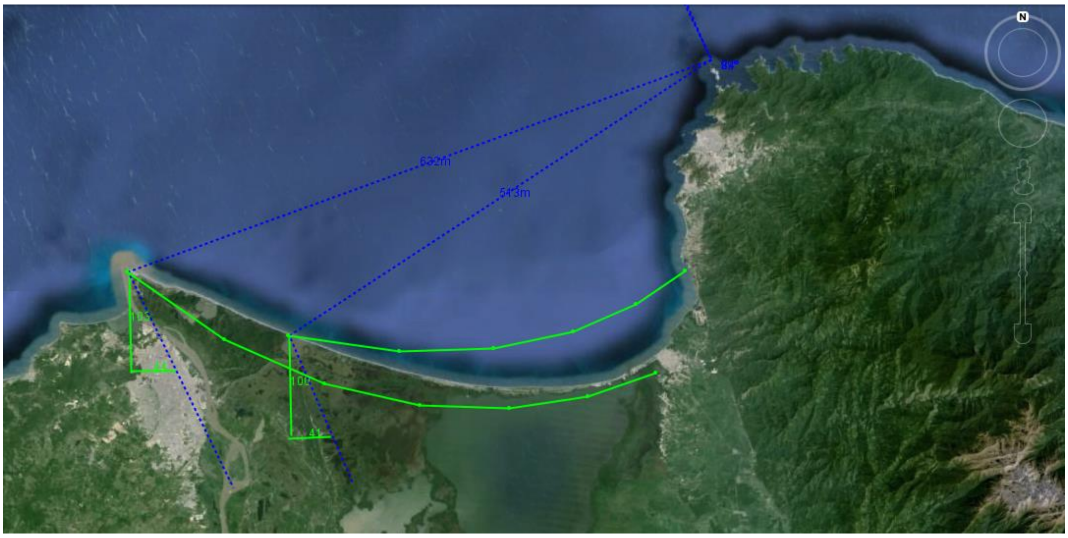


Figure 89: Sensitivity to changes in control point

Figure 90: Sensitivity to changes in diffraction point

F: Lagoons & Vegetation

The presence of lagoons has a major influence on the coastline development since less sediment is available per meter of coastline. This is expected to lead to an increase in erosion rates and fast changes in coastline orientation. However the lagoons, both on small scale like Ciénaga el Torno just to the west of KM-19 as Ciénaga Grande de Santa Marta, are protected by sandbars. This appendix provides an overview of the lagoons present in the area and shows the historic development of the sand bars at Ciénaga el Torno.

The formation, growth and decay of sandbars involves many other processes besides alongshore transport of sediment and are therefore not expected to be correctly represented in the model. The lagoons are therefore not schematized in the model, but replaced with land.

In contrast to the lagoons the presence of mangrove can provide protection against erosion and storm surge according to (Gedan et al. 7-29). They also state the effect on shoreline integrity over longer time scales by peat accretion. Vegetation may also provide indirect protection by modifying the soil parameters. (Feagin et al. 10109-10113) The local variation in vegetation can influence the coastline development by slowing erosion rates locally. However protection with only vegetation is not possible when large scale regional erosion is taking place. (Gedan et al. 7-29) The variation of the vegetation in the area of interest is very high, which is presented in the second part of this appendix. A dense mangrove forest is present in the western section, while along the Salamanca bar only single bushes and trees are present. A single tree in the coastal zone is not expected to have a significant influence on long time scales, but a forest remains present during the entire considered period of 50 years and will therefore have a lasting impact on the coastline development.

To account for the presence of lagoons and vegetation an average active height is estimated in Chapter 5, representing these influences.

F.1 Local lagoons

Along the bay between Barranquilla and Santa Marta multiple lagoons are present, as can be seen in Figure 91.

1) Ciénaga La Calestra
2) Ciénaga De Las Playitas
3) Ciénaga el Torno
4) Ciénaga Grande de Santa Marta

Lagoons are shallow lakes with varying sizes, separated from the Caribbean Sea by a sand bar. The presence of lagoons has a major impact on the coastline development, since the available sediment per metre of coastline is reduced. The effects on the coastline development are studied in more detail for Ciénaga el Torno, which is closely located to KM-19 and is close to other sections of the RN90 as well.

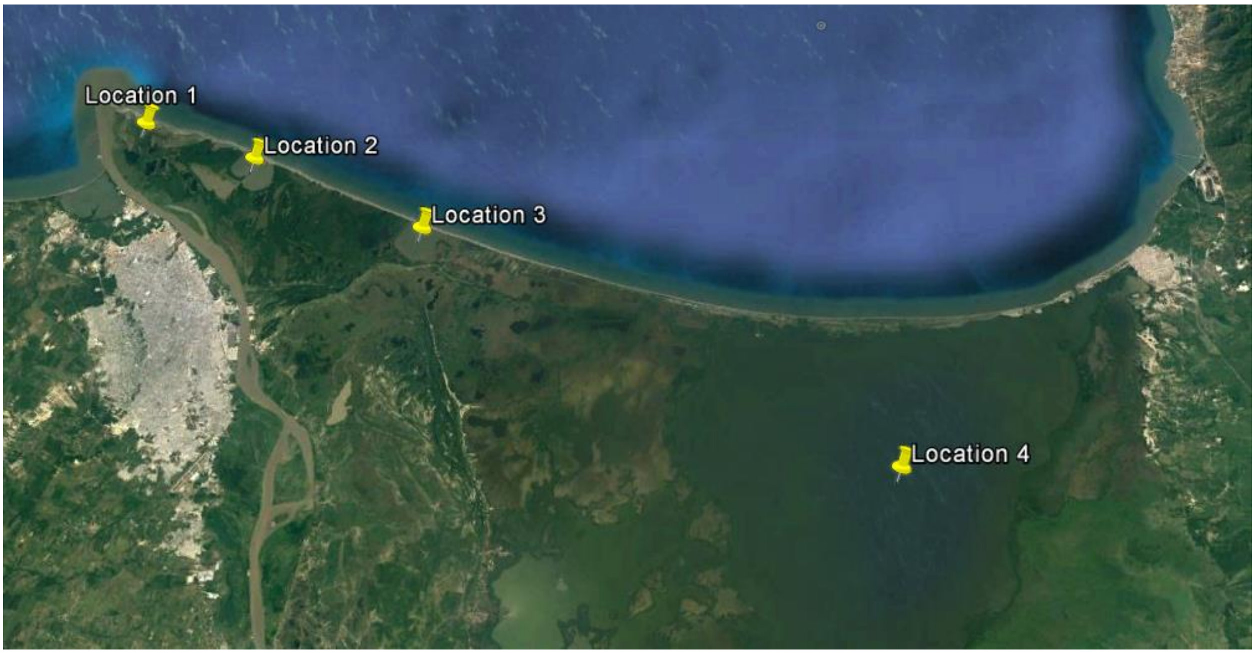


Figure 91: Locations of local lagoons

F1.1 Ciénaga el Torno

Landward migration of sand bar

Figure 92 shows Ciénaga el Torno in March 2003 with the yellow line as approximation of the shoreline location at this moment. The line will be repeated in all other figures in this Appendix to provide reference. After a period of 12 years Figure 93 is taken which shows a landward migration of the sandbar over a distance of 100 metres at the west and 200 metres at the east. A slight change in coastline orientation can be seen as well, since the coastline is no longer parallel to the approximated coastline of 2003.

Breach of sand bar and development in time

Figure 93 shows a narrow but intact sand bar in front of the Ciénaga el Torno, which is located just west of KM-19. In between March 2015 and January 2016 a breakthrough has occurred, as can be seen in Figure 94. After seven months the gap has moved approximately 400 metres to the west as can be seen in the Figure 95 taken in August 2016. The transformation of the gap shows a spit-like feature from the eastward end of the coastline in westward direction, forming a sandbar. Over time this is expected to relocate the gap to the westward end and thereby restore the coastline.

Impact on coastline development

The sandbar development in time indicates the presence of cross-shore transport mechanisms which are not represented in the modelling approach. Enhanced erosion as a result of a lower active height cannot be concluded from the historic data, since the sand bar migrates landward in accordance with the surrounding erosion. The direct impact on the coastal development therefore is complicated to estimate.

The lagoon can be considered a sink for alongshore sediment, since passing sediment is used for maintenance and migration of the sandbar. The retained sediment causes a decrease in sediment transport along the lagoon, leading to increased erosion in the downstream area.

No interaction with critical locations is expected since the lagoons are located westward of KM-19 and KM-28. Due to the limited importance of the lagoons and the lack of detailed information, sinks are not applied in the model. The influence on the coastline development should however be taken into consideration when interpreting the model results in Chapter 4.

Figure 92: Ciénaga el Torno in March 2003

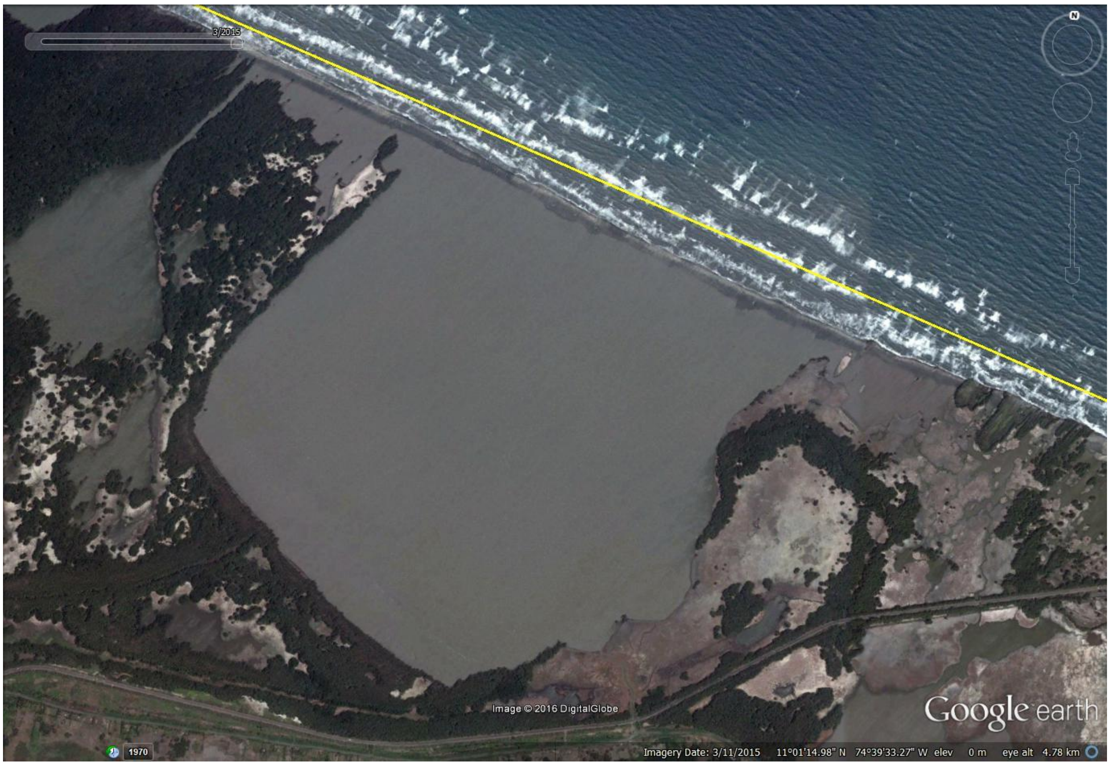


Figure 93: Ciénaga el Torno in March 2015

Figure 94: Ciénaga el Torno in January 2016

Figure 95: Ciénaga el Torno in August 2016

F.2 Characteristics of Vegetation

This appendix provides an impression of the vegetation present in the coastal zone. Using 'Google Street View' pictures are taken at eight representative locations along the RN90. For all eight locations a figure in seaward (north) and landward (south) direction is presented to show the vegetation present in 2016 at both sides of the RN90.

It should be noted that locations with a wide view are preferred with this method, resulting in an over-representation of areas with limited vegetation.

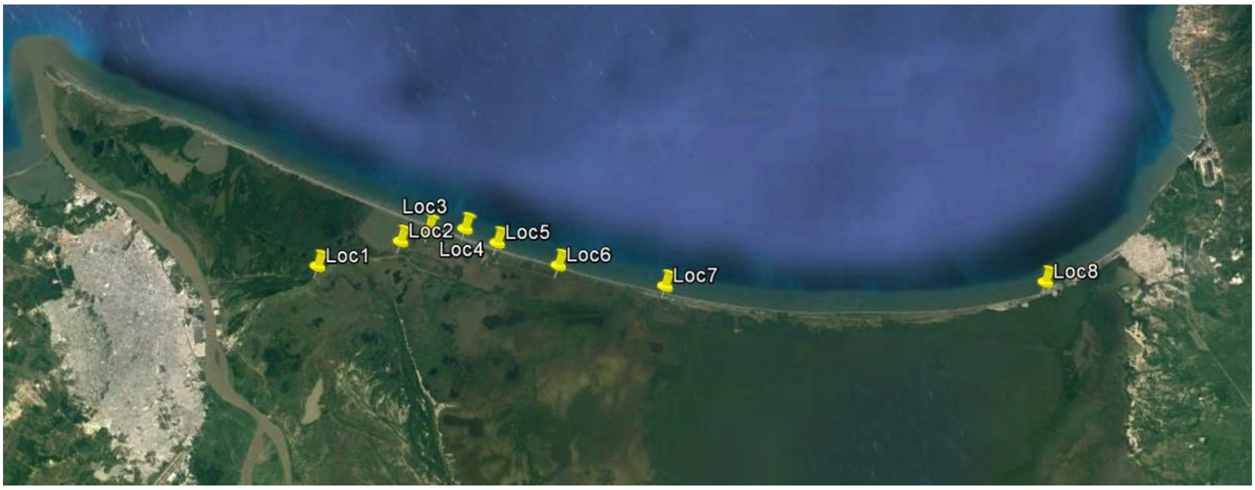


Figure 96: Location detailed figures

The densest vegetation is present in the western part, indicated by the dark green area above location 1 in Figure 96. Figure 97 and Figure 98 are the best representation of vegetation here, showing a variety of vegetation from bushes and plants to high trees. Eastward of location 3 the vegetation becomes less dense, especially at the seaward side of the RN90.

Overall the figures show a high variety of vegetation along the RN90, which generally more developed vegetation landward of the RN90. The road itself is elevated above the surrounding land, and we see large inundated areas along the RN90 in the figures Figure 103, Figure 105, Figure 107 and Figure 109.

Due to the high variety and unknown direct effect against structural erosion vegetation is not schematized in the model. The expected impact will be taken into account with the interpretation of the results in Chapter 4.

Location 1:

Figure 97: Impression of vegetation in seaward direction at location 1

Figure 98: Impression of vegetation in landward direction at location 1

Location 2:

Figure 99: Impression of vegetation in seaward direction at location 2

Figure 100: Impression of vegetation in landward direction at location 2

Location 3:

Figure 101: Impression of vegetation in seaward direction at location 3

Figure 102: Impression of vegetation in landward direction at location 3

Location 4:

Figure 103: Impression of vegetation in seaward direction at location 4

Figure 104: Impression of vegetation in landward direction at location 4

Location 5:

Figure 105: Impression of vegetation in seaward direction at location 5

Figure 106: Impression of vegetation in landward direction at location 5

Location 6:

Figure 107: Impression of vegetation in seaward direction at location 6

Figure 108: Impression of vegetation in landward direction at location 6

Location 7:

Figure 109: Impression of vegetation in seaward direction at location 7

Figure 110: Impression of vegetation in landward direction at location 7

Location 8:

Figure 111: Impression of vegetation in seaward direction at location 8

Figure 112: Impression of vegetation in landward direction at location 8

G: Cost Estimation

This appendix contains the considerations for the estimation of the cost per alternatives, as presented in Chapter 5. To start the reference projects are introduced and unit prices are determined. An overview of the final costs of all components is presented in Table 25, while Table 26 contains the corresponding descriptions. The following paragraphs elaborate on each of the alternatives. The level of detail varies between the alternatives since the focus for this study is on coastal engineering.

Table 25: Cost overview

Alternatives	Temporary measure (M USD/year)	Capital Costs (M USD)	Maintenance costs (M USD/year)	Risks & Opportunities
Extension	Not applicable	Not applicable	0.5 M USD	0.8 M USD / year
Revetment	Not applicable	14.4 M USD	0.3 M USD	Not applicable
Breakwater	Further research	4.3 M USD	0.1 M USD	Not applicable
Groin field	Not applicable	6.5 M USD	0.1 M USD	Not applicable
Nourishment	Not applicable	Not applicable	5.5 – 9.8 M USD	Not applicable
Relocate Road	0.5 M USD/year	10.8 M USD	Not applicable	-5.5 M USD

G.1 Coastal protection reference

The emergency measure constructed at KM-19 is used as reference. To generalize the costs for coastal protection works an average is taken of the total costs over the total construction volume. This unit price is based on the design performed by SISCO (Sisco Ingeniería, 2015) for the emergency measures taken at KM-19. Figure 113 provides an impression of the structure at KM-19.

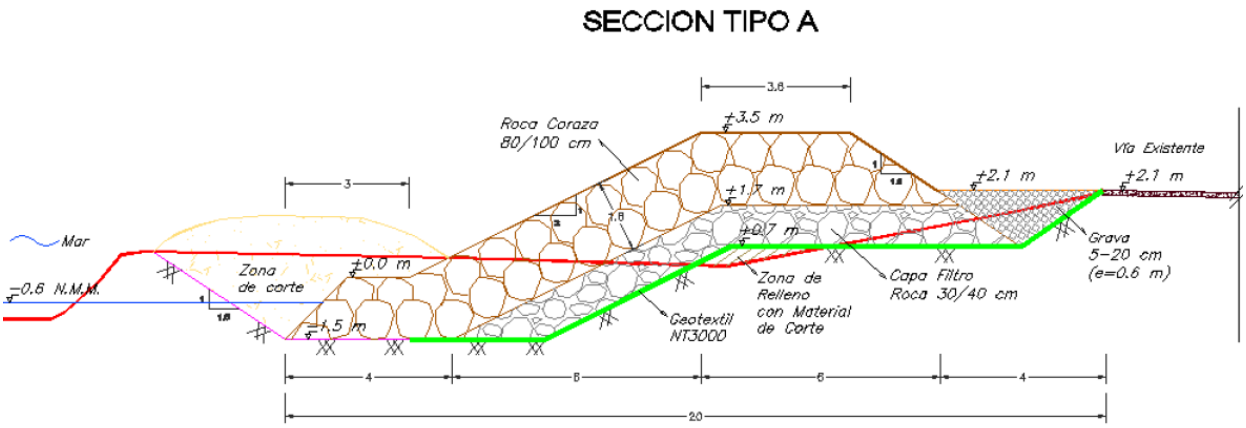


Figure 113: Typical cross-section of the emergency measure at KM-19 (Sisco Sisco Ingeniería, 2015).

From the reference project an average cost of 130 USD/m3 was deduced. This is applied to the coastal structures of the alternatives.

G.2 Infrastructural reference

A new highway was constructed in 2015 between Sabanalarga and Palmar de Varela, in the department of Atlántico. With a total length of 19.18 km and a total investment of 105,000 M COP, the unit price is 2.3 M USD per km of highway. (Portal ANI, 2017) Figure 114 gives an impression of the highway, which consists of double lanes in both directions.

Figure 114: Impression of the reference project between Sabanalarga and Palmar de Varela

G.3 Summary Cost Components

Table 26 provides background information to Table 25, where a summarizing overview was presented. The figures are supported by more detailed information per alternative in the following paragraphs.

Table 26: Cost component overview

Alternatives	Temporary measure	Capital Costs	Maintenance Costs (yearly)	Risks & Opportunities
Extension	Not applicable	Not applicable	Average extension of 36m/year at KM-19 and 29m/year at KM-28 Scour maintenance based on 'Revetment' cross-section	Additional costs for monitoring and remaining risk 150%
Revetment	Not applicable	Structure length of 1800m at KM-19 Structure length of 1000m at KM-28	2% of Capital Costs	Not applicable
Breakwater	Further research required	Structure length of 800m at KM-19. Structure length of 200m at KM-28	2% of Capital Costs	Not applicable
Groin field	Not applicable	21 groins of 200m each constructed at KM-19 3 groins of 200m each constructed at KM-28	2% of Capital Costs	Not applicable
Nourishment	Not applicable	Not applicable	240,000 – 385,000 m3/year supplemented at KM-19 216,000 – 432,000 m3/year supplemented at KM 28	Not applicable
Relocate Road	Extension alternative for first five years at KM-19 only	Structure length of 2250 at KM-19 Structure length of 2450 at KM-28	Not applicable	Road expansion to 2x2 included in measure

G.4 Continuous Extension

For this alternative no Temporary measure or Capital costs are considered, since the construction of an extension is assumed to take place on a yearly basis. Additional scour protection is included to match the total volume of rock of the alternative 'Revetment'. This is included to make sure the structure will be able to last for 50 years.

For this alternative a risk fee is included to account for the remaining risk of road collapse, detailed monitoring and frequent mobilisation of equipment.

G.5 Revetment

For this approach no temporary measure are required, since the revetment is built directly at the critical location.

Capital costs are considered for the structure of an 1800 metre long revetment at KM-19, and a similar structure of 1000 metre at KM-28 after 15 years. Extensive scour protection is included in the design to provide the intended lifetime of 50 years. The design is made using the approach of Van der Meer (1995) and the following assumptions:

- Similar materials and equipment are required as with the emergency measure
- Erosion depth of 3m over 50 years)

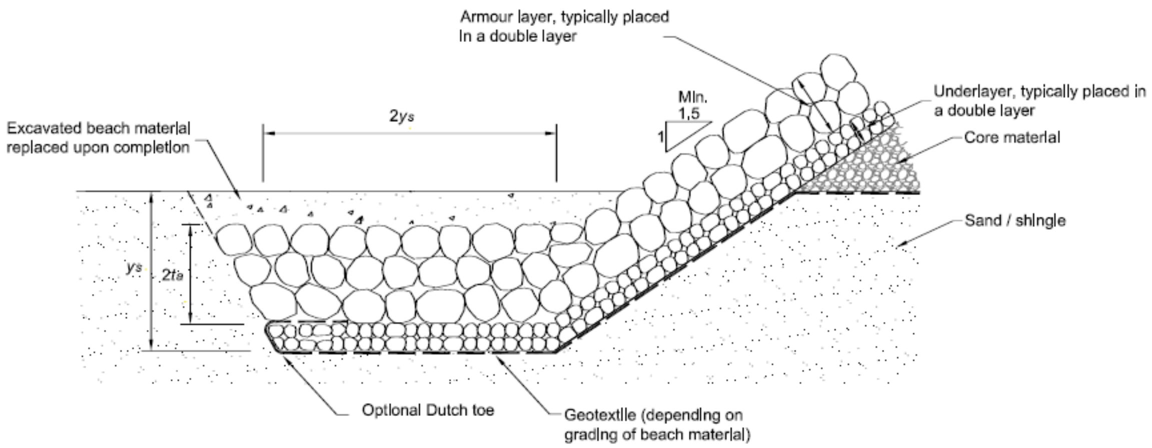


Figure 115: Toe detail for severe scour, with excavation (CIRIA, CUR, CETMEF, 2007)

Figure 115 gives an impression of the toe construction required for this situation. Since the revetment itself requires excavation the additional excavation for the toe trench is of minor nuisance during construction but yields a significant advantage on the volume of required material.

The total structure requires approximately 71100 m^3 material, with an estimated total cost of 9.25 M USD. Maintenance costs are estimated to be in the order of 2 per cent of the total capital costs.

G.6 Breakwater

No temporary measures are included for this alternative; however additional research is required to provide certainty on the short term coastline development.

Capital costs consist of the breakwater of 800m at KM-19 and a breakwater of 200m at KM-28 after 15 years. The volume of the structure is estimated based on the following assumptions:

- Natural bottom slope 1:200
- Structure slope 1:2.5
- Crest width of 3m
- Crest height of 1m relative to MSL

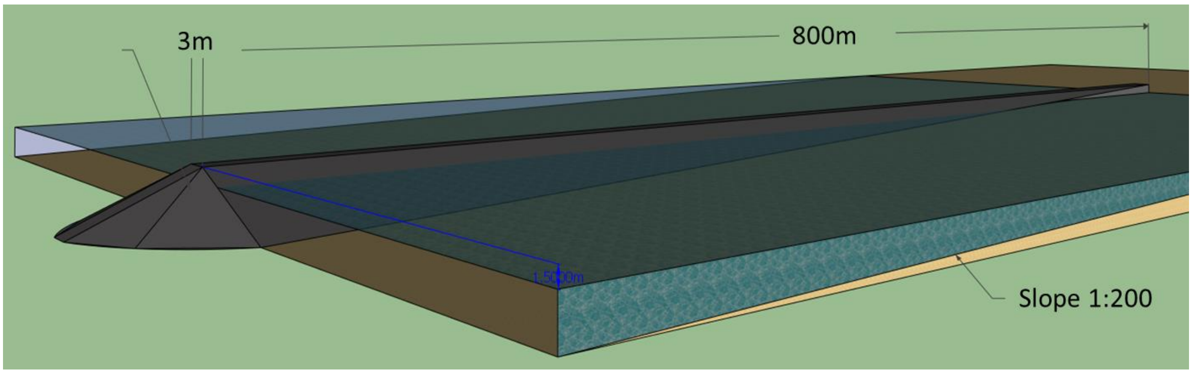


Figure 116: Impression of the alternative "Breakwater"

Figure 116 gives an impression of the structure, and Figure 117 shows the relation between the chosen breakwater length and the total construction volume. With increasing depth and fixed slope the total construction volume increases exponentially with increasing groin length.

As a result the breakwater at KM-19 has a volume of 27,500 m^3, and the smaller breakwater at KM-28 requires 1,850m^3.

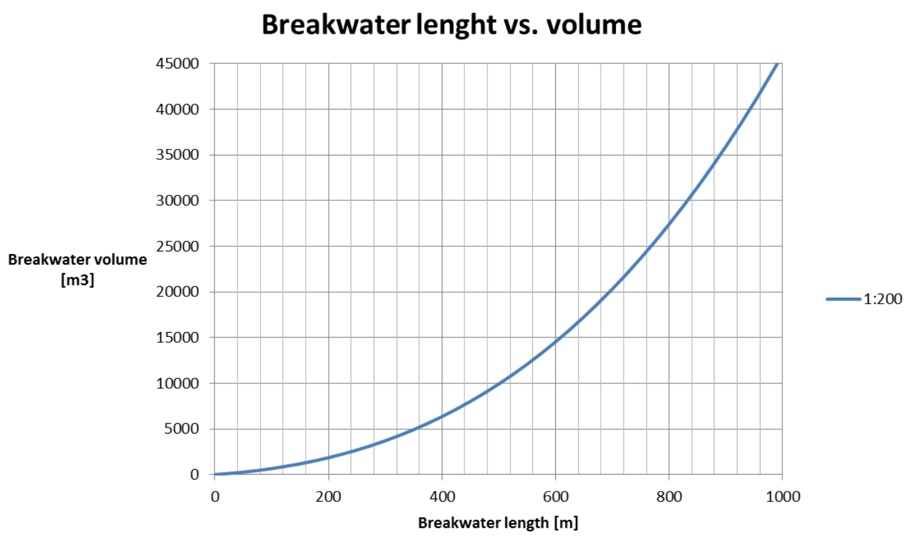


Figure 117: Breakwater volume related to the length of the breakwater

Erosion is expected to take place at the head of the breakwater. To prevent damage to the structure, scour protection was designed using Figure 118 and the following assumptions:

- Scour depth of 2 metres at the breakwater head. H_{max} = 0.5 h_s (unbroken wave height = 0.5 local water depth for flat profile) Y_{max} = H_{max} (Max scour depth = Max unbroken wave height)
- Severe scour potential
- No excavation

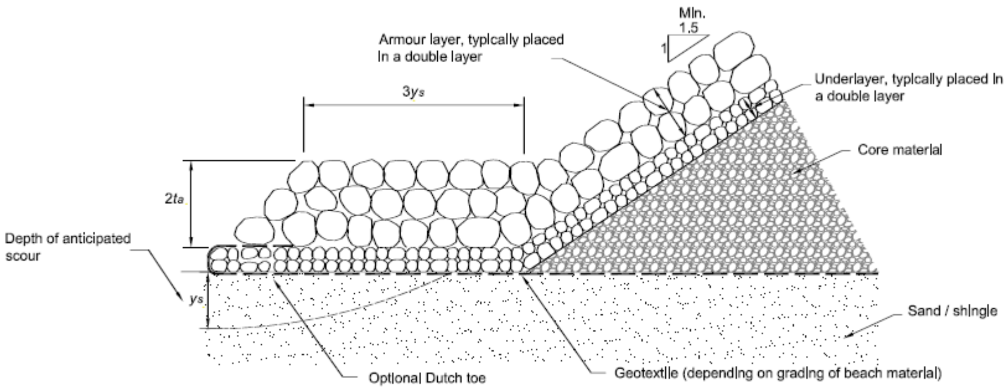


Figure 118: Toe detail for severe scour, without excavation (CIRIA, CUR, CETMEF, 2007)

In addition to the calculated rock volume above scour protection of 670 m^3 will be placed around the breakwater head aimed at protecting the structure for long term scour.

The breakwater must also be protected against sideways erosion, since the coastline downstream of the breakwater moves backward. To prevent the erosion from reaching the base of the structure is extended landward for 200m, requiring another 1850 m^3 of rock.

The measure does not seem sufficient since the expected erosion directly downstream of the breakwater is over 1000 metres. However the model is calibrated for larger time and spatial scales, so detailed coastline deformation adjacent to structures should be interpreted first.

Sheltering from a section of the wave spectrum occurs directly next to the breakwater, altering the local wave conditions. The highest erosion therefore takes place slightly more westward compared to the model results.

Maintenance costs are estimated to be in the order of 2 per cent of the total capital costs.

G.7 Groin field

No temporary measures are included for this alternative, as the groins have a smaller reaction time compared to the 'Breakwater' alternative.

Capital costs are determined by using the same assumptions and formula as was introduced for the 'Breakwater' alternative. However the length of the groins is significantly shorter, leading to only 1850 m^3 per structure. The construction of the groin is similar to breakwater, with the length of the structure as the main difference.

Scour protection (85m^3) and prevention of sideways erosion (1850m^3) is determined using the same methods as introduced for the 'Breakwater' alternative. The prevention of sideways erosion will only be applied at the downstream located groin of each critical location.

G.8 Nourishment

For the cost estimation of the nourishment 12 USD/m3 (Sisco Ingeniería, 2016) is used. Based on volumes from the modelling runs the costs for a nourishment scheme vary in accordance with the required volumes from 5.5 to 9.8 M USD/year (456,000 - 816,000 m^3/year).

G.9 Relocate Road

The highway is relocated behind the set-back line of 50 years and positioned parallel to predicted coastline to prevent forming future critical locations.

A buffer of 50 metres is used to provide sufficient safety as the coastline will approach the road again in 50 years. At KM-19 a new road of 2250m will be constructed, and at KM-28 a road section of 2450m is required.

The benefit of already executing the planned highway upgrade will be incorporated in costs by multiplying the superfluous existing RN90 by half the unit price for the construction of a new road.

Figure 119: Suggested road relocation of 2250 m at KM-19

Figure 120: Suggested road relocation of 2500m at KM-28

Bibliography

Alvarado Ortega, M. (2008). *Río Magdalena, navegacion maritima y fluvial (1986–2008)*. 1st ed. Universidad del Norte, pp.572-621.

Andrade, C. and Barton, E. (2000). *Eddy development and motion in the Caribbean Sea*. Journal of Geophysical Research: Oceans, 105(C11), pp.26191-26201.

Booij, N., R. C. Ris, and L. H. Holthuijsen (1999), *A third-generation wave model for coastal regions: 1. Model description and validation*, J. Geophys. Res., 104(C4), 7649–7666, doi:10.1029/98JC02622.

Bosboom, J. and Stive, M. (2015). *Coastal dynamics I*. 1st ed. Delft: Delft Academic Press.

Botero, L. and Salzwedel, H. (1999). *Rehabilitation of the Cienaga Grande de Santa Marta, a mangrove-estuarine system in the Caribbean coast of Colombia.* Ocean & Coastal Management, 42(2-4), pp.243-256.

Bryson, J. (2004). *What to do when Stakeholders matter.* Public Management Review, 6(1), pp.21-53

Cardona, P. and Botero, L. (1998). *Soil Characteristics and Vegetation Structure in a Heavily Deteriorated Mangrove Forest in the Caribbean Coast of Colombia.* Biotropica, 30(1), pp.24-34.

CIRIA, CUR, CETMEF, (2007). *The Rock Manual. The use of rock in hydraulic engineering*. 2nd ed. London: CIRIA.

Correa, I., Alcántara-Carrió, J. and González, D. (2005). *Historical and Recent Shore Erosion along the Colombian Caribbean Coast.* Journal of Coastal Research, (Special Issue 49), pp.52-57.

Correa, I. and Morton, R. (2010). *Caribbean Coast of Colombia. In: Encyclopedia of the World's Coastal Landforms*, 1st ed. Dordrecht: Springer Netherlands, pp.259-264.

da Fontoura Klein, A., Vargas, A., Raabe, A. and Hsu, J. (2003). *Visual assessment of bayed beach stability with computer software.* Computers & Geosciences, 29(10), pp.1249-1257.

Data.worldbank.org. (2017). Internally displaced persons (number, low estimate) | Data. [online] Available at: http://data.worldbank.org/indicator/VC.IDP.TOTL.LE?year_high_desc=true [Accessed 9 Mar. 2017].

Dee, D. P. and co-authors. (2011), *The ERA-Interim reanalysis: configuration and performance of the data assimilation system.* Q.J.R. Meteorol. Soc., 137: 553–597. doi:10.1002/qj.828

Deltares, (2011). *UNIBEST-CL+ Manual*.

Díaz-Granados, P. (2014). *El mar ya está a 8 metros de la vía Barranquilla-Santa Marta.* El Heraldo.

Estrada, F. (2006). *The Plio Quaternary Magdalena Turbidite system.* In: *SEPM/GEological Society of London conference*.

Feagin, R. A. et al., *Does Vegetation Prevent Wave Erosion Of Salt Marsh Edges?*. Proceedings of the National Academy of Sciences 106.25 (2009): 10109-10113. Web.

Gedan, Keryn B. et al. *The Present And Future Role Of Coastal Wetland Vegetation In Protecting Shorelines: Answering Recent Challenges To The Paradigm*. *Climatic Change* 106.1 (2010): 7-29. Web.

Hofstede, G., Hofstede, G. and Minkov, M. (2010). *Cultures and organizations*. 1st ed. New York, N.Y.: McGraw-Hill.

International Association for Public Participation (2007). *IAP2 Spectrum of Public Participation.*

Jouanno, J., Sheinbaum, J., Barnier, B., Molines, J., Debreu, L. and Lemarié, F. (2008). *The mesoscale variability in the Caribbean Sea. Part I: Simulations and characteristics with an embedded model.* Ocean Modelling, 23(3-4), pp.82-101.

Kjerfve et al. (2002). *Caribbean Basins: LOICZ Global Change Assessment and Synthesis of River Catchment/Island-Coastal Sea Interaction and Human Dimensions; with a desktop study of Ocean Basins.* LOICZ Reports & Studies. Texel, The Netherlands: LOICZ, pp.p.110- 113.

Kjerfve, B. (1981). *Tides of the Caribbean Sea*. Journal of Geophysical Research, 86(C5), pp.p. 4243 - 4247.

Martinez, J., Pilkey, O. and Neal, W. (1990). *Rapid formation of large coastal sand bodies after emplacement of Magdalena river jetties, northern Colombia*. Environmental Geology and Water Sciences, 16(3), pp.187-194.

Ministerio de Transporte (2012). *Plan estratégico intermodal de infraestructura de transporte.*

Ortiz Royero, J. (2011). *Exposure of the Colombian Caribbean coast, including San Andrés Island, to tropical storms and hurricanes, 1900–2010.* Natural Hazards, 61(2), pp.815-827.

Pérez Díaz, V. (2015). *Cartagena, Barranquilla y Santa Marta quedarán conectadas con dobles calzadas.* La Republica.

Restrepo, J., Zapata, P., Diaz, J., Garzonferreira, J. and Garcia, C. (2006). *Fluvial fluxes into the Caribbean Sea and their impact on coastal ecosystems: The Magdalena River, Colombia.* Global and Planetary Change, 50(1-2), pp.33-49.

Rijksoverheid (2012). *Colombia, Vietnam and South Africa, in transition from aid to investment.* The Hague: Desk Top Publishing.

RVO (2015). *Informe Final Diálogo Colombo Holandés KM19 | Final Report Colombian Dutch Dialogue KM 19.*

Sisco Ingenieria (2015). *Diseño de las obras complementarias a mediano – largo plazo para la estabilizacion costera del sector km 19-20 de la via que conduce de barranquilla a santa marta (ruta 90).*

Sisco Ingeniería (2016). *Modelación de la evolución de la línea de costa en el km-19, km-28 y km-40 para escenarios de 30 y 50 años de la vía que de barranquilla conduce a ciénaga.*

Tolman, H. L. (2009). *User manual and system documentation of WAVEWATCH III TM version 3.14. Technical note*, MMAB Contribution, 276, 220

USGS, (2016). *Caribbean Coast: Introduction - Coasts of Colombia*. [online] Coastal.er.usgs.gov. Available at: https://coastal.er.usgs.gov/coasts-colombia/caribbean/caribbean-intro.html [Accessed 7 Nov. 2016].

U.S. Army Corps of Engineers (2006). *Coastal Engineering Manual*. 1st ed. Washington, D.C.: U.S. Army Corps of Engineers.

van Rijn, L. (2011). *Coastal erosion and control.* Ocean & Coastal Management, 54(12), pp.867-887.

Von Erffa, A. (1973). *Sedimentation, Transport und Erosion an der Nordkuste Kolumbiens zwischen Barranquilla und der Sierra Nevada de Santa Marta.*

van Rijn, L. (2007). *Unified View of Sediment Transport by Currents and Waves. II: Suspended Transport. Journal of Hydraulic Engineering*, 133(6), pp.668-689.