VARADERO BEACH EROSION PROJECT

Designing a solution for the erosion problem in front of the Iberostar Varadero Hotel

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Cover Image

Picture of beach in front of Iberostar Varadero Hotel

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Date	6 January, 2017	
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General notice to the reader

In the academic programme for Civil Engineering there is in the 5th year (i.e. in the second year of the Master Programme) the possibility that students can do a group project in a group of four to six persons. It is officially called "Multidisciplinary Project". During this project they should make a full design of something. The work should be integral, starting with terms of reference, and ending with the real design. This can be a structure, but it can also be a harbour lay-out, a policy plan design, etc. The total time available for the project is in the order of two months and will provide 10 European Credits. It has to be practical and applied.
It is certainly not an M.Sc. thesis assignment (the thesis work is individual, 6 months and more focussed on research or advanced design work on details). But it is also not an apprenticeship, internship or traineeship where the student has to work together with a group of experienced people. For this project they have to solve the problem on their own (of course with guidance).

This report is the result of such a Multidisciplinary Project. This report will be assessed by staff of TU Delft. It will be provided with a passing mark (i.e. a mark between 6 and 10 on a scale of 10), and considered sufficient for publication, when passed.

However, this work has not been fully corrected by TU Delft staff and therefore should be considered as a product made in the framework of education, and not as a consultancy report made by TU Delft.

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Faculty of Civil Engineering and Geosciences
Delft University of Technology

Preface

This report is the result of a seven-week study on the structural erosion problem on the beach of the Iberostar Varadero hotel. This multidisciplinary project is executed by four students from the Delft University of Technology as a part of their MSc-program. In this report the causes of the erosion problem are identified, the used models are explained, the sediment transports are quantified and a solution (including construction and maintenance proposal) has been designed in order to avoid the further structural erosion. Finally, also some recommendations are presented for future research.

The study has been performed at the Universidad Tecnológica de la Habana José Antonio Echeverría (CUJAE) in Havana in cooperation with the Hydraulic Investigation Centre (CIH). During our research and stay in Havana we had a lot of help from many different people. We would especially thank our supervisor, prof. dr. ir. L. F. Córdova López for his great support as he provided a lot of data and information and was always available for questions. Furthermore, we want to thank our supervisor at the Delft University of Technology, Ir. H. J. Verhagen for the preparation and the opportunity to do this project.

We would also thank the people working at Deltares, who were willing to help us with the difficulties in the software programmes. The information from Ir. Dirk-Jan Walstra was of great importance for the Delft3D model, Ir. Bas Huisman answered our questions about UNIBEST and Ir. Robert McCall gave us some crucial information about the Xbeach model. Besides the people from Deltares, we also want to thank the company in general for making their models available for us. We are also very grateful for the wind and wave data BMT Argoss has provided us.

Furthermore, we want to thank the people at our casa particular for our stay. They took great care of us and were willing to help us to explore the Cuban life.

Finally, we would thank our sponsor Van Oord for their financial support.

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Havana, January 2017

Summary

The main objective of this report is to find the cause of the erosion problem and to design a solution for the problematic situation in front of the Iberostar Varadero Hotel, Cuba.

Varadero is a holiday destination 130 kilometres east of Havana, located in the province of Matanzas. This is the biggest tourist resort in the whole Caribbean with its 22 kilometres of perfect white beaches along the Hicacos peninsula. Along this beach a lot of hotels are located, including the Iberostar Varadero hotel that is located almost at the most eastern point. The hotel is situated in the coastal area of Los Tainos, which runs from the headland Punta Chapelin in the west towards Punta Francés in the east.

For almost 40 years erosion problems are present at the Varadero resort area on the Hicacos peninsula. The income from tourist industry at the Hicacos peninsula is of vital importance for the economy of Cuba, and therefore the erosion problems at the peninsula form a potential threat for the Cuban economy. At this moment, especially the erosion problems around the Iberostar Varadero hotel are severe and need direct attention.

To find the causes of erosion the problem is split up in a contribution by basic longshore transport, different cross-shore transports during extreme conditions and transports due to more complex hydrodynamic processes around the Iberostar Hotel. For the basic longshore transport the model Unibest LT, part of the Unibest CL+ package, is used to calculate the quantities and distribution of the longshore sediment transport over the cross-shore profile. The model is calibrated by doing an extensive sensitivity analysis and validated by comparing the results with values of different earlier studies done on erosion at the Hicacos peninsula.

For the contribution of cross-shore processes to the erosion problem, the model XBeach is used. First the model is run in 1D with 1D wave input by SwanOne to see the basic behaviour during storm and hurricane conditions and to calibrate various parameters. Thereafter the model is extended to a 2D model, with a full 2D wave input by SWAN (in the appearance of Delft3D-WAVE). In the end one representative storm and one hurricane condition are used to see the behaviour of the current coast as well as the effect of possible solutions. For the transport due to more complex hydrodynamic processes Delft3D is used. At first a large grid is made to look at the large scale flow patterns around the peninsula, and thereafter a smaller grid has been used to zoom in at the flows around the Iberostar hotel and the headland.

During this analysis some interesting flow patterns are found, which partly explain why there is structural erosion at the Iberostar Hotel. Hereafter the behaviour of the beach with complete yearly conditions are modelled to try to represent reality. To limit the computational time wave input reduction has been performed, reducing the computational time by a factor two.

It turns out that the causes of erosion can be subscribed to a combination two processes. Firstly, the general westward directed flow causes erosion west of the headland. Secondly, complex flow patterns occur during northwest wave conditions which often also cause erosion in front of the Iberostar Hotel. The negative influence of both processes on the recovery of the beach after storm and hurricane conditions is important. After explaining the causes of erosion the optimal solution for the structural erosion is investigated.

To do this, multiple requirements are developed and used as input for the design of multiple solutions. Visible, hard solutions like groynes and emerged breakwaters are no options, therefore only two realistic solutions remain. One consists of a large nourishment to strengthen the coastal profile and increase the beach width, the other of a submerged breakwater with an additional nourishment.

After an MCA and cost analysis, the nourishment turns out to be the optimal solution because no additional complex flow patterns are created, the sustainability is higher and it is easier to construct and maintain. The nourishment is further optimised and the behaviour is modelled for multiple years. After modelling of the solution it seems that a nourishment of 100,000m^3 is sufficient to provide a good beach width for a period of 5 years.

Compared with the current solution, relocating the dunes in landward direction, the main difference is that the problem is not shifted, but solved. With as main goal the widening of the beach for tourists, relocating the dunes fulfils its requirements. However, the erosion problem is not solved for the long term with this solution as the yearly net erosion will still continue and the beach area will decrease again.

It turns out that the construction time and construction method of the nourishment are very important. In 2012 there a large nourishment was placed in the region of the Iberostar hotel, with a very low effectiveness. This low effectiveness can be explained by the bad timing of the placement and the problems in the construction method. Better timing and better construction, will increase the effectiveness of a nourishment.

With this in mind, the following solution is proposed. A beach nourishment of 100,000 m^3 in front of the Iberostar hotel, with a lifetime of 5 years and an approximate total cost of 1.1 million CUC. Since the erosion problems are structural, new nourishments are needed in the future. When making a nourishment maintenance schedule, costs can be saved.

In that case, for a period of 50 years, the costs can be decreased to 12.8 million CUC, taking into account additional nourishments after possibly occurring hurricanes and extreme events. In this way the structural erosion problems can be dealt with in a cost effective, visually attractive and flexible way.

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1. Introduction

1.1 General information about Cuba

1.1.1 History

Around 2000 BC, the first humans from South America reached Cuba. These people are nowadays known as Indians. The Indians were still the only inhabitants until the 27th of October in 1492. At that specific day Cristopher Columbus (Cristóbal Colón) arrived in Cuba on his first discovery. He described Cuba as the most beautiful land on the whole earth. After its discovery, the island was developed as a Spanish colony, which lasted about 400 years. For the Spanish colonialists Cuba was the gateway to the other colonies in Latin-America. The city centres of Havana, Santiago de Cuba and Trinidad still refer to this era. From 1868, Cuba was struggling to become an independent country, which led to the military occupation by the United States in 1898 after the Spanish-Cuban-American war. This clearly marked the definite end of the Spanish influence on Cuba. In 1902, the neoclassical republic was established with a strong American influence. During this period, a lot of violence and corruption was normal in Cuba, which marked the period under dictator Batista.

On July the 26th 1953 Fidel Castro started the last independence war along with other freedom fighters like Ernesto 'Che' Guevara, Camilo Cienfuegos and his brother Raúl Castro. This resulted in the current communist republic, founded on the 1st of January in 1959. As a communist country it had a strong (economic) bond with the former Soviet Union. When this country collapsed, this also resulted in a decrease of 60% of the Cuban economy. This misery lasted several years until Castro decided to legalise the US dollars (later replaced by Cuban dollars) and tourism. Legalising tourism has proven to be a good decision as it is nowadays one of the main incomes for Cuba.

In 2008, Fidel resigned as the president of Cuba after almost 50 years. His brother Raúl Castro became the new president and decided to reform the economy even further. He allowed the Cubans also to enter the tourist hotels, buy mobile phones, cars and even allow them to buy or sell their houses. This lead to a further increase of the economy.

During our stay in Cuba in November 2016, Fidel Castro unfortunately died at the age of 89. This had a big impact in the whole world and especially on the Cuban people as he was a big inspiration to them.

1.1.2 Demography

Nowadays, the Republic of Cuba has a population of over 12 million people. 75% of this population lives in urban areas. The capital Havana has over 2 million inhabitants, while the population of Santiago de Cuba also exceeds the one million. The population density is 100 residents per square kilometre.

The people from Cuba have a lot of different origins. The Indians were the first inhabitants, followed by the European colonialists. The Europeans also brought slaves from Africa towards the Caribbean region and thus to Cuba. Finally, also people from Asia moved to Cuba for working purposes. These different cultures have merged, which is visible in for instance the people themselves, food, architecture and many other characteristics.

The main language has been Spanish since the colonialization, like in the other Caribbean regions. The religion is mainly catholic, although a big part of the population can be considered as atheist.

1.1.3 Geography

Cuba is located just southwards of the Tropic of Cancer, in the heart of Central America. It is the largest Caribbean island and has an area of approximately 111,000 km^2 [1]. This area also contains the many smaller islands, which are also part of the Cuban territory. The Atlantic Ocean is located in the North and East of Cuba, while the Gulf of Mexico is on the western side. The Caribbean Sea is located on the southern side of the island.

Between the islands of Cuba and Jamaica a deep ridge, called Cayman Trench, is the boundary between the North American and Caribbean tectonic plates. The movement of these tectonic plates resulted in a generation of earthquakes and the tilting of the island. This resulted in lower mangrove swamps in the Southern part of the island with beaches which are much rockier, swampier and darker than in the North. The tectonic activity resulted also in the creation of limestone cliffs in the Northern part of the Island, while the beaches are much gentler with whiter sand.

The island itself is largely flat as it contains only four mountain ranges. The highest point is the Pico Turquino in the Southeast of the island and is 1,974 meters high.

1.1.4 Climate

As Cuba is located between the Tropic of Cancer and the equator, the Cuban climate is sub-tropical. This results in a high average temperature of 27°C. In August the average monthly temperature rises to 32°C and in January this decreases to a minimum of 18°C. The sea temperature has also an average temperature of 27°C. The relative humidity is on average 73%.

The summer months (from May to November) can be distinguished as the wet season, because 80% of the yearly rainfall falls in these months. The other 20% of the average annual rainfall falls in the dry season between December and April. During the dry season also cold fronts can appear from the North, which may cause strong winds, heavy rainfall and high waves. The geographical location of Cuba also results in a hurricane season between July to November. During this period multiple hurricanes passed Cuba over the last years, of which some can be characterised as extreme.

1.2 General information about the study area

Varadero is a holiday destination 130 kilometres east of Havana, located in the province of Matanzas. This is the biggest tourist resort in the whole Caribbean with its 22 kilometres long white beach. Along this beach a lot of hotels are located. Also the Iberostar Varadero hotel is located at this peninsula, almost at the most eastern point, see Figure 1-1.

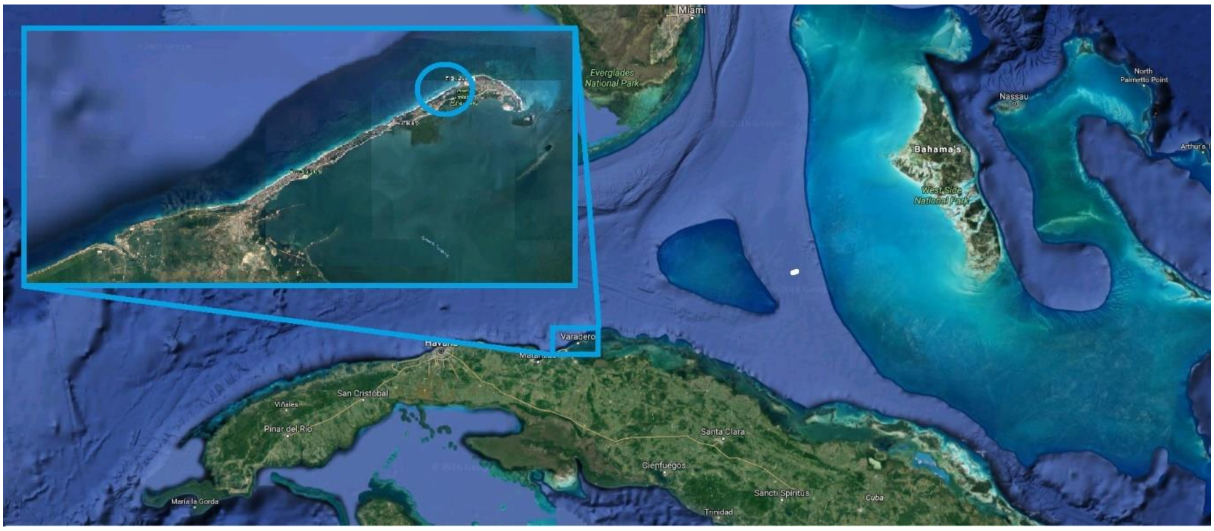


Figure 1-1 Varadero on the peninsula of Hicacos with the location of the Iberostar Varadero hotel [2]

Zooming in even further at our study area shows some information, see Figure 1-2. First it should be known that the length of the Iberostar hotel is approximately 500 meters. It can be seen that a headland is located eastwards of our study area. This is the Punta Francés, while at the western part of the area another headland (Punta Chapelin, not on the picture) is located, at a distance of approximately four kilometres from Punta Francés.

It is clearly visible that the beach in front of the Iberostar hotel is much smaller than the beaches around it. Furthermore it can be observed that there have not been built any obstacles yet.

Figure 1-2: The Iberostar area [2]

A more detailed image of the location of all the hotels is given in Figure 1-3.

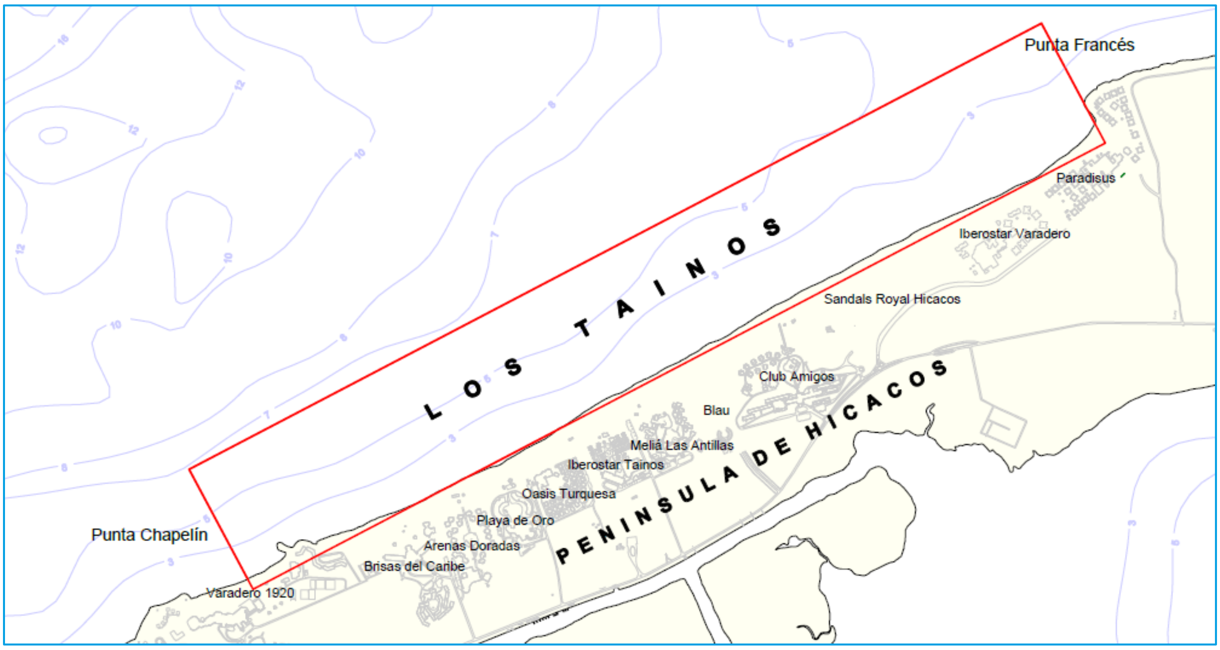


Figure 1-3 Overview location hotels **Fout! Verwijzingsbron niet gevonden.**

2. Problem description

2.1 Problem definition

For almost 40 years erosion problems are present at the Varadero resort area on the Hicacos peninsula. The income from tourist industry at the Hicacos peninsula is of vital importance for the economy of Cuba, and therefore the erosion problems at the peninsula form a potential threat for the Cuban economy. At this moment, especially the erosion problems around the Iberostar Varadero hotel are severe and need direct attention.

While the beach at other locations on the Hicacos peninsula reaches to a cross shore distance of 30 metres, the beach in front of the Iberostar hotel only reaches to a cross shore distance of a couple of metres. The stretch of this beach section is approximately 500 metres long and partly includes the beach in front of Hotel Paradisus Varadero at the eastern side. Research needs to be done on this erosion problem and a solution has to be made which includes the construction and maintenance of the Iberostar beach section, this in order to recover the recreational and aesthetic values of the beach section.

2.2 Objective

To set the objective of the project, a main research question and five sub questions are defined. The objective of the project is to find an answer on these research questions. The main research question is defined as follows:

What is the cause of the erosion in front of the Iberostar Varadero hotel and what is the optimal solution to solve the problem?

To be able to answer this question, several sub questions have to be answered. These questions are written down below:

A. *What is the contribution of basic longshore transport to the total amount of erosion?*

B. *What is the contribution of the different cross-shore processes to the total amount of erosion?*

C. *Are there any complex hydrodynamic processes around the Iberostar Hotel beach which may contribute to the erosion problem?*

D. *What is the best solution to the erosion problem?*

E. *How to construct the solution?*

2.3 Approach

Finding the cause of the erosion is the main focus on the project. It is necessary to really understand the underlying erosion processes to come up with a good solution. For research on different processes, different models are needed. In case of this project, UNIBEST, XBeach and Delft3D are used to determine the contribution of different erosion processes. In the overview below, the focus and belonging sub question of each model is elaborated. Sub question (E) is the only sub question which can be answered without the use of a model, nevertheless an answer to this question is of great importance as a solution is worthless if the construction of the solution is not feasible.

Unibest LT

Basic - Quantitative - Answering sub-question [A]

Unibest is used to get an idea of the quantities of sediment transport due to basic longshore processes. The model is calibrated by doing an extensive sensitivity analysis and validated by comparing the results with values of different earlier studies done on erosion at the Hicacos peninsula.

XBeach

Advanced – Quantitative and qualitative - Answering sub-question [B]

XBeach is mainly used for an analysis on the system response for cross-shore transport during cold fronts, storms and hurricanes. Important is how much sediment is transported offshore, if sediment gets lost and how this contributes to the total erosion problem. The result of the study is compared and combined with the longshore transport quantities to get more insight in the erosion problem.

Delft3D

Advanced - Qualitative - Answering sub-question [C]

Delft3D is used to find more hydrodynamic processes contributing to the erosion problem. Due to the limited amount of information and the limited available time, the study is done in a qualitative way. The Delft3D model is divided in two parts: first the flow patterns around the total peninsula are studied, and secondly more detailed flow patterns and erosion in the area in front of the Iberostar Hotel are investigated.

3. Analysis

3.1 Introduction

In this section, research is done on all important conditions, processes and characteristics for the study area around the Iberostar Varadero hotel. This information is needed to be able to properly investigate the causes of the erosion problem and to come up with a good final solution.

The first important analysis is the stakeholder analysis, in which it is the aim to know the different stakeholders, their interests and their relation to the project. Secondly, the coastal analysis will be executed in which all the major coastal processes and characteristics are studied. This is followed by an erosion analysis, based on the coastal processes of the previous analysis. Possible causes of erosion are investigated qualitatively, without the use of mathematical models. The erosion analysis is eventually used in section 4.5 to determine all the causes of erosion. Finally, the nourishment executed in 2012 is analysed to get more insight in the behaviour and effects of measures taken in the past.

3.2 Stakeholder analysis

To be able to execute the project properly, it is important to know which stakeholders are involved in the project, and especially what the power and interests of these stakeholders are. Furthermore insight in the relations between the different stakeholders helps to understand the role and position of different stakeholders in the project.

3.2.1 Stakeholders and their relations

The government of Cuba is the most important stakeholder. The relevant interests of the government are distributed over five ministries which are responsible for the different goals set by the government.

Logically, the Ministry of Tourism is involved in the project. The Hicacos peninsula is one of the most visited places in Cuba and therefore the Varadero region is of vital importance for the Cuban economy. The Ministry of Tourism is either partly or fully owner of the hotels at Varadero and therefore a very important stakeholder in the Iberostar project, as they want the beach to be as attractive as possible for the tourists.

A part of the Ministry of Tourism is called the Investment Office. They are responsible for all the real estate related to tourism. The tasks for the construction and maintenance of these buildings is even further distributed to a sub-organisation called ALMEST. Another part of the ministry of Tourism is the Exploitation Office, which is responsible for the management of the hotels. As some hotels are partly owned by the government, the other part is mostly owned by hotel companies from Europe and Latin America. So, they should be also considered as a stakeholder. Finally, also the tourists visiting the hotels have its influence on the project, as they can give a valuable opinion about the severity of the erosion problem.

Next to the Ministry of Tourism, also the Ministry of Science, Technology and Environment (CITMA) is a very important stakeholder. In our case, the Matanzas department of the ministry is the relevant stakeholder. CITMA is responsible for all maintenance and protection of the coastal zone. Therefore also the research carried out on the Hicacos peninsula is one of their responsibilities. When research has to be carried out, CITMA decides which company or institute may carry out the research. Research is often done by a governmental institution called the 'Oceanographic Institute'. In this project, earlier research done by the Oceanographic Institute is used as reference. It should also be stated that the institute CISAM is responsible for the environmental issues in our study area. They also can be considered as a stakeholder.

Another stakeholder is the Ministry of Higher Education, although their interest and power is limited. Project group MP210 with external students from TU Delft carries out the research under guidance of the Technical University of Havana CUJAE. The CUJAE is part of the Ministry of Higher Education.

The next important stakeholder is the Ministry of Construction. They are responsible for the construction and maintenance of the solution. They have the equipment and manpower to construct the chosen solution. They also connect to a contractor (from abroad) when the work can not be carried out by the Ministry of Construction itself.

Finally also the Ministry of Economics and Planning is involved in the project, as they decide about the amount of money which is available for the different governmental stakeholders.
Although the Hicacos peninsula is part of the Matanzas province, the Matanzas province does not have to deal with the erosion problems at the peninsula. Because of the importance of the Varadero area for the whole country, the area is under direct influence of the government and

its ministries. Matanzas province is only represented by the Matanzas department of the CITMA ministry.

Next to the previous five ministries, also the municipality of Varadero can be considered as a stakeholder as they are responsible for the protection of their inhabitants. Therefore the interest is quite high for this stakeholder. This also holds for the locals. They live in Varadero and are largely depending on the income by the tourists. An unattractive beach will result in less tourists and thus in less income.

In the figure below, the relation between the different stakeholders is given. The blue and purple colours represent the Cuban government on different scales. The green boxes are the governmental organisations. The grey boxes represent the private companies from abroad. Finally, the black boxes represent the individual people.

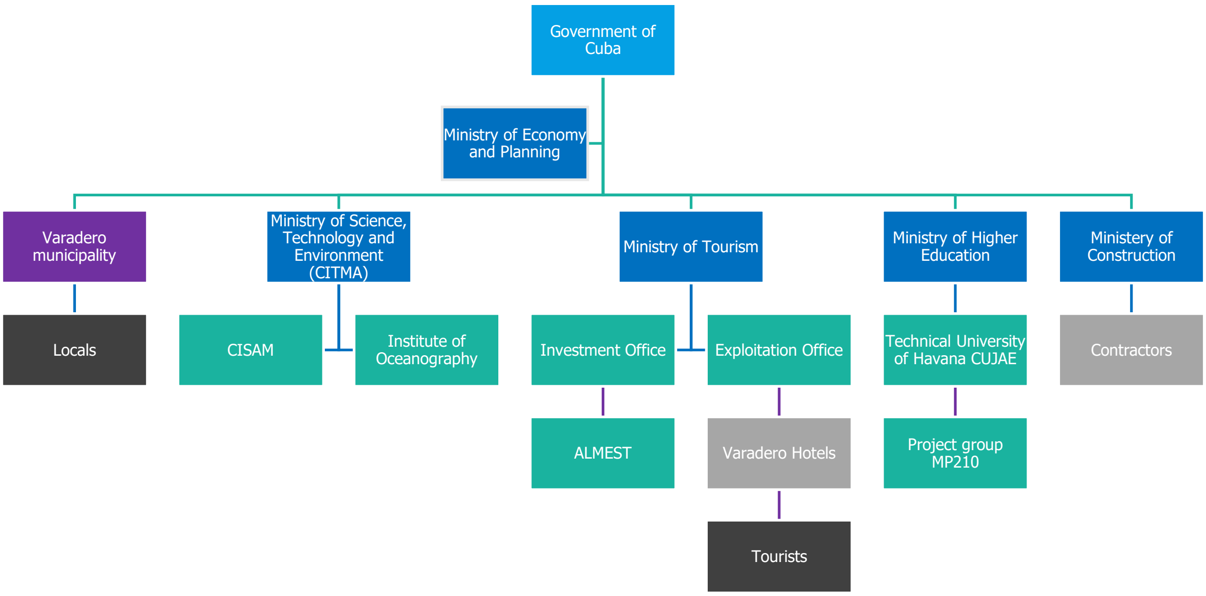


Figure 3-1 Stakeholders and their relations

3.2.2 Power and interest

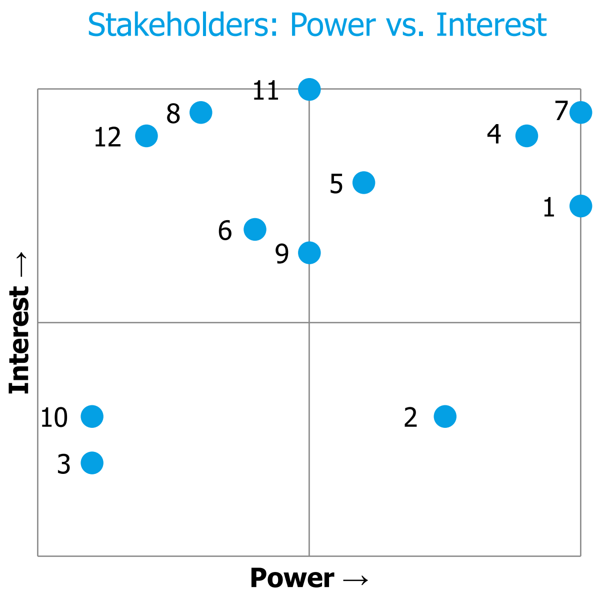
In this section the power and interest of the different stakeholders are explained. This is done for all different stakeholders, see Table 3-1.

Stakeholder	Interest	Goal	Power
Ministry of Economy and Planning	Earn money on the Varadero peninsula	To allocate the money to the reliable projects	High influence: Political
Ministry of Construction	Responsible for the construction of the solution for the erosion problem	To construct the hard solution and contact the contractors when they cannot build it	High influence: Political, manpower, equipment and knowledge
Contractors	Earn money by building the solution for the erosion problem	To offer best solution and to build this solution	Low influence: manpower, equipment and knowledge
Ministry of Science, Technology and Environment (CITMA)	Responsible for the environment and scientific research	Maintain the natural ecosystem in the coastal area	High influence: Political and knowledge
CISAM	Responsible for the environment in Varadero	Maintain the natural ecosystem in the Varadero coastal area	Reasonable influence: Regulations and knowledge
Institute of Oceanography	Obtain funds to research the project	Finding the best solution for the erosion problem, which they can execute	Moderate influence: Knowledge
Ministry of Tourism	Responsible for the development of tourist activity in Varadero. Earn money	An attractive environment for tourists to spend their holiday: large beaches	High influence: Political

Varadero hotels	Responsible for a good holiday for their guests	Have the best environment for the guests: big white beach	Some influence: Money from the private companies
Tourists	Have a nice holiday at the beautiful beaches	Large enough beach to enjoy a holiday	Moderate influence: Money
Ministry of Higher Education / CUJAE	Obtain research	Find the best solution for the problem	Low influence: Knowledge
Varadero Municipality	Responsible for protection of the Varadero population and earn money	Protect the environment and have an attractive area for the tourists	Moderate influence: Political and on the locals
Locals	Living in Varadero	Improve the living conditions	Low influence

Table 3-1 Stakeholders with their interest, goals and power

In Table 3-1, it can been read that there are several groups with different (even contradicting) kind of interests. Some stakeholders have as main concern the attractiveness of the beaches for the tourist, while on the other hand the stakeholders are more interested in maintaining the ecosystem. There are also some stakeholders interested in both concerns or they have a different main interest.



Nr.	Stakeholder
1	Ministry of Economy and Planning
2	Ministry of Construction
3	Contractors
4	Ministry of Science, Technology and Environment (CITMA)
5	CISAM
6	Institute of Oceanography
7	Ministry of Tourism
8	Varadero Hotels
9	Tourist
10	Ministry of Higher Education / CUJAE
11	Varadero Municipality
12	Locals

Figure 3-2 Stakeholders relation between power and interest

It is important to know the importance of the different stakeholders. In Figure 3-2, a power-interest grid is presented. On the vertical axis, the interest of the stakeholder is found, while the power of the stakeholder is found on the horizontal axis. Clearly visible is that almost all stakeholders have big interest in the project. The exceptions are the Ministry of Construction, the contractors and the Ministry of Higher Education or CUJAE. Also visible is that the governmental institutions have the highest influential power.

3.2.3 Conclusion

The most important stakeholders are taken out of the power-interest grid by looking in the quadrant with the highest power and interest, which is the upper right quadrant. The Ministry of Tourism, the Ministry of Economy and Planning and the Ministry of Science, Technology and Environment (CITMA) can be distinguished as the main stakeholders in the project. They all have both big interest as well as high power. Most of the other important stakeholders can also be described as governmental organisations. This is no surprise as Cuba is a mainly government-controlled country. Hardly any private organisations are involved in the project. The only non-governmental stakeholders with influential power are the tourists. If the tourists are not attracted by the beach at the Hicacos peninsula, they will plan a vacation at another beach (and maybe even in another country), which is clearly not what the government of Cuba wants.

In section 5, the different (even conflicting) goals from the stakeholders are translated in a list of requirements, which are used to design different solutions for the problem.

3.3 Coastal analysis

For a good model use, the coastal processes should be analysed. These are important as it is the input for the models. In this section several coastal processes are treated. First the bathymetry is explained, followed by the geology, climatology, hydrology, oceanography and finally the sedimentology. At the end of the section, the values of the parameters are presented in the summary. It should be noticed that the nautical directional system has been use in the rest of the report.

3.3.1 Bathymetry

The bathymetry in the Varadero area is quite complex. The Florida Strait is located north of Cuba and has a width of to about 150 kilometres. The bottom is very deep due to the fact that the Gulfstream flows through it, deepening the strait. On the North of our study area the width of this deep channel has been reduced to 40 kilometres with an average depth of 1,500 meters. On the other side of the peninsula the Cardenas bay is located, which is shallow lagoon area.

Nautical charts from Navionics [4] are presented in Appendix B. When zooming to the scale of our study area, it can be seen that the slope in front of the beach is very gentle. Further away from the coast, the slope becomes relatively steep towards the larger depths. The gentle slope can be easily seen in Figure 3-3. The steep slope is located outside of this figure, but can be found Appendix B.

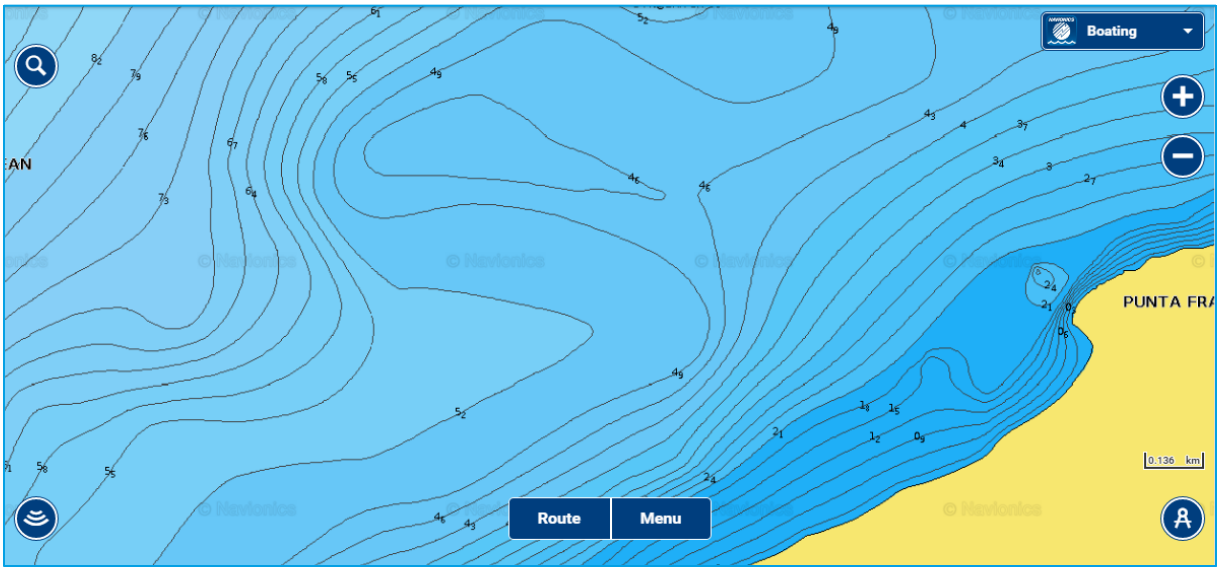


Figure 3-3: Bathymetry of the bottom profile in front of the Iberostar Varadero hotel [4]

The final bathymetry which is used in the models, is obtained by GeoCuba [5]. This bathymetry contains data for the whole peninsula with some additional cross-sections and beach profiles around the Iberostar Varadero hotel.

Some cross-sections were also obtained from the research on the Iberostar erosion by Iversiones Gamma S.A. and Apoyo al CITMA (Matanzas) [3]. More information on the bathymetry data can be found in Appendix C.

3.3.2 Geology

The geology of Cuba is a very complex system. There are many tectonic plates, which have a big influence on the shape of the country. This results in the big ocean depths south of Cuba, where the Caribbean plate moves towards the North American plate. These tectonic movements have tilted the island somewhat and created limestone cliffs in the north of Cuba and low mangrove swamps in the southern part of Cuba. Nowadays, Cuba can be stated as geological stable, as the geology is changing very slowly in time.

The Peninsula of Hicacos

The peninsula can be described as a natural barrier between the Florida Strait and the bay south of the peninsula. Although it looks like a spit, it is formed from a large number of small limestone islands. In time they were connected by the sand, which was produced by algae fields northeast of the peninsula. The wind brought these sediments to the islands to fill the gaps, which are the beaches nowadays. The rocky limestone islands can still be seen in the headlands separating the beaches.

The Iberostar Varadero area

When zooming in on our study area, it can be seen that the Iberostar hotel is situated at a location filled up by the sand. Just northeast of the Iberostar area a rocky headland (Punta Francés) is present and a few kilometres southwards of the study area another rocky headland (Punta Chapelin) can be observed. It is assumed that at these locations the sediment transport will be partly blocked. The area between the headlands has a length of 3.85 km and is called Los Tainos. The Iberostar area itself is 500 meter long.

A note has to be made about the length of the Iberostar area. Some available measurement data, used later in this report are done in an area called the Iberostar *section*. This section is not only the area in front of the Iberostar hotel, but also a containing a part of the Paradisus hotel, more on the east. To prevent confusion from now on there is a distinction between the Iberostar area (beach in front of Iberostar) and the Iberostar section.

The coastal profile at the Iberostar hotel can be characterised by a steep slope (s=0.333 m/m), from the Florida Strait up to a few kilometres offshore. From that point a very gentle slope (s = 0.005 m/m) can be observed until the waterline is reached. The cross-section above the waterline can be characterised by a small and steep beach (≈ 1.00 meter above the water level), a scarp (on the beach or at the start of the dunes) and a storm ridge (dunes up to 4.00 meters).

On top of these dunes grows a lot of vegetation, maintaining the dunes during the storm conditions. At most cross-sections there is also a sandy terrace behind the dunes.

In Figure 3-4 a cross-section of the Iberostar area can been seen. The hotel is located at the area called "Post Duna".

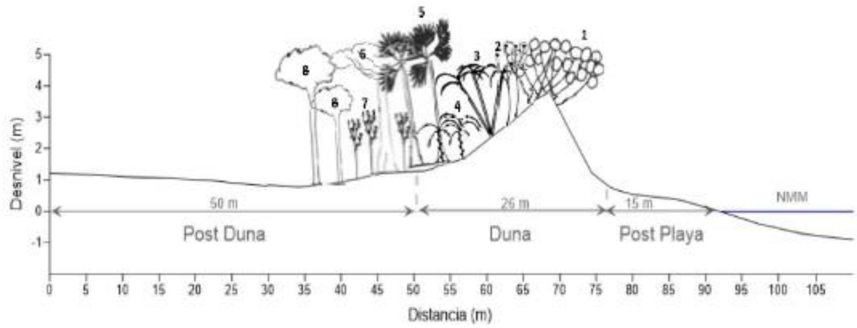


Figure 3-4: Cross-section in front of the Iberostar hotel [3]

3.3.3 Climatology

In this section the meteorological situation for Cuba will be explained in order to understand the characteristics in the sea. These characteristics are closely connected to the climate characteristics and the seasonal variations.

The Cuban climate is a subtropical climate. Despite the fact that there is little variation between the seasons, the climatological year can be easily divided in two parts: the dry season between December and April and the wet season between May and November. Between July and November you can also expect several tropical cyclones in the Caribbean, which sometimes affects the Cuban coast.

Rainfall

The annual rainfall in Cuba equals 1317 mm within 85 to 100 rainy days. As can be expected from the previous section, most of the total annual rainfall (80%) falls during the wet season between May and November. During these months the humidity is also high. Most of the showers don't last longer than 30 minutes.

One exception is during hurricanes and strong cold fronts from North America, when it is possible to rain for several days, marking the record high rainfall of 234 mm for just one day during hurricane Michelle. The average monthly rainfall in June is equal to 212 mm, which is the highest average monthly rainfall of the year. The lowest monthly rainfall is in March with an average rainfall of 53 mm [6].

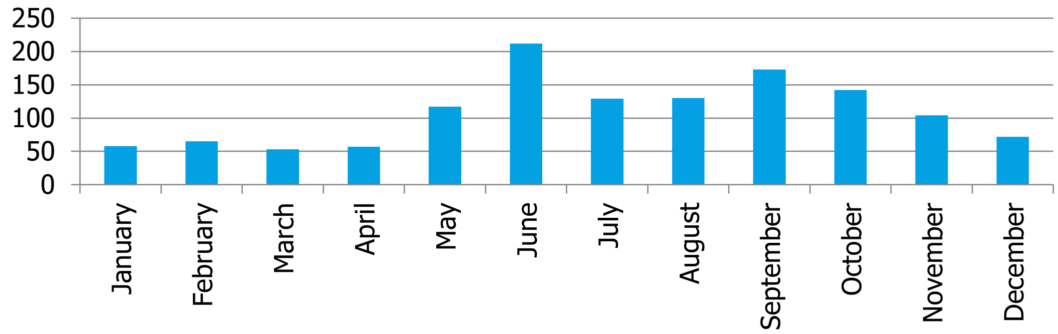


Figure 3-5: Average monthly rainfall (1970-2006) [6]

Temperature

The annual average temperature in Cuba is 27°C, which does not vary a lot between the winter and summer season. During the coolest months (January and February), the average minimum temperature is 18°C and has a maximum of 24°C. In the hottest months (July and August), the temperature rises from an averaged minimum temperature of 24°C to an averaged maximum temperature of 32°C [6].

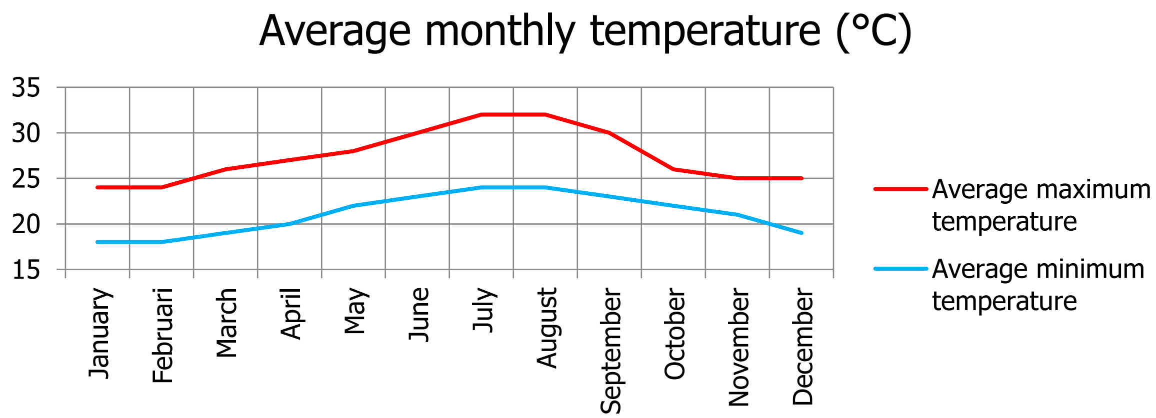


Figure 3-6: Average monthly air temperature [6]

Wind

Cuba is located in the subtropics (between 10° and 30°) on the Northern Hemisphere. As a result, Cuba lies in the area where trade winds blow due to the global wind system. These trade winds are directed from (north)east to (south)west and are the main winds experienced in Cuba. Sometimes these winds vary temporarily with the seasons. In the figure below, the wind rose is shown for the distribution of winds over the directions. On the right the distribution of the averaged three-hour wind speeds and frequency are presented for different the wind directions.

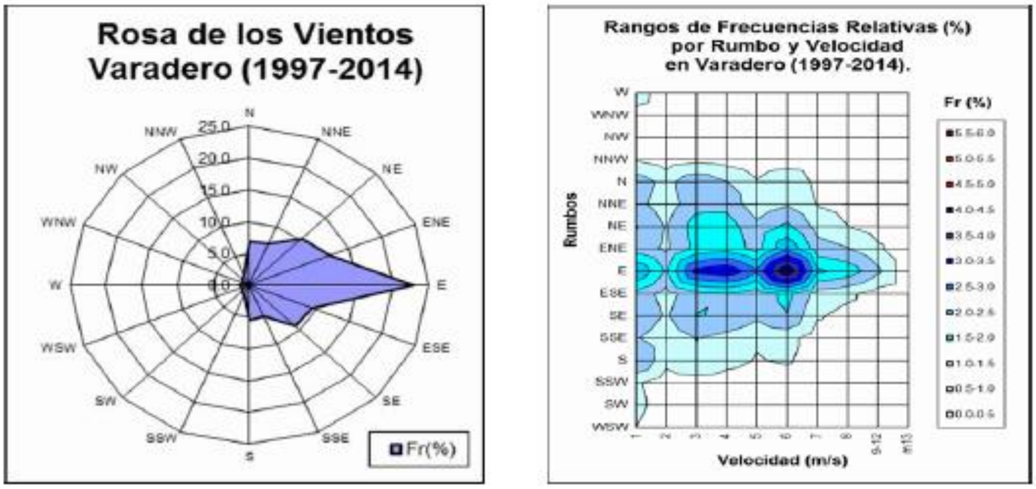


Figure 3-7: Distribution of wind speed, frequency and direction [7]

From Figure 3-7 it can be seen that the predominant wind direction is indeed from the east (22.8% of the year). There are also a lot of winds from the east-northeast (12.2%) and northeast (10.4%). The average wind speed over three hours is 4.14 m/s with a maximum measured winds speed over 3 hours of 7.0 m/s. From the predominant east, the average wind speed is equal to 4.78 m/s.

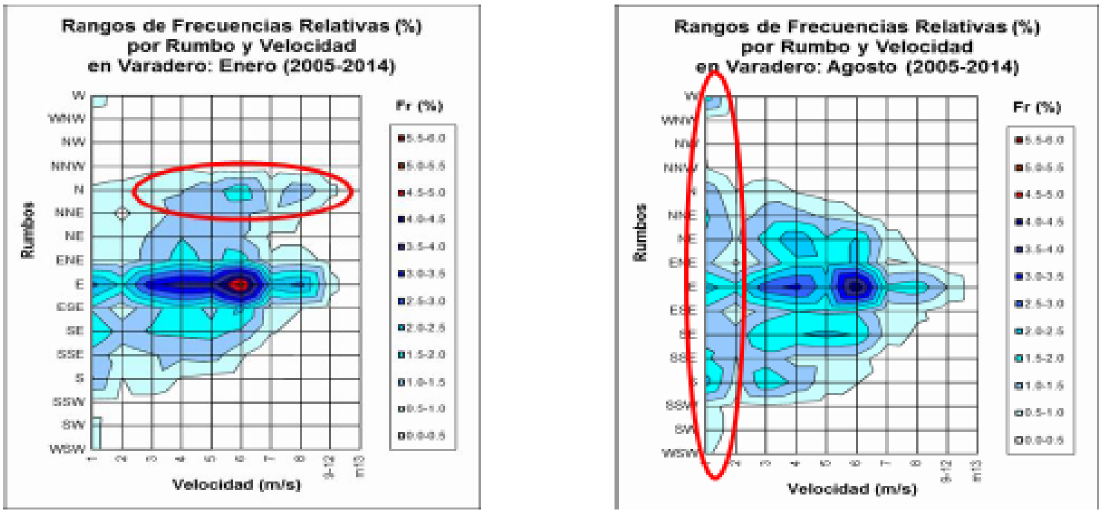


Figure 3-8: Distribution of wind speed, frequency and direction in January and August [7]

Figure 3-8 shows the differences in wind patterns between the dry and wet seasons. In the summer season the weather pattern is much calmer than during the winter. This results is much more relatively weak breezes, coming from all directions. In the winter, a lot more winds from northern direction are present. These are the so-called cold fronts, which will be explained in the next section. Another extreme event are hurricanes, which will also be treated further in the report.

Cold fronts

The Cuban coastal area has to deal with multiple types of extreme events over the year. These events (storms) can be divided into cold fronts, hurricanes and "regular" storms. Cold fronts arrive from the Gulf of Mexico. During the dry winter season approximately 20 cold fronts per year strike Cuba. This is a surface that separates the hot/humid air of lower attitudes from the cold/dry air at higher attitudes. The cold fronts bring a lot of cold wind accompanied by rainfall from North America. The winds can be very strong, especially when it comes from the Northwest due to the big fetch. These big winds result in the generation of big waves at the Gulf of Mexico towards the Cuban coast. The cold fronts can be classified by their maximum mean wind velocity in the following way:

Classification	Maximum mean wind velocity (km/h)
Weak	<35
Moderate	36-55
Strong	>55

Table 3-2: Classification of cold fronts by wind velocity [8]

Besides their strength, cold fronts are also classified by their origin based on the turning of the winds at the surface. This results in the following cold fronts:

Type	Characteristics
Classical cold front	First winds from the South, but when the low centre moves to Cuba the wind changes to West to Northwest. This change in wind direction results in an increasing wind velocity.
Secondary cold front	One/Two days after classical cold front. It only results in small discontinuities in the weather.
Revision cold front	These fronts produce a wind in the Northern to Eastern direction, accompanied by temperature fall, cloudiness and rainfall.

Table 3-3: Classification of cold fronts by type [8]

The Cuban meteorological institute has been measuring the cold fronts over the last 60 years. From these measures it can be seen that the maximum number of cold fronts hitting Cuba in one year equals 35, while the minimum is equal to 11 in one year. On average there are 21 cold fronts per year and hit Cuba in general between December to April [7]. Because of the big wind velocities and big waves, the cold fronts have a big effect on the coastal characteristics of the Varadero coast.

In this report a minimum wind speed of 35 km/h is used for a weak cold front, while at least a wind speed of 50 km/h is needed for simulating a strong cold front.

Hurricanes

Another (even more) extreme event is the occurrence of hurricanes. The biggest probability of a hurricane hitting Cuba is in the period between July and November. Sometimes these hurricanes hit the Cuban mainland, which causes a lot of casualties and damage.

Tropical hurricanes start developing from a low-pressure area in the Atlantic Ocean just Northwards of the equator at locations with a temperature of the upper sea layer above 26.5°C. During their lifetime they can grow to low pressure areas with a diameter of 1000 km. These low-pressure areas can transform in a hurricane, which results in extreme rainfall, swell, big set-up of the water levels and extreme wind velocities.
In the centre of the hurricane, the air pressure drops to an extreme low level, which also results in a rise of the water level in deep waters. The hurricanes can be classified by their air pressure in the centre and the maximum wind velocity by Saffir-Simpson (1974):

Category (Saffir-Simpson)	Pressure in the centre (hPa)	Maximum wind velocity (km/h)	Classification
1	>980	118-153	Small
2	979-965	154-177	Moderate
3	964-945	178-209	Extensive
4	944-920	210-250	Extreme
5	<920	>250	Catastrophic

Table 3-4: Classification of hurricanes

The following return periods were found for the different category of hurricanes directly affecting Cuba:

Category	Relative frequency	Return period
1	0.34	3 years
2	0.23	4 years
3	0.12	8 years
4	0.08	13 years
5	0	-

Table 3-5: Relative frequency and return period for different hurricane categories [7]

Through the fact that hurricane produces higher wind velocities, higher wave heights, higher set-up of the water levels and more rainfall, the cold fronts still causes more (economic) damage because of the more frequent cold fronts. For simulating the hurricanes a wind speed of at least 118 km/h is used.

3.3.4 Hydrology

In this section, the characteristics of the seawater are shown. The average annual sea temperature is 27°C and varies from 32°C in the summer to 24°C in the winter, which can be seen in Figure 3-9 [6].

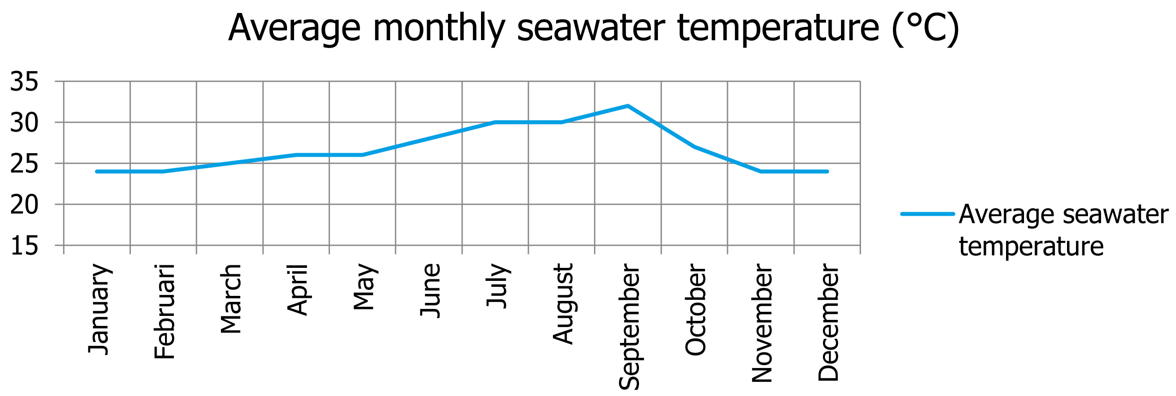


Figure 3-9: Average monthly seawater temperature [6]

Another important parameter is the salinity. This fluctuates during the season between 35.4 ppt and 35.6 ppt. It is assumed that it is sufficient to use the average salinity of 35.5 ppt as our timescale is much longer than one year.

By using the seawater temperature and salinity, the density can be calculated by the program CRESS. This resulted in a density of 1022 kg/m^3. The program was also able to compute the kinematic viscosity of the seawater by using the temperature. This is $0.866 \cdot 10^{-6}$ m^2/s for the seawater in our study area.

3.3.5 Oceanography

In this section, the characteristics of the ocean are shown. The main currents, tide, waves and storm surge characteristics are explained. Finally, climate change is also taken into account.

Tide

The character of the tide at the Peninsula of Hicacos can be described as a mixture between diurnal and semi-diurnal characteristics. Due to this mixture, an inequality between the tides is distinguished.

The magnitude of the tide is a result of water depth and the shape of the coast. As the Florida Strait and the Gulf of Mexico can be seen as an enclosed sea, the magnitude of the tide will be small. This results in a mean spring tidal range less than 1.5 meter.

In general, the average tidal range for the coast of the peninsula is 0.5 meters and a maximum range of about 1.0 meter. Due to the differences in the bathymetry and the shape of the coast in front of the Iberostar hotel, the average tidal range is even smaller at this location (0.4 m). The maximum tidal range (during springtide) is around 0.8 meters.

The amplitudes of the different tidal components are obtained from Havana IHO [9], a tidal observation station located near Havana. The tide components are shown in Table 3-6, while the tidal movement is plotted in Figure 3-10.

Tidal signal	Amplitude (m)	Tidal period (days)
M2	0.127	28.986
O1	0.101	13.943
K1	0.094	15.044
S2	0.042	30
P1	0.026	14.956
N2	0.026	28.436
Q1	0.023	13.398
K2	0.012	30.075
M4	0.004	57.968
M6	0.002	86.952

Table 3-6 Tidal Components from tidal station Havana IHO [9]

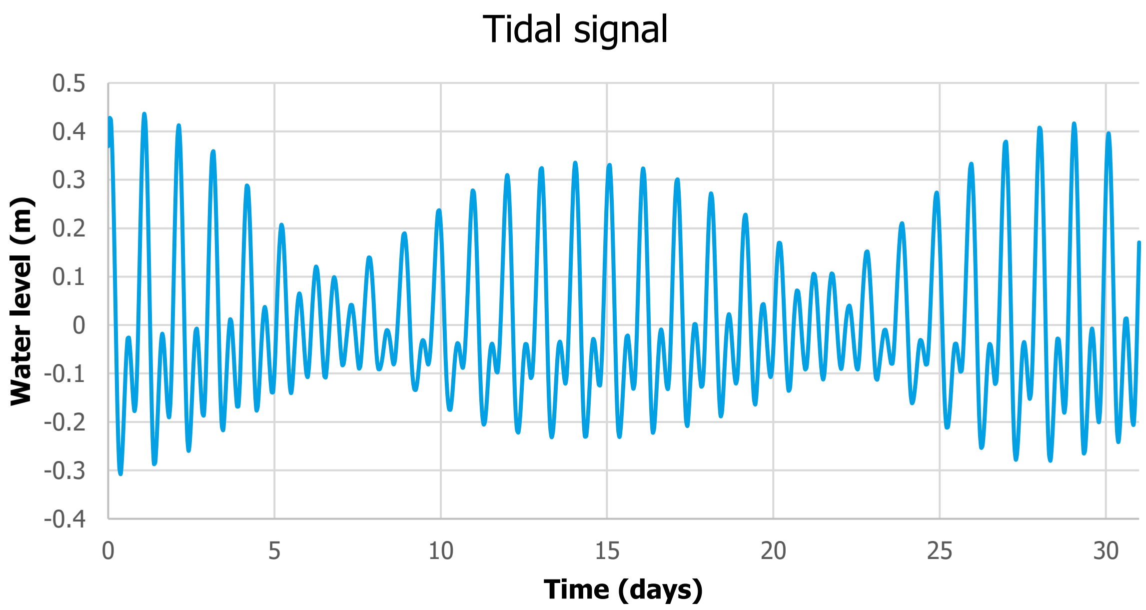


Figure 3-10: Tidal components and tidal signal

Currents

The currents along the beach at the beaches of Varadero are induced by the winds and tides. The distribution of the winds has been treated before. Along the coast this has a net direction from East to West measured over the year.

More offshore, the Gulfstream is the only influence on the direction of the currents. In the Florida Strait, this current is located from West to East. This current is mainly from the South Atlantic Ocean, flowing towards the Gulf of Mexico and then through the Florida Strait.
The main direction of the resulting tidal current is during flood towards the East-North-East, while its main direction is West-South-West during ebb. The average velocity is 0.1 m/s and the maximum velocity is 0.37 m/s [10].

Another forcing for currents is differences in temperature, salinity and density. Due to the small differences in temperature, salinity and density in our study area, it is assumed that these currents have such small velocities that they are neglected.

Waves

The main source of wave data is obtained from Argoss [11]. The data set consists of wave measurements from 1992 till 2014 for every three hours. The location of the measurements can be seen in Figure 3-11.

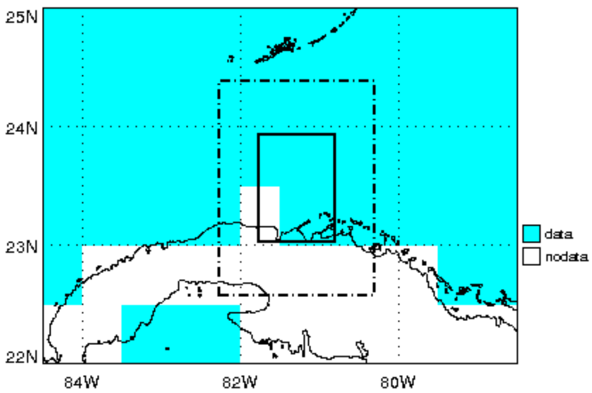


Figure 3-11 Location measurements Argoss wave data set [11]

The amount of data is enormous, so to make it usable different types of analyses have been executed:

- Weather condition analysis
- Wave reduction analysis
- Hurricane analysis

For each analysis it is stated that the data set should be summarized into a couple of wave conditions, which can be used as input, representing reality in some way. Depending on the objective of the model using this input, the wanted type of data can differ.

In section 4.1 (Figure 4-1) the whole modelling plan is schematized. It's also shown which wave analysis is used by each model. Below the method behind each analysis is described and additionally the resulting wave input data.

Weather condition analysis

If one wants to easily analyse some patterns occurring during certain conditions, the wished input for a model would be a uniform wave pattern which represents a typical weather condition. The main objective of the models using this analysis is to give a qualitative description about the situation resulting from these conditions. So the main target of the analysis is not to represent reality, but to divide the full wave climate into multiple conditions, which are analysed separately. For more information about this analysis and the way it is executed, see Appendix D.1. The results of the analysis are shown in Table 3-7.

	H_s (m)	H_{dir} (°)	T_p (s)	U_s (m/s)	U_{dir} (°)	Occurrence (%)
Weak storm NE	2.17	43.9	5.97	10.60	51.0	3.47
Weak storm NW	2.16	265.1	7.60	8.75	350.2	2.82
Heavy storm NE	4.30	52.8	8.11	16.29	48.0	0.04
Heavy storm NW	4.90	280.8	9.68	13.83	287.5	0.05
Normal condition NE	0.81	42.4	6.33	5.52	45.2	25.5
Normal condition N	0.85	320.3	5.86	4.89	6.0	19.1
Normal condition NW	0.85	359.9	6.08	5.57	25.6	17.1

Table 3-7 Overview of the results from the weather condition analysis

It has to be noticed that storms coming from the northwest are mainly caused by cold fronts. These cold fronts are a well-known phenomenon and cause large damage to the coastal area. From Table 3-7 it can be verified that the heavy storms from the northwest are on average stronger than from the north east.

Wave reduction analysis

To obtain the most realistic results for input, the wave reduction analysis is executed. The main idea behind this analysis is that a limited amount of wave conditions approach reality as accurate as possible. A part of the method is calculating the relative importance on sediment transport for each wave condition, to eventually choose the most important wave conditions which can represent the whole data set. For more information about this analysis and the way it is executed, see Appendix D.2. The results of the analysis are shown in Table 3-8.

Box id (-)	H_s (m)	Dir (deg)	T_p (s)	S*P block (m^3)	S*P rep. (m^3)	F (-)	P_0 (%)	P_{tot} (%)	P_{tot} (days/ year)
1	2.75	258.75	6.5	0.231	0.018	12.77	0.006	0.077	0.282
2	2.75	281.25	8.4	1.418	0.204	6.93	0.060	0.412	1.505
3	5.75	281.25	10.2	0.168	0.053	3.18	0.004	0.014	0.052
4	1.75	303.75	7.8	1.452	0.457	3.18	0.625	1.987	7.251
5	3.25	303.75	9.2	1.197	0.316	3.79	0.071	0.271	0.987
6	1.75	11.25	5.7	0.953	0.686	1.39	0.409	0.568	2.074
7	2.25	11.25	6.3	0.793	0.448	1.77	0.232	0.411	1.500
8	0.75	11.25	6.7	0.241	0.086	2.80	1.756	4.924	17.972
9	1.75	33.75	5.5	1.062	0.390	2.72	0.652	1.774	6.474
10	2.75	33.75	6.7	0.757	0.388	1.95	0.147	0.287	1.046
11	4.75	33.75	7.8	0.317	0.081	3.90	0.006	0.023	0.087
12	1.75	33.75	5.5	0.999	0.344	2.91	1.469	4.267	15.575
13	3.25	56.25	7.1	0.865	0.382	2.64	0.155	0.408	1.489
14	1.75	56.25	6.3	0.878	0.262	3.34	0.478	1.597	5.829
15	1.75	348.75	6.8	0.189	0.055	3.43	0.687	2.361	8.616
Total				11.52	4.17	-	6.757	19.38	70.7

Table 3-8 Overview of the results from the wave reduction analysis

Hurricane analysis

For the modelling of hurricane conditions, the wave conditions are not captured by the weather and wave-reduction analysis. Hurricanes occasionally impose extreme conditions on the coast with possible destructive effects. To convert general hurricane characteristics into wave condition boundaries for Varadero, models have to be used.

For two hurricanes that are known to have caused serious erosion at Varadero, Michelle and Wilma, this study was made by Noriega [12] and Garrote [13]. The general characteristics of the hurricanes and the time-series can be found in Appendix D.3, the maximum occurring conditions during the hurricanes are presented in Table 3-9.

	H_s	T_p	Dir	W_{lev}
Michelle	3.85	7.76	22.00	1.11
Wilma	4.93	12.89	310.22	1.60

Table 3-9 Maximum offshore wave conditions during hurricanes Michelle and Wilma

These wave and water level conditions are available as hourly data and in Delft3D-WAVE converted to nearshore boundary condition to be used in XBeach. In this way the behaviour of the Iberostar section during extreme hurricane conditions can be modelled adequately.

Surge

Storm surge is the water level set-up induced by extreme conditions. This is a temporary rise of the water level due to the atmospheric pressure, wind set-up and wave set-up.

When the atmospheric pressure drops 1 mbar, then the water level rises with 0.01 meters. The lowest atmospheric pressures will be located at the eye of a hurricane. This can lift the water levels up to 1 meter above the water levels in normal atmospheric conditions (1,013 mbar). During hurricanes the water level can be raised more than one meter due to this phenomenon.

Onshore directed wind results in a wind set-up at the coast. This a water level rise due to the shear stress of the wind on the water surface. Using CRESS with a maximum hurricane wind velocity results in a wind set-up of 0.90 meters. CRESS (Coastal and River Engineering Support System) is an offline calculation software used multiple times during the project.

The wave set-up is the water level rise due to breaking waves in the surf zone. This can be derived from the balance between the water level slope and the radiation stress change. This wave set-up is variable under different wave directions, wave heights and breaker indices.

During hurricanes a maximum storm surge level of 1.5 meters have been measured. The factors mentioned above can result in even slightly higher storm surges. So, the maximum storm surge in front of the Varadero coast can be theoretically around 2.5 meter, but it is not assumed as a realistic value. For the maximum atmospheric set-up, just 0.30 meter is taken into account. This is much smaller than mentioned above, but the extreme set-up can only occur in the eye of the hurricane where only a small fetch exists. It should also be stated that it is unlikely to have a big wind set-up at the same time as the wave set-up. The maximum wind set-up will occur during the short time of the storm itself. The maximum wave set-up will be reached a few days after the storm has passed, due to the incoming swell waves. So, as a final maximum storm surge of 1.6 meter is assumed.

Climate change

A result from climate change is the sea level change. Due to the melting ice caps the sea level rises in the whole world. The Institute of Oceanology [14] has measured a rise of 1.84 mm/year during the last century. They also calculated that the sea level rise will increase to 2.9 mm/year, which is in agreement with several international calculations.

3.3.6 Sedimentology

The sediment is treated in this section. It is very important in order to understand the processes of sediment transport, the beach profiles and the areas where accretion and erosion take place. Therefore the origin, composition and characteristics of the sediment and the morphological changes will be treated.

Origin and composition

The sediment in front of Iberostar is originating from the bottom of the ocean. Due to the limited terrestrial sediment supply, the sediments are mainly carbonated sands. The biogenic composition can be found in the report by Gamma (2015) [3] and gives the following values:

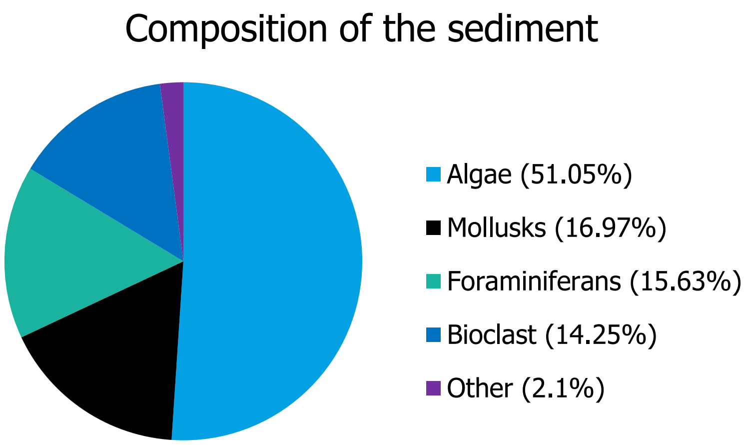


Figure 3-12: Composition of the sediment

As seen in Figure 3-12, the composition of the sediment is almost entirely from algae, shells or other organic deposits, which confirm the fact of limited terrestrial sediment supply. The main source seems to be the Halimeda algae, which grows in fields 10 kilometres Northeast of the Iberostar beach. The Institute of Oceanology [15] has estimated that the sand production is 10 kg/m^2/year in that area.

Characteristics

In the Gamma report (2015) [3] several cross-shore profiles around the Iberostar hotel are presented. These cross-shore profiles and their location are shown in Appendix C.

The same report also mentions the grain diameter of the sediment in the Iberostar hotel area. It was found out that the mean diameter of the sediment (D_{50}) is equal to 0.27 mm. For the D_{90} a value of 0.74 mm has been measured. This means that the sand can be characterised as course sand.

The density of the sediment is also an important factor. 'Normal' sand has a density of 2650 kg/m^3, but the sand at our beach contains a lot of calconite. This has a specific density of 2716 kg/m^3. Therefore it is assumed that the sediment at our coast has a saturated sediment density of 2700 kg/m^3. The relative density can be calculated by using formula:

$$\Delta = \frac{\rho_s - \rho_w}{\rho_w} = \frac{2700 - 1022}{1022} = \frac{1678}{1022} = 1.64\ [-]$$

The porosity for this coarse sand should be 0.35 according to CRESS.

The Chézy-coefficient can be calculated when the grain size is known. For normal conditions with an offshore significant wave height of 0.53 m, the wave height will be just 0.44 m. At this location the water depth is just 1.2 meters deep and the bottom roughness may be assumed to be equal to 3 times the D_{90}, which is equal to 3 * $7.4 \cdot 10^{-4}$ = 0.00222 m.

$$C = 18 * \log\frac{12 * h}{r} = 18 * \log\frac{12 * 1.2}{0.00222} = 68.62\ \sqrt{m}/s$$

Where:

C	Chézy-coefficient	[√m/s]
h	water depth	[m]
r	bottom roughness	[m]

Knowing these data, the fall velocity can be computed. This is the maximum velocity of a particle when the gravitational force equals the drag force on the particle. The fall velocity is a function of the shape and density of the sediment particles. The fall velocity can be computed by using CRESS. This results in a fall velocity (w_s) of 0.041 m/s.

3.3.7 Summary

In this section all the variables are shown which have been used in the different models.

Section	Type	Average	Extreme conditions
Bathymetry (for more information, see Appendix C)			
Geology			
Coastal length	Los Tainos Iberostar hotel	L = 3.85 km L = 500 m	- -
Slope	Further from coast First 2 kilometres	s ≈ 0.333 m/m s ≈ 0.005 m/m	- -
Climatology			
Rainfall	Seasonal	1,317 mm/year	Jun: 53 mm/month Mar: 212 mm/month
Temperature	Sub-tropical	T = 27°C	Jan: minimum 18°C Jul: maximum 32°C
Wind	Wind	U_{av} = 4.77 m/s from NE/E	Weak CF u>35 km/h Strong CF u>55 km/h Hurricane u>118 km/h
Hydrology			
Temperature	Sub-tropical	T = 27°C	Feb minimum 24°C Sep maximum 32°C
Salinity	Seasonal	S = 35.5 ppt.	35.4-35.6 ppt.
Other	Seawater density	ρ_w = 1022 kg/m^3	-
	Kinematic viscosity	$\nu = 0.86 \cdot 10^{-6}$ m^2/s	-
Oceanography			
Tide	Semi-diurnal	Average TR = 0.4 m	Spring tide = 0.8 m
Currents	Generated by tide	v = 0.1 m/s	v = 0.37 m/s
Waves (analyses)	Weather condition	See Table 3-7 and Appendix D.1	
	Wave reduction	See Table 3-8 and Appendix D.2	
	Hurricane	See Table 3-9 and Appendix D.3	
Surge	Storm surge	-	ζ = 1.6 m
Climate change	Sea level rise	+2.9 mm/year	-

Sedimentology			
Grain sizes	Course sand	D_{50}=0.27 mm D_{90}=0.74 mm	-
Density	Calconite sand	ρ_s = 2700 kg/m^3 Δ = 1.64	-
Porosity	Coarse sand	p = 0.35	-
Roughness	Chézy	C = 68.62 m$^{1/2}$/s C_{90} = 77.20 m$^{1/2}$/s r = 0.0022 m	-
Fall velocity	Van Rijn	w_{50} = 0.041 m/s	-

Table 3-10 Overview of fixed parameters

3.4 Erosion analysis

The coastal system is subject to a lot of forces. The changing gradients in sediment concentration result in locations with accretion or erosion. Subsequently this is the cause of shifting of the coastline and decreased or increased width of the beach.

In order to design the optimal solution for the beach erosion problem at Iberostar Varadero, the different sediment transport processes should be known. In this section first some general information about sediment transport is given. This general information is about initiation of motion and the different transport modes. Next the observations at the Iberostar hotel are presented. The first part is about schematization of the area and the second part is about the different possible causes of erosion or accretion. Finally, the expected sediment transports under the normal conditions and under extreme conditions are explained qualitatively.

3.4.1 Sediment transport mechanisms

Initiation of motion

Sediment transport can only take place when the water movements generates a big shear stress. When it exceeds a specific critical shear stress, the grains will be transported. The forces that start this transport due to the shear stress are the drag force F_D and the lift force F_L. This should be bigger than the gravity force F_G, which keep the sediment at its place. The motion is started by the force due to flow, which can be the result of either waves, tide or wind. Depending on the force of the flow, different forms of sediment transport are found. These are bed load transport and suspended load transport. The bed load transport is located close to the bed by rolling or sliding sediment, while the suspended load transport is a transport of sediments in suspension of the water. Suspended load transport increases when larger turbulence stresses are present.

Transport modes

The sediment transport is defined as volume of sediment moving through a plane. This plane is in vertical defined between the bed level and the water level. In horizontal direction this has a size of the surf-zone. This is done to consider the total wave-induced sediment transport in front of the coast.

The transport of sediments is a continuous process with different directions and amounts over time. The net cross-shore transport is the net amount and direction of the sediment transport perpendicular to the coast. This sediment transport is generally caused by orbital velocities, undertow and gravity along the slope. The gradients in cross-shore sediment transport directly influence the coastline by erosion or accretion.

On the other hand, the net alongshore transport is the net amount and direction of the sediment transport parallel to the coast. This sediment transport is generally induced by the radiation stress of non-perpendicular incoming waves. It does not directly influence the coastline, but it introduces gradients in transport, which results in erosion and accretion areas along the coast.

There is also a difference in short-term and long-term sediment transport. Cross-shore transport is mostly generated during an extreme event, which is important during short-term sediment transports. During most cases of extreme events, this leads to a short period of severe erosion. This extreme sediment transports are only found a few times a year. Structural erosion is part of the long-term sediment transport.

3.4.2 Observations at the Iberostar Varadero hotel

Schematization of the area of interest

A littoral cell is a part of the coastline in which all processes of the sediment transport are connected. In theory it should have zero longshore sediment flow through its updrift and downdrift boundaries. This can be the case when on both sides of the littoral cell a headland is located which blocks all the longshore sediment. On the land and sea side it can contain some source or sink terms, where sediment will be added or extracted. An example of a littoral cell is presented in Figure 3-13.

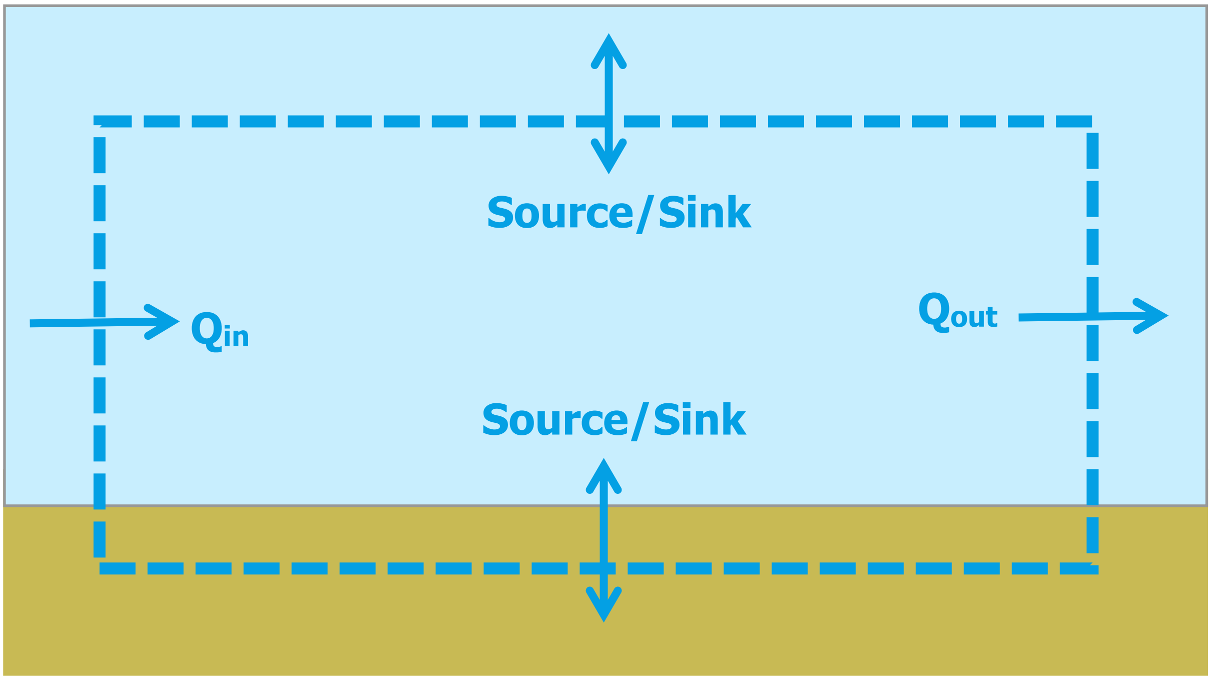


Figure 3-13: Cell schematisation

Punta Francés and Punta Chapelin do not reach far enough into the sea to block the full sediment transport. Therefore the cell between the headlands cannot completely be considered as a littoral cell. It can still be seen as a cell, but with some input and output of sediments on the boundaries.

Possible causes for erosion or accretion

There are different causes for sediment transport, resulting in erosion or accretion, which all influence the terms for Q_{in}, Q_{out}, and for sources and sinks. The most important ones are explained in the remaining of this section.

- Bathymetry irregularities
- Bed material irregularities
- Extreme conditions
- Human interference
- Relative sea level changes
- Sediment transport gradients

Bathymetry irregularities

Irregularities in the bathymetry have a big influence on the flow. Natural groynes may block (a part of) the longshore sediment transport. In our study area the Punta Francés can been seen as a natural groyne, which blocks a part of the alongshore sediment transport.

Natural breakwaters can block the cross-shore sediment transport, because a part of the sediment will not be able to pass this breakwater anymore. At our study area there are no natural breakwater located, so this cause of erosion can be neglected.

Irregularities in the bathymetry can also result in the occurrence of rip-currents. This is a current along the coast converging with another current in the opposite direction. At the location where they meet, the direction changes towards the deep ocean. These currents have a high flow velocity and generates a sediment transport to an area far offshore.

Finally, irregular bathymetry can also result in convergence or divergence of waves due to refraction. When the waves converge, the wave height will increase, leading to a larger sediment transport and possibly a location with erosion. Diverging waves result in lower wave heights and thus smaller impact, leading to a decrease in sediment transport and possible accretion.

Bed material irregularities

Changes in bed material will change the profile of the beach. The bigger the grain sizes, the steeper the equilibrium beach slope. As the sediment supply is from the algae field approximately 5 kilometres from the study area, it can be assumed that the composition and grain sizes of the sand are constant in our study area.

Unless the same diameter and composition of the sand, there are still some differences by bed material. Spread across the study area, some rocks can been found. Behind these rocks (from current point of view), there is a transition between rock and sand, which decreases the sands ability to settle. In our study area hardly any rock can been found, so this cause of erosion can be neglected.

Extreme conditions

Extreme conditions are short-term periods in which most often strong erosion takes place. This big amount of erosion is mainly induced by the cross-shore sediment transport. There are different extreme conditions which could lead to this erosion.

Storms (cold fronts and hurricanes) result in two different processes which affect the coastline. Due to the low pressure the water level will be increased which causes erosion at the higher locations along the coast as the waves have an impact on these higher locations. And these wave impacts will be also increased by the increased wind velocities. This results in more material moving from the upper beach to an offshore location. When the storm has passed it takes some time for the sediment to return in order to satisfy the equilibrium beach profile. When there is not enough time between the storms, there is not enough time to recover to this equilibrium profile. This can result in a structural erosion of the coast.

Another form of an extreme condition is extreme rainfall. During the extreme rainfall, the rainwater which falls on land wants to go to lower areas, for instance the sea. This results in small streams from land to sea, which erodes the beach. Finally, the sediment eroded by the streams ends up in the sea. In the Varadero region extreme rainfall takes place several times per year, but the wind recovers these eroded areas quite fast. Also the amount of sediment transported due to rainfall is very low compared to the transport due to waves, therefore this process is not taken into account. When rivers are present close to the area of interest, the influence of extreme rainfall is larger, however, in this project this is not the case.

Human interference

The interference of humans along the coast can have a big influence on the coastal processes. This interference can take place in several ways. For instance when changing the beach profile, the original sediment transports changes considerably due to the changed beach profile. This profile is out of equilibrium and this results in a gradient in sediment transport around the location of human interference. For the current solution, see section 6.1.5, also changes in the beach profile are made by shifting the dunes in landward direction. This probably has a significant impact on the erosion during storm conditions, when the water will flow over the newly created beach.

Another form of human interference are artificial constructions which block (part of) the sediment transport. Examples are groynes or breakwaters. In our study area no hard structures have been built, so this can be neglected. Also smaller forms of human interference are possible, for instance the presence of stairs to cross the dunes. However, the influence of these small structures is relatively low and only present during storm conditions when the water reaches the dune. Therefore, these human interferences are also not taken into account.

Relative water level changes

The relative change of the water level is generated by different processes. At the Varadero coast, this is a relative water level rise, which results in a wave impact located much higher on the beach. This induces erosion at this location. It also has an influence on the wave impact on the sea bottom and on the flow velocities.

The most important factor of the relative change in water level can be assumed to be the global sea level rise. This will lead to a rise of 2.9 mm/year as was explained in the section 3.3.5. Also tectonic activity and compaction of the soil can have an influence on the relative water level.

Sediment transport gradients

Gradients in sediment transport are the cause of the changes in bathymetry. The unstable bathymetry changes towards the new stable bathymetry by accretion and erosion of sediments at the locations with an unstable bathymetry. There are several reasons for the sediment transport gradients.

Longshore sediment transport

The longshore sediment transport is the net sediment transport parallel to the coastline. This is in the same direction of the coastline and is induced by oblique incoming and refracting breaking waves. Due to these waves a shear component of the radiation stress arises, which finally results in the wave induced longshore current.

Most of the sediment transport takes place in the surfzone as the breaking waves induce most turbulence, which brings the sediments in suspension. Another phenomenon which induces the sediment transport is the orbital motion of the waves, where the magnitude of the shear stress changes over the wave cycle. During its peak the sediment can be mobilised and transported.

When the gradient of the sediment is positive, more sand will go out of the area which results in erosion. A negative sediment transport results in accretion due to an increase in sediment material in the area.

This gradient can be influenced by differences in incident angles along the coast, wave heights along the coast and the wind and wave driven currents. In the study area this possible erosion cause should be definitely taken into account.

Cross-shore sediment transport

The cross-shore transport is the net sediment transport perpendicular to the coastline. This sediment transport is directed normal to the coastline and plays a main role in the creation of the cross-shore profile. This varies over time, but remains between some extreme conditions, so theoretically no sediment will be lost in the cross-shore profile.

In the upper shoreface the cross-shore sediment transport is generated by undertow, short wave asymmetry, wave breaking turbulence and bound and free waves. In the lower shoreface the sediment transport is induced by the wave asymmetry, boundary layer streaming, and bound long wave.

The slope of the cross-shore profile is mainly set by the wave height, grain size and the distance to the shore. During the winter period, heavier storms pass Varadero and this results in a more gentle profile. The sand from the higher areas has been brought to the deeper areas more offshore.

During calm conditions in the summer, the steeper beach will be slowly recovered. When there is not enough time for the recovery, then structural erosion takes place. The cross-shore sediment transport gradient should be taken into account for normal and especially the extreme conditions.

Aeolian transport

Aeolian transport is the transport of sediments by wind. The wind transport has a big influence on the cross-shore direct above the waterline. For example, this transport is the main cause in the formation of dunes. The amount of sediment transported depends on the width of the beach and the wind velocity.

To protect the dunes from erosion by aeolian transport, the dunes should have vegetation. The roots of these plants keep the dunes together. When vegetation is absent, the dune will ultimately erode, which results in a loss of beach sediment. This kind of sediment transport should be kept in mind as a cause of the erosion.

3.4.3 Transport during normal conditions

During normal conditions, the flow and therefore sediment is mainly transported in longshore direction, from east to west. Although the region between Punta Francés and Punta Chapelin (Los Tainos) cannot been seen as a coastal cell, the influence of these headlands on the area of interest is still very large.

Due to the bathymetry around the headland, the waves during normal conditions may cause a horizontal eddy in front of the beach of hotel Iberostar, leading to an increase in sediment transport and therefore an increase of erosion in front of the Iberostar hotel.

To get an idea of the influence of the headland, results from the Gamma report can be used. Gamma (2015) [3] computed a coastline retreat of -0.30 m at the whole Los Tainos area during one year of conditions, while for the beach in front of the Iberostar hotel only, this was -5.85 m/year between 2012 and 2015. Important to keep in mind is that a nourishment has been executed in 2012, which induces large erosion as the equilibrium beach profile has been disrupted. Therefore the 'normal' coastline retreat will be lower than the values presented earlier. However, taking everything into account, it still can be concluded that at the beach in front of the Iberostar the erosion quantities are larger than at the surrounding beach areas.

3.4.4 Transport during extreme conditions

Extreme conditions are common in Cuba. In section 3.4.2 the coastal processes have been explained shortly. The main source for these short-term extreme conditions are extreme rainfall and big storms. During extreme conditions the Varadero, also big cross-shore sediment transports can take place which are not present during normal conditions. During a heavy storm, the high water levels can reach the dunes. This can lead to a large offshore directed cross-shore sediment transport, which will change the beach profile. Therefore, during extreme conditions it is very likely that erosion takes place, but this may (partly) recover during calmer conditions.

3.4.5 Summary

In Table 3-11 the different possible causes for the erosion at the beach in front of Iberostar Varadero have been presented.

Cause of erosion	Relevant	Taken into account by:
Bathymetry		
Natural groynes	Yes	Model results
Natural breakwaters	No	-
Rip-currents	Yes	Model results
Diffracting waves	Yes	Model results
Bed material irregularities		
Grain size and composition	No	-
Material change	No	-
Extreme conditions		
Storms	Yes	Model results
Rainfall	No	-
Human interference		
Dune/beach changes	Yes	Qualitatively analysed
Artificial constructions	No	-
Other	No	-
Relative water level changes		
Global sea level rise	Yes	Manual calculation
Tectonic activities	No	-
Compaction	No	-
Sediment transport gradients		
Longshore transport	Yes	Model results
Cross-shore transport	Yes	Model results
Aeolian transport	Yes	Not taken into account

Table 3-11: Possible causes of the erosion

3.5 Recent Nourishments

In the past, multiple nourishments have been carried out on the Varadero peninsula. In 2012, a nourishment was placed in the Tainos area, see Table 3-12.

Year	Location	Length (km)	Volume (m^3)	Measured volume after nourishment (m^3)	Nourished Effectively (%)
1998	Punta Chapelin - Oasis	12	1,087,835	910,291	84
2008	Calle 51 - Calle 29	1.97	136,934	115,315	84
2009	Calle 29 - Punta Blanca	4.5	394,969	376,437	95
2010	Sol Palmeras - Americas	1.4	142,382	131,063	92
2012	Tainos - Punta Hicacos	3.21	413,779	264,663	64

Table 3-12 Overview recent nourishments [3]

The amount of sediment nourished in 2012 in front of the Iberostar hotel was 97,651 m^3, but only 61,905 m^3 was measured after the nourishment. From the table it can be seen that these percentages of losses are very large in comparison with earlier nourishments at similar locations. The relatively large losses can partly be explained by the way the nourishment is executed.

Timing

The nourishment was performed during October and November. During these months there is still a possibility on hurricanes and the cold front season just starts (see section 3.3.3). In Table 3-13 an overview is given of the weather conditions during the months the nourishment took place and December, the first month after the execution. The wave data is obtained from Argoss [11].

	May - July		October - December	
Year	Occurrence of storm conditions: Hs > 1.6 (%)	Hs average (m)	Occurrence of storm conditions: Hs > 1.6 (%)	Hs average (m)
2008	3.3	0.82	25.0	1.22
2009	4.9	0.67	18.4	1.06
2010	17.0	0.91	17.3	1.18
2011	10.3	0.84	37.0	1.41
2012	**9.5**	**0.81**	**28.1**	**1.25**
2013	5.6	0.92	29.1	1.24
2014	11.7	0.81	21.0	1.10
Average	**8.9**	**0.83**	**25.1**	**1.21**

Table 3-13 Overview of weather conditions of different periods

It can be seen that during the months of execution the conditions are way more heavy than during May till July. The percentage of storm conditions is approximately three times larger and also the significant wave height is higher. During the nourishing, also hurricane Sandy passed, which was off course not favourable for the effectiveness of the nourishment.

Equipment

No bulldozers were used to distribute the sand equally over the area, which is needed as the control over the distribution with a pipeline is very limited.

After the nourishment

Measurements were done in the years that followed after the execution of the nourishment. These measurements are presented in Table 3-14. It can be seen that only the section in front of the Iberostar and Paradisus hotel have to deal with erosion, while at the rest of the Tainos accretion is present. The second observation is that shortly after the nourishment, the erosion is decreasing over time. This can be explained as erosion is usually larger shortly after a nourishment is placed.

For locations hotels, see Figure 1-3	**November 2012 – February 2015**	**Mayo 2013 – February 2015**
Complete Tainos area	Monthly: -0.49 m^3/m Annual: -5.94 m^3/m Total: -22,869 m^3/year Tendency of erosion	Monthly: -0.22 m^3/m Annual: -2.59 m^3/m Total: -9,971.5 m^3/year Tendency of erosion
Brisas del Caribe - Royalton Hicacos	Monthly: 0.11 m^3/m Annual: 1.35 m^3/m Total: 3,847.5 m^3/year Tendency of accretion	Monthly: 0.25 m^3/m Annual: 3.02 m^3/m Total: 8,807 m^3/year Tendency of accretion
Iberostar Varadero – Paradisus	Monthly: -2.31 m^3/m Annual: -27.71 m^3/m Total: -27,710 m^3/year Tendency of erosion	Monthly: -1.66 m^3/m Annual: -19.89 m^3/m Total: -19,890 m^3/year Tendency of erosion

Table 3-14 Erosion measurements after nourishment in 2012 [3]

The measurements in this table will not only be used to analyse the failed nourishment, but are also usable as an indication for the structural erosion in front of the Iberostar hotel. The erosion rate of 19.89 m^3/m/year is expected to be a good estimation of the structural erosion in future years.

3.6 Conclusion

From the analysis in can be concluded that the beach in front of Iberostar Varadero suffers from structural erosion. As the tourist industry is an important part of the Cuban economy, it is needed to take action. Measurements should be taken to improve the beaches and also to be able to deal with the erosion in the future.

The main stakeholders in this project are the Cuban governmental organisations. Cuba is a strict government-controlled country and as it is a public project, they will logically have the biggest interests and powers. The main interest of these stakeholders are tourism and environment. The most important non-governmental stakeholder is the tourist themselves. Their power is reasonable as they can go to other holiday resorts if they do not like the beach. The alternative solutions should be designed in such a way that is satisfies the stakeholders wishes.

During the two different weather conditions, different kind of erosion processes take place. During calm conditions, the longshore current is the most important factor for the sediment transport. Due to the oblique incidence of the waves, the sediment will be transported along the shore.

During extreme conditions (for example during hurricanes of cold fronts), the cross-shore current is the main contributor of the sediment transport. The high waves and big wind set-up brings takes the sediment from the beach and brings them to the deeper waters. In calm conditions this slowly recovers.

The Iberostar Varadero hotel is located at the leading tourist area of the country. In order to serve the guest a good holiday, the structural erosion problem on the beach should be solved.

4. Modelling

To find the causes of the erosion and their relative importance, the situation should be modelled. With the right models, the sediment transport, erosion rate and morphological changes can be computed.

Because of all possible causes (see section 3.4) and different directions of transport (longshore and cross-shore), different kind of models will be used. A short summary will be given about the different kind of models used. For each model the set-up is explained and the results are shown.

At the end of this chapter, a summary of the quantification of the causes of erosion is given. This is in order to determine the actual causes of erosion and come up with the right solutions, done in chapter 6.

4.1 Introduction to the modelling

Every choice made during this project is eventually based on the task to answer the main research question and sub-questions (A, B, C, D, E) described in section 2.2. So the choice of model usage can be best explained by using these sub-questions, which are repeated below:

A. *What is the contribution of basic longshore transport to the total amount of erosion?*

B. *What is the contribution of the different cross-shore processes to the total amount of erosion?*

C. *Are there any complex hydrodynamic processes around the Iberostar Hotel beach which may contribute to the erosion problem?*

D. *What is the best solution to the erosion problem?*

E. *How to construct the solution?*

In order to answer these questions, the models used for this project have to fulfil some objectives. The main objectives of the modelling-part of this project are:

First Objective:
Determining the causes of erosion in order to answer sub-questions A, B and C.

Second Objective:
Checking the alternatives (see section 6) on the project requirements (see section 5.3.2) in order to answer sub-question D.

Below for each model is summarized what their contribution to these main objectives are. This will eventually determine the way the models are set-up and which results are used.

Unibest

The Unibest LT-tool is a part of the Unibest CL+ package. It is used to calculate the quantities and distribution of the longshore sediment transport over the cross-shore profile, for more information about Unibest see Appendix E.1.

Unibest is used to carry out the wave reduction analysis, which is described in section 3.3.5. The analysis is used by Delft3D as input for the Delft3D-WAVE part.

XBeach

XBeach is an open-source numerical model which is originally developed to simulate hydrodynamic and morphodynamic processes and impacts on sandy coasts with a domain size of kilometres and on the time scale of storms [16]. In this project it is mainly used to investigate the cross-shore processes. For more information about XBeach, see Appendix 0.

The weather condition analysis is used as wave input for the SwanOne/Delft3D-WAVE and XBeach models, in order to contribute to the first main objective of the modelling-part of this project: determining the causes of erosion. By running different weather conditions, the quantitative contribution of the cross-shore processes to the total erosion problem can be determined.

For these different weather conditions a *worst case* can be chosen, the weather condition which causes the most shoreline retreat. This *worst case* is later used (see chapter 6) to check if the alternatives can still fulfil the requirements described in section 5.3.2, after a big storm has passed. This contributes to the second objective of the modelling part.

Delft3D

Delft3D is a modelling framework for 3D computations developed by Deltares. It can carry out numerical modelling of flows, sediment transport, waves, water quality, morphological developments and ecology. In contrast with XBeach it is better capable of simulating longshore processes, while it is a more complete software than Unibest.

The contribution to the first objective of the modelling-part is a more accurate determination of the longshore contribution to the total erosion problem. For this part the weather condition analysis and the wave reduction analysis are used as input. Delft3D contributes to the second objective by simulating a solution for five morphological years to check if it fulfils the requirements.

In Figure 4-1 the usage of the models is schematized. For more information about the differences of calculation method and included processes of XBeach and Delft3D, see Appendix E.5.

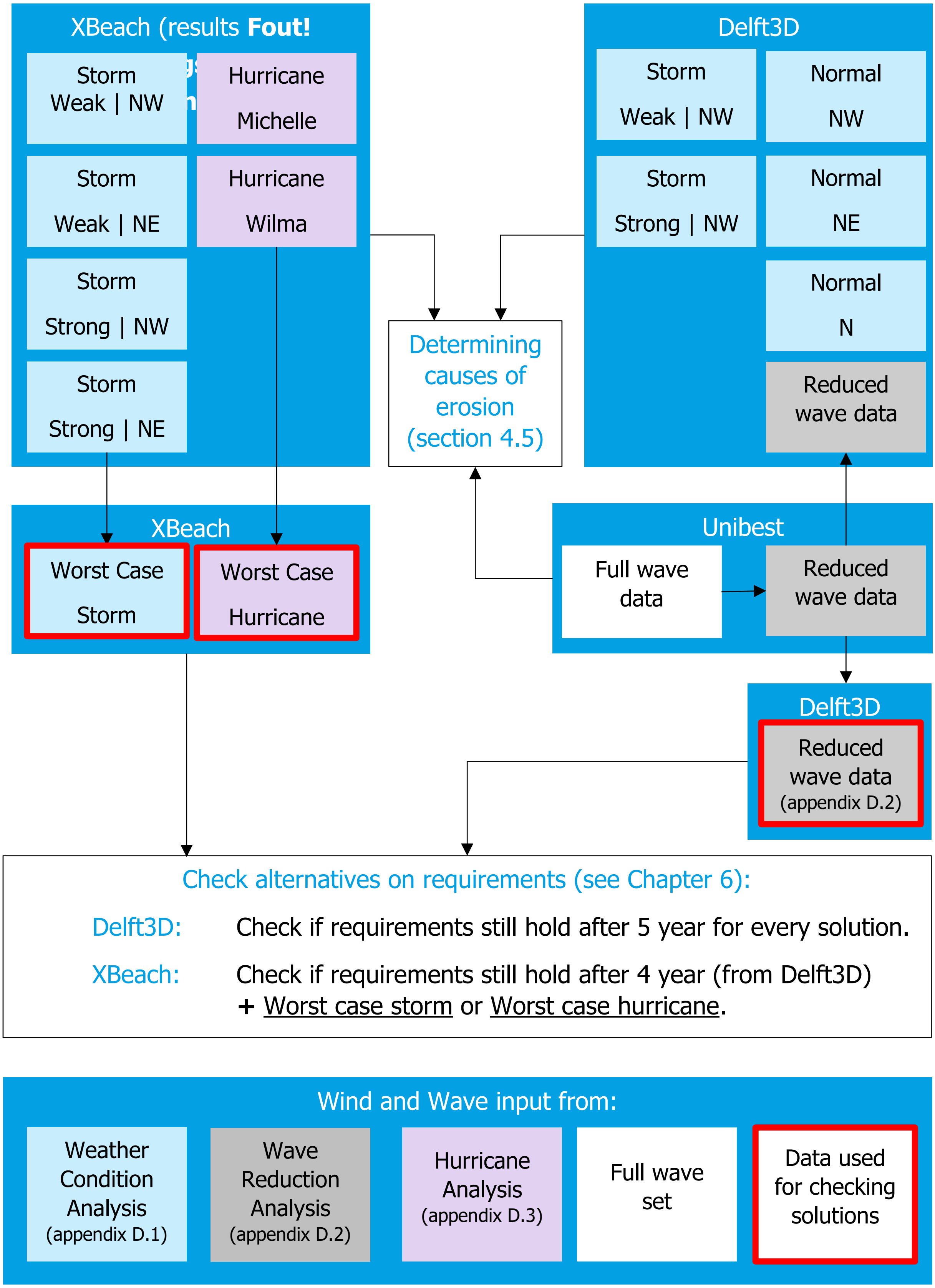


Figure 4-1 Schematization modelling done by XBeach, Delft3D and Unibest

4.2 Unibest

The main objective of the Unibest model is to get insight in the contribution of the longshore transport to the erosion problem. In order to reach this goal, the region in front of the Iberostar Varadero hotel (which also includes the Paradisus hotel) is schematized as a cell with longshore transport boundaries, see Figure 4-2. In this cell, the cross-shore processes are excluded because only the longshore losses have to be investigated.

Unibest LT is used to compute approximate transport at two different coastline angles for the boundaries left and right of the cell. The difference between these two transports is equal to the erosional loss at the project area, because it is assumed that the longshore processes in this case are the only relevant processes.

The coastline angles at both sides of the cell are computed by averaging the coast angle over the range respectively west and east of the Iberostar hotel. West of the hotel, the average coast angle is set on 330° N, which is also the mean angle for the whole area used in the rest of the report. East of the Iberostar hotel more close to the headland, the coast angle is set on 334° N. The Iberostar Varadero hotel is located exactly at the location between these sections with different average coastline angle. The result of this difference in coastline angles is a gradient in longshore transport.

This gradient probably is an important cause of the erosion problem, because increasing longshore sediment transport in longshore direction leads to erosion. Important to note is that Figure 4-2 is only meant to give an impression for the method used to compute the erosional loss, the drawn angles and boundaries are not matching reality.

Figure 4-2 Cell schematization in front of Iberostar hotel

4.2.1 Model setup

An extensive description of the Unibest LT model setup can be found in Appendix F.1. Eventually both the Bijker and van Rijn transport formulae are used to investigate the problem. The choice for these formulae is explained in Appendix F.3. Both formulae give sediment transport values close to the reference value, while other transport formulae are not able to compute realistic sediment transport values for the project situation. The bottom profile is initially extracted from the complete bathymetry around the Hicacos peninsula at a location in front of the Iberostar Hotel. As wave input, a scenario derived from the complete wave time series from Argoss BMT [11] is used. The duration of this scenario is 121.7 days per year and includes wave heights between approximately 0 and 3 meter.

4.2.2 Results

In Table 4-1 the results of the longshore transport computations are given. For each coast angle, the net sediment transport is computed for the whole wave scenario. If the transports at both boundaries are subtracted, a value for the sediment loss in the Iberostar section is obtained. With an assumption for the longshore length of the Iberostar section, the annual loss in m^3/m can be found. This section includes also a part of the Paradisus hotel, but is from now on called the Iberostar section.

The length will be in the same order of magnitude as the length of the section according to Gamma (2015) [3], which is 1000 meter. The reference value for the erosional loss at the Iberostar section is also given in the table, more information about this value can be found in section 3.5.

Sediment transport	Transport Eastern bound. (m^3/year/m)	Transport Western bound. (m^3/year/m)	Total loss Iberostar section (m^3/year)	Loss / meter Iberostar section (m^3/year/m)
Bijker	-1,134	-18,777	-17,643	-17.6
Van Rijn	6,031	-8,509	-14,540	-14.54
Gamma [3]	-	-	-19,890	-19.89

Table 4-1 Longshore sediment transport Unibest

Clearly the computed values are close to the reference values of Gamma (2015), which indicates that erosion due to gradients in longshore transport is very important. The gradient is highly depending on the assumed coastline angle at both boundaries. Changing the coast angle with one degree would change the total loss with approximately 1,000 to 4,000 m^3/year. In that case, the computed values still would be in the same order of magnitude.

Also the difference in results between the Bijker and van Rijn formula is limited, although van Rijn predicts more transport in eastern direction close to the headland (Punta Francés). This transport in eastern direction can be easily declared by looking at the angle of the coastline and the accumulation of sand which can be observed close to the headland (Figure 4-2).

The difference in transport directions is caused by the difference in coast angle for which the transport shifts from western to eastern direction. In case of Bijker this is around 335° N, for Van Rijn it is around 333° N. More details about the transport for different coast angles and transport formulae can be found in Appendix F.3.

Conclusion

The total erosion is according to the measurements from Gamma (2015) [3] 19,890 m^3/year. These values are probably still influenced by the earlier executed nourishment, but give a good indication of the order of magnitude.

By drawing a littoral cell in front of the Iberostar section and determining the coastal angles of the two outer boundaries, the differences in longshore transport are calculated. The values for the erosion due to longshore transport are in the same order of magnitude as the results from Gamma (2015) [3]. In the case of working with Bijker, the values are approximately equal (= 17,643 m^3/year), while in case of computing transport with van Rijn the values are slightly lower (= 14,540 m^3/year).

The exact values heavily depend on the calibration of the model, which is very difficult with the lack of measurement data in the area. The computed values for the total loss at the Iberostar section therefore do not exactly represent reality, but do give us the desired interest in the importance of erosion due to longshore transports.

Remarks about the Unibest model are that complex processes are not taken into account, so it is difficult to draw conclusions from the results. However, because the model is only used for a simple quantitative approximation, it is concluded that the longshore sediment losses have a large contribution to the total erosion problem.

4.3 XBeach

In this section the XBeach modelling part of the project is described. First the main approach of the modelling is explained. Thereafter the different steps in developing a full XBeach2D model are explained, based on the approach. For more information about the XBeach software, see Appendix 0.

Approach

To model the behaviour of the beach in front of the Iberostar hotel during cold front, storm and hurricane conditions, the model XBeach is used. The model is perfectly suitable to simulate erosion during storm conditions (cold fronts) and extreme conditions (hurricanes). This is necessary as these strong conditions can have a large impact on the coast and can (temporarily) transport a lot of sand into cross-and longshore direction. To find the cause of the erosion problems of the Iberostar beach it is necessary to know how much sediment is transported compared to normal conditions and whether sediment is lost is cross- or longshore direction during strong conditions.

To tackle this problem a certain strategy has been followed to make a robust and reliable XBeach model. The idea is to start simple, test this simple model and when it performs well, extend and advance the model. Therefore there has been chosen to first make a 1D model with a cross-shore profile of the beach. Hereby the general behaviour of the XBeach model can be tested, as well as the sensitivity to certain parameters without getting lost in (possibly wrong) occurring spatial patterns. Because a 1D model for XBeach was used, also the nearshore wave input could be calculated using a longshore uniform wave model: SwanOne.

SwanOne converts the deep-water wave spectrum into a nearshore wave spectrum that can be directly used as boundary input for XBeach. The model hereby accounts for relevant processes as refraction, dissipation and shoaling. The advantage of using the 1D version of Swan in the beginning of the project was that results can be obtained very fast without already having to make a more complicated 2D grid. It was no problem that the needed accuracy and grid size were not already known and in this way the working of XBeach could be tested in an early stadium.

After the 1D model was fully tested, calibrated and as good as possible validated, the switch to a 2D XBeach model could be made. Now spatial effects in front of the hotel can be modelled during strong conditions. This could indicate whether curtain erosion patterns in front of the Iberostar hotel occur during cold front and/or hurricane conditions. Because the wave input is still in 1D, and the same as the XBeach1D model, the behaviour of both models can easily be compared. When after running the 2D a cross-section is made at the location of IBE11, the similarity in results of both models can be assessed.

When the behaviour of the 2D XBeach model has been approved, the modelling can be completed by using the full 2D version of wave input model Swan (via the Delft3D-WAVE interface). Hereby possible spatially induced refraction, diffraction and shoaling effects are included. This would complete the tools for adequately model the behaviour during cold fronts and hurricanes. Also when applying longer time scales, this can be used to model recovery during normal conditions.

So summarising the approach:

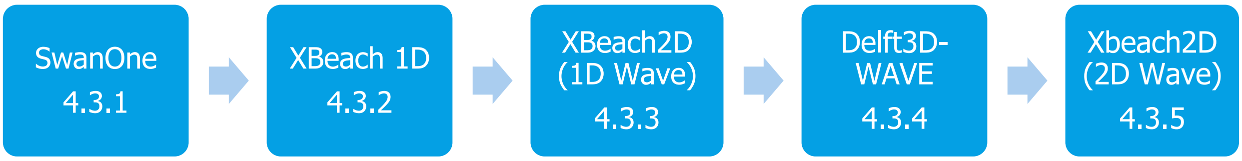


Figure 4-3 Swan / XBeach main approach

4.3.1 SwanOne

In SwanOne multiple storms, extreme and also normal conditions were converted from deep water into a nearshore depth of 10m, which can be used for XBeach1D. The model SwanOne needs as input a x,z-bottom profile as well as the specification of currents, water levels, wind conditions and wave parameters. The generation of the bottom profile at the location of the Iberostar hotel is explained in Appendix **Fout! Verwijzingsbron niet gevonden.** and resulted in the following profile:

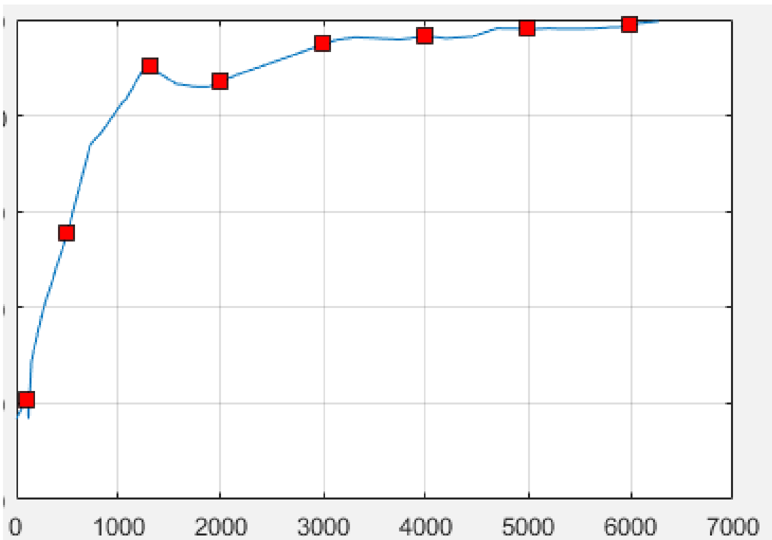


Figure 4-4 Bottom profile for SwanOne

As further input for the first simple model, no currents, a water level with respect to mean sea level and wind- and wave parameters based on Master Thesis Miguel Izquierdo Álvarez (2004)

[17] were used, since the *Wave analyses* were not yet ready. Two normal conditions, two cold front conditions and one hurricane condition are modelled (see Appendix G.2).
After specifying a grid size of 100 steps (giving $dx = 62.75m$) SwanOne gives as output per grid point multiple parameters as Hs, Tp, water depth, wave angle, wave spreading and many more for the particular wave condition that is performed. The results of the grid point with a water depth of 10m are extracted from the table to use in XBeach. Furthermore the model internally can plot certain graphs like shown in Figure 4-5.

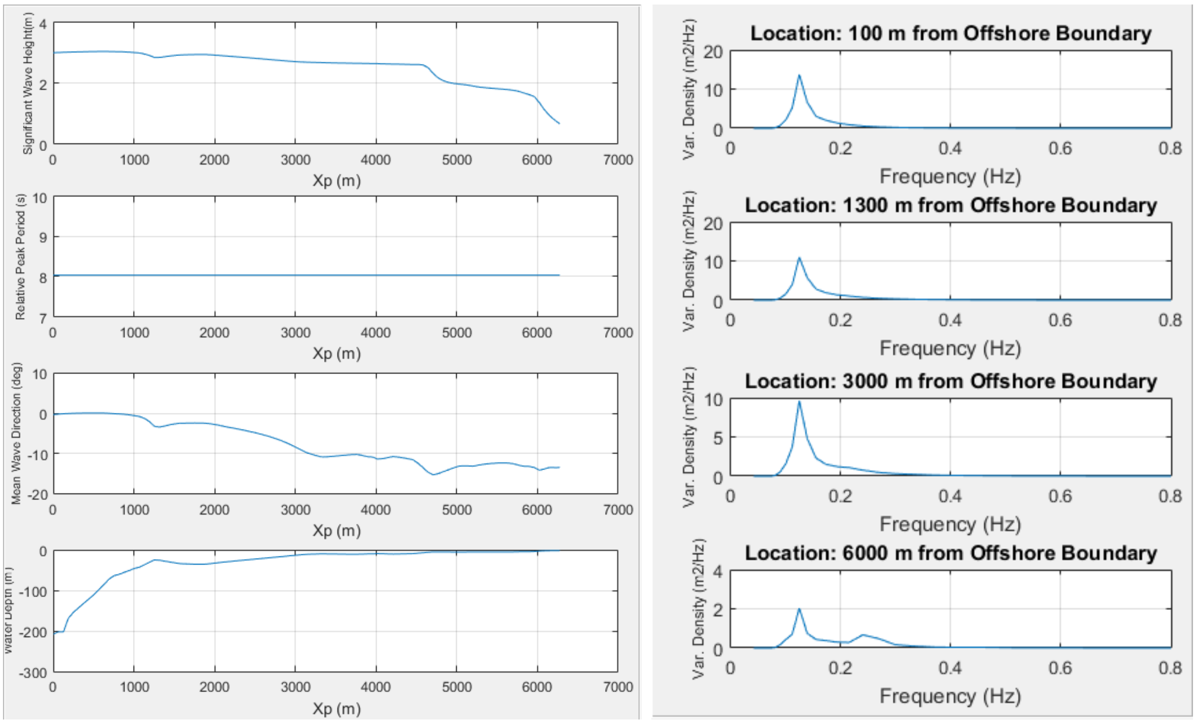


Figure 4-5 Results SwanOne

The general pattern following from the SwanOne wave conversion is that the waves transform significantly when travelling from offshore (200m depth) to the nearshore boundary. Around 1300m from the offshore boundary there is some dissipation and refraction because of the 'peak' in the bathymetry where some waves start to feel the bottom. A bit closer to the shore you see the opposite effect because the water depth increases a bit after this peak.

Around 4700m away from the offshore boundary there is quite some refraction for the normal conditions and significant dissipation for the other two conditions, hence a part of their waves break due to their larger waves. The remaining wave energy is largely dissipated from 6000m and further, close to the shore.

In general normal wave conditions refract more than the hurricane waves. The waves of the cold fronts refract the least because their angle is closer to the normal of the beach. None of the wave conditions approach the coast completely perpendicular, creating the possibility for a longshore current.

Looking at the spectrum outputs the general pattern is that the location of the frequency peak of the waves does not change and that a lot of energy is dissipated travelling towards the shore. As expected, the dissipation is the largest for the hurricane conditions and the lowest for the normal conditions.

4.3.2 XBeach1D

XBeach setup

After the setup of the SwanOne wave conditions the first XBeach 1D model could be made. XBeach has been used in 1D surfbeat mode, but with retaining directional spreading and corresponding allowance of obliquely incident waves and resulting longshore current [16]. The grid was based on the measurements of profile IBE11, see Appendix C. Because these measurements were only done from 1 meter water depth and higher, including the dunes, the profile had to be extended.

This was done using the same data file and method as for the SwanOne model, but then at the exact location of IBE11 and with a higher accuracy. In this way a non-equidistant cross-shore profile was obtained spanning the area from a water depth of 10 meter until the dunes. Because most processes happen in this active zone of the coast this water depth is sufficient to model the response during cold fronts and hurricanes.

The result was the following profile:

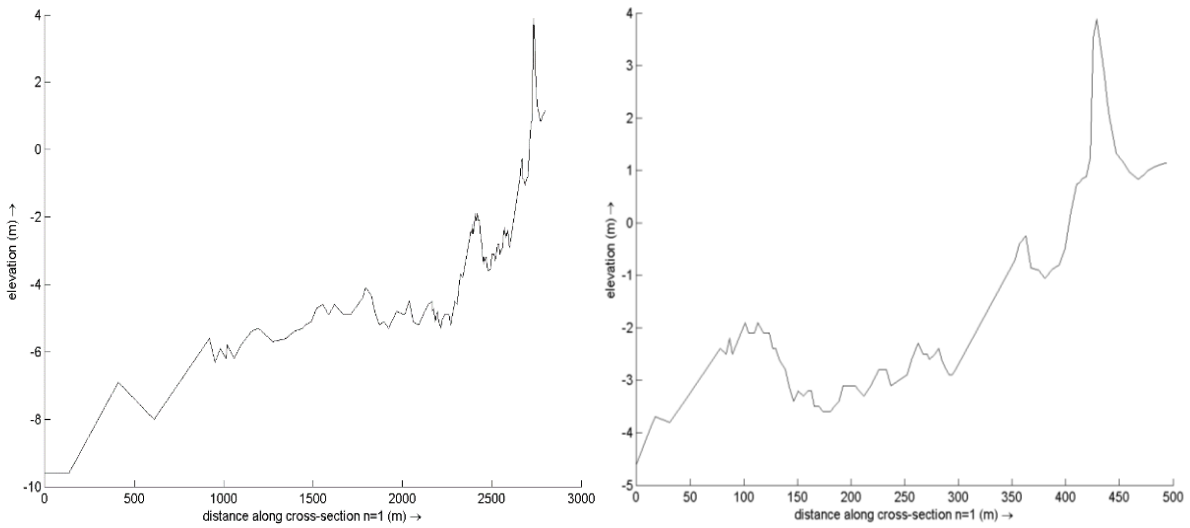


Figure 4-6 Full bed level profile (left) and zoomed in close to the beach (right)

For the other input it is advised is to precisely specify a few parameters and run the rest on default [16]. Here only the most critical parameters are explained, for other specified parameters see the example input-file in Appendix L.1.
The separate files for the Jonswap spectrum and the water levels consist of the conditions specified by the SwanOne output (see Table G- 1).

It turned to be very critical how to specify the simulation time 'tstop' when using a morphological scale factor 'morfac'. The idea of using a morfac>1 is that one time step of computer intensive hydrodynamic computations is used for more than one time steps of morphological computations, controlled by the parameter morfac.

The critical point is now if you specify your preferred simulation time in morphological time, and letting the model internally divide the computations by the specified morfac, or in hydrodynamic time, and multiply this with morfac to get the preferred simulation time. The first is specified by 'morfacopt=1' and is default, the second is asked with 'morfacopt=0' and has to be specified explicitly as it is not the default option. For this project it is chosen to specify everything in morphological time, in this way also all tide and jonswap inputs can be in real (morphological) time.

During the initial setup of the XBeach1D model and the calibration phase there has been made use of the 2010 V21 version. Hereafter the 2015 Kingsday version became available and was used because the model had multiple upgrades. Both versions of XBeach use morphological time input as a default.

Post-processing

The results of the performed runs with the V21 version were all processed using Deltares' Delft3D-QUICKPLOT. Delft3D-QUICKPLOT has been developed using Matlab to be a user-friendly, flexible and robust tool for interactive data visualisation and animation [18]. During the time the switch was made to the Kingsday version of XBeach, there was also chosen to switch the post-processing to self-written Matlab codes. Using own Matlab files was necessary to automatically calculate sediment transports and waterline movements, which was not possible in QUICKPLOT. The 2D version of the used script can be found in Appendix L.2.

Calibration

The calibration phase consists of first looking at the general behaviour, a sensitivity analysis on various parameters and a comparison of V21 and Kingsday version. Here only the recommendations based on the previous will be presented, the individual parts can be found in G.3.

The result is that in the end that the general behaviour of the model is good. That the parameters morstart, taper and random are used in the default mode. The D90 is kept at

0.00074m, the density is changed to 2700 kg/m^3 for uniformity with the rest of the project and the latitude is set to 23 degrees.
The values that turned out to be more import are the D50, Chezy, rt, morfac and water level. The D50 is kept at 0.00027m, the Chézy value is set at 68 as calculated in section 3.3.6, rt is bypassed specifying a time-varying jonswap spectrum, the morfac seems to perform well at a value of 10 but should be supervised and this also holds for the water level.

Furthermore it has been showed that, in particularly for cold front modelling, it is better to use the 2015 Kingsday version.

Validation

For the validation there has been looked at a real storm and a real hurricane, namely the 2001 hurricane Michelle which had a large impact on the beaches of Varadero. This has been done to look what the behaviour of the model is when forcing it with more realistic conditions and how the results compare with similar reports. For the realistic storm a 45 hour section of the Argoss BMT [11] has been used, selected based on the weather condition analysis (see Appendix D.1).

The hurricane modelling is based on the same hurricane Michelle as Melia Hotels (2010) [20] and Oasis (2014) [19] to validate the results hence these beaches are also on the Hicacos Peninsula not far from the Iberostar hotel. The wave and water level dataset consists of 51 hours and is the same as Oasis (2012) and retrieved from Noriega (2014) [12] (see Appendix D.3).

Modelling these hurricane conditions gives the following results:

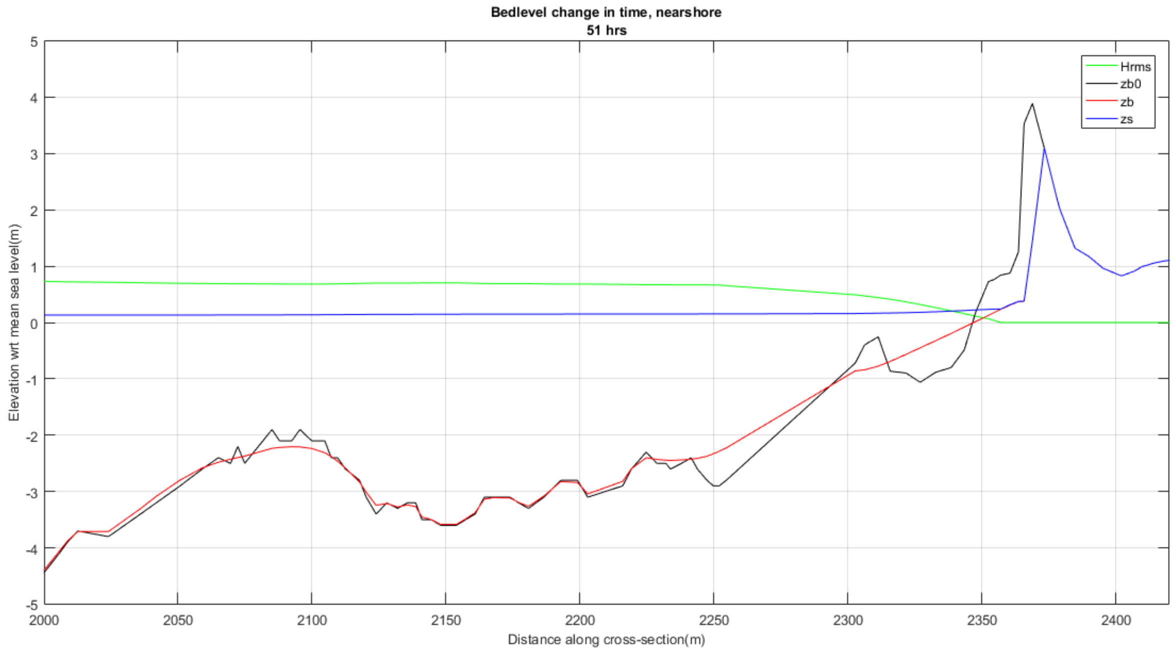


Figure 4-7 Profile after Hurricane Michelle conditions (only section until 5 meter water depth is shown)

The result of the hurricane is that a part of the dune is eroded due to avalanching and that a large part of the dune foot is eroded away, this sediment is transported offshore but not to large depths. For a figure of the cumulative sedimentation/erosion, see Figure G- 18. The calculated values are that the total sedimentation in the grid= 20.15 m^3/m, the total erosion = 20.29 m^3/m and so the total balance = -0.14 m^3/m, this sediment can be transport offshore of the grid or in longshore direction (this can be found out in the 2D model). Furthermore there is calculated that the waterline has retreated 0.30m.

When we compare these results with the other reports, there can be seen that their order of magnitudes is the same. Oasis (2014) talks about 25.525 m^3 sediment that is transported offshore per meter width and Melia Hotels (2010) talks about 25.42 m^3/m. So this gives confidence that our model is performing well, differences in magnitude can occur because of for instance a different bed slope or an older XBeach model.

When modelling the real storm the result is seen in Figure G- 3. The calculated values are that the total sedimentation in the grid= 7.499 m^3/m, the total erosion = 7.502 m^3/m and so the total balance = -0.0024 m^3/m, this sediment can also be transported offshore out of the grid or in longshore direction. Furthermore there is calculated that the waterline has retreated 3.3223 m. Because now there is no dune avalanching to fill up the erosion, the retreat of the waterline is more than for the hurricane condition. The cumulative sedimentation/erosion can be seen in Appendix G.2 When we now try to compare these results with other reports it gets more difficult.

The available research on the Varadero area that has modelled cold fronts is the report of Oasis [19]. But with this report only sedimentation patterns can be compared, unfortunately no transport quantities of single cold fronts are present. Nevertheless the general pattern of the real cold front modelling looks quite plausible. Only a part of the beach is eroded compared to the hurricane, no avalanching occurs and the offshore movement of the first bar related to smoothing of the coastal profile seems realistic. Also the depth until where significant sediment transport is noticed is limited, just as for the hurricane modelling and the other reports. Therefore there is assumed that the model is capable of modelling cold front conditions.

When we try to model the recovery of the beach the results are less positive. Modelling of two days of cold front 2 conditions and 5 days of normal 2 conditions shows a little bit of recovery of a bar but the result is not very robust. Furthermore correspondence with Robert McCall gave the insight that XBeach might not (yet) be perfectly equipped to model the recovery of beaches during calm conditions. The model misses a couple of hydrodynamic and aeolian processes to simulate the relevant processes.
This could be overcome when having good calibration data, but since this is not available for this project the conclusion is that we cannot model recovery of the beach after storm conditions. For the project this will later be tried to estimate based on previous reports.

Conclusions

When combining the results of general behaviour, calibration and validating phase it can be concluded that the XBeach1D model performs well enough to model cold front and hurricane conditions. The results and sediments during the hurricane conditions compares well to previous reports. Modelling cold front conditions also leads to plausible behaviour and characteristic features are found. In contrast, it seems not to be possible to accurately model the recovery of the beach after storm conditions in the current XBeach model. Therefore this will not be tried to model in this report. Summarising, the 1D model of XBeach is ready to be upscaled into a 2D model. Because the 1D model is extensively calibrated, time can be saved when applying the 2D model.

4.3.3 XBeach2D (1D Wave)

Model information

For expanding the XBeach model with an extra dimension, a 2D grid should be made. The used grid was later further optimised for simulating the solutions in collaboration with Delft3D while using the same grid, see Appendix N.1. The used grid for the zero state runs are made by Delft3D' RGFGRID and QUICKINN and consists of the following:

- A curvilinear grid of 178 (longshore) by 127 (cross-shore) cells
- Longshore length of 2200m and cross-shore 1440m
- Minimum grid sizes of 10m longshore and 4m cross-shore grid sizes around water line at the Iberostar Hotel

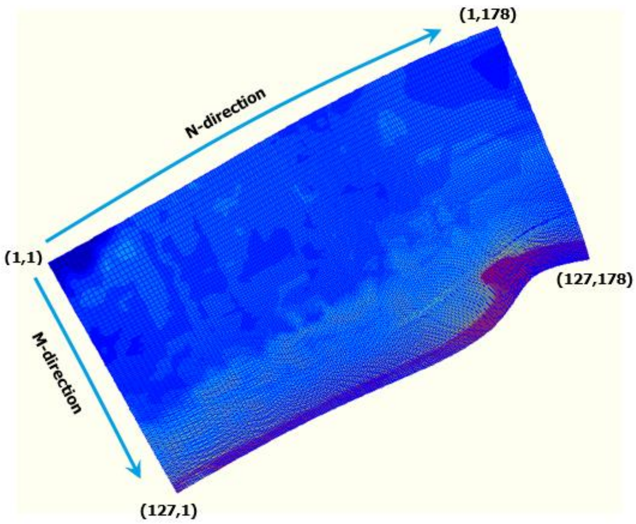


Figure 4-8 Grid sizes used in XBeach2D

The most important bathymetry characteristics are:

- Max water depth of 8m and a maximum dune height of 4m
- Non-erodible layer at headland

With this 2D model the dunes, active coastal zone and headland are captured. The resolution around the waterline and dunes is sufficient to adequately model reality and make sensible computations. Important to notice is that the origin of the grid is in the upper left corner because in XBeach the x-axis (M-direction) should be define towards the coast and the y-axis (N-direction) in longshore direction.

The exact input and post-processing files of the XBeach 2D model are shown in L.2 and L.3, the files are for the full SWAN computations. Comparing with the 1D input model the most important changes are that the absorbing-generating (weakly-reflective) boundary now is in 2D, that the grid is in Delft3D format, the wave input in SWAN format and that a non-erodible layer is added at the headland.

Validating 2D model

To test the working of the model the same cold front is used as in the XBeach 1D validation so both models can be compared. For the comparison a cross-section of the 2D model is made at the IBE11 location. There has to be noticed that the boundary conditions were exactly the same but that the water depth of the offshore was not the same (10m vs 8m in 2D model). Hereby the resulting wave attack at the beach is (a bit) stronger in the 2D model. The comparison of both results can be seen in Appendix G.3. The results are not completely the same but are good enough and the differences are explained. The sedimentation/erosion results are shown in Figure 4-9.

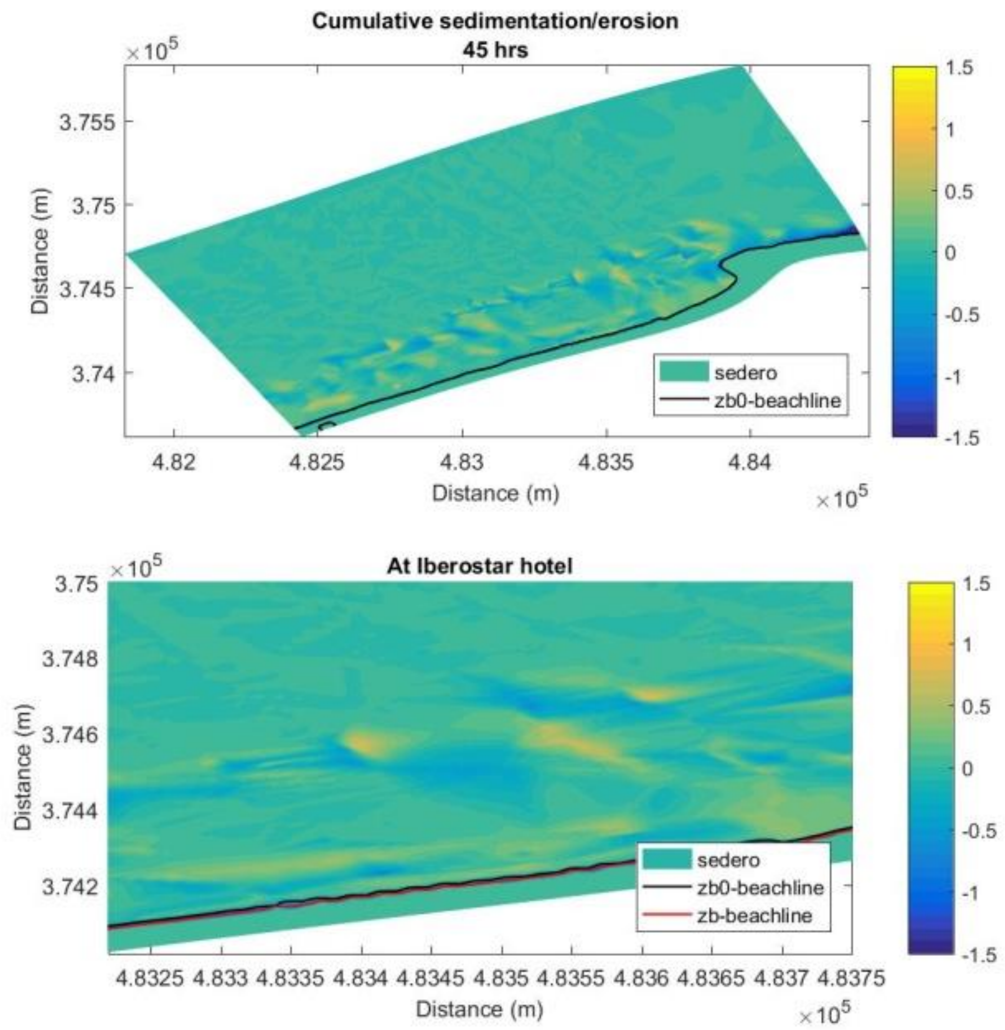


Figure 4-9 Sedimentation/erosion for realistic cold front

Interesting patterns can be seen around the hotel section and the headland, it looks like there is more sedimentation west of the headland and more erosion in front of the Iberostar hotel. Because the 2D model seems to be working fine, the next step with the 2D wave model can be performed.

4.3.4 SWAN (Delft3D-WAVE)

To improve the wave input, SwanOne has been replaced by the full SWAN 2D computation (as implemented in Delft3D-WAVE). The idea is to implement the four characteristic cold fronts/storms as described in D.1 and the two hurricanes as described in Appendix D.3. These offshore wave conditions are transformed into nearshore wave conditions using the large grid which was available from the Delft3D model section, see Appendix H.2. For every hour in case of hurricanes and every three hours in case of normal storms, the offshore values H_s, T_p, direction and directional spreading are specified.

The SWAN computations create output at specified locations, being the left, middle and right grid points at the offshore boundary of the grid used by XBeach. When specifying this in XBeach, SWAN output files are directly used in XBeach.

An example result of the 2D effects included in SWAN from the large grid is shown in the figure below, the same conditions in different directions give very different results.

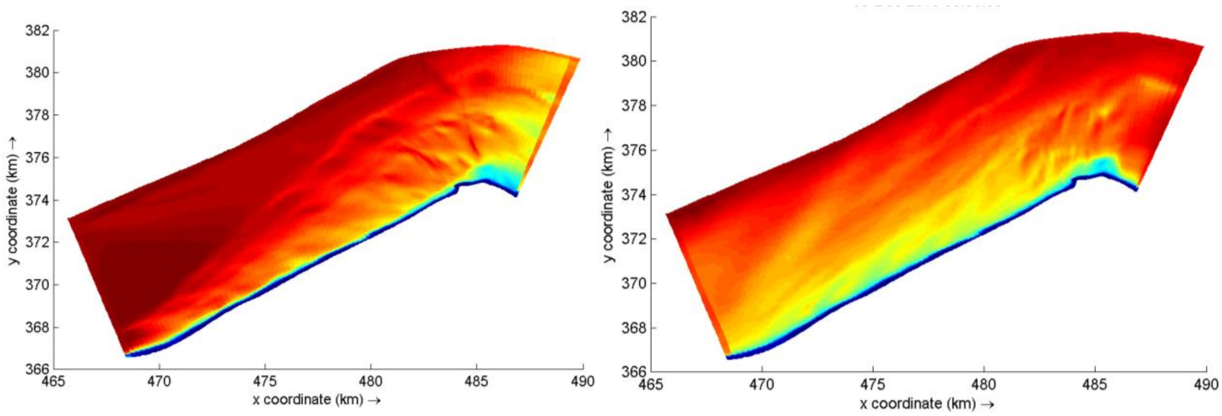


Figure 4-10 Hs for northwest (left) and north east conditions (right)

The pattern is that for northwest conditions the waves break much closer to the shore than for north east conditions. The waves from the north east travel a much longer distance over shallow water depth resulting in larger wave dissipation and breaking offshore.

4.3.5 XBeach2D (2D Wave)

After making sure that the coupling with 2D SWAN worked correctly, the zero state runs for the four storm conditions and the two hurricanes could be performed with the full 2D XBeach model using the full 2D wave input. The specific figures and calculated values are given in Appendix G.3, but the main results will be given here.

Storm conditions

When looking at the cold fronts from the northwest the difference in coastal response between the weak and strong wave conditions can easily be observed. For the weak conditions only sediment around the waterline and at the bar close to the shore is mobilised. Otherwise for the strong conditions the sediment transport also occurs much further away from the shore, at the location of the second bar. These bars get levelled out and sediment is also moved offshore. But when looking at Table G- 7 the amount of beach retreat does not reach much higher values. This can be explained by the occurring avalanching at the dunes, because the waves reach the dune foot. This explains why the retreat of the shoreline is larger than the reduction of the width of the beach.

When now the two storms from the north east are compared, the same pattern can be observed. The amount of transport that is initiated is in both cases lower than for the northwest conditions. This can be explained by the wave breaking patterns shown in Figure 4-10, waves from the north east break more offshore creating weaker wave conditions closer to the shore. The result is that for the strong and weak wave conditions hardly any sediment is transported at the second bar. When looking at the beach width and shore line retreats, the values do not differ much. So when taking this all into account it is concluded that for storm conditions, the strong front from the northwest is taken as the most critical condition. An impression of the impact is given in Figure 4-11.

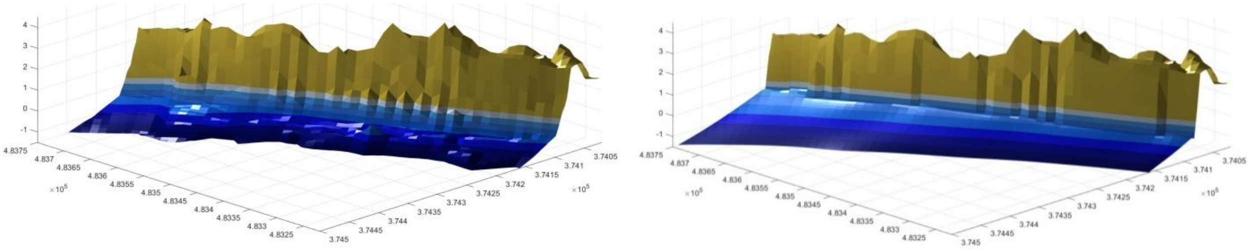


Figure 4-11 Bed level of Iberostar section before (left) and after (right) a NW heavy storm

Here you also see the resetting and smoothing of the bars, the development of an equilibrium profile of the beach for the storm conditions and some avalanching of the dunes. Based on Table G- 7 in Appendix G.3 something can be said about the general beach width before and after a storm. During storms the average shoreline retreat is between 5 and 8.5 meters and the reduction of the beach width between 5 and 6.5 meters, with spatial variability along the Iberostar section. Requirements will be based on these numbers and will be calculated again for the solutions.

Hurricanes

When comparing the results of the hurricane Michelle and Wilma it turned out that according to the model, hurricane Wilma was much more destructive than Michelle. This can be explained by the higher significant wave height, higher water level setup and a wave direction that was from the destructive northwest direction during the maximum of the hurricane, as was shown in Figure 4-10. Unfortunately there are no measurements available to verify this massive erosion in the Iberostar section.

Especially for the hurricane Wilma, there is a lot of dune avalanching because of the high waves and large water level setup. This sediment is accumulated around the first bar close to the shore, where a gentler slope is created as an equilibrium profile to the extreme conditions. Hereby a lot of sediment transport in the cross-profile is initiated, as well as an increase of the beach from the sediment of the dunes. However still spatial variability occurs as can also be seen in the breach of the dunes during Wilma:

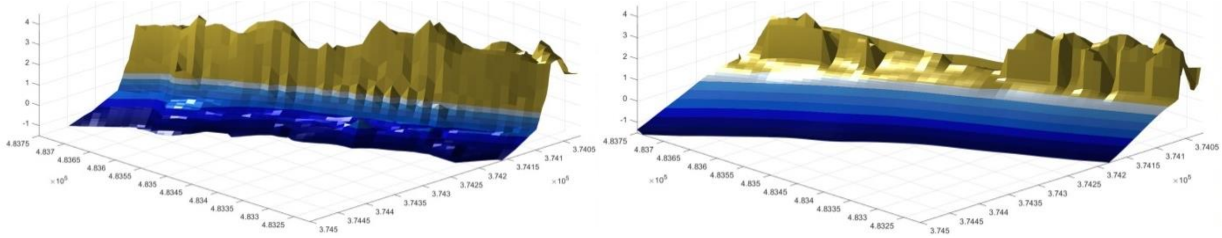


Figure 4-12 Bed level of Iberostar section before (left) and after (right) hurricane Wilma

The destructive power of a hurricane is clearly shown, in the middle of the Iberostar section there is a weak spot where overwash occurs. There has to be noticed that this result can vary strongly from one hurricane towards another:

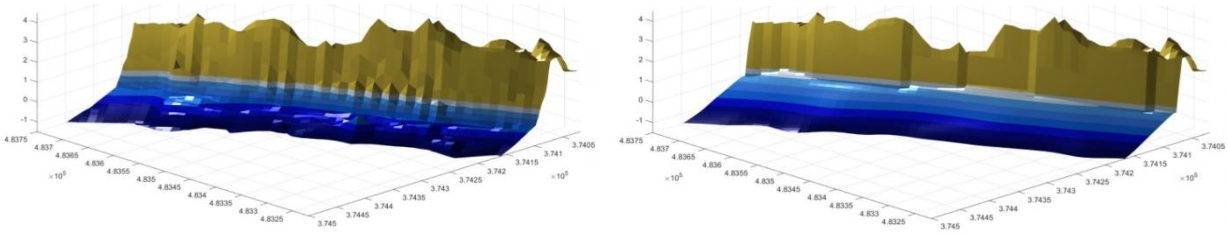


Figure 4-13 Bed level of Iberostar section before (left) and after (right) hurricane Michelle

Because hurricane conditions are so severe compared to heavy storms, no solution can completely survive such conditions. So therefore the requirements for hurricanes will differ from those of cold fronts. Furthermore cold fronts or strong storms occur much more frequent, so in the end the total cross-shore transport initiated by hurricanes is less.

Conclusion

When looking at a year of conditions, cross-shore sediment transport by storms is more important than occasionally passing hurricanes. Also because often a hurricane does not have the right path to really impose critical wave conditions on the coast.

Generally there has to be noticed that the spatial variability along the Iberostar section is rather large. The cross-shore profiles differ quite much between the left, middle and right of the section, so erosion in one profile does not necessarily mean that this happens along the entire section.

This also means that the sediment that is transported in offshore direction does not have end up back at the beach during normal conditions. Favourable for the Iberostar section is that the sediment is not transport very far offshore, generally speaking only towards maximum 5m water depth. So it assumed that no sediment will leave the coastal zone at the offshore boundary and that the transported sand in principal could return to where it was eroded during a storm.

However, a longshore current is present that is generally directed towards the west, large quantities of sand initiated by cross-shore processes can be transported longshore before it can recover the beach at the same place. Sediment transported offshore, will later be transported back to the shore from where it can be picked up by the longshore current in the breaker zone. This problem can be even larger if not just the beach itself is eroded but also the dunes during stronger conditions. It is even harder to let natural processes bring back all this sand to the dunes to recover them. Therefore it is necessary to prevent that dune avalanching with a resulting scarp occurs.

Concluding, the cross-shore sediment transport does not lead to losses at the offshore boundary, but it moves sediment offshore from where it can be transport longshore by the general longshore current. In this way cross-shore processes during storm conditions can be part of the erosion problem.

4.4 Delft3D

In this section the Delft3D modelling part of the project is described. First the main approach of the modelling is explained. Secondly the setup will be summarized and finally the results are shown. For more information about the Delft3D software, see Appendix E.4.

4.4.1 Approach

Delft3D is used in multiple ways during this project. To come up with a good solution for the erosion problem, the exact causes of the problem need to be understood. When these erosion causes are understood (and quantified), solutions can be designed to counteract these problems. Delft3D will be used to help determining those causes and to design and test different solutions.

The first step will be to get a stable and accurate model, which can represent reality well. This is achieved during the calibration process. The calibration process is based on a model with a morphological time of one year. After the model is calibrated, a zero-state model is created. By inducing the correct types of wave input on this zero-state model, the desired results can be obtained. These results eventually vary from observed flow patterns to morphological changes after five years.

For practical purposes, the Delft3D modelling part can be divided into three model types based on their main objective:

- Calibration
- Determining causes of erosion
- Simulating alternatives

In the remaining of this Delft3D section, these division will be used to explain several choices and input parameters.

4.4.2 Input

In this section the input for the different model types will be summarized. For an extensive description about the full setup, see Appendix H.2.

Domain

The used bathymetry is obtained from GeoCuba [5] and is shown in Appendix C.

In order to make the computations more efficient, two different grids are used. A larger grid which contains the whole Varadero peninsula and a smaller grid, nested into the larger one, only containing an area of approximately 2 km around the Iberostar hotel. A quick impression of the two used grids is given in Figure 4-14 and Table 4-2. For nearly all computations, the combination of both grids is used.

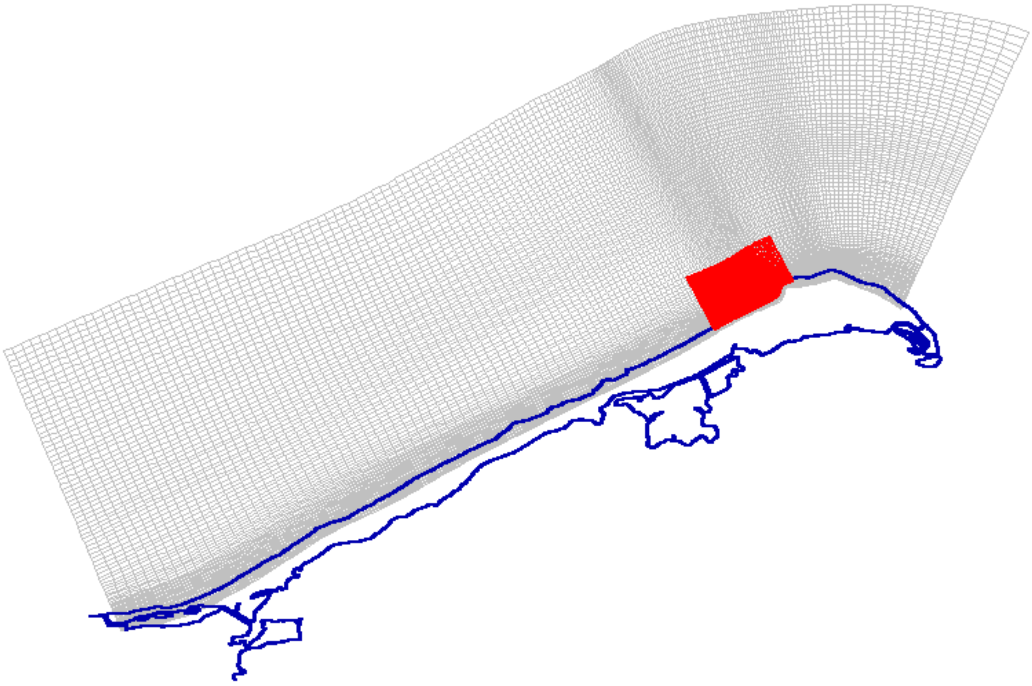


Figure 4-14 Small grid (red), nested into the larger grid (grey). Varadero coastline is shown in blue.

		Large Grid	Small Grid
Cells in longshore direction	(-)	180	100
Cells in cross-shore direction	(-)	135	120
Resolution in area of interest	(m)*(m)	≈ 35*10	≈ 10*5
Cross-shore distance	m	7,000	1,440
Longshore distance	m	22,000	2,200

Table 4-2 Overview main properties used grids

Time frame

The necessary simulation time depends on the objective of the model. The models used to determine the cause of erosion do not have to take morphological changes into account in general. They are mainly used to observe flow patterns and wave heights. The simulation time for these models are mostly in the order of one day.

The models that do need morphological changes in order to fulfil their objective, have a longer simulation time, dependent on the morphological factor. The simulation times of these models are in the range of two till eight days.

The time step for the computation is chosen to be 0.05 minute, mainly based on the Courant number.

Boundary Conditions

The boundary conditions can be separated as input for the Delft3D-FLOW and Delft3D-WAVE modules. In the Delft3D-FLOW module it is chosen to set water levels as the boundary condition for the models. The obtained tidal data from section 3.3.5 is converted into different harmonics, which are eventually used as forcing type of these water levels.

The boundary conditions of the Delft3D-WAVE modules must exist of wave conditions. The type of wave condition depends on the desired output. For the models used for determining the causes of erosion, different (constant) wave conditions are used as input, obtained from the weather condition analysis (see Appendix D.1). The models which are used to simulate the alternatives use the input from the wave input reduction, which represents are full year wave climate (see Appendix D.2). For more information about the results of these analyses, see respectively Table 3-7 and Table 3-8 for the weather condition analysis and the wave input reduction.

Physical and Numerical Parameters

The way the physical parameters are obtained, differs for each parameters. Some of the parameters have a physical background and can be calculated, while others are more difficult to determine and choices are often based on reference projects. Another type of parameter is the multiplication/calibration parameter, which is only used to calibrate the model such, that the final results are as expected. Numerical parameters do not have any physical background, but are more computation related.

The exact values, the way they are obtained and the calibration of certain parameters are listed in H.2.

Output parameters

The output of the model is stored in maps for every 30 minutes. Other output files of the Delft3D model are communication files. These files are used by Delft3D-FLOW and Delft3D-WAVE to interact with each other. The interval between these communication files is set to 20 minutes.

4.4.3 Results

In this section the obtained results from the Delft3D model are shown. Also the results are divided for the type of model objective. First the most important calibration results are shown and secondly the results for the models determining the causes of erosion. Again, for more results, see Appendix H.3.

The results of the simulation of the different alternatives are shown in chapter 6.

Calibration

The first remark about the calibration process is that the calibration is done with a model with a morphological change of one year. The calibration is mainly based on visual observations from the CISAM [21], because no exact quantities are available. These two facts result that there is are possible errors made during the calibration process.

The first step of creating the model is making sure the wave and flow results are as expected. When this is fulfilled, the morphological changes can be calibrated.

The adjusted parameters for calibrating the morphological changes:

- Horizontal eddy viscosity (m/s2)
- Horizontal eddy diffusivity (m/s2)
- Current-related reference concentration factor (-)
- Current-related transport vector magnitude factor (-)
- Wave-related suspended transport factor (-)
- Wave-related bed-load transport factor (-)

The results of these calibrations are also shown in Appendix H.3.

The final calibration/validation step performed is the check if the wave reduction analysis (see Appendix D.2) is accurate enough to use. The cumulative erosion/sedimentation patterns are shown in Figure 4-15.

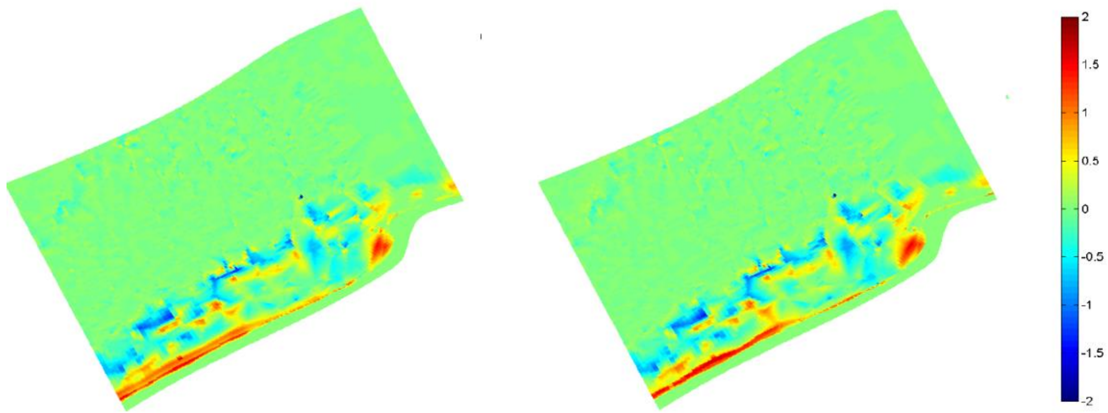


Figure 4-15 Comparison of full wave data set (left) and reduced wave data set (right)

From these results it can be concluded that the wave input reduction is accurate enough to be used for the Delft3D models.

Determining cause of erosion

After the setup and calibration of Delft3D, the models can be used to obtain the desired results.

To be able to determine the causes of erosion, firstly the general flow patterns in the large grid were analysed for different weather conditions from the weather conditions analysis. Additionally the same is done for the flow patterns occurring in the small grid and with these two results combined, some conclusions can be drawn from about the possible cause of erosion.

To verify if these qualitative drawn conclusions are valid, the wave reduction analysis is used and one morphological year is simulated with Delft3D. An overview of the main results is shown below and for more information, see Appendix H.3.

Weather Conditions
By using different weather conditions, general patterns can be analysed during the year. For the most conditions the results in terms of flow and erosion are as expected. The listed results are obtained from the small grid:

- Wave conditions from the north east and north induce currents directed westwards. The general sedimentation/erosion patterns are that along the whole beach small uniform erosion is observed.
- Stronger wave conditions (storms) induce the same currents, but in a higher order of magnitude and the result is that relatively more erosion occurs.

However, the conditions from the northwest induce a more complex flow pattern, which is shown in **Fout! Verwijzingsbron niet gevonden.**.

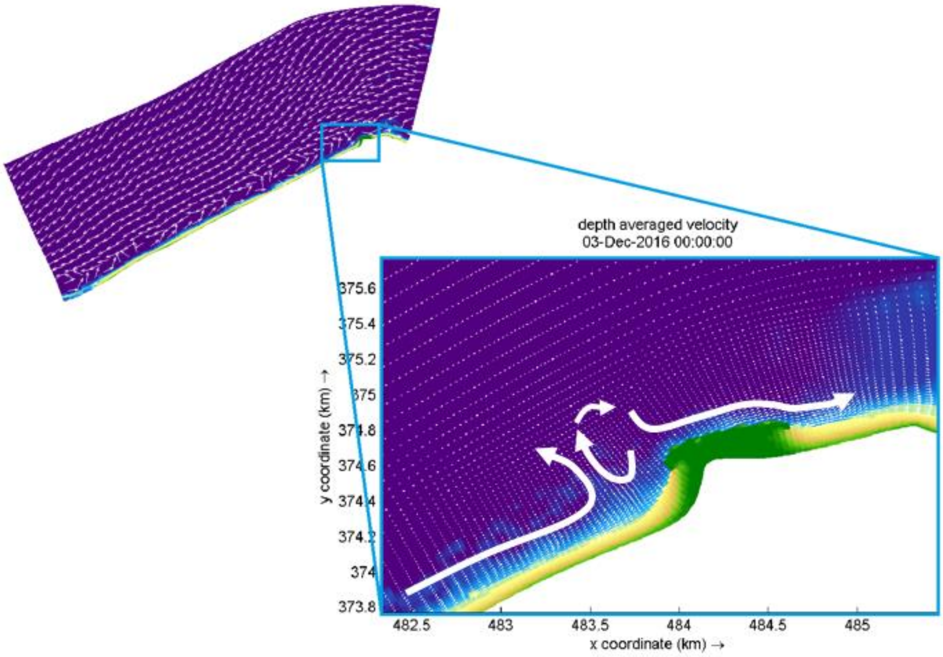


Figure 4-16 General flow patterns observed during normal conditions from the northwest

These results were found before the smaller grid was nested into the larger grid. After nesting, the results of the same condition for the small grid in Figure 4-17. The figure on the right shows the nautical direction of the flow, indicate by different colours. This way directional changes can be indicated more clearly.

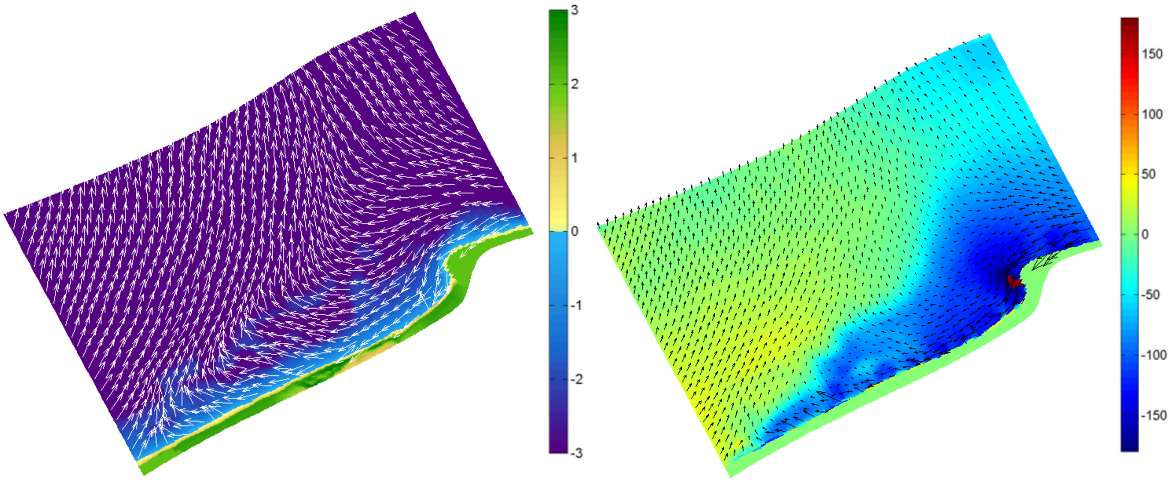


Figure 4-17 Normal conditions NW; bed level and depth averaged velocity as normalised arrows (left), depth averaged velocity as nautical flow direction angles in colour and real vectors in black (right)

The morphological changes due to these flow patterns are shown in Figure 4-18.

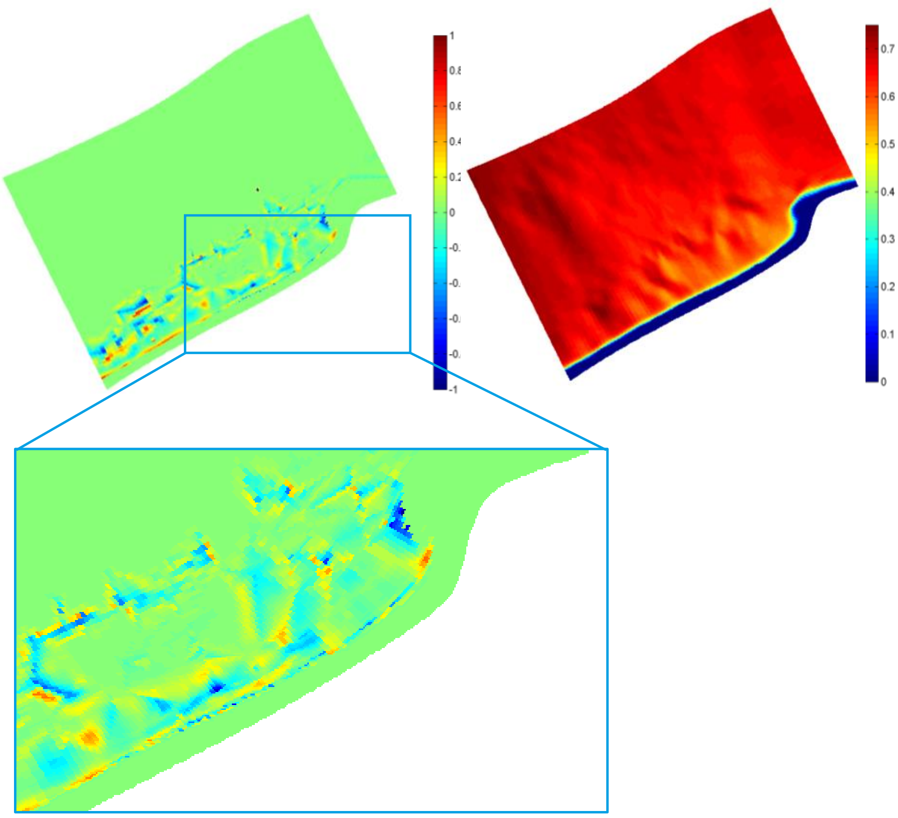


Figure 4-18 Sedimentation/erosion patterns during normal condition from the northwest

To draw conclusions based on these observation, the situation is schematized in Figure 4-19.

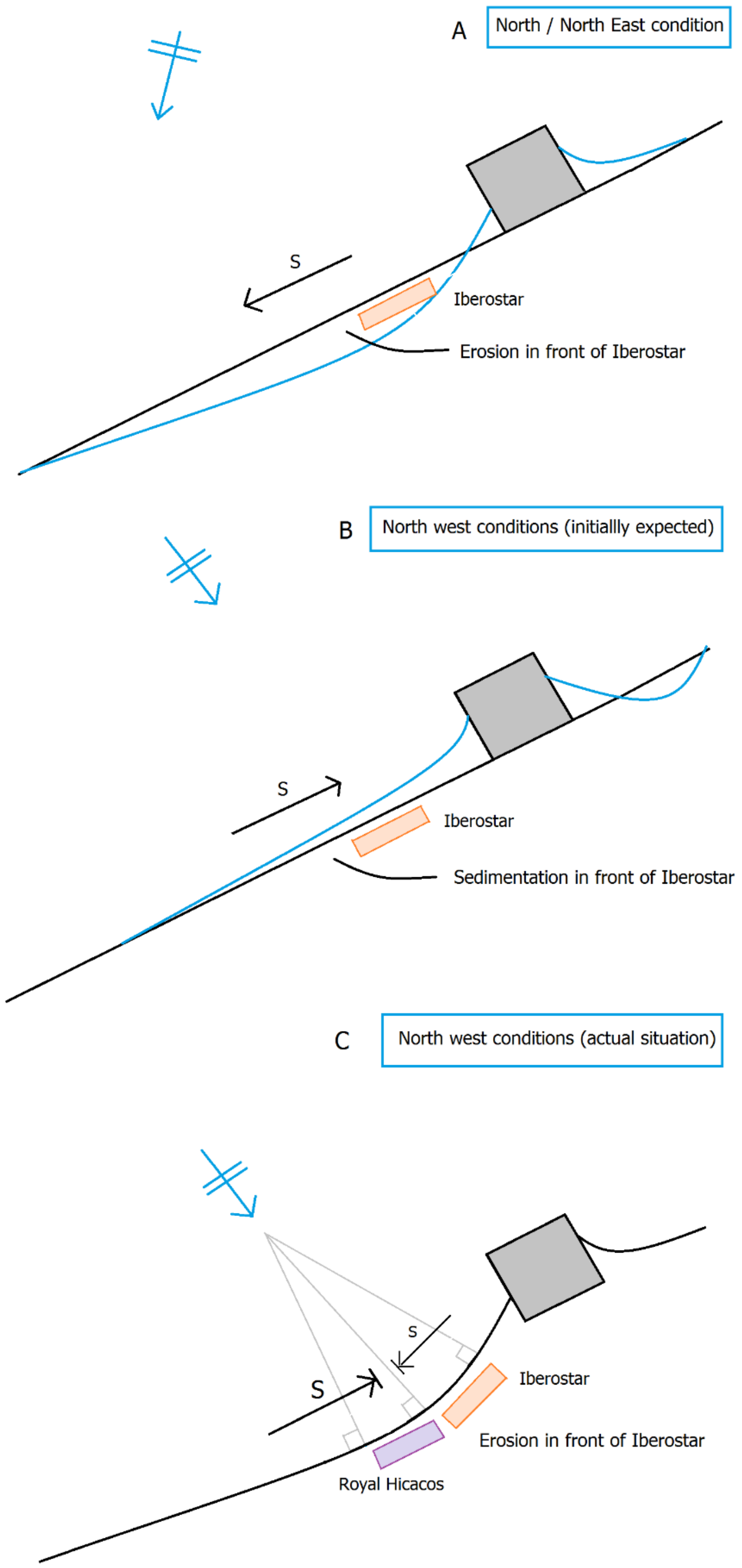


Figure 4-19 Schematization of the behaviour during different weather conditions

The angle of the perpendicular to the coastline is approximately 330°. Waves coming in from directions larger than this angle (~ 350° - 70°) will induce a westward current. The wave climate is dominated by waves from these directions (north and north-east), see Table 4-3.

During these conditions an erosion area will occur west of the headland (see A in Figure 4-19). The headland will result in a blockage of the sediment transport and therefore the beach on the lee side will start to erode.

Waves directed from the northwest induce the opposite process. The sediment transport will be directed towards the east, so a blockage by the headland will result in sedimentation at the western side of the headland (see B in Figure 4-19). Eventually one would expect net erosion on the western side, because the waves from the north east dominate the wave climate. Waves from the northwest would reduce the amount of erosion regularly, because the two processes show the exact opposite behaviour.

However, this expected behaviour is not shown during the northwest conditions by the Delft3D model, see Figure 4-17. The induced flow far away from the headland are indeed directed eastwards, however closer to the headland the flow is directed westwards. This can be explained by the differences in coastal angle over the coastline.

The difference between the coastal angle nearby the headland and more to the middle of the Tainos is approximately 20°. At the western boundary of the small grid, the angle is 330° while at the headland the angle is 310°. This means that for waves directed from 310~330° the currents have different directions over the area around Iberostar.

This is not a strange phenomenon for waves moving more or less perpendicular to the coast, however in this case it is problematic for the Iberostar hotel. Almost no waves come in from an angle smaller than 300°, which means that almost all the waves from the northwest induce these different directed currents.

Direction (°)	255 - 275	275 - 295	295 - 315	315 - 335	335 - 355	355 - 15	15 - 35	35 - 55	55 - 75
Occurrence (%)	2.10	4.51	11.9	12.6	10.6	10.0	11.5	18.6	17.3
Effect (-)	Sedimentation					Erosion			
Total (%)	~ 10%			~ 30%			~ 60%		

Table 4-3 Cumulative occurrence of waves from different directions [11]

To see where the translation area of the currents directions is located, multiple wave angles are simulated by Delft3D.

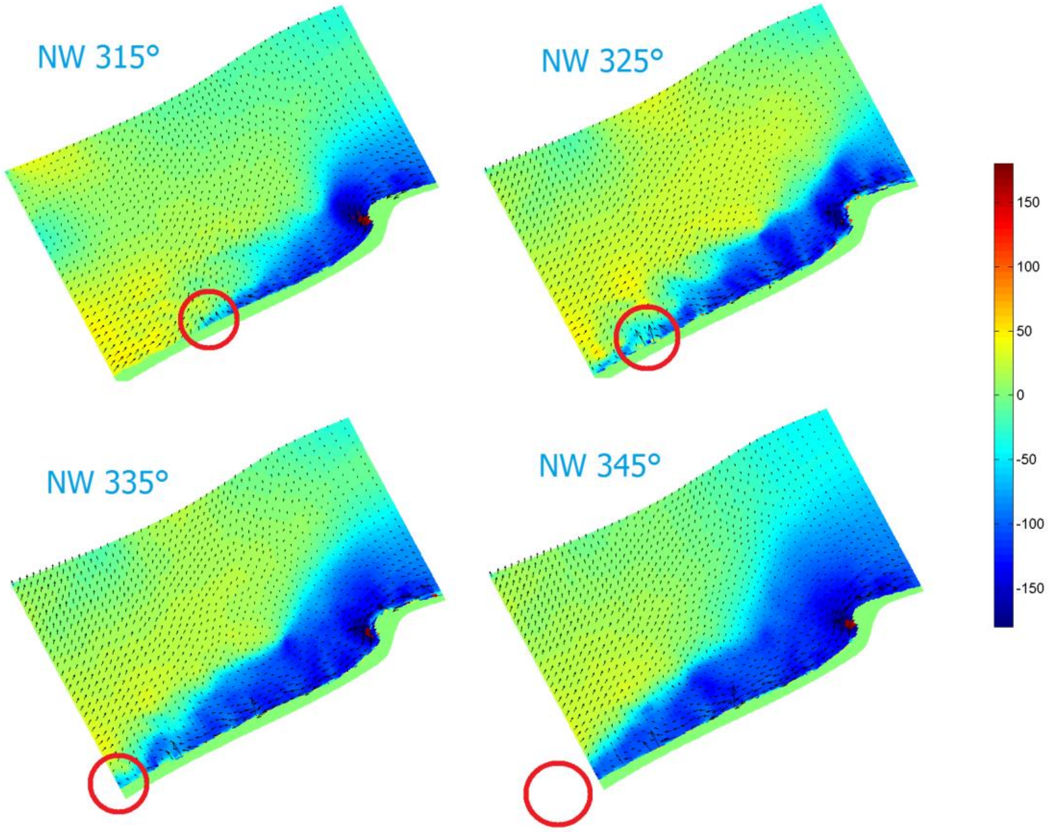


Figure 4-20 Resulting flow directions due to different wave angles

Figure 4-20 confirms that waves from 315° till 345° indeed induce this special flow pattern. At the transition area near the beach, the two currents come together. This means that the two sediment transports collide at that point and sedimentation is being expected at this area. These areas are indicated by the red circles. When the same locations are indicated on a satellite image of the current situation, the following can be seen.

Figure 4-21 Expected sedimentation locations plotted on satellite image

It can be confirmed that sedimentation occurs around these spots. With the expected behaviour confirmed, the consequences for the Iberostar area can be determined. In case of waves directed from the northwest (with a minimum angle of ~310°), the current in front of the hotel is directed to the west. The erosion caused by waves coming from the north east is therefore not compensated by waves from the northwest, see Figure 4-18. In fact, there is even a possibility that erosion will occur during these conditions.

With all these observations in mind, the following can be concluded about the Iberostar area:

- During conditions from the north and north east erosion will occur, due to the sediment blockage of the headland and therefore an increasing in sediment transport over the Iberostar area.
- During conditions from the northwest (>310°), no sedimentation will occur and even erosion can occur.
- During conditions from the northwest (<310°), sedimentation will occur. However the percentage of occurrence is too low to have a real impact on the total situation.

Final conclusion: Erosion is (almost) always present, resulting in structural erosion at the Iberostar beach section.

One year morphological time
Another way to validate the conclusions is using the wave reduction analysis as input for the Delft3D model. The wave input represents one morphological year. The results are shown in Figure 4-22.

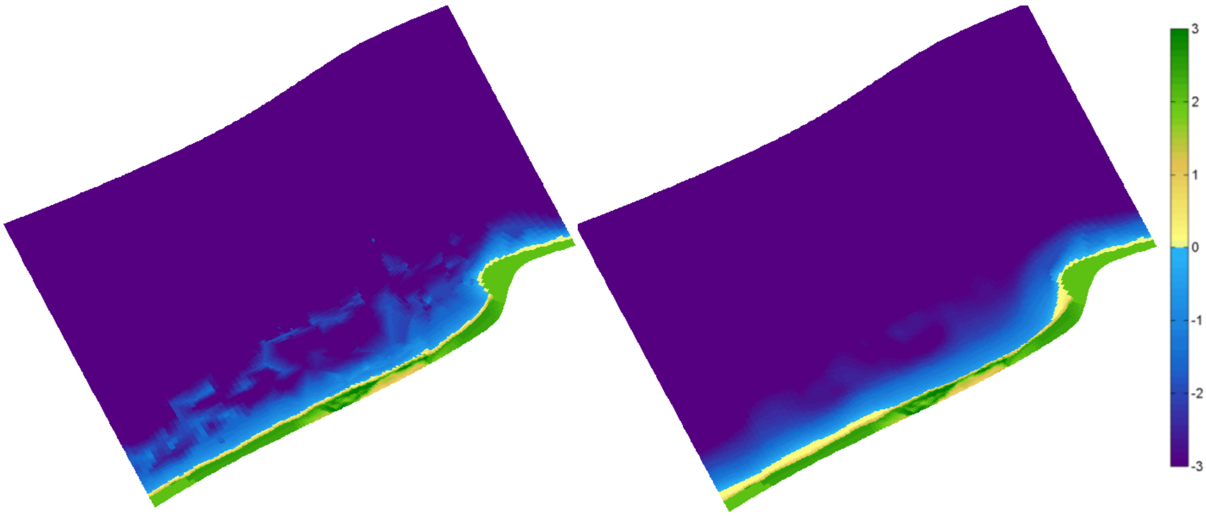


Figure 4-22 Initial bathymetry (left) and bathymetry after one morphological year (right)

The simulation also confirms the conclusions about the erosion in front of the Iberostar area. The accretion near the headland can be explained by situation A in Figure 4-19. The accretion west of the Iberostar hotel is due to the behaviour explained during the analysis with the different wave conditions.

This one year morphological model is the result of the calibration process and is used as the zero-state model. This holds that this model is used to design the different alternatives, which is done in chapter 6. In chapter 7 the model is used to test if the final chosen solutions hold for several requirements.

Multiple years morphological time

The result for three years of morphological time with the same wave input is shown in Figure 4-23.

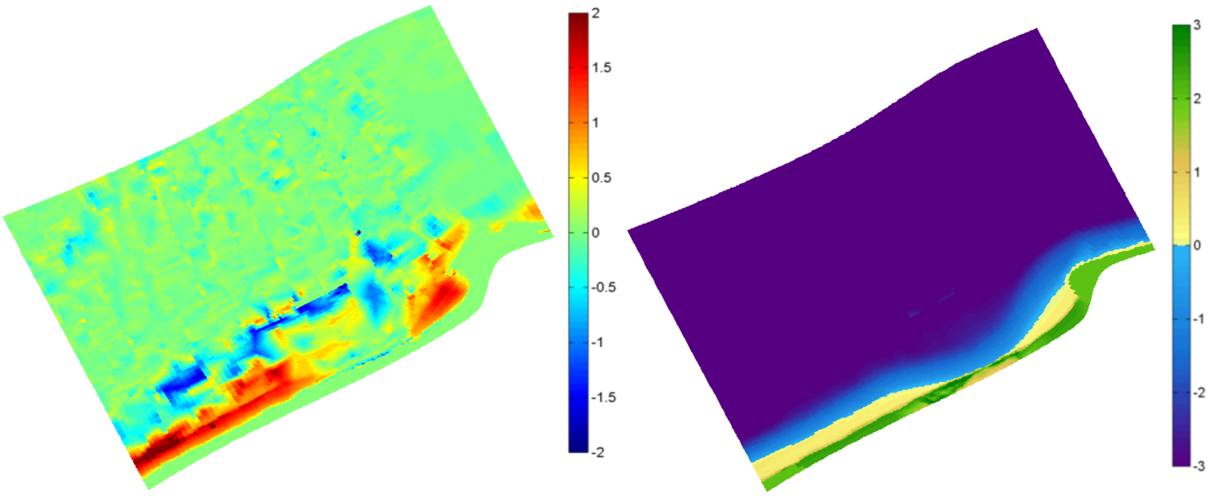


Figure 4-23 Three years morphological time, left: cumulative sedimentation/erosion and right: bathymetry changes

As seen from the results, the behaviour is not entirely as expected. Some remarks about the model have to be made, see section 4.4.4.

4.4.4 Remarks about Delft3D model

In this section some remarks about the Delft3D model are made. The results for the simulation (for multiple morphological years) does not represent the expected behaviour well, which has some consequences.

With the current Delft3D model it is not possible to accurately quantify certain processes. The bathymetry changes, beach width, sediment transports and sediment losses are representative in a general and qualitative way. However, after five year of morphological change, the induced errors are too large to still be able to obtain accurate, useable values. This does not mean that the results obtained in this section are useless. The errors are probably induced by morphological parameters and processes. It is safe to make that statement, as the behaviour of all the hydrodynamic processes are as expected and also the resulting morphological changes are represented well in a qualitative way.

The causes of the errors and their specific consequences are described below.

Wave reduction analysis

The wave reduction analysis is proven to be accurate during the calibration/validation process. Although the net longshore transports are approximately the same as for the whole wave set, cross-shore processes are not taken into account during the analysis and may differ from reality. The use of the wave reduction analysis does not explain the errors over the whole morphological year, but do explain the smoothing of the bars. When looking to Figure 4-22, it is clearly visible that all the bars and other irregularities are smoothing out over time.

The reduced wave data mainly consists of strong wave conditions which represent the whole wave climate. During strong wave conditions the equilibrium profile may change into a storm/winter profile, see Figure 4-24. The permanent smoothing of the bars does not happen in reality, so obtained the results are not completely accurate.

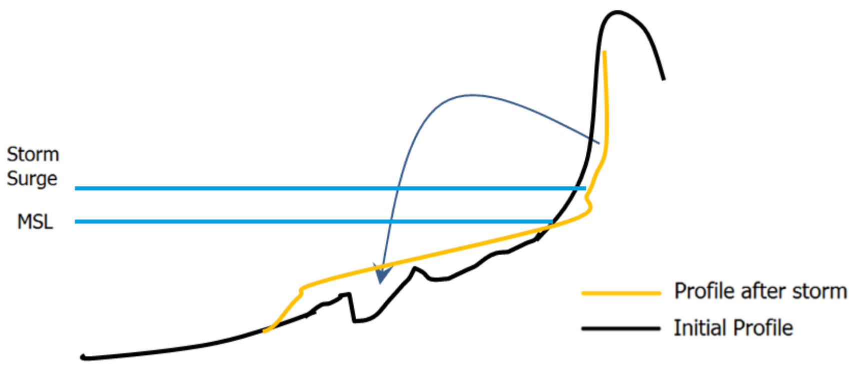


Figure 4-24 Profile changes due to high waves

Cross-shore processes Delft3D

Some important cross-shore processes are not taken into account in the Delft3D models. These processes can also partly explain the smoothing process of the bars in front of the beach. For more information about the missing cross-shore processes in Delft3D, see Appendix E.5.

Calibration based on visual observations only

Because there is a lack of information about the development of the coastline over time, the whole calibration is mainly based on visual observations. One of those visual observations is for instance that erosion takes place in front of the Iberostar hotel. Besides, the calibration is based on simulations of one morphological year, while the final results for five years where desired. A run of five morphological years takes approximately 35 computational hours and it was therefore impossible to calibrate the model for five years during the short time that was available for the project.

Because only visual observations were available as calibration material, some errors will be induced during the calibration of the one year model. When using the parameters of this model for a five year model, the made errors increase even more. So summarized, due to the lack of time, measurement data and computational force it was not possible to calibrate the model accurate enough to use the results quantitative.

No sensitivity analysis performed

During the setup of the model no sensitivity analysis is performed. A sensitivity analysis would have increased the knowledge about the effect of certain (calibration) parameters and maybe could have given better calibration results. However, again due to the lack of time and computational force it was not possible to perform a good sensitivity analysis.

4.5 Results for determining causes of erosion

In this section the first main objective of the modelling part will be fulfilled: Determining the causes of erosion. By doing this, sub-questions A, B and C (chapter 2) are answered.

All the results from Unibest (4.2), XBeach (4.3) and Delf3D (4.4) are used to answer the questions and qualify the different erosion problems. Finally, the resulting conclusions and quantities are used in chapter 5 for making some assumptions and in chapter 6 to design the different alternatives.

Based on the erosion analysis executed in section 3.4, all the causes of erosion will be determined, explained and, if possible, quantified in this section. In Table 3-11 an overview is given of all possible causes and in the second column it is stated for each of the causes if it is relevant for this project or not. If the cause is not relevant, it is not taken into account during this section.

Human interference

Human interferences can have influence on the morphological processes in the coastal area. For the current solution it is chosen to change the beach profile and shift the dunes landwards in order to create more beach. The consequences of this adjustment are hard to quantify, because all the available data measurements are done before this adjustment was performed.

The structural erosion was already a problem, before the new solution was executed, otherwise the new solution would not have been performed at all. For this reason, it is assumed that the new adjustment does not have a large influence on the total cause of erosion and therefore no quantification is given.

None-the-less, a representing bathymetry has been created to simulate the effect of a storm with XBeach on the new beach profile. This is done in order to get insight if the new solution may work or not. The results are given in the "Solutions" chapter, see section 6.1.5.

Sea Level Rise

The sea level is rising and this phenomenon has influence on almost all coastal areas around the world. The sea level rise is defined at 2.9 mm/year (see section 3.3.5). The resulting shoreline retreat depends on the slope of the beach profile and because the slope is very gentle in front of the Iberostar hotel, sea level rise can play a significant role in the total erosion problem. If it is not desired for the coastline to retreat, one should counteract the sea level rise by placing nourishments and the required volume for the nourishments can be calculated. This calculation is described in Appendix M.4.

If the dune height is taken d = 3 meter and the water depth h = 3 meter, the fill distance is can be determined from the bathymetry in front of the Iberostar hotel: L = 400 meter. With these parameters, the shifting a = 19 cm/year = 0.19 m/year. With this shoreline retreat, the sediment loss would be 1.62 m^3/m/year (for conversion, see Appendix M.3).

Longshore sediment transport

The longshore sediment transport is the amount of sediment that moves parallel to the shore. The longshore processes for a full year wave climate are researched with Unibest LT, and extensively with Delft3D, which results in the conclusion that the Iberostar area has to deal with structural erosion.

Values are required in order to be able to design a good solution. Different numbers are obtained for the longshore sediment losses in the Iberostar section. An overview of these values is given in Table 4-4. For all the values, some remarks have to be made. These are listed in the third column.

Obtained by	Erosion	Remarks
Gamma (2015) [3]	19.89 m^3/m/year	Possibly influenced by nourishment performed in 2012 (high); Measurement of total losses, not only longshore (high);
Unibest LT (Bijker)	17.6 m^3/m/year	Only simply longshore processes taken into account (inaccurate); Estimated wave angles are used which can have a large impact (inaccurate);
Unibest LT (Van Rijn)	14.54 m^3/m/year	
Delft3D (IBE6)	1.25 m/year	Delft3D model seems to have too much accretion in general (low and inaccurate);
(high: value probably too high, low: value probably too low, inaccurate: value inaccurate)		

Table 4-4 Overview obtained values for longshore sediment transport

When the remarks in the third column are taken into account, it is clear that for this project it is hard to determine a solid value for longshore sediment losses. To get a better insight in the right value to choose, see Figure 4-25. The shoreline retreat from Delft3D is converted to m^3/m/year according to Appendix M.3.

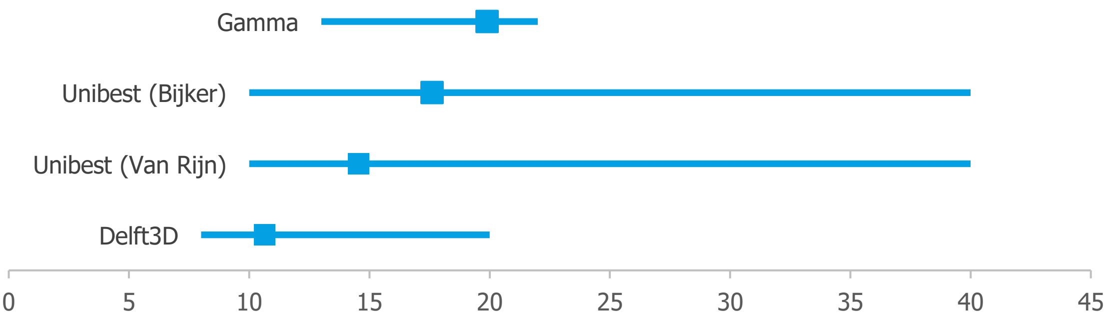


Figure 4-25 Longshore sediment losses (m3/m/year), expected errors included

The expected possible errors are also plotted in the graph, but only to give a visually interpretation and no actual calculated values are used. It must be clear that from these obtained values it is not possible to choose a longshore sediment loss which can surely give an accurate representation of reality.

Therefore, based on Figure 4-25, only an assumption can be made: The longshore sediment losses in the Iberostar section is 15,000 m^3/ year during this project.

Cross-shore sediment transport

The cross-shore transport is the net sediment transport perpendicular to the coastline. Extreme events have a large impact on the cross-shore processes and can change the equilibrium profile. However, if the time period between these extreme events is large enough, it is possible that the beach recovers. The short-term profile changes are simulated by XBeach and the results are summarized in Table 4-5. For an overview of all the zero-state results, see Table G- 7.

Condition	Sedimentation (m^3/m)	Erosion (m^3/m)	Balance (m^3/m)	Depth - no changes (m)
Weak Storm NW	9.42	16.36	-6.94	4.95
Heavy Strom NW	79.65	72.71	6.94	5.01
Weak Storm NE	9.15	12.28	-3.12	3.97
Heavy Storm NE	15.04	32.50	-17.46	4.97
Hurricane Michelle	19.09	18.01	1.08	4.97
Hurricane Wilma	58.83	71.14	-12.31	4.99

Table 4-5 Average values of short-term erosion/sedimentation after extreme events

From Table 4-5 it can be seen that the depth at which no changes in profile occur anymore is approximately 5 meter for the extreme conditions. This value is the same order of magnitude as the estimated closure depth, which is 5.5 meter (see Appendix **Fout! Verwijzingsbron niet gevonden.**). All the morphological changes due to extreme events happen inside the active zone and therefore it is assumed that net cross-shore losses at the offshore boundary do not have to be taken into account.

Two other remarks must be made about the cross-shore transport:

Dune avalanching during hurricanes
Due to the high water levels which are present during hurricanes, the erosion is located higher on the profile. Because of this, although the wave conditions are way heavier, the maximum depth of influence is in the same order as for cold fronts. The other consequence is that more erosion during hurricanes takes place at the foot of the dunes. This results in avalanching of the dunes, which is highly destructive to the coastal profile. When the dunes are heavily damaged, the possibility of recovery is decreased. The following assumption is that for hurricanes of category 3 or 4, the amount of sediment that will not recover is equal to 20 m^3/m. Hurricanes of these categories occur 0.2/year (see section 3.3.3). This assumption is fully described in section 5.3.3 (Assumptions) and is also taken into account during the design phase.

Increased longshore processes
In the column 'Balance' of Table 4-4 it can be seen that the amounts of sedimentation and erosion are not the same. This means that sediment is transported longshore during the storm conditions. Furthermore sediment eroded at the beach is transported more offshore. During normal conditions this sediment is transported back to the coast, but because there is also a longshore current during normal conditions not all this sediment will return to its original location. The final result is that extreme events move sediment offshore from where it can be transport alongshore by the general longshore current. In this way cross-shore processes during storm conditions can be part of the erosion problem. The final quantification of this problem will be categorized as longshore, but it has to be kept in mind that the cross-shore processes increase the problem.

Aeolian transport
The aeolian transports are mainly important during the recovery of the dunes after a severe storm. When the dunes are damaged and the water level has reduced again, the wind takes care of the recovery of the dunes. These are very important processes if one wants to determine cross-shore losses. However XBeach and Delft3D, do not take aeolian transports into account and therefore these processes are not computed for this project.

Final overview quantification
In order to make those observations usable in the design process, the processes are quantified. In Table 4-6 an overview is given of all the determined quantities for the remaining processes. The conversion of the values in the table is in accordance with Appendix M.3.

Losses	m3/m/year	m/year	m3/year (Iberostar section*)
Sea Level Rise **	1.61	0.19	1,610
Longshore	15.0	1.76	15,000
Cross-shore ***	4.0	0.47	4,000

Table 4-6 Overview of quantification for the causes of erosion

* The Iberostar section is not only the beach in front of Iberostar, but also a partly extended to the east of the hotel. This is already mentioned earlier, but repeated to avoid confusion.

** The computation of the Sea Level Rise is only done in order to get insight in the relative effect of this phenomenon. The calculation is empirical and based on many assumptions, nevertheless the sea level rise has to be taken into account for the future, if the coastline is desired to stay at a certain location.

*** The cross-shore losses are due to avalanching occurring during heavy hurricanes. This value is obtained by multiplying the assumed loss of 20 m^3/m by the frequency of the hurricanes: 0.2/year. The average annual loss will be 4 m^3/m/year, but this value is very dependent on the occurrence of extreme events. The value is only shown in the table to give more insight into the scale of the problem.

5. Project Requirements

In this chapter the list of requirements is made for the possible solutions. This can be done as the stakeholder analysis has been executed and the interest from all parties has been explored. This results in the definition of the core values. Afterwards the requirements can be derived, which leads to the final list of requirements.

5.1 Core values

The core values can be derived from the interests from the stakeholders. The core values are the basis of the final requirements and therefore of the solution. For this project there are generally three core values.

The first core value has to deal with Cuba. It should be taken into account that the proposed solution should not be too difficult to construct and maintain. This has to do with the limitation of the available funds and the final solution should also be within the technical capabilities. On the other hand, a lot of costs can be saved by using local materials and local workers. So this core value is to make an optimised solution, but within the possibilities for Cuba.

The tourists bring the money, so their interest is therefore also the interest of the producer. In this case this is the Ministry of Tourism and the Ministry of Economy and Planning. The core value can be found by finding what tourists wants when they are on holiday in Cuba. This seems to be a big white beach, which looks attractive. Therefore the attractiveness of the beach can be seen as a core value.

The final core value has to deal with the second main interest of the stakeholders, which is the environment. As the beach is a natural barrier which protects Varadero against the sea, the preservation of the beach and its ecosystem are very important. So the final core value is the preservation of the ecosystem.

5.2 Functional values

The functional values are followed from the core values. In general, the functional values are the core values, but they are explained in more detail and are more specific towards some subjects. The functional values are listed below, separated for each core value described in section 5.1.

5.2.1 Constructional & Maintenance quality

- Cuban beach protection funds are limited. The cost should be kept as low as possible, while the solution should still fulfil the other core values and requirements.
- The solutions lifetime should be as long as possible and should meet the international regulations. Therefore a sustainable and durable solution should be designed.
- The Cuban government prefers soft structures. The hard structures mostly only shift the problem and it does not look attractive for tourists. Therefore a proven and reliable technology should be used, when a hard structure is found to be the best solution.
- Solutions in shallow water are also preferred by the government. These solutions do not need special equipment for deep water and then also large constructions are avoided.
- Construction material should be available on Cuba. Equipment and materials available on the island are less expensive than from abroad, but the equipment for construction projects is limited.
- The technical knowledge on construction works can also be considered as limited. A solution, which is easy to construct, is therefore preferred. When the construction cannot be executed by the Ministry of Construction, international contractors should be hired. This is not preferred by the government of Cuba.
- There are no available funds to relocate the Iberostar Varadero hotel (or other hotels) to another location in or close to the project area.

5.2.2 Tourism quality

- The beach should be attractive to the tourist. It should have a comfortable slope both above and below the waterline. It is preferred that there is no scarp at the beach, which is not comfortable for the tourist. It is also preferred to have enough sediment on the whole beach area and at the first meters below the waterline. This should cover possibly occurring small rocks on the bottom, which can be considered as uncomfortable.
- The fine grain sizes on the Varadero beaches is one of its attractiveness. So in case of nourishments small grain sizes are preferred.

- The beach should not be too crowded. Therefore the beach should be large enough to be sure that a minimum beach area per tourist can be met.
- It is preferred to design a solution which should not be higher than the waterline. This can be considered as hindrance on the open ocean view. As the tourists wants to have an open view, the structures above the waterline should be minimised when there is no good submerged option.
- The construction hindrance should be minimised. Therefore it is preferred to construct not during the tourist season.

5.2.3 Environmental quality

- The solution should be environmental friendly. It is preferred to use sustainable materials.
- The measures may not result in new environmental problems.
- Nourished sand has to be similar to the original sand.
- During construction of the solution, the impact on the ecosystem has to be low.
- To preserve the natural ecosystem, the flora and fauna at the dunes should be protected from the sea. This can be done by maintaining a large beach.

5.3 Program of requirements

The list of conditions and demands can be derived from the previously mentioned functional values. Some of these values can be translated into hard demands that should be met. Other conditions without hard demands should be kept into mind, while designing the solution. This program of requirements can be seen as a framework for the design of the alternative solutions.

The program of requirements consists of three different parts: boundary conditions, design requirements and assumptions. These three components will be shortly explained below.

Boundary conditions are the conditions, which should be strictly met. These conditions are unavoidable statements and are determined by the natural and human environment.

Design requirements are the project specific requirements and demands. These are normally formulated together with the supervisor, but in our case they are formulated by ourselves.

Assumptions are statements, which were not verified yet. These statements, mostly simplifications, are made in order to design proper alternative solutions.

5.3.1 Boundary conditions

Beach Properties

- The length of the Iberostar hotel beach is in alongshore direction 500 meter.
- The present beach has an average width between 10 and 25 meters across the study area.
- There is a very gentle slope present in front of the beach (s = 0.005 m/m)
- The Iberostar hotel beach contains fine grainsizes. D_{50}=0.27 mm and D_{90}=0.74 mm.

Wind and waves

- The significant wave heights H_s, peak period T_P and other wave parameters are different for the different wave directions and wind conditions. These numbers can be found in section 3.3.5 and more information in Appendix D.

Cold fronts and hurricanes

- A design strong cold front lasts for 17 hour on average and occurs 0.7 time per year;
- A design weak cold front lasts for 29 hour on average and occurs 22 times per year.
- A design hurricane lasts 2 days.

Water level

- A global sea level rise of 2.9 mm/year is used.
- The tides are given in section 3.3.5.

Seasons

- The cold fronts appear between December and April.
- The hurricane season is between July and November.
- The wet season is between May to November, in which period 80% of the annual rain falls.
- The tourist season is from September to April.

Practical limitations

- Beach protection funds are limited in Cuba.
- Low budget for maintenance costs.
- Equipment and expertise for construction works is also limited.

- Landside accessibility of the construction site is limited.

Environment

- Environmental damages must be minimised.
- The measures may not result in new environmental problems.

5.3.2 Design requirements

Time scales

- The lifetime of the solution should be 50 years. For nourishments this also holds, but then the nourishment repetition has to be good enough to hold for the next 50 years.
- The design storm conditions on which the solution is based, can be found in Appendix D.3.

Beach requirements

- The minimum beach area for each guest present on the beach is 10 m^2. The maximum number of guests counts 1000, see Appendix A. However, according to the hotel management approximately 45% if the guests is present at the beach on the middle of the day. This results 4500 m^2 of beach. This is equal to a minimal beach width of 9 m with the beach length equal to 500 m.
- The beach should still fulfil the requirements after a weak storm (for the definition of a weak storm, see Appendix D.1).
- During a heavy storm (see Appendix D.1) no dune avalanching should occur, in order to increase the chance of a good recovery of the beach.
- The solution should not be visible from the beach.
- The solution is not allowed to shift the erosion problem to another part of the beach.
- Sand from a nourishment should have similar grain sizes and colour as the original sand.

Swimmer safety

- The flow velocities in front of the beach should not exceed 1 m/s. Below this flow velocity the swimmer safety of the tourists can be guaranteed.
- The occurrence of rip currents caused by the construction should be avoided.

Construction

- During the hurricane and tourist season no offshore construction can be executed, so this should take place between April and June.

- All measures are taken to avoid hindrance for the tourists and the local community during construction.
- The solutions do not form any danger for persons or the constructors themselves.

Environment

- No constructions may be built on top of the dunes or just behind it.
- The vegetation on the dune and beach should be maintained or compensated.

5.3.3 Assumptions

- The sand on the beach of the Iberostar hotel has the same characteristics across the whole study area. The only exception is Punta Francés, which is a rocky headland just northeast of the location of the Iberostar hotel.

- Only waves with an angle from 247.5° and 67.5° are considered to have any effect on the beach of Varadero. These are waves from the west, northwest, north and northeast.

- Some adjustments had been made on the bathymetry files, which were obtained by GeoCuba [5]. Some points in the original bathymetry file had some strange depths, which were manually changed. In Appendix C more information is given about the adjustments of the bathymetry.

- The longshore sediment losses are equal to 17 m^3/m/year. For more information about how this value is obtained, see section 4.5.

- The beach will (almost) fully recover after a weak or heavy storm. Only hurricanes of category 3 or higher do cause damage to a nourishment in such extend that the beach will not recover fully during normal conditions. An additional nourishment has to be carried out. The volume of the additional nourishment is on average 20.000 m^3.

- A breakwater will also suffer from extreme events. Hurricanes of category 4 or higher do cause damage to a breakwater in such extend that repairing operations are necessary. The costs for a reparation of a damaged breakwater, is half the amount of the costs for the initial construction of that breakwater.

6. Solutions

With the project requirements known from chapter 5 and the main causes of erosion determined in chapter 4, it is now possible to design solutions in order to solve the erosion problem.

In this chapter an evaluation of all possible solutions will be carried out. First all the possible solutions will be listed, describing their pros and cons and all the relevant variable design parameters. After that, all the solutions will be filtered on the design requirements given in section 5.3.2.

From the remaining solutions different alternatives are created. For these alternatives a preliminary design is made, see sections 6.2, 6.3 and 6.4. Most important in these preliminary designs is that they must fulfil the requirements described in section 5.3.2 and are not allowed to be largely overdesigned. For each design a rough cost estimation is made in section 6.6.

In section 6.5 a Multi Criteria Analysis is carried out in order to choose the best alternative. Later in chapter 7, the final solution is optimized and a more accurate cost analysis is done.

6.1 Possible solutions

In coastal engineering a lot of solutions are possible in order to solve a coastal problem. However, the exact behaviour of the coastal region when a solution is applied is hard to predict. Therefore some coastal interferences in practice, especially in developing countries, fail in solving the problem. Fortunately, with modern technology the predicting gets more accurate. Nevertheless, when designing a coastal solution, one should always keep the limitations of a numerical model in mind.

For all possible coastal solutions a division can be made in "hard" and "soft" solutions. Hard solutions are made of for instance rock, concrete or wood and are permanent structures which influence the situation.
A soft solution is made of sand or other natural material that was already present in the project area (coral reefs, mangroves, salt marshes) and mainly recovers the coastal system instead of interfering in the system.

In this section an overview is given of all possible solutions, together with their pros and cons, the parameters which influence the design the most and the additional design risks.

6.1.1 Groynes

Groynes are structures built perpendicular to the coastline. A groyne traps the longshore transport and can widen the beach by doing so. Groynes can be placed in the category of hard solutions. The main principle of the working of a groynes can be seen in Figure 6-5.

Pros

- Relatively cheap and easy to construct.
- Not much maintenance needed (except if destructed during extreme events).
- Permanent solution.

Cons

- Only shifting problem. The erosion will be shifted downstream.
- Hard solution and above water level, so decreases attractiveness of the beach.

Design parameters

- Length of the groyne into seaward direction.
- Longshore location.
- Amount of groynes along the coast.
- Construction material

Design risks

- Exact location of erosion and accretion can be different from computation.

6.1.2 Breakwaters

Breakwaters are structures built parallel to the coast and are also hard solutions. The main task of breakwaters is to break the waves and reduce the wave energy near the coast. Directly behind the breakwater an accretion zone will arise, but at both sides erosion zones will be formed.

A distinction can be made in types of breakwater. A breakwater can be emerged (above water level) or submerged (below water level). The advantages of a submerged breakwater are that they cannot be observed from the beach, so they will not reduce the attractiveness of the beach. However the flow patterns around submerged breakwaters are hard to predict and therefore it is difficult to design a submerged breakwater.

Depending on the length of the breakwater and its location (cross-shore) different accretion patterns can occur. See Figure 6-6. If the breakwater is relatively short and far away from the coast, it is more likely a salient will be formed (left), but if the breakwater is long and relatively close to the coast, a tombolo is more likely (right). In case of submerged breakwaters, only salient type accretion patters are observed.

Pros

- Relatively cheap and easy to construct, but more difficult than groynes (especially submerged)
- Not much maintenance needed (except if destructed after extreme events).
- Permanent solution.
- Submerged breakwater: Below water level so doesn't influence attractiveness of the beach.

Cons

- Merely shifting the problem. The erosion zones will be formed at both sides of the breakwater.
- Emerged breakwater: Hard solution and above water level, so decreases attractiveness of the beach.
- Submerged breakwater: Behaviour hard to predict, so hard to design and relatively high chance of failure.

Design parameters

- Length of the breakwater
- Longshore location.
- Cross-shore location.
- Emerged or submerged.
- Number of breakwaters in front of the coast.
- Other dimensions (height, width).
- Construction material

Design risks

- The behaviour is hard to predict, mainly for submerged breakwaters.
- Amount of erosion and accretion hard to determine.
- Formed type of shape hard to predict (salient or tombolo).

6.1.3 Nourishment

A nourishment is a soft solution and the idea is to supplement sand by artificial means. This can be done by dredging (shoreface/beach) or by truck (beach/dunes). In this project, the problem is structural erosion, so a nourishment is not a permanent solution.

If the nourishment is selected as best choice, a plan should be made about the return period for the nourishments. Normally this period is around 5 years. To make a nourishment plan, a minimal requirement must be stated. This requirement should be fulfilled all the time, which is shown in Figure 6-1.

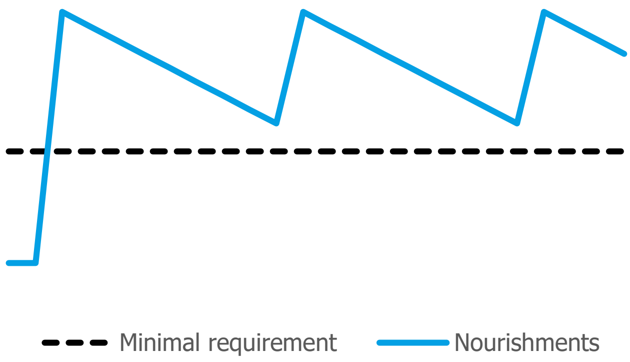


Figure 6-1 Nourishment return

The location of the nourishment is also a very important factor to determine. The idea is that if the sand is supplemented in the active zone (from dune to end of surfzone), the sand will be spread by all kind of coastal processes and an equilibrium profile will be formed again.

The option most far away from the coast are the nourishments at the shoreface, the end of the surfzone. The dredging vessels can still reach this area and can supplement the sand by opening a hatch at the bottom of the ship. Closer to the coast no nourishments are possible, because the ships are not able to get there and the breaker zone is too rough to supplement the sand easily. So the next option is to supplement directly on the beach. This is approximately two times as expensive as shoreface nourishments. The advantages are that the sand will be used more efficiently and the beach is directly at optimal size.

It is also possible to supplement the sand on the dunes, at seaside or at landside. This option is more used for coastal defence purposes than recreational beach extensions.

Pros

- No reduction of attractiveness of the beach.
- No negative effects on neighbouring hotels.
- Easily adjustable design if behaviour differs from computation.

Cons

- No permanent solution (must return for every 5 years).
- Relatively expensive compared to hard solutions.

Design parameters

- Location cross-shore (shoreface/beach and dredging/truck).
- Location longshore.
- Volume.

- Grainsize.

Design risks

- Hard to compute correct amount of sediment to cover 5 years, but the return period is variable so no permanent failure.

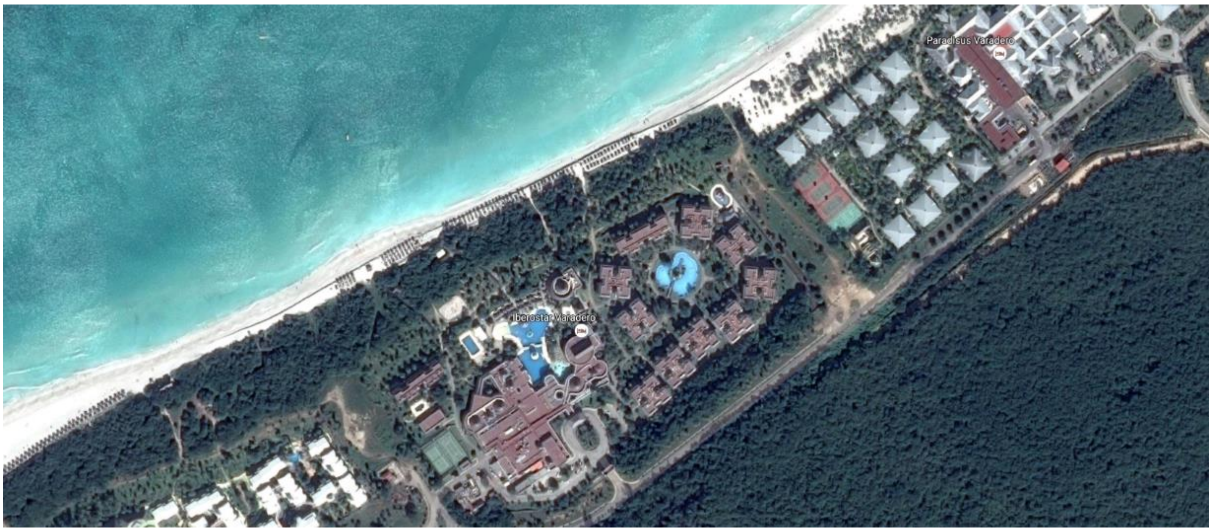
6.1.4 Bypass system

A special form of a soft solution is a bypass system. A bypass system artificially restores a blockage of sediment. This blockage can be human-induced (port) or a natural object (headland). The bypass system can be in the form of a small cutter dredger which continuously dredges the sand from an accretion zone to the problematic erosion zone. The sand can be transported through a pipe, see Figure 6-8 and Figure 6-9.

The system is a permanent solution, but relies heavily on good maintenance.

6.1.5 Current solution

In the current situation, the area and capacity of the beach are increased by relocating the dunes in landward direction and filling up the newly created area with sand. In other words, by modifying the dunes and services of the hotel, there has been anticipated on the changed conditions. These changed conditions mainly cover the small width of the beach due to erosion problems in the last decennia and especially in the last years after the nourishment in 2012 (see section 3.5). In Figure 6-2, first the original situation is shown. In the second figure, the area at which a new beach is created is highlighted in orange.



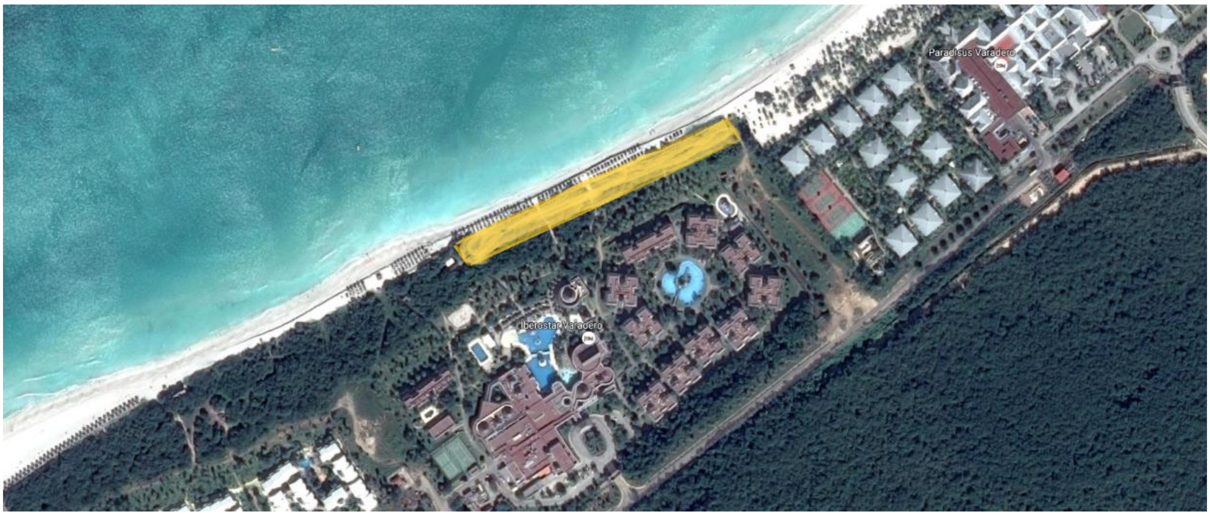


Figure 6-2 Original and new situation in front of Iberostar beach

Directly left from the highlighted area, a wooden bridge is located which crosses the dunes and forms the connection from the hotel area to the beach. At the end of this bridge, a small restaurant/cafeteria is located on top of the dune. Originally, the dunes at the eastern side of this bridge consist of only one dune row close to the beach. This dune row is removed and relocated 20 to 30 meters more landward to increase the beach area over a longshore distance of approximately 350 meters (see Appendix A for more pictures).

An important note is that sand is only placed on the newly created area, the shoreline is not reinforced. On the new dune vegetation and fences are placed in order to increase the sand retaining capability of the dune. The higher the sand retaining capability, the quicker the dune will reach its equilibrium profile and therefore its full strength. Also some hotel services have been removed together with the dune. Initially a small bar was located at the former dune edge, this bar is removed to increase the capacity of the beach and to prevent high erosion around the structure. Drinks and food can nowadays be ordered at the cafeteria in the dunes.

On the western side of the bridge, the dunes exist of two dune rows, as can be seen in Figure 6-3, in which the original dune rows are highlighted in red. Keep in mind that the situation shown in the figure, is the situation before the current solution was applied. For the future, plans are made to also remove the first dune row on the western side and strengthen the second dune row, which is in line with the newly created dune row on the eastern side.
In this case, also the cafeteria has to be relocated more landward, as it is no more protected by the dunes when they are removed on both sides.

The main goal of the current solution is to increase the tourist beach area and therewith the attractiveness of the beach on the short term. Next to this, the new dunes still have the function to defence against the impact of the flow and waves during erosive events.

Therefore, the hotel area still is protected, while the beach area is increased. With the main goal of the solution in mind, the solution fulfils its requirements. However, the erosion problem is not solved for the long term with this solution as the yearly net erosion will still continue and the beach area again will decrease.

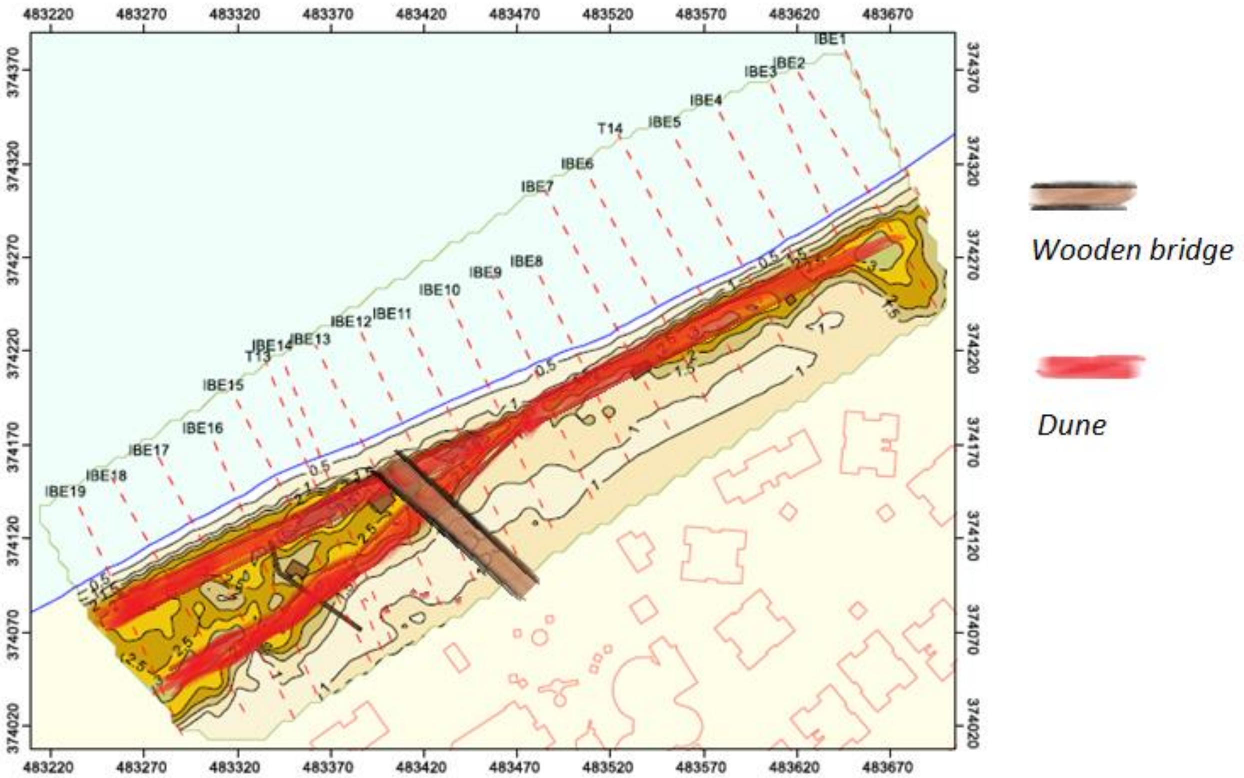


Figure 6-3 Overview of the Iberostar beach area

The short-term solution only becomes a long-term solution of the beach if it reaches its equilibrium profile. Whether this is the case at this moment is very hard to predict. On one hand, the erosion in the last couple of months was very low and even some accretion was observed during cold front events from the northwest.

On the other hand, the erosive trend over the last years shows that the erosion will probably continue in the coming years, with a decreasing recreational area and decreasing protection for the hotel during storms as a consequence. In our opinion it is therefore better to protect the coast with a long-term solution, taking into account the yearly net erosion.

6.1.6 Overview of general solutions

In this section an overview is given of the described general solutions by schematizations of the way they work. At the end of this section for each solution is checked if they possibly can fulfil the main requirements from section 5.3.2.

Figure 6-4 General solutions - Original situation

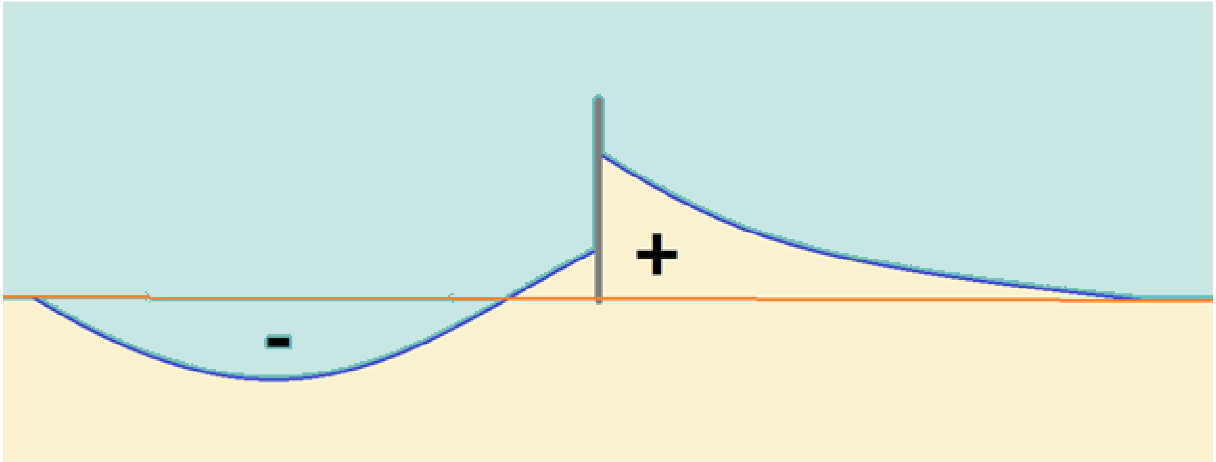


Figure 6-5 General solutions - Groyne

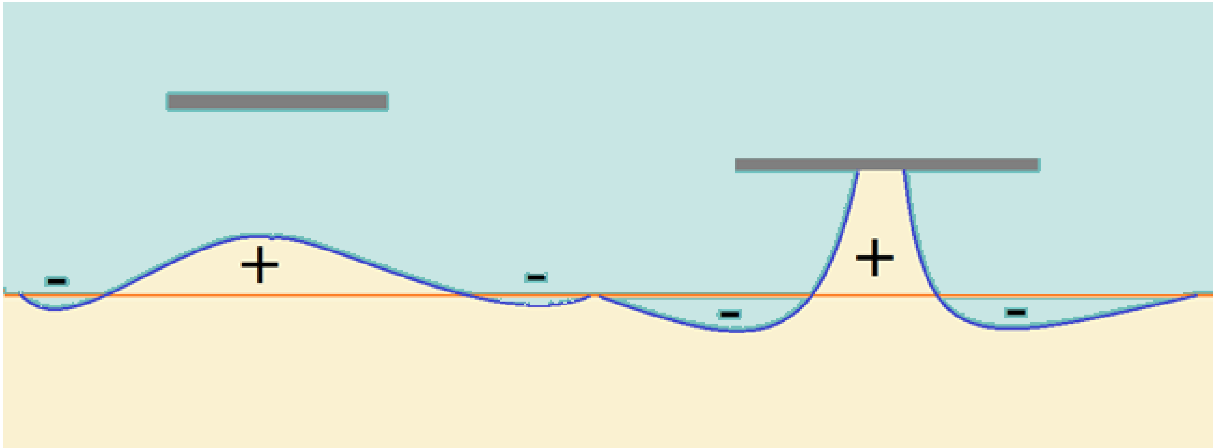


Figure 6-6 General solutions - Breakwaters

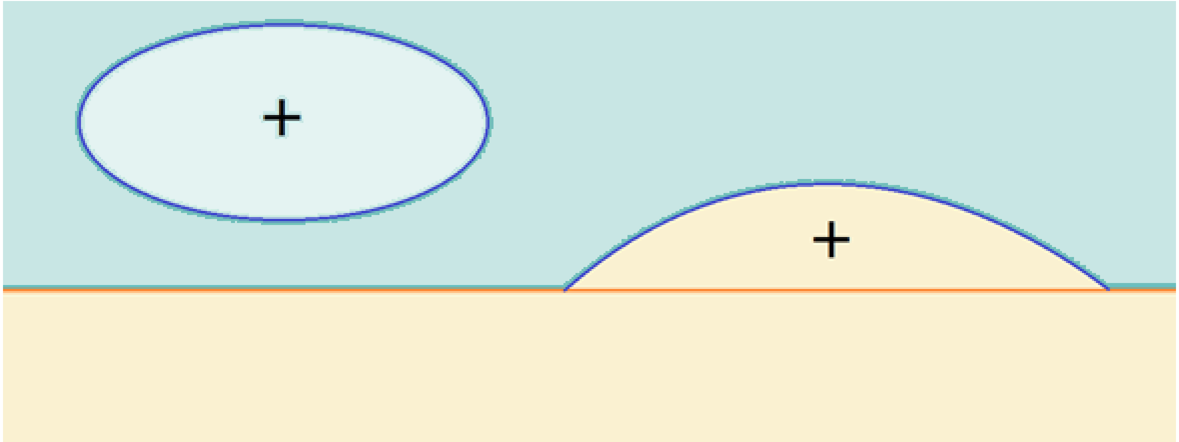


Figure 6-7 General solutions - Nourishment

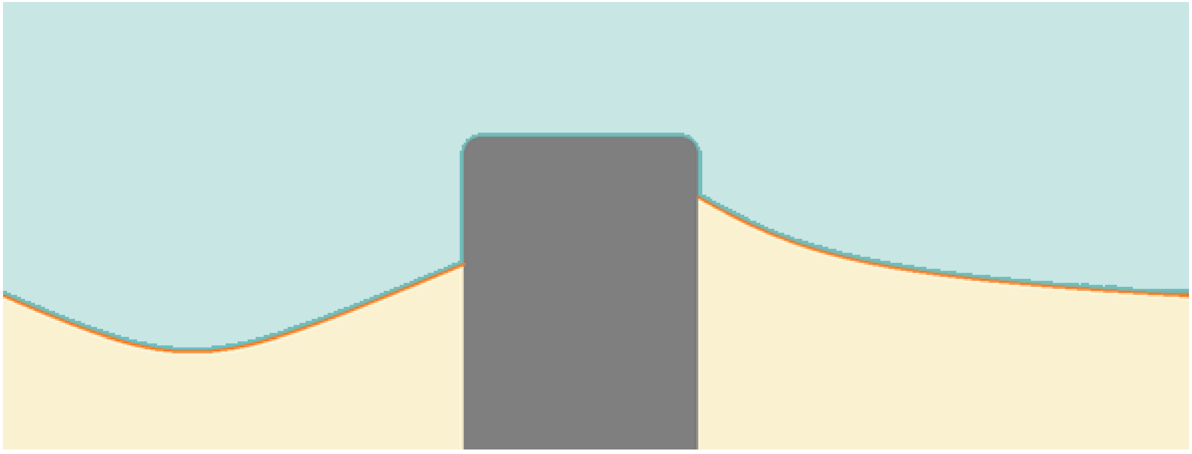


Figure 6-8 General solutions - Original situation with headland

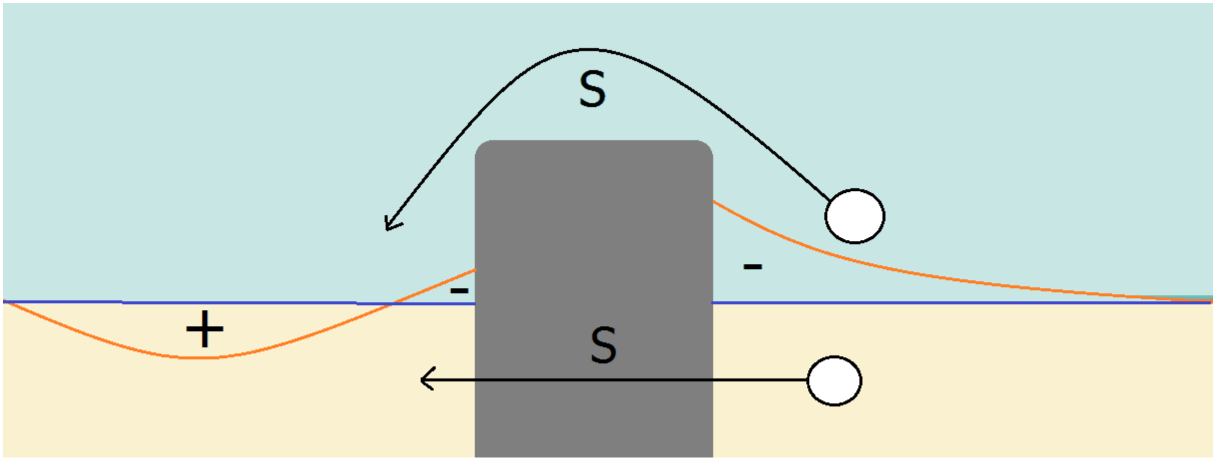


Figure 6-9 General solutions – Sand-bypass

Solution	No impact on attractiveness of the beach or ecological system.	Easily constructible, possible without international contractors.	Not shifting the problem towards other parts of the beach.

Groynes	🔴	🟢	🔴
Breakwaters (emerged)	🔴	🟢	🟠
Breakwaters (submerged)	🟢	🟠	🟠
Nourishment (shoreface)	🟢	🟠	🟢
Nourishment (beach)	🟢	🟢	🟢
Artificial bypass	🟢	🔴	🟢

🔴 The solution cannot fulfil the requirement and cannot be taken into account.

🟠 The solution cannot (completely) fulfil the requirement, but can still be taken in consideration.

🟢 The solution can fulfil the requirement.

Table 6-1 Possibility check of solutions can fulfil main requirements

From Table 6-1 follows that only one solution can fulfil the main requirements, which is the beach nourishment. Furthermore it follows that the submerged breakwater and shoreface nourishment can still be taken into account. So eventually there are three possible solutions, but some remarks have to be made for all of these solutions.

Beach Nourishment

As stated before, structural erosion is already present for a couple of years in the Iberostar hotel area. In recent history beach nourishments are carried out multiple times in recent history, but failed badly. These failures were shown more extensively in section 3.5. This is also one of the reasons behind the choice for the current solution (see section 6.1.5). If the beach nourishment is eventually chosen as the solution, a good design has to be made in order to ensure all the stakeholders this nourishment won't fail.

Shoreface Nourishment

In case of a shoreface nourishment, dredging vessels must be able to reach the shoreface to supplement the sand. However, looking at the bathymetry in front of the Iberostar hotel and taking into account the minimum depth required for the dredging vessels (6.29 m, Appendix J.5), the shoreface nourishments should take place at almost 2 km out of the coast. With this distance a shoreface nourishment is risky, because it is very hard to predict the effect of the nourishment in this case.

Besides, the XBeach results show that in case of a depth larger than 5 m the impact of the waves on the bed is low. Therefore, the shoreface nourishment is not taken into account as an option.

Submerged breakwaters

The submerged breakwater is a relatively hard part of the coastal engineering field. Very few guidelines are available and a lot of questions are still unanswered. Using a submerged breakwater as a solution can therefore be very risky. Besides, submerged breakwaters have only limited effect on storm-induced erosion, because the large waves will still pass the structure and reach the beach. Supplementary beach nourishments are often required in order to make a submerged breakwater effective [22].

Therefore, also a *Combination Alternative* will be designed, in which a nourishment is combined with a submerged breakwater, see section 6.4. The submerged breakwater alternative will still be investigated, in order to see the effect of a submerged breakwater if no nourishments are carried out.

So, eventually three alternatives are remaining:

- Submerged breakwater alternative (**Fout! Verwijzingsbron niet gevonden.**).
- Beach nourishment alternative (**Fout! Verwijzingsbron niet gevonden.**).
- Combination alternative (6.4).

In section **Fout! Verwijzingsbron niet gevonden.** the modelling results of the alternatives are described, in section 6.5 a MCA is carried and combined with the financial part of the alternative (see section 6.6) in section 0 the choice for the right solution is made.

6.2 Breakwater Alternative

The intention of the placement of a submerged breakwater is to decrease the wave action at the landward side of the breakwater and therefore decrease the erosion. Sometimes, a submerged breakwater succeeds in decreasing the wave action but does not succeed in decreasing the erosion. Examples are known in which more erosion was present after construction of the submerged breakwater, in comparison with the initial situation.

Complicated circulation currents around a submerged breakwater due are the main reason of the erosion, as they can carry high amounts of sediment offshore. The circulation currents are generated by water level differences around the breakwater. Wave breaking at the breakwater location causes water level set up, which is the reason of the water level differences. Processes like the circulation current can easily counteract the accretion due to decreasing wave action, especially when the submerged breakwater is placed too close to the shore [22].

With some rules of thumb, four preliminary designs will be made to give quick insight in mainly the best location of the breakwater. Unfortunately almost no design rules are known for submerged breakwaters as the effect and therewith the ideal shape of a submerged breakwater is still subject of research. Therefore design rules known for the location and length breakwaters are with a basic design. From this design, three other design are made in which the location is the most important parameter. All the breakwaters are modelled in a simplified Delft3D model to see the influence on wave action and the coastline changes. For all parameters, in the end, a consideration has to be made between initial costs and effectiveness, which decreases maintenance costs for the shore.

Location and length of the breakwater(s)

The location and length of the breakwater are the characteristics which have the most influence on the sedimentation and erosion patterns. For attractiveness of the beach, a salient is preferred above a tombolo, therefore the breakwater has to be located not too close to the coast. Also the negative effect of complex currents around the breakwater decreases when a breakwater is placed at a larger distance from the shoreline, because the set-up which causes the currents is limited in this case. On the other hand it is important that the breakwater has to be placed not too far away in order to get an area with decreased wave action close to the shore.

To be able to say something about the best location for the submerged breakwater, breakwaters at different distances from the coast are modelled. A basic breakwater, a design based on design rules for emerged breakwaters is used, which states that salients are found for a ratio of length L over cross shore distance D equal to $0.5 < L/D < 1.3$ [22]. It is decided to use a ratio of 0.7 and a breakwater length of 500 m for the first design, which results in a cross shore distance of approximately 700 m. For the other breakwaters, the length is equal to the length of the basic breakwater, while the cross-shore distance varies.

Next to varying the cross-shore distance, the design also is changed by using two breakwaters. An important parameter in this case in the length of the gap between the two breakwaters. Gaps should not be too large, in order to avoid high wave action and resulting erosion at the location of the gaps, but also the gaps should not be too small, in order to avoid high velocity offshore currents which also will induce erosion. These high velocity offshore currents are, similar to the circulation currents, a consequence of set up behind breakwater. For the design with two breakwaters, a gap length of 100 m is used, with two breakwaters of 150 m length. The lengths and cross shore distances for all four preliminary designs can be found in

Height of the breakwaters

The big advantage of a submerged breakwater, compared to an emerged breakwater, is the fact that it is not visible from the beach. In order to accomplish this, the distance between the crest of the breakwater and the MSL should be large enough. However, if this distance is too large, the breakwater can lose its effectiveness. So to come up with a good height, the tide must be taken into account in order to keep the breakwater below water level. The lowest astronomical tide at the Hicacos peninsula is -0.32 m MSL (see section 3.3.5). To be on the safe side, it is chosen to design the breakwater with the crest on -0.5 m MSL.

The total height of the breakwater is dependent on the depth at the location of the breakwater.

Design	Length (m)	Distance to shore (m)	Crest height (m)
1	500	700	-0.5 MSL
2	500	500	-0.5 MSL
3	500	300	-0.5 MSL
4	150 (2) 100 (gap)	250	-0.5 MSL

Table 6-2 Different types of submerged breakwaters

Other Dimensions

The type of material used, the width of the crest and the slope of the breakwater are still to be determined. The exact dimensions are mainly important for the cost estimation and strength of the breakwater, which becomes important when the final design of the breakwater is made. In that case, increase in strength, which decreases maintenance costs, has to be compared with the higher initial investments costs for stronger breakwaters. The influence on decrease in wave action is relatively low for these parameters.

Simulation

The effect of the breakwaters is simulated with Delft3D. A simplified grid and bathymetry is used to be able to simulate all breakwaters in one model run. The bathymetry is based on a representative cross section of the shore in front of the Iberostar hotel. This cross section is used over a longshore range of approximately six kilometres. All breakwaters are placed in this bathymetry on large distance from each other to be sure that the breakwaters do not influence the results of neighbouring breakwaters. The duration of the simulation is set on one year to be able to see the influence of the breakwaters with the full year wave climate. The locations of all breakwaters and the results of the simulation are shown in the figures below.

In Figure 6-10 the locations of all breakwaters can be found in light blue (-0.5 MSL), the shore line is in between the dark blue and light blue range. Please note that in the legend, the positive depth direction is downwards. From left to right, breakwater 1 to 4 are located. The fifth breakwater on the right is smaller in width and only used to check the model behaviour.

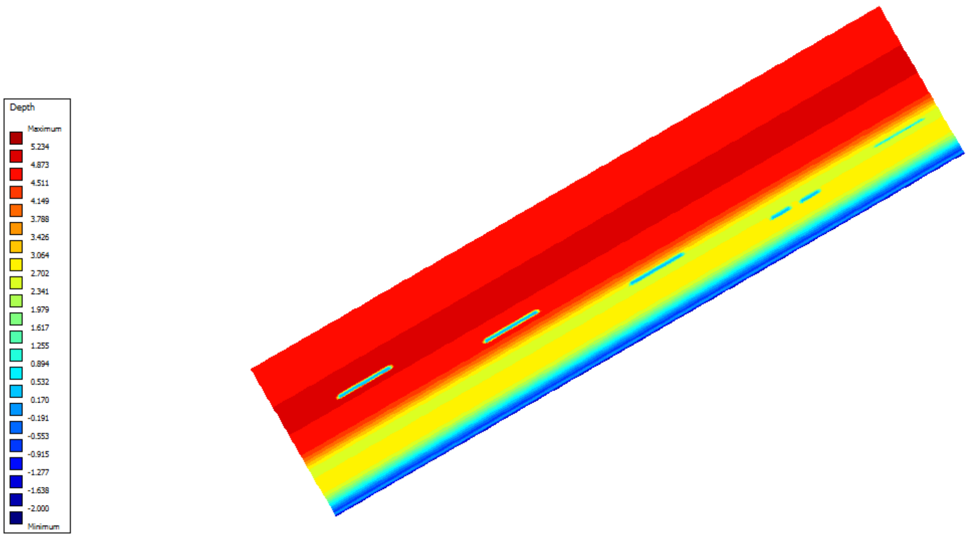


Figure 6-10 Overview location and shape of the breakwaters for testing

In Figure 6-11 the influence of the breakwaters on the significant wave height shown. Clearly visible is that for each breakwater the wave action behind the breakwater decreases. Remarkable is that for the two most offshore breakwaters, the 'plume' with decreased wave action does not fully reach the shoreline. In case of the third breakwater at 300 meter from the shoreline, it does reach the shoreline completely. Also visible is that the effect of the two smaller breakwaters (fourth option) on the wave height is low compared to the case with one larger breakwater. For decreasing the wave action, breakwater option 3 gives the best results.

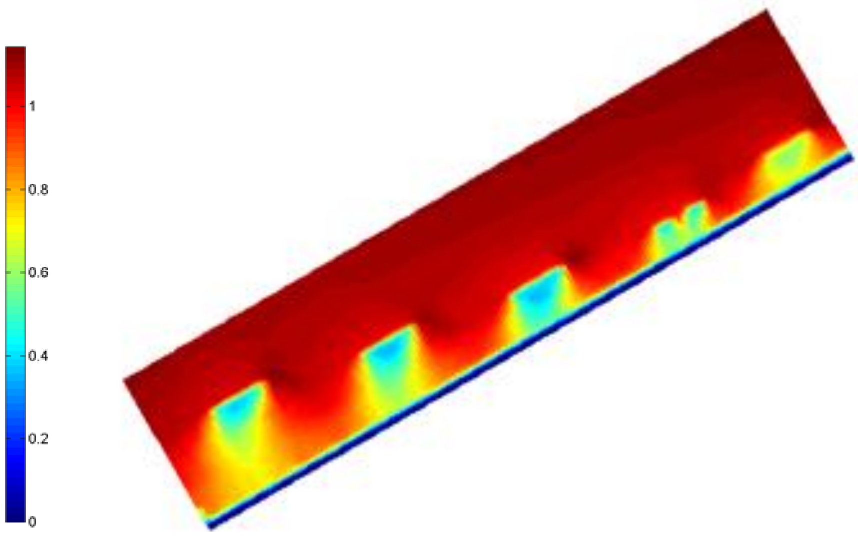


Figure 6-11 Effect of the breakwaters on wave height

Figure 6-12 shows the water level set up, again the influence of the breakwaters closest to the shore is largest. In this case, this is not favourable, as water level set up can cause circulation currents. The water level set up still is very small, in the order of 0.05 to 0.1 m, and therefore no severe circulation currents are expected. Nevertheless, water level setup has to be treated with caution.

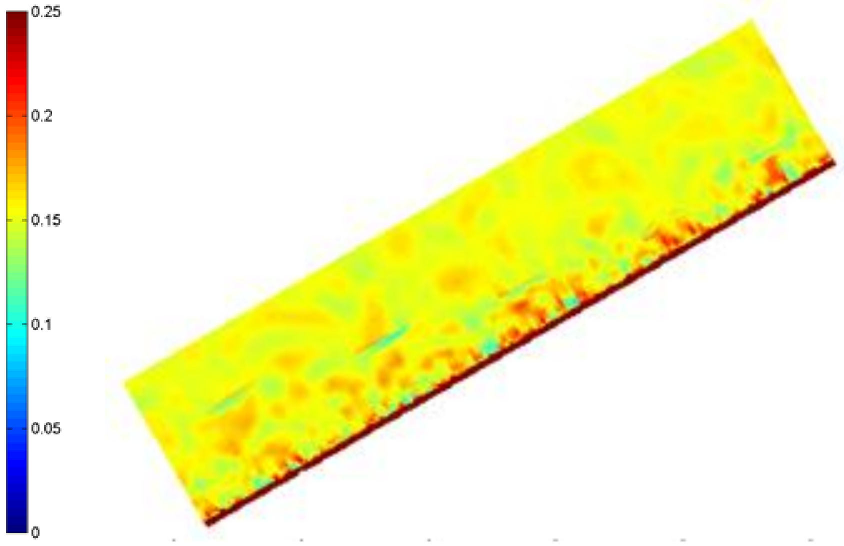


Figure 6-12 Water setup due to waves in breakwater model

In Figure 6-13 the bed level after the simulation of one year is presented. Although the difference is limited, more accretion at the shoreline is found for the breakwater at 300 meter from the coast.

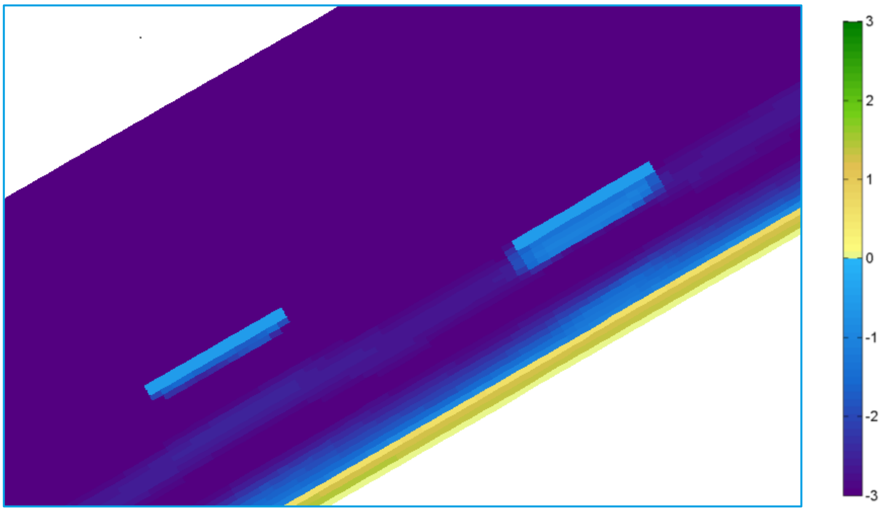


Figure 6-13 Bed level after one morphological year

Conclusion

In the field of coastal engineering, there are still a lot of questions that need to be answered about the submerged breakwater. The behaviour is very unpredictable and therefore need to be studied carefully if used in this project.

Besides, from Figure 6-13 it can be seen that the effect on the coastline is relatively small. The structural erosion in front of the Iberostar beach is probably in another order of magnitude and the current state of the beach does not meet the project requirements (see section 5.3.2).

It must be noticed that for the test model the used bathymetry does not represent reality well and the used grid cells are large.

Eventually, in the most positive case that the behaviour of the breakwater is as predicted and it is effectively protecting the beach, probably additional erosion will occur at the not protected areas (see Figure 6-6).

For these three reasons, it is very likely that the submerged breakwater will not be chosen as the final solution. Although, despite all the reasoning against breakwaters, it could be possible that the breakwater is still capable of protecting a nourishment. The relative erosion at the lee-sides could be compensated by the nourishment and additional sedimentation will not be necessary, because the nourishment will take care of the structural losses. The task of the breakwater is to protect the nourishment and reduce the amount that has to be nourished.

Therefore the combination alternative (see section 6.4) still is a good alternative to compete with the beach nourishment alternative (**Fout! Verwijzingsbron niet gevonden.**). The preliminary design created in this section, will be used by the combination alternative as an initial design.

6.3 Nourishment Alternative

The main idea of a nourishment is to fill up the sediment which is missing in the system by supplementing sand into the active coastal zone. The currents in the active zone will then redistribute the sediment up to a new equilibrium profile is reached. If the nourishment of the sand not executed properly, the redistribution of the sand will happen inefficiently, which can result in a fast loss of sediment. For more information about the 2012 nourishment, see section 3.5. The location of the nourishment will be in the Iberostar section, which is approximately 1000 meter long.

For now, four types of nourishments are defined:

- Initial nourishment (first nourishment carried out)
- Regular nourishment (nourishments with a certain return period)
- Additional nourishment (nourishments carried out after extreme events)
- Reshaping nourishment (nourishments when beach profile has been changed)

Return period

Because of the structural erosion, one nourishment will not be enough to guarantee a wide beach in front of the Iberostar hotel for the long term. A good maintenance plan should be made in order to keep the beach wide enough for the tourists in both the near and far future. For this maintenance plan, usually a return period of 5 years is chosen and so is for this project.

Volume

The nourishment will have two purposes: Improve the current situation and secondly to compensate for the future structural losses. Therefore the first nourishment should be larger than the nourishments carried out during the remaining 50 years. The needed sand volume to initially fulfil the project requirements has to be determined first.

The project requirements (section 5.3.2) state that the minimum beach width is in the order of 9 meter. The current width of beach is in the range of 9 till 11 meter wide. However, the project requirements also state that the beach should still fulfil this requirement after a weak storm. The waterline retreat during a weak storm (see section 4.3) is approximately 5.5 meter. Therefore the wished initial beach width is in the range of 16 meter. The required related initial volume which is needed to reach this beach width is approximately 15,000 m^3.

Secondly, the future structural erosion should be compensated. In section 4.5 it is concluded that the annual wave related sediment losses are in the order of 15,000 m^3. With a return period of 5 years, to total volume becomes 75,000 m^3. When an additional safety volume of 10,000 is added to compensate for sea level rise, see section 4.5., the nourishments should have a volume of 85,000 m^3, with a return period of 5 year.

Eventually, in chapter 7, the needed nourishment volume is further investigated. For now the volume of the first nourishment will be 100,000 m^3 and later nourishments will contain 85,000 m^3 of sediment. The nourishments are summarized in **Fout! Verwijzingsbron niet gevonden.**.

Extreme events

Besides the regular nourishments it is expected that additional nourishments after extreme events are also necessary to keep fulfilling the project requirements. Cuba has to deal with hurricanes and cold fronts which can cause severe damage to the nourishment. Mostly during normal conditions the beach will recover to its equilibrium profile and the amount of lost sediment cross-shore will be relatively low. However, XBeach is not really capable of reproducing this beach recovery, because some processes are missing. So it is hard to say when a cold front or hurricane causes permanent damage to a nourishment.

During extreme events avalanching can occur and therefore not only the beach, but also the dunes can be heavily damaged. In the case of damaged dunes, the natural recovery process to the equilibrium profile will be way more difficult. According to the requirements stated in section 5.3.2, during heavy storms this dune avalanching is not allowed to happen.
With this in mind, it is logical to say that only hurricanes can result in a need for an additional nourishment.

To say more about additional nourishments, two assumptions have to be made. First, it is assumed that only hurricanes of category 3 or higher damage the beach in such extend that the nourishment will not recover fully during normal conditions (see section 5.3.3). The damage to the dunes depends on more factors than only the category. For example the fetch and track of the hurricane are maybe evenly important, however still this assumption is made in order to be able to estimate a frequency of occurrence.

Secondly, it is assumed that regardless of the state of the nourishment at that time, 20,000 m^3 will be lost after such a hurricane. This value is obtained by looking at the results obtained from the zero-state runs of the XBeach model (see Appendix G.3, Table G- 7). For Wilma (see Appendix D.3) the amount of (dune) erosion was in the order of -40 m^3/m. With a section length of 1000 meter, the total required volume of an additional nourishment should be 40,000 m^3. Wilma was a very destructive hurricane, but when we look at the values from Michelle (see Appendix D.3) the erosion was approximately -20 m^3/m. This would result in an additional nourishment of 20,000 m^3. Because some of the recovery will happen naturally, not the total volume loss has to be taken into account so 20,000 m^3 chosen as the average volume of additional nourishments.

It is known that errors are made by making these assumptions, but the assumptions are only made to easily estimate the amount of additional nourishments and their required volume. The actual nourishment volumes needed after certain extreme events are not handled in this report and are depending on the situation.

The characteristics of regular nourishments and an additional nourishment do not only differ because of their objective, but also because of the location they should be executed. The main purpose of additional nourishments is to rebuild the dunes for protection. A positive side effect is that the natural recovery may speed up. Regular nourishments however are meant to add more sediment into the system to compensate structural erosion.

Because of the differences between the regular and additional nourishment, those two will be handled separately. Off course they can be carried out combined, but if this is possible depends very much on the situation, the type and amount of damage and the available equipment.

Reshaping nourishments

The final nourishment which should be covered is the reshaping nourishment. This nourishment should be executed when a lot of sand have been transported from the area around the waterline towards the more offshore locations, but no sediment volume is lost from the system. This can occur after some extreme conditions.

Normally the beach shape will be recovered during the normal situation, but sometimes there is not enough time for this recovery process. This is very unfavourable, because if a new extreme event could potentially damage the beach even more. To speed up the recovery, some human interference has to be carried out.

The sediment from the reshaping nourishment will be dredged in the more offshore areas of the active zone. This will then by transported to the upper shore face, where it will be dumped. It is assumed that the total reshaped volume will be 10,000 m^3, although this will not consist of new sediment coming from the borrowing zone. The objective of this nourishment is only to restore the beach profile in order to prevent extreme sediment losses in the near future.

Summary

The total lifetime for the solution is 50 years (see section 5.3.2), which results in 10 regular nourishments during the lifetime, including one initial nourishment. The cumulative frequency of category 3 and 4 hurricanes is 0.2 / year. This means the expected amount of additional nourishments is 10 during the lifetime of the solution. The cumulative frequency of unfavourable conditions, which leads to the need of a reshaping nourishment is 0.4 / year. This results in a total need of 20 reshaping nourishments during its lifetime.

Name Nourishment	Frequency	Volume (before optimization)	Objective
Initial	1 in 50 years (in year 1)	100,000 m^3	Minimal required beach profile + 5 year structural erosion
Regular	9 in 50 years (every 5 year)	85,000 m^3	5 year structural erosion
Additional nourishment	10 in 50 years (extreme event)	20,000 m^3	Dune reinforcement for protection
Reshaping	20 in 50 years (occasionally)	10,000 m^3	Reshaping of the beach profile

Table 6-3 Overview of nourishments

Placement of nourishment (initial and regular)

With the return period and volume known, the next step is to determine the location and the shape of the nourishment. The location of the nourishment could be created in front of the Iberostar hotel, but could also be extended eastwards till the headland is reached.

Figure 6-14 Possible initial nourishments (red) and general expected patterns after time t (purple)

In Figure 6-14, both nourishments are schematized and their general behaviour is drawn. It has to be noticed that the nourishment and the behaviour are both exaggerated in order to describe the general idea.

Because the main longshore transport is directed towards the west, both nourishments are expected to shift and spread towards the west over time. Only near the headland different patterns occur, which can result in a small eastward transport. The extended nourishment is also advantageous for the Paradisus hotel in the beginning, but will start to shift towards the Iberostar hotel (except for the sediment close to the headland) and eventually further westward.

Before the best option can be chosen, some considerations have to be made. These considerations are not only based on the quantitative effectiveness but also on some other important values/requirements.

Aesthetic value of the beach

A wide beach is favourable for the Iberostar hotel, however if the width becomes too large, the aesthetic value of the beach may decrease. Tropical beaches are often characterized by blue waters and green vegetation on the dunes, but an enormous beach could disturb this typical view.

Iberostar hotel

If the nourishment is extended towards the headland, not only Iberostar will profit from the nourishment, but also the Paradisus hotel will have a wider beach in the beginning. From Iberostar point of view this may looks like an unfavourable investment, but from an integral point of view it is the better option.

Effectiveness of nourishment

The effectiveness of the nourishment is, besides the quality of the execution, also dependent on a good design. A nourishment should not change the morphology such that the sediment transports differ from the initial situation. This could result in additional losses due to a different coastal angle, induced by the nourishment. With this consideration in mind, the extended nourishment would be the better option, however the Delft3D model results should confirm this first.

Simulations

In order to get insight in the better nourishment design, the two nourishments are modelled and simulated in Delft3D for a whole year wave climate. The results of Delft3D show the amount of erosion after one year, in order to be able to compare the nourishments, see Figure 6-15.

Nourishment Iberostar	**Nourishment extended to headland**
Initial situation (upper)	Initial situation (upper)
Situation after 1 year (middle)	Situation after 1 year (middle)
Sedimentation/erosion (lower)	Sedimentation/erosion (lower)

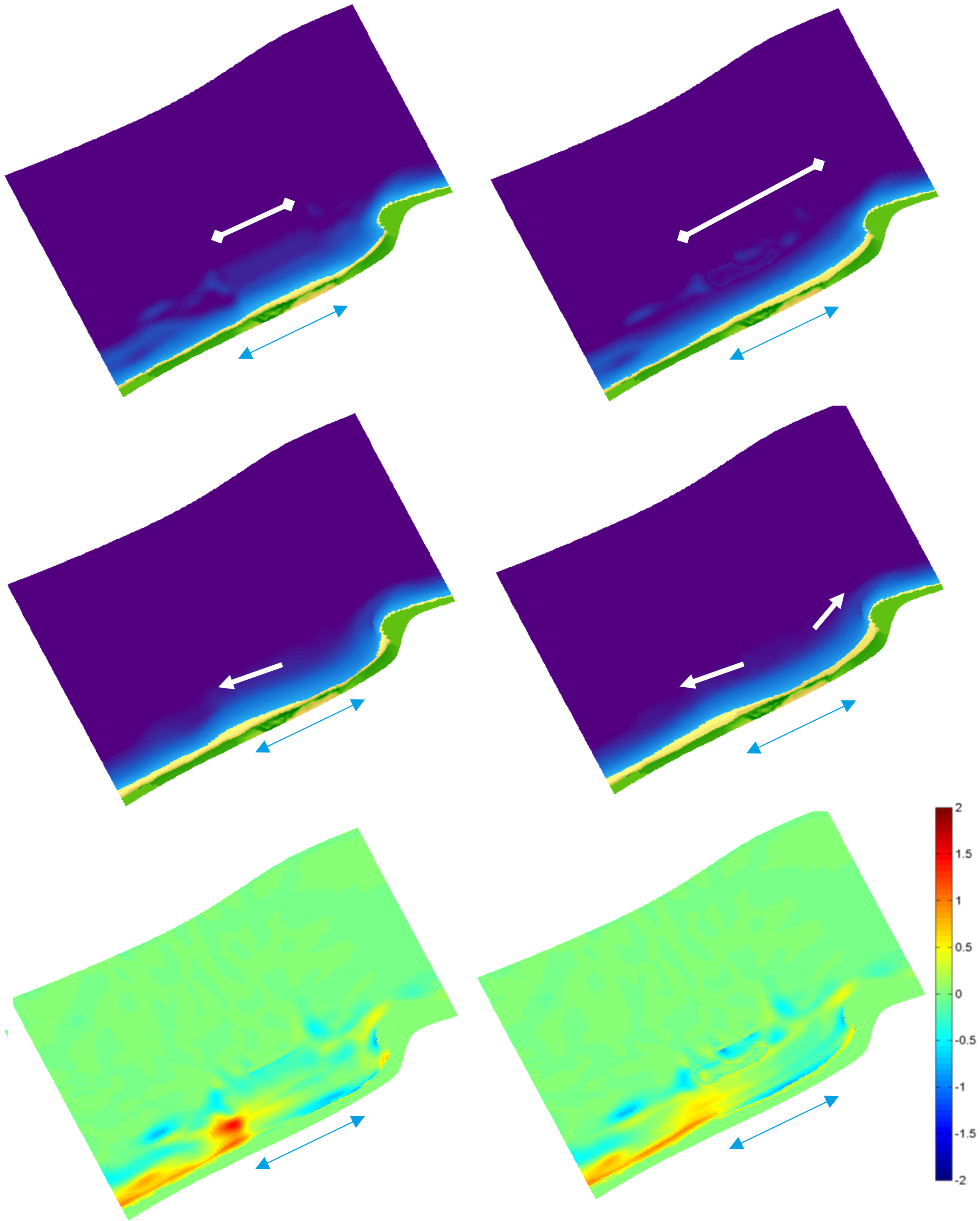


Figure 6-15 Comparison of the different nourishments

Conclusion

As seen from Figure 6-15, the nourishments behave as expected. The nourishment in front of the Iberostar hotel simply shifts towards the west and the Iberostar section will lose beach width over time. The western part of the extended nourishment will also shift westwards, but the eastern part will shift towards the headland (east). The disadvantage of this nourishment is that not all the sediment will reach the Iberostar section, but will stay at Paradisus. The advantage is however that a bigger length of a nourishment will increase the time it takes for the nourishment to completely pass the Iberostar section. This means that the nourishment will be effective for a longer time.

So, the best solution would be a nourishment which extends more eastwards to increase the effective time of the nourishment, but not entirely to the headland, because that could result in lost sediment in terms of the direction it is transported to. This optimised solution is modelled (Figure 6-16) and also used in the combination alternative (see section 6.4).

It can be seen that after one year of modelling the beach width is now spread more evenly over the length, although the movement of sediment towards the west is still visible.

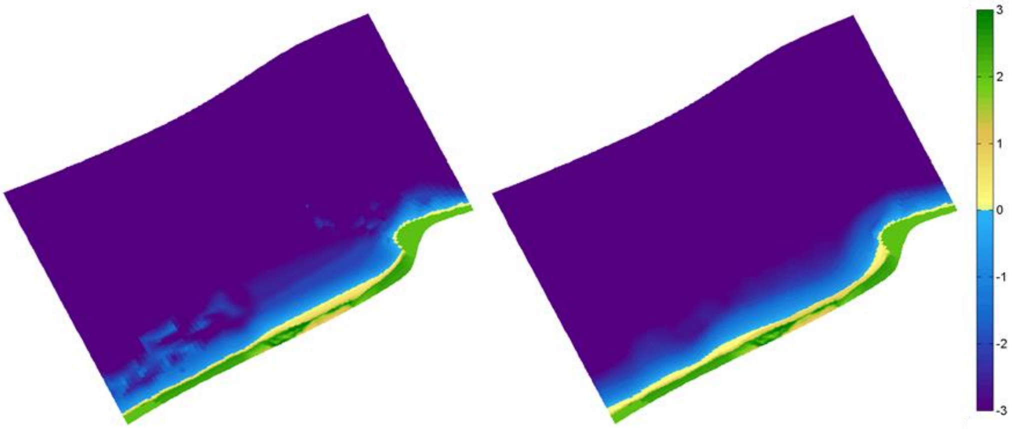


Figure 6-16 Behaviour of the nourishment alternative

6.4 Combination Alternative

In case of the combination alternative, a beach nourishment is combined with a submerged breakwater. The main objective of the nourishment is to compensate for the structural erosion and the objective of the breakwater is to decrease the transport due to wave action on the nourishment.

Similar to the situation with the breakwater alternative, the location and length of the breakwater are very important. Depending on the design of the breakwater, the breakwater will succeed in protecting the nourishment or will have a negative effect on the lifetime of the nourishment. If the breakwater succeeds in protecting the nourishment, the nourishment volume can be lower relative to the case without a breakwater. Whether the addition of the breakwater is preferred above a larger nourished sediment volume without breakwater has to be investigated with the help of an MCA and an estimation of the difference in cost between both cases.

Breakwater

The breakwater design is initially made with the help of Delft3D model runs in which breakwaters are tested on a uniform coastline, with a bottom profile comparable to the bottom profile at beach in front of the Iberostar hotel. Results of this simulation can be found in the section for the breakwater alternative (section **Fout! Verwijzingsbron niet gevonden.**).

Nourishment

The characteristics of the nourishment are already described in section **Fout! Verwijzingsbron niet gevonden.**. Eventually, if the combination alternative is chosen, the volume of nourishment may be decreased, because the breakwater in theory reduces the longshore sediment losses. It is also possible that the breakwater will decrease the damage of hurricanes on the dunes due to the wave breaking.

However, it should be noted that during heavy hurricanes a lot of breakwaters are destroyed and if that should be avoided, an unaffordable breakwater of with very large dimensions is required. Besides, due to the breakwater extra wave setup can occur, which eventually can strengthen the avalanching process at the dunes. For these reasons the same values and assumptions are made as for the nourishment alternative.

Conclusion

The combination alternative exists of a breakwater based on section **Fout! Verwijzingsbron niet gevonden.** and the nourishment from section **Fout! Verwijzingsbron niet**

gevonden.. The breakwater that performed the best turned out to be a 'small' breakwater of 300 meters wide and approximately 250 meters from the coast.

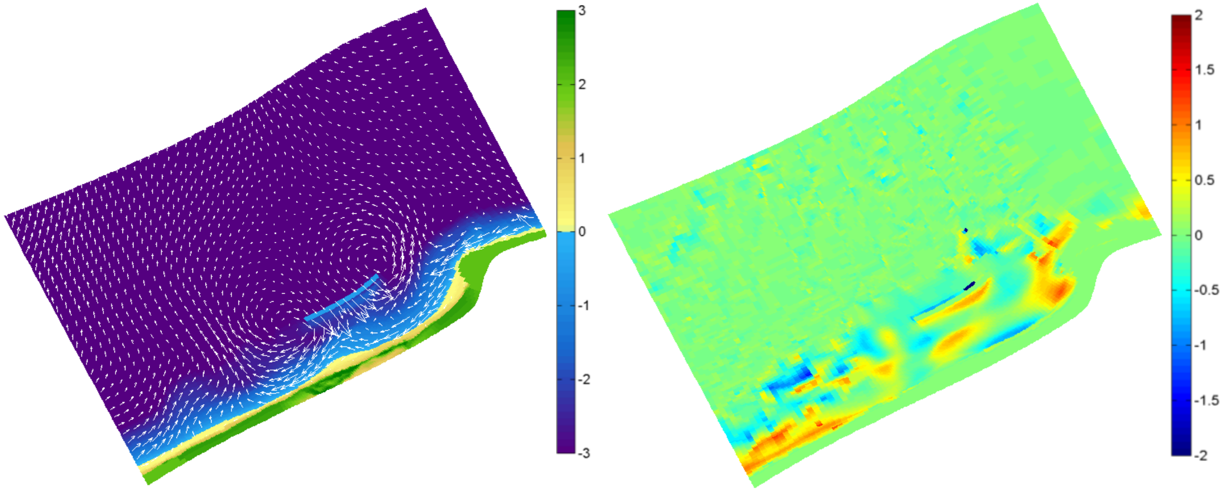


Figure 6-17 Bed levels and flow directions (left) and cumulative sedimentation/erosion (right)

It can be seen that after a year of modelling, the beach in front of Iberostar is retained and at some locations even extended. But there also has to be noticed that around the other hotels to the left and right, more erosion is present. Around the breakwater circulating patterns can occur, as shown with the white arrows in the left figure.

6.5 Alternatives: Multi Criteria Analysis

A Multi Criteria Analysis (MCA) is a way to evaluate different alternatives in a systematic way. A MCA will always be executed without taking finances into account. The criteria are formulated in section 6.5.1 and these are weighted in section 6.5.2.

6.5.1 Criteria

When a MCA is applied, first the relevant criteria have to be formulated. This results in five groups of relevant main criteria, which are divided into multiple sub criteria. These criteria and their sub criteria can been found in Table 6-4.

Criteria	Sub criteria
Functionality	Beach width
	Stabilisation of the coastline
	Swimmer safety
	Reliability
Constructability	Presence of materials
	Presence of equipment
	Experience
	Complexity
Maintainability	Lifetime
	Durability
	Maintenance complexity
Sustainability	Influence on ecology during construction
	Influence on ecology during operational time
	Influence on ecology during removal
Spatial quality	Visibility

Table 6-4 Criteria and sub-criteria for the MCA

In order to understand the criteria from Table 6-4, they will be shortly explained by describing the sub criteria in Appendix I.1.

6.5.2 Weighting factor

A MCA uses weighted factors, because the importance of the different criteria is not equal. Therefore, the different criteria have been compared with each other in order to find out which criteria are the most important. If the first criterion is more important than the second one, then the first criterion gets a point.

Per criterion these points will be added in order to compute a weight factor. This can be calculated by adding an extra point to the total points of the criterion and then dividing by the total number of points of all criteria. This extra point per criteria is added in order to have no weight factor of zero.

This process has been executed for the main criteria and can be seen in Table 6-5. A blue square means that the left criterion is more important than the upper criterion. A grey square means the opposite.

Criteria	Functionality	Constructability	Maintainability	Sustainability	Spatial quality	Total	Total + 1	**Weighting factor**
Functionality						4	5	**0.33**
Constructability						2	3	**0.20**
Maintainability						1	2	**0.13**
Sustainability						0	1	**0.07**
Spatial quality						3	4	**0.27**
Total							**15**	1.00

Table 6-5 Determination of the weighting factor of each criterion

From the table it can be seen that the criterion functionality has the highest weighting factor. This is not a surprise as the prevention of the structural erosion is the main goal of this project. Also the spatial quality has a high weighting factor as the tourist do not like a solution which is visible from the beach. This can be seen as a hindrance to their ocean view. The third highest weighting factor has been awarded to the constructability, because of the complexity of the construction is an important factor in the choice of the solutions. The maintenance has been chosen to be less important, although it should be done in a correct way to have a reliable solution. Finally, the sustainability has been chosen to have the lowest weighting factor, but this does not mean that it will not be taken into account for the final choice.

6.5.3 Results

For the three remaining alternative solutions, scores will be awarded per criterion. This will be a score between 1 (bad solution) to 5 (good solution). Together with the previously calculated weighting factors, the final MCA-scored can be calculated.

This final score can be obtained by adding all values of each criterion multiplied by the weighting factor of that specific criterion. The given scores per criterion for each alternative is further explained in Appendix I.2. The MCA and the final score can be seen in the Table 6-6.

		Breakwater		Nourishment		Combination	
Criterion	Weighting factor	Score	Total	Score	Total	Score	Total
Functionality	0.33	1	0.33	4	1.32	4	1.32
Constructability	0.20	3	0.60	5	1.00	2	0.40
Maintainability	0.13	4	0.52	4	0.52	3	0.39
Sustainability	0.07	2	0.14	5	0.35	2	0.14
Spatially quality	0.27	3	0.81	5	1.35	4	1.08
Total	**1.00**	**-**	**2.4**	**-**	**4.54**	**-**	**3.33**

Table 6-6 Results Multi Criteria Analysis

In Table 6-6 it can be seen that the breakwater has the lowest overall score (2.40). Therefore the breakwater solution can be assumed to be a bad solution as it does not fulfil the requirements. This resulted in the choice that the breakwater will not be taken into consideration for the final solution.

The nourishment has the highest overall score (4.54) and can be assumed to be the best solution according to the criteria. This is mainly caused by the good overall score. In every criterion within the MCA the nourishment did not seem to be a bad solution.

The combination solution has a good functionality, which is the main aspect of the project. Also the second most important factor, the spatial quality, is very good for this solution. On the other hand, the complexity of this solution makes it hard to construct and maintain. This is the reason why the solution can be assumed to be the second-best solution (3.33).

6.6 Alternatives: Financial

Next to the results of the MCA, also costs have to be considered in order to be able to make a decision between the alternatives. The cost comparison is mainly dependent on the relative effect of the breakwater on the nourishment. The breakwater has high investment costs, but if the reduction of the sediment losses is high enough, it could be profitable. So the main quantity that has to be computed is the difference in sediment loss for both alternatives.

Unfortunately, the Delft3D model is quantitatively not accurate enough to compute the differences in sediment loss for several years in a situation with and without breakwater. Therefore, to determine the relative effect of the breakwater in terms of cost, an alternative method is used for the financial calculations. With the current available results, this is the only way to be able to easily compare the approximate costs of the two alternatives. A detailed cost calculation will be done for the final solution in chapter 7.

First some assumptions have to be made, before this calculation can be started:

- Independent on the shape of the nourishment, the erosion rate is uniform over time (15,000 m^3/year). By doing this assumption, the error of using a simulation for only one year of morphological change is taken into account.
- The costs for each nourishment are linearly depending on the volume of the performed nourishment. The fixed costs are also related to the volume.
- It is assumed that the breakwater always decreases the needed nourishment volume with the same percentage, independent of the nourishment volume.

This last assumption is made to still be able to use the Delft3D results for breakwaters. Although the model results are not in accordance with expected sediment losses (see section 4.5), by scaling the effect of the breakwater on a given nourishment, the effect of the breakwater can still be calculated for every nourishment.

With the assumptions in mind, the cost calculation is carried out. The nourishment alternative and the combination alternative are compared for a total period of 50 year. The total costs are defined as:

C_{N50}	Total costs for the nourishment alternative	[$]
C_{C50}	Total costs for the combination alternative	[$]

Nourishment alternative

The total costs of the nourishment alternative are the sum of an initial nourishment, the regular nourishments, the additional nourishments and the reshaping nourishments (see **Fout! Verwijzingsbron niet gevonden.**).

$$C_{N_{50}} = C_{m3} * V_0 + C_{m3} * N_R * V_r + C_{m3} * N_A * V_A + R_{m3} * N_{RE} * V_{RE}$$

Where:

C_{m3}	Costs of nourishing per cubic metre	[$/m^3]
R_{m3}	Costs of reshaping per cubic metre	[$/m^3]
V_0	Initial nourishment volume	[m^3]
V_R	Regular nourishment volume	[m^3]
V_A	Additional nourishment volume	[m^3]
V_{RE}	Reshaping nourishment volume	[m^3]
N_R	Amount of regular nourishments in 50 years	[-]
N_A	Amount of additional nourishments in 50 years	[-]
N_{RE}	Amount of reshaping nourishments in 50 years	[-]

In order to compute the C_{m3}, the costs of a nourishment of 100,000 m^3 is calculated in Appendix K.1 with based on the information from the PRECONS [23]. It seemed that the total price for the initial nourishment would be in total approximately $ 1.2 million, which is $ 12 per m^3. This cost estimation is quite general, but include the equipment, loan and materials for the different nourishing activities. With this value known, the total costs of the nourishment alternative C_{N50} can be calculated, which is about 16.1 million CUC.
The costs of the reshaping per cubic meter is assumed to be half of the costs of the nourishing costs per cubic meter. This is chosen as no new sediment has to be added in the active zone.

The amount of regular nourishments is 9, the amount of additional nourishments will be 10 on average and the amount of reshaping nourishments during the total lifetime will be on average 20 (see **Fout! Verwijzingsbron niet gevonden.**).

$$C_{N_{50}} = 12 * 100{,}000 + 12 * 9 * 85{,}000 + 12 * 10 * 20{,}000 \ + 6 * 20 * 10{,}000$$
$$= \$\ 14{,}0\ million$$

Combination alternative

The main objective of the breakwater in the combination alternative is to protect the nourishment and decrease the sediment losses. In order to compute the effectiveness of the breakwater, the same nourishment is simulated two times with Delft3D, one with breakwater and one without. The resulting differences in sediment loss eventually determine the relative effect of the breakwater, which can later on be used in the calculation.

$$E_B = \frac{S - S_B}{S}$$

Where:

E_B	Relative effect of the breakwater	[-]
S	Sediment losses without breakwater	[m^3]
S_B	Sediment losses with breakwater	[m^3]

From a Delft3D simulation the differences in sediment losses are computed in front of the Iberostar hotel. As said before, these resulting volumes are too small, as the general behaviour of the Delft3D model can be described with too much accretion. The two sediment losses are determined to be S = 3676 m^3 and S_B = 3026 m^3, the resulting E_B is equal to 0.18.

It is already assumed that the relative effect of the breakwater is constant for a varying amount of sediment losses. To come up with the right volume for the nourishment in the combination alternative, the relative effect is multiplied with the earlier determined sediment losses (=15,000 m^3). With this value known, the volume of the required nourishment is determined for the combination alternative.

$$V_{C0} = V_R * (1 - E_B) + 15{,}000$$
$$V_{CR} = V_R * (1 - E_B)$$
$$V_{CA} = V_A * (1 - E_B)$$
$$V_{CRE} = V_{RE} * (1 - E_B)$$

Where:

V_{C0}	Initial nourishment volume for combination	[m^3]
V_{CR}	Regular nourishment volume for combination	[m^3]
V_{CA}	Additional nourishment volume for combination	[m^3]
V_{CRE}	Reshaping nourishment volume for combination	[m^3]
R_B	Relative effect of the breakwater (=0.18)	[m^3]

$$V_{C0} = 85{,}000 * (1 - 0.18) + 15{,}000 = 84{,}700\ m^3$$
$$V_{CR} = 85{,}000 * (1 - 0.18) = 69{,}700\ m^3$$
$$V_{CA} = 20{,}000 * (1 - 0.18) = 16{,}400\ m^3$$
$$V_{CA} = 10{,}000 * (1 - 0.18) = 8{,}200\ m^3$$

The construction of the breakwater itself is also a large investment. The calculated value for the construction of a breakwater is approximately 840.000 CUC. This calculation can be found in Appendix K.1, which uses the costs provided by PRECONS [23].

It is assumed (see section 5.3.3 for more assumptions) that the breakwater is destructed by hurricanes with a frequency of 0.08 per year. This means that the breakwater is destructed four times on average over the lifetime of 50 years. It is also assumed that the costs for reparation are half the construction costs.

C_B	Costs of the breakwater	[$]

With all this information given, the total costs for the combination alternative can be calculated by using the formula below.

$$C_{C\,50} = C_{m3} * V_{C0} + C_{m3} * N_R * V_{CR} + C_{m3} * N_A * V_{CA} + R_{m3} * N_{RE} * V_{CRE} + C_B + \ 0.5 * C_B * N_B$$

Where:

C_{m3}	Costs of nourishing per cubic metre	[$/m]
CR_{m3}	Costs of reshaping per cubic metre	[$/m]
V_{C0}	Initial nourishment volume for combination	[m^3]
V_{CR}	Regular nourishment volume for combination	[m^3]
V_{CA}	Additional nourishment volume for combination	[m^3]
V_{CRE}	Reshaping nourishment volume for combination	[m^3]
N_R	Amount of regular nourishments in 50 years	[-]
N_A	Amount of additional nourishments in 50 years	[-]
N_{RE}	Amount of regular nourishments in 50 years	[-]
N_B	Amount of time the breakwater will be damaged	[-]

$$C_{C\,50} = 12 * 84700 + 12 * 9 * 69{,}700 + 12 * 10 * 16{,}400 + 6 * 20 * 8{,}200 + 840{,}000 + 0.5 * 840{,}000 * 4 = \$\ 14.0\ million$$

6.7 Conclusion

For both alternatives a Multi Criteria Analysis (see section 6.5) and a cost estimation (see section 6.6) have been made. In this section, by comparing those analyses, the best alternative will be determined. This best alternative will be used as the final solution and will be further designed in chapter 7.

6.7.1 Comparison based on MCA

The nourishment had a good functionality as it protects the coast from strong coastal erosion. It can also be considered as a safe solution as it is a very reliable solution. Finally also the swimmer safety is preserved as the flow velocities will be not very high.

The constructability of the nourishment is quite easy as the Cuban government owns all equipment and knowledge needed for the execution of a nourishment. Also the maintainability got a high score as measurements can be easily done.

The sustainability is only influenced during the execution of the nourishment. During its lifetime it will hardly effect the ecosystem as the nourishment is a soft solution. Finally it can also be stated that the spatial quality has a good score as the nourishment cannot be seen from the beach.

The combination solution however has some downsides on the functionality. Although the beach width will be maintained a bit better than the alternative without breakwater, the flow patterns are quite dangerous for swimmers. It also has a low reliability as the behaviour of the submerged breakwater can be very unpredictable.

The constructability and maintainability of the combination alternative are less. In Cuba, there is hardly any knowledge in the execution of a submerged breakwater. This also holds for the special equipment needed to build a submerged breakwater. The combination of the nourishment and the submerged breakwater makes this combination even more complex.

The hard structure on itself will affect the ecology, while also the changing flow patterns and velocities affect ecology. The spatial quality of the combination alternative is very good as both the nourishment and the breakwater cannot be seen from the beach and the ocean view is therefore not hindered.

It can be concluded that the nourishment is a good solution for all the criteria used in the MCA, while the combination alternative has some weak points. This resulted in the higher final MCA score for the nourishment alternative (4.54) than for the combination alternative (3.33).

6.7.2 Comparison of the costs

The beach nourishment can be constructed with sand, which can be found at a location just 10 kilometres away from the construction site. As this option needs more sediment volume for the nourishments than the combination alternatives, the nourishments itself will be somewhat more expensive. On the other hand, no other costs are needed for constructing a hard solution.

The costs of the combination alternative are computed in a rather alternative way as the Delft3D model does not perfectly simulate the longshore sediment transport. Therefore the effect of the breakwater is used by the scaling of the effects of the sediment transports with and without breakwater. In the end this effect was 18%. This difference in longshore sediment losses results in less volume needed for the nourishments. The construction cost for the submerged breakwater are quite high as the breakwater has to be built with rocks, which should be quarried, transported and be placed on the breakwater.

In section 6.6, the costs have been calculated over a time of 50 years. This resulted in a total cost of 14.0 million CUC in case of the nourishment alternative. The combination alternative will also be approximately 14.0 million CUC. It can be concluded that the smaller nourishment volumes for the combination alternative compensate for the extra costs for the execution of the submerged breakwater.

6.7.3 Final decision

The comparison between the two alternatives shows that the nourishment alternative is the better option. It has a higher score on the MCA and the cost estimation is equal to the other alternative. Besides the results from the two analyses, it again must also be noted that, especially with waves from all different kind of directions (see section 4.5), it is very hard to design a well-functioning breakwater which has an easily predictive behaviour.

7. Design Solution

So far it has been shown that there is a serious erosion problem at the beach of the Iberostar hotel, but that there are possibilities to solve the problem. The chosen solution of the nourishment (chapter 6) will not take the structural erosion away, but it reinforces the coastal profile so that the beach width will always be sufficient for recreation and it will be able to withstand extreme events. Detailed characteristics of the final solution are presented in this chapter.

7.1 Design of the nourishment

In this section the design of the nourishment is explained. This includes the volume of the nourishment and the shape of the nourishment.

7.1.1 Volume of nourishments

Based on the analysis on the longshore transport (section 4.5) there has been determined that a nourishment of 100,000m^3 should be sufficient to keep a nice beach width for a period of five years. But because there is uncertainty in the amount of transport, also a 150,000m^3 nourishment is modelled for if the transports turn out to be larger. When looking at the bed levels after a period of one year modelling the results are the following:

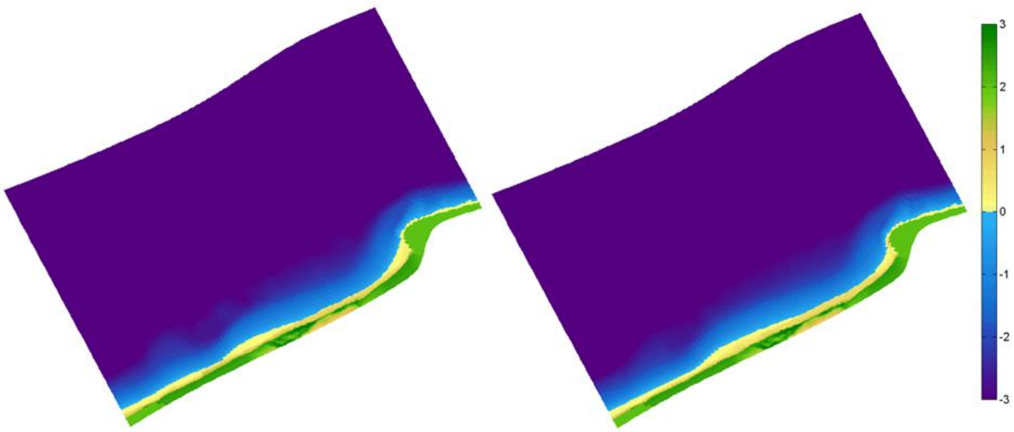


Figure 7-1 Nourishment of 100,000m3 (left) and 150,000m3 (right) after one year

It can be seen that the beach logically is larger for the 150,000m[3] nourishment, which can be showed more clearly using the beach widths:

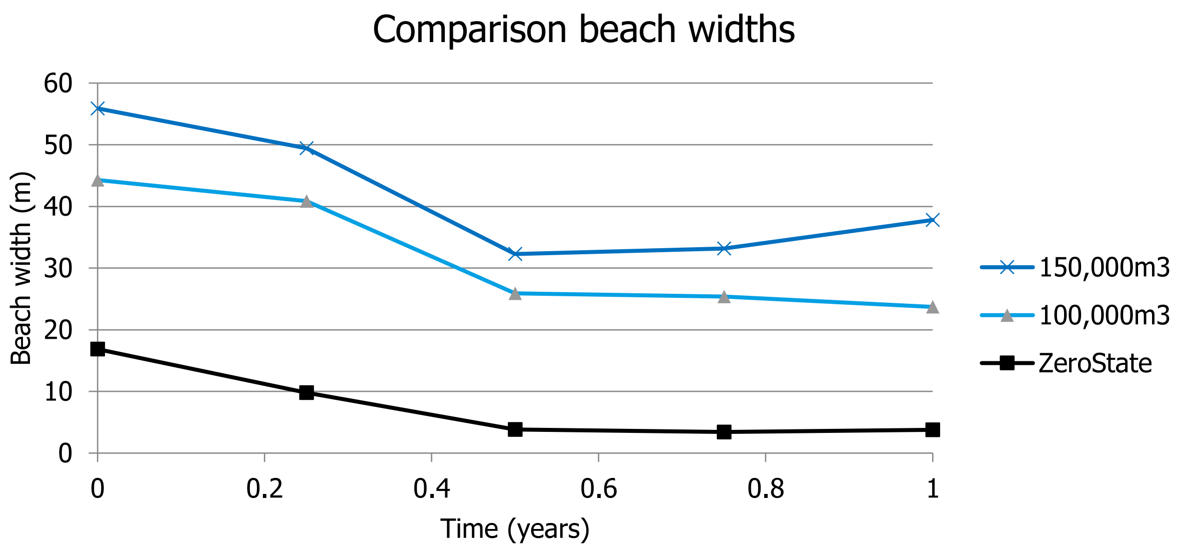


Figure 7-2 Beach widths after one year of modelling

This proves that the nourishments have a positive effect on the beach width comparing with the zero state, when nothing is done. For the zero state hardly any beach would be left, so the addition of at least 20m of beach by nourishing is necessary. For the three situations the initial profile and the profile after one year look like this:

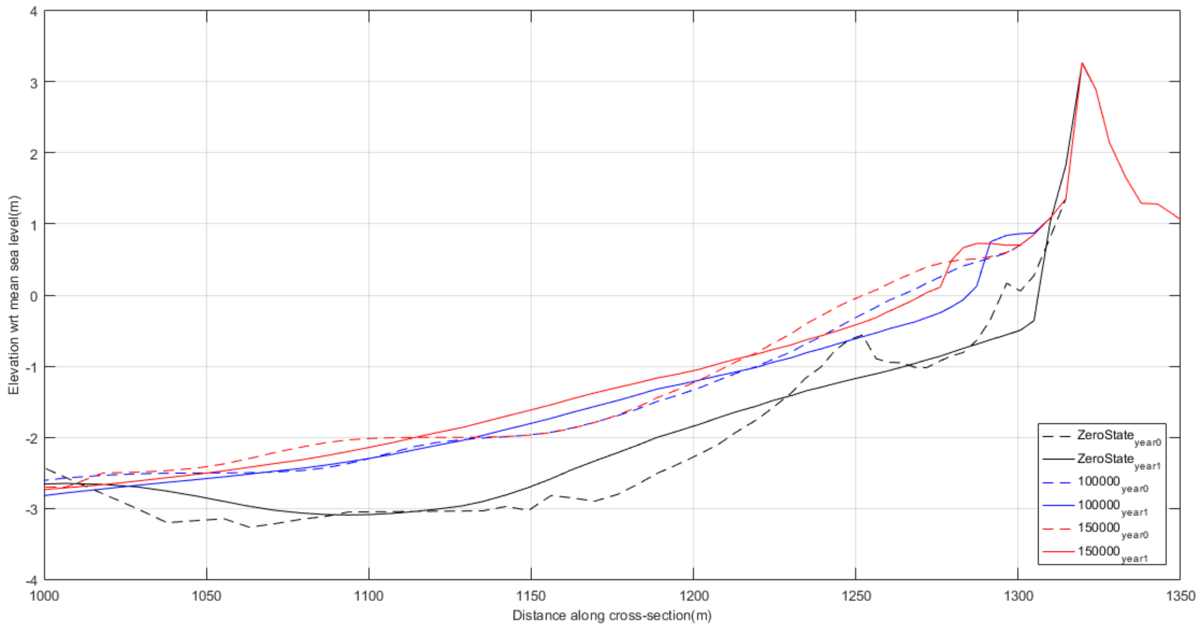


Figure 7-3 Initial profiles and profiles after one year of modelling

It can be clearly seen that the beach is wider when supplying more extra sediment into the system. The profile close to the coast is less steep and therefore it can better withstand extreme events, as the wave energy will be dissipated at a larger distance from the dunes.

It has to be noticed that the amount of sedimentation and erosion in the model is larger than in reality. This means that the erosion of the sediment in the profiles is exaggerated, but that the behaviour is modelled correctly. Because the beach width, even with the exaggerated erosion, for the 100,000 m^3 seems to be in line with the requirements (Figure 7-2), this volume is still used for the final design.

So now we can look at the different kinds of used nourishments, based on section 6.3. The initial nourishment should increase the beach width to the new requirement (10 meter), which should be met in all occasions except the extreme conditions mentioned earlier. To be able to meet this requirement, the beach width is even enlarged in order to be sure that after five years of normal conditions the minimum beach width is still met. The initial nourishment in this case has a volume of 100,000 m^3 and is located at the beach of the Iberostar Varadero Hotel.

During five years of wave conditions, the nourishment will be reshaped and the nourished sediment will be transported longshore to the adjacent beaches. This results in a loss of sediment for 5 years, after which the new beach width requirement is reached. In order to also keep the minimal 10 meter beach width requirement for the future, a regular nourishment should be executed every 5 years. It is assumed that the total volume of the regular nourishment is equal to 85,000 m^3 sand for every five years.

Finally, also some nourishments have to be executed after extreme conditions. These extreme storms or hurricanes can destroy (a part of) the nourishment, which should be recovered after the storm. As the extreme event can result in a maximum of 20,000 m^3 of erosion, the same amount of sediment should be added to the system during the additional nourishments.

During the reshaping nourishments, the profile of the cross-section will be reshaped. This will only be executed when after a long period of bad wave and flow conditions the sediment has been transported from the upper shore face tot the lower shore face. When there is not enough time recovery to the equilibrium profile before a new cold front period starts, then it can be chosen to reshape the nourishment mechanically. The volume of this nourishment is assumed to be 10,000 m^3. Important is that this sediment has to be dredged at the lower shore face, and not at the sand mining zone further offshore. Therefore no new sediment is added to the system, only the coastal profile is reshaped.

The HOLLAND method [22] states that an extra 40% of the sediment should be added to the nourishment in order to compensate for the losses of sand during construction. This 40% has been derived from several foreshore nourishments. In our case mainly beach nourishments are carried out. Therefore it is assumed that 'only' 20% of extra volume should be added, which will be used in further calculations.

7.1.2 Shape of the nourishment

The sediment is mainly nourished in the area right before the beach of the Iberostar Varadero hotel. It is both dumped on the near foreshore and the beach. If it was only nourished at the beach, the slope around the waterline would become very steep. This would result in faster erosion of the nourishment, as it would be very far from equilibrium. A steep slope is also not preferable for the recreational activities as the tourist like a very mild slope. More information on the shape of the nourishment can be found in section 6.3, the shape of the nourishment will not be further explained in this section.

7.2 Expected behaviour of the nourishment

The volume and shape of the nourishment is influenced by different processes, which are explained in this section. These processes are forcing the coastal profile into a certain equilibrium profile.

During the first period right after the nourishment, the beach width will decrease quite fast. This is the result of the reshaping of the cross-shore profile by the waves and currents into the new equilibrium. Many people will see this as erosion, but this is actually only a coastline retreat. Over time, this retreat will reduce when it gets closer to the equilibrium coastline. When this equilibrium profile is being reached, the sedimentation and erosion processes will be stopped. However, in reality this equilibrium will never be reached due to the changing wave and flow conditions.

This results in a constant changing sedimentation and erosion pattern. Over a longer time, the wave, wind and flow characteristics will lead to a certain general pattern. In our case this means that the sediment from the beach nourishment will be transported towards the adjacent coasts on the west and also to the beach of Hotel Paradisus close to Punta Francés in the east.

7.2.1 Different sediment grain sizes

The behaviour of the nourishment depends not only on the shape and the wave conditions, but also on the used grain sizes in the nourishment. In section 7.4.1, it is explained that the sand used in the nourishment will have different characteristics than the original beach sand. The influence of this difference in grain sizes can be explained with the Bruun rule and Dean rule.

Bruun and Dean have been investigating the behaviour of the sand in an equilibrium profile. This resulted in some empirical relations, which are shown in Appendix M.1. Bruun proposed an empirical formulation for the equilibrium beach profile. In this formulation the relation between the offshore distance to the waterline and the water depth can be found, depending on a shape factor.

When also using Dean's empirical relation, the necessary shape factor can be computed. In this way it can be calculated how the coastline changes due to changing sediment characteristics (median grain size). This calculation is shown below.

Dean's formulation is used to compute the shape factor for both sediment characteristics.

$$A = 0.5 w_s^{0.44}$$

For original sediment: D_{50} = 0.27 mm → w_s = 0.041 m/s → A_o = 0.123
For nourishment sediment: D_{50} = 0.38 mm → w_s = 0.059 m/s → A_n = 0.144

Bruun's formulation is used to compute the beach profiles.

$$h = A(x')^{2/3}$$

The equilibrium beach profiles for both sediment characteristics can be seen in Figure 7-4. From the figure it can be seen that the beach profile is much steeper for the sediment with a larger mean grain diameter. You can also see that the beach width will be much larger for this bigger grain size as the water depth should be equal at a certain point, where the sediment is undisturbed.

In our case, the beach will not transform towards the nourishment equilibrium as the sediment is a mixture between the original and nourishment sediment. Mixtures of sediment with different grainsizes behave different than non-mixtures. This behaviour makes the design of the nourishment even more complicated and should be taken into account for the final solution.

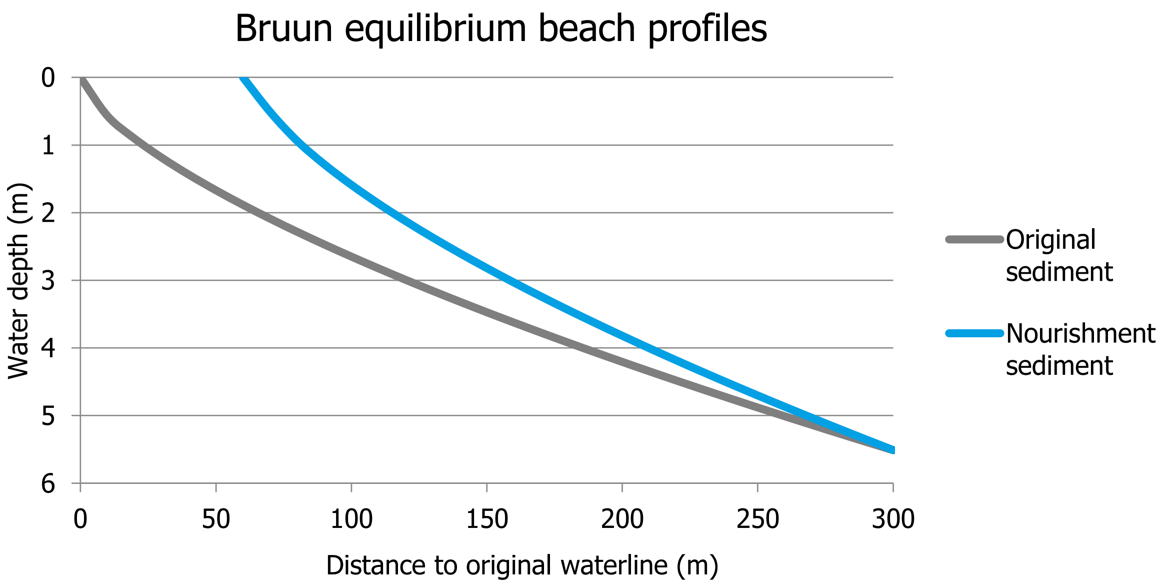


Figure 7-4 Bruun equilibrium profile for different sediments

7.3 Results final solution

Now the final solution is chosen, it can be modelled in Delft3D if the nourishment is sufficient for 5 years. Thereafter in XBeach the behaviour during extreme conditions is modelled. At last this is compared with the current executed solution.

Delft3D

Plotting the bed levels and sedimentation/erosion patterns after one, three and five years:

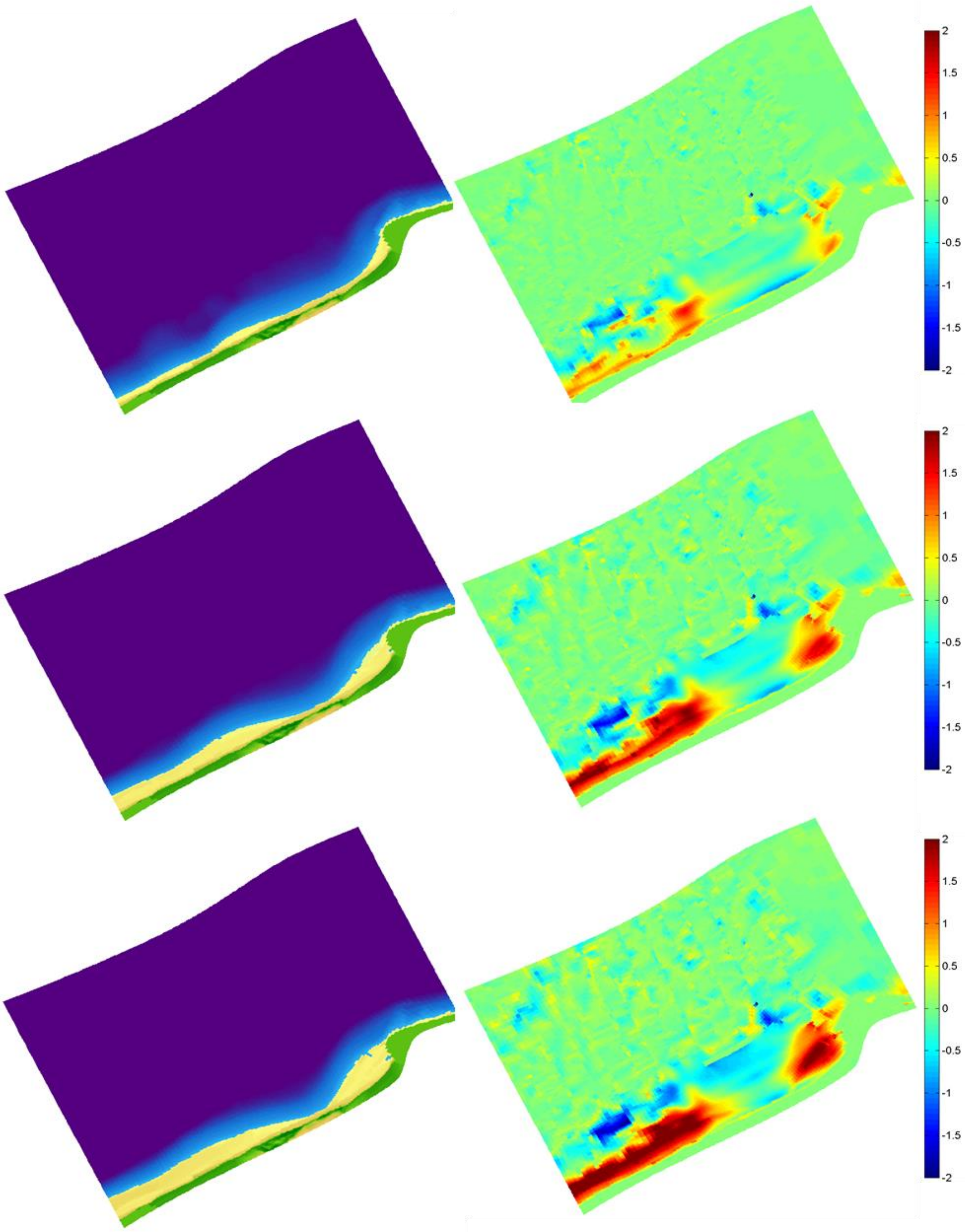


Figure 7-5 Bed levels (left) and sedimentation/erosion after one, three and five years

Figure 7-5 shows that the amount of sedimentation west and east of Iberostar is severe according to the model. The magnitudes are too large, but these errors are taken into account (see section 4.4.4). Nonetheless, the general sedimentation and erosion patterns seem to coincide with reality. When plotting the widths of profile IBE6, located at the heart of the hot spot in front of Iberostar hotel the patterns in time are as follows.

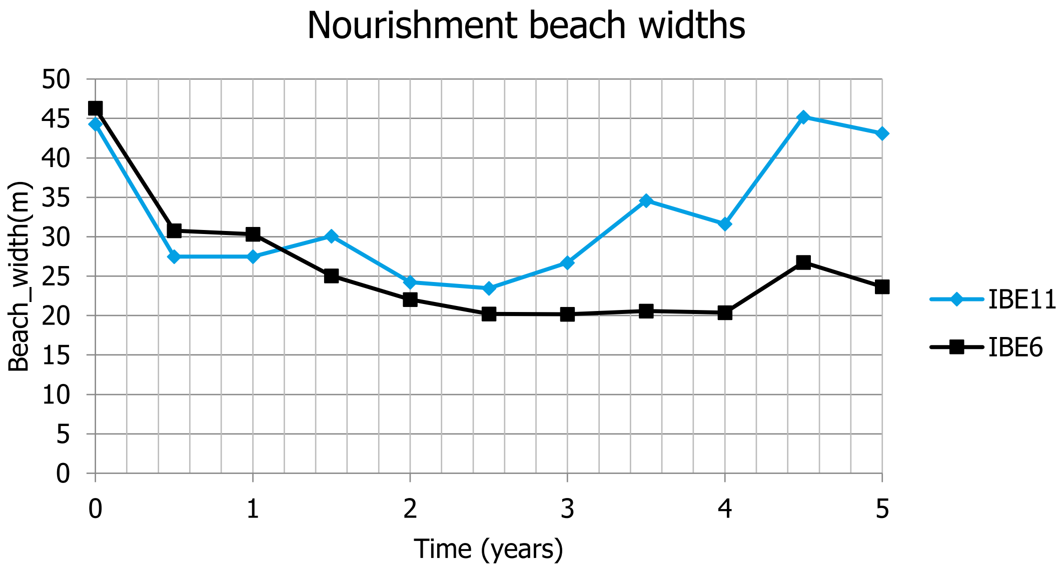


Figure 7-6 Beach widths in time for the chosen nourishment

This shows that only the pattern at IBE6 looks realistic, the pattern at IBE11, more at the boundary of the area of interest shows no realistic behaviour. However, the beach width after five years in both cases has a minimum of 20 meters and is sufficient to fulfil the requirements. Although the results are not reliable as both erosion and sedimentation quantities are exaggerated, according to the Delft3D model the nourishment of 100,000m^3 seems to be sufficient to meet the requirements during the entire lifetime. In the figure below, the erosion over the full cross section is presented over the years.

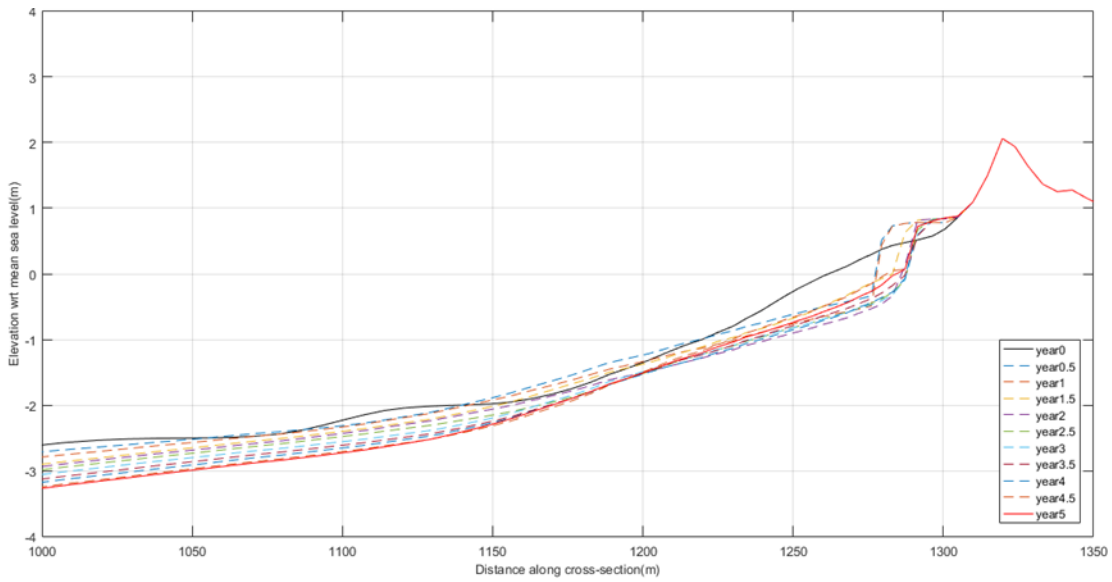


Figure 7-7 Profile development in time for cross-section IBE6

Important is that the beach in the first half year has the strongest profile change. There after the profile change more slowly in time. At the end the profiles are around a sort of equilibrium with quite a sharp slope around the waterline. This sharp slope seems to be more of a modelling problem then reality, as Delft3D does not take into account avalanching (see Appendix E.5). This large scarp influences the beach width calculations, however, it is assumed that the calculation method of beach widths gives the right orders of magnitude.

To conclude, the 100,000 m^3 nourishment seems to be sufficient for the required beach width according to Delft3D, despite the calibration problems.

XBeach

Now there will be looked what happens to the nourishment solution when an extreme event occurs. Because bed levels after a certain amount of years modelled in Delft3D do not represent reality well, these profiles are not tested in XBeach. Only the initial nourishment is tested. After testing of the nourishment, the current solution is modelled with the same extreme events, after which a comparison can be made. For this computations a different XBeach grid is used, which is equal to the Delft3D grid. This is explained in Appendix 0.

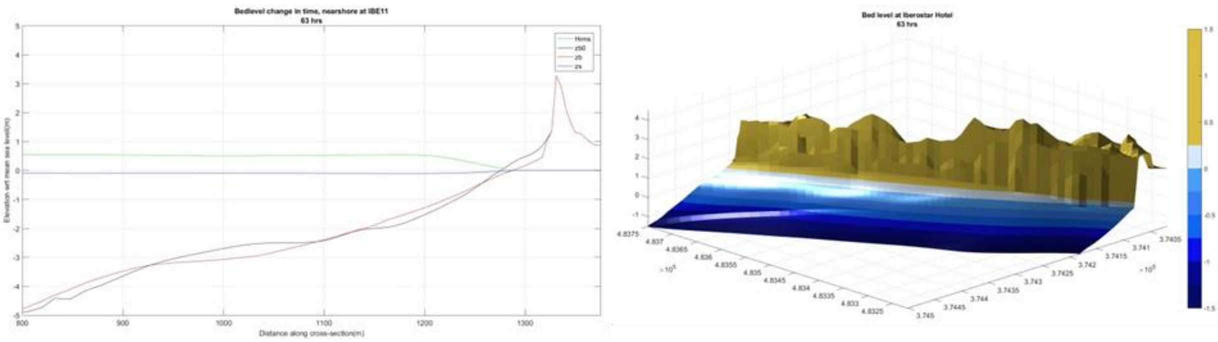


Figure 7-8 Bed levels at cross-section IBE11 (left) and in 3D (right) during a strong NW cold front

So in the figure it can be seen that there is serious erosion, but that the end result is better than for the zero state. The coastal profile in front of the beach is more stable and now no avalanching occurs. Respective calculated values can be seen in Table 7-1 further below.

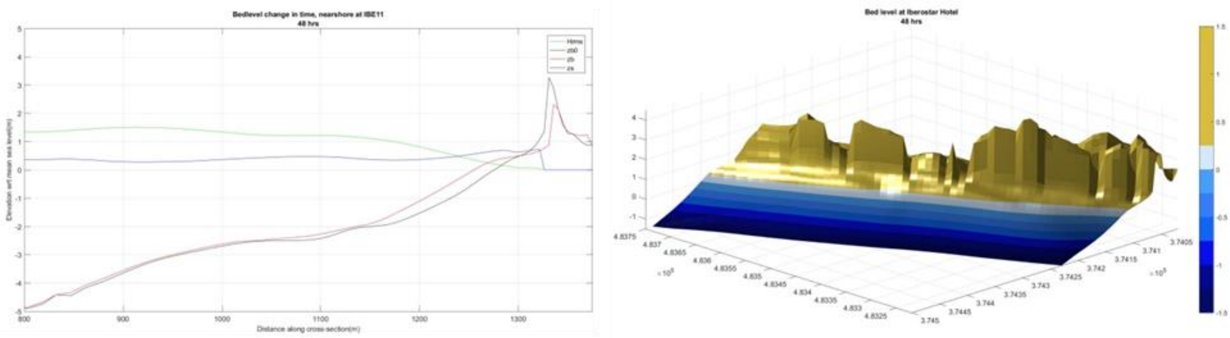


Figure 7-9 Bed levels at cross-section IBE11 (left) and in 3D (right) during hurricane Wilma

This shows that the end result is also better than for the zero-state situation without nourishment, there is still overwash but now less than before. Because the hurricane Wilma has such destructive hydrodynamic conditions, no solution can completely protect the dunes. After such extreme conditions, additional nourishments are needed.

Also the current solution (shift of the dune) is modelled with these extreme conditions, figures can be found in Appendix N.2. For a strong northwest cold front, for both solutions no avalanching occurs which is an improvement of the zero-state condition. However, the results also show that the created beach is eroded, leading to a situation in which the dune foot is still reached by the waves. When calculating corresponding values for IBE1 cross section where the current solution is situated, the following is obtained:

IBE1	beach width initial (m)	beach width end (m)	beach width balance (m)
Zero state	11.33	3.65	-7.68
Nourishment	48.42	37.57	-10.86
Current solution	22.49	6.76	-15.73

Table 7-1 Beach response during strong northwest cold front conditions for profile IBE1 for initial profile

This shows that both solutions are better than the zero state, but that the nourishment provides a much better beach after a heavy cold front.

When the results during hurricane Wilma are compared, it can be seen that the current executed solution performs better than the nourishment solution. But there has to be noticed that the main cause of this is that in making the model bathymetry for the current solution, the dune row is made wider than in reality. Due to the wider dune, the amount of overwash is less than in reality and this is not caused by the wider beach. Although the model fails in representing reality, it does show that it is a good idea to reinforce the dunes as it will decrease the amount of overwash and therewith the sediment loss during hurricanes.

Finally, the zero-state solution shows that there is a weak spot in the middle of the Iberostar section, where there is only a single dune row.

7.4 Construction method of the nourishment

The nourishment has a specific way of construction. This construction is explained in this section. This section also covers the characteristics of the sand from the borrowing area.

7.4.1 Sand extraction

Sand has to be extracted from a borrowing zone near the island Cayo Mono. This extraction area is about 10 kilometres away from the nourishment area and has a total capacity of 5.000.000 m^3 per year. The sand characteristic from this site is a bit coarser than the fine sediment on the beach. It has average mean diameter (D_{50}) of 0.38 mm, while the sand on the beach has a D_{50} of 0.27 mm. However, the mean diameter changes between 0.15 mm and 0.66 mm across the borrowing zone. It is preferred that the nourishment sand will not be much bigger than the original sand, so we have assumed that the coarsest grain sizes will not be used. Therefore, we assumed that the D_{50} will be equal to the average mean diameter of the borrowing site (=0.38 mm). Unfortunately, it was not possible to easily insert these different sand characteristics into the Delft3D model especially for the nourishment. Therefore it is recommended to have a good research on this topic for the design and the modelling of the nourishment of the final solution.

7.4.2 Construction method

For the construction of the nourishment the following process should be followed:

First the sand has to be extracted from the previously mentioned borrowing zone. This can be done by the trailing suction hopper dredger, which is owned by the Cuban government. This trailing suction hopper dredger will transport the sand close to the coast. As the water depth is not very deep at the construction site, the trailing suction hopper dredger is not able to dump the sediment directly via its bottom doors. Other possibilities are rainbowing and pumping via a pipeline, for both methods the equipment is available. In general, the efficiency in case of pumping via pipelines is higher than in case of rainbowing, therefore pumping via pipelines is used as nourishing method.

In addition, no extra measures have to be taken in order to improve the sediment as the nourishment sediment characteristics are quite similar to the original sediment characteristics. Finally, after pumping the sand on the shore, a smooth beach can then be created by spreading out of the sand with the use of several machines, like bulldozers and scrapers.

The process above can be used for the initial, regular and additional nourishment. For the reshaping nourishment another method for the nourishing activity should be used. During this

nourishment the sediment should be transported from a water depth of approximately 5 meters to the areas close to the waterline. The trailing suction hopper dredger cannot be used for this purpose as the draught of this ship is too big compared with the water depth. A smaller dredging ship should be used to dredge the sand from this location. From this dredging ships the nourishment sand can be pumped through the pipeline towards the desired dumping area. This sand will be spread out by the natural flow and by bulldozers.
As the smaller dredger vessel does not have to sail to the borrowing zone, the sailing time will be not needed. Therefore a continuous process of nourishing can be executed for this reshaping nourishment.

7.5 Construction planning

In this section the construction planning will be presented. In order to make a global planning, it is first needed to know the capacity of the trailing suction hopper dredger. Thereafter the number of days needed per activity can be estimated. These activities can be depending on each other, but sometimes this can also take place simultaneously. The dependencies can then be found in this construction planning. This will in the end result in a time schedule with a critical path, which should get extra attention by the constructor.

7.5.1 Time schedule

The trailing suction hopper dredger has a maximal capacity of 2,500 m^3 (see Appendix J.5) With a total number of 100,000 m^3 for the initial nourishment, a total number of 120,000 m^3 should be pumped taking into account the efficiency (see section 7.1.1). It will take 48 trips for the vessel to nourish the total volume. It is assumed that the vessel is not fully loaded on every trip, so an extra 4 trips have been assumed to be sure that the 100,000 m^3 nourishment has been executed. With a maximal pumping capacity of 5,000 m^3/h, a sailing speed of approximately 24 km/h, a distance of 10 kilometres between the borrowing area and de project area, the total round trip time will be approximately 6 hours. This gives a total initial nourishment time of 12 days. For the regular nourishments with a volume of 85,000 this takes 11 days, and the nourishing activities take 3 days for the additional nourishments of 20,000 m^3.

The reshaping nourishment has a different nourishment activity as the Trailing Suction Hopper Dredger cannot be used for the dredging purposes. Therefore a smaller dredging vessel should be used. It is assumed that this dredging vessel has a pumping capacity of 500 m^3/hour. With a reshaping nourishment of 12,000 m^3 (120 % of the total needed sediment volume) this will take at least 24 hours. Sometime should also be taken into account for the vessel to move to a new location for the suction of the sediment. It is therefore assumed that the reshaping nourishment activity takes maximal 2 days.

For the spreading out of the sand by the bulldozers and other machines, one week is taken into account for the initial nourishment. This can already take place when there is still sand transported from the vessel to the beach. The construction of the pipelines is assumed to be one day, while the removal of this 1,000 meter long pipeline also takes one day. In the end also one day of buffer time has been included to account for unexpected problems in the construction.

In Appendix J, the total time per activity has been showed. For simplicity these activities are divided in the design phase, preparation phase, construction phase, finishing phase and other. Per activity it is shown at which dates it should take place as it is preferred to execute the nourishment during the off-season and during calm wave conditions. Luckily, this is the case for the months May and June, so the initial and regular nourishments should take place in these months. The planning has been executed for the initial nourishment, the regular nourishment, the additional nourishment and the reshaping nourishment. The total construction times for these nourishments are 68 days, 39 days, 15 days and 15 days respectively.

In Figure 7-10, the time schedule for the initial nourishment is shown. This Gantt chart can also be found in Appendix J where the time schedules for the regular nourishment, the additional nourishment and the reshaping nourishment can also be found. The differences between these schedules will be also explained there.

As most activities have to be executed after each other, most of the activities are part of the critical path. This path indicates which activities directly influences the construction time. When one of these activities is delayed, then the whole project is delayed. Therefore these activities need extra attention. In the Gantt chart the activities on the critical path are showed in the blue colour, while the other activities are shown in grey colours bars.

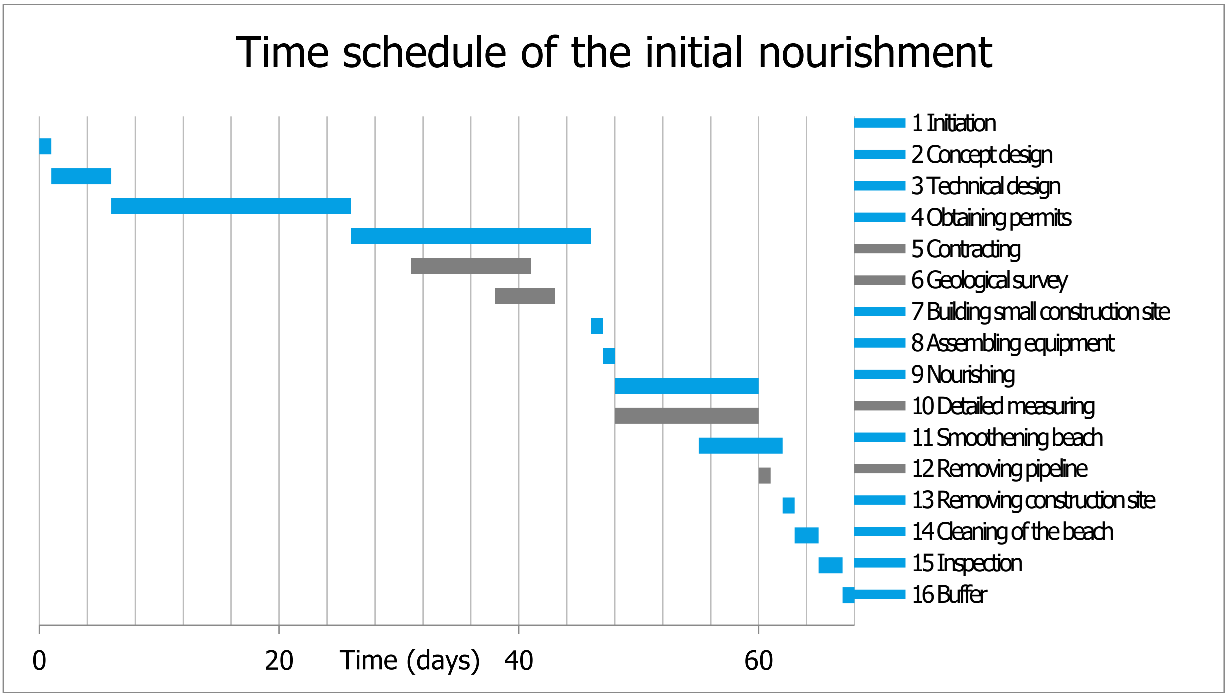


Figure 7-10: Gantt chart for the initial nourishment (critical path is indicated in blue)

7.6 Measurement program

During the execution of the nourishment several measuring activities should be done to be able to monitor the behaviour of the nourishment. The cross-shore profile at the nourishment should be measured every week during this period, over distances of 50 meters.

When the nourishment is finished, the final nourished volume has to be measured. The measurements should all use the same vertical reference level and should also cover the distance until the bed level does not change anymore, in order to take all sediment transport (cross-shore and longshore) into account. The cross-shore distance of the active zone is approximately 300 meters offshore.

During the lifetime of the nourishment, the effect of the nourishment should also be measured. Due to the new beach profile and the different flow and wave patterns, the longshore and cross-shore transports change. This measurement programme should be extensive in order to be able to optimize the maintenance plan based on the measurements. For this purpose, the profile should be measured every three months during the whole five year period between two regular nourishments. With the new measurements it is also possible to update the nourishment design in order to be more effective during the next nourishment.

Extra measurements should also be done after major storms, because they are generating the short-term extreme erosion processes. During these measurements it can be determined if an additional or reshaping nourishment is needed to restore the beach.

Finally, also sand samples should be taken from the nourishment area just before the nourishment, just after the nourishment and thereafter every year. By determining the grain sizes, the sediment transport can be computed.

7.7 Costs of the nourishments

For the detailed cost estimation of the construction of the nourishments the PRECON [23] catalogue is used. The values of this catalogue are based on a cost estimation for different activities in Cuba. It can be used for design, construction, reparation, maintenance and demolishing of structures. In this section the detailed costs of the nourishment are explained. This is followed by the cost estimation of the final solution.

7.7.1 Overview of the total costs

In this section the overview of the total cost of the nourishment solution are presented. In Appendix K.2 more details of the calculation can be found. In this appendix first some additional information is given about the finances, the working hours per activity per nourishment have been calculated and the PRECON-catalogue has been summarised.
In this procedure the costs are separated in primary cost and secondary costs. The primary cost are the costs which are directly linked to the project (e.g. material, equipment and labour costs). The secondary costs are not directly linked to the project, but are costs resulting from the organisation and management (e.g. material storage, construction site and transport of material).
This explanation is followed by a detailed calculation of the costs per nourishment type. The final calculation contains the calculation of the cost for the entire lifetime of the solution. The last step will be briefly shown in Table 7-2.

Type of nourishment	Costs per nourishment [$]	Number of executions	Total costs [$]
Initial	1,091,294.47	1	1,091,294.47
Regular	908,694.30	9	8,178,248.70
Additional	227,486.29	10	2,274,862.90
Reshaping	39,156.62	20	783,132.40
Buffer			500,000.00
Total			**12,827,538.47**

Table 7-2: Total cost of the solution over the entire lifetime

It can be seen that the total solution costs approximately 12.8 million CUC. This costs include the costs for design of the design, the preparation of the construction site, the construction of the solution, the removal of the construction site. The buffer money is added to deal with an eventual period with a lot worse wave and flow conditions than average. This can result in more additional or reshaping nourishments than predicted.

To avoid this problem, some money has to be kept apart for this purposes, which is chosen to be $ 500,000 in our case.

7.8 Design requirements

In Table 7-3 the design requirements are summed up and whether the criteria are met.

Design requirements		Requirement	Obtained	Remark
Time scales				
	Lifetime	50 years	+	A nourishment program for 50 years is designed
Beach requirements				
	Minimum beach width	9m	+	Minimum of 20m is obtained
	Minimum beach width after weak storm	9m	+	Min. 35m for initial profile, so assumed sufficient after 5 years
	Avalanching during heavy storm	no	+	
	Structure visible from beach	no	+	There is no structure used
	Erosion problem shifted	no	+	Other areas only get more sediment
	Similar grain size	yes	+	Same source as previous nourishment
Swimmer safety				
	Maximum flow velocities	1m/s	+	No structures are bended coastlines are constructed
	Occurance of rip currents	no	+	See above
Construction				
	Construction outside hurricane and tourist season	yes	+	Nourishment is executes in May and June
	Hindrance for tourists	no	+	See above
	Danger for executors	no	+	No dangerous activities during nourishing
Environment				
	Constructions on top of or behind the dunes	no	+	Nothing is built at the dunes
	Reduction of vegetation around dune	no	+	The amount of vegetation is not effected

Table 7-3 Design requirements

So this shows that the proposed design fulfils all the project requirements

8. Conclusion

The main reason for the execution of this project is the structural erosion problem in front of the Iberostar Varadero Hotel, Cuba. The problem and possible solutions are investigated using the following research question:

What is the cause of the erosion in front of the Iberostar Varadero Hotel, and what is the optimal solution to solve the problem?

To answer this question, it is separated into three sub questions regarding the cause of the erosion and two sub questions regarding the optimal solution to solve the problem. In this conclusion first all the sub question will be answered, leading to conclusion about the main research question.

A. *What is the contribution of basic longshore transport to the total amount of erosion?*

In the coastal area of Los Tainos, where the Iberostar Varadero Hotel is situated, the mean wave direction is from the north and north east. These wave directions drive a longshore current towards the west and cause erosion because of the headland eastward of the Iberostar section (Punta Francés). Here the sediment is blocked and this leads to a lack of sediment, which is eroded away from the coast around the hotel. During northwest conditions a part of the sediment could return to Iberostar, but the amount is not sufficient to counteract the erosion. The conclusion is that erosion is (almost) always present and has a magnitude of 15,000 m^3/ year as longshore sediment losses in the Iberostar section.

B. *What is the contribution of the different cross-shore processes to the total amount of erosion?*

After modelling in XBeach it turns out that all the morphological changes due to extreme events happen inside the active zone. Therefore it is safe to assume that net cross-shore losses at the offshore boundary do not have to be taken into account. What on the other hand can be important is that during (strong) storms and cold fronts, significant quantities of sediment are transported in offshore direction. In potential this sediment could return to its original location during normal conditions, but the longshore current described above partly prevents this. The final quantification of this problem will be categorized as longshore, but it has to be kept in mind that the cross-shore processes increase the problem.

Next to this also problems occur when the conditions are so extreme, for instance during a hurricane, that dune avalanching occurs. The conditions are already unfavourable for full recovery during storm conditions, so when parts of the dune start to erode during extreme conditions full recovery will definitely not happen. When looking at an entire year, the total amount of cross-shore transported sediment due to storms and cold fronts is larger than due to hurricanes, because the percentage of occurrence is much higher. However, because the cross-shore transport in a short time is larger for hurricanes, it is assumed that for hurricanes of category 3 or 4 the amount of sediment that will not recover is equal to 20 m^3/m. Hurricanes of these categories occur 0.2/year. For cold front and storms, it is assumed that the beach is able to recover. Measurements have to prove whether this assumption is right.

C. *Are there any complex hydrodynamic processes around the Iberostar Hotel beach which may contribute to the erosion problem?*

To further pinpoint on the causes of the erosion, the flows during northwest, north and north east were closely investigated. It turns out that during northwest conditions a complex flow pattern occurs. Waves from the northwest reach the coast almost shore normal, and because the coast is a little bit curved around Iberostar and the headland the transport directions change over the longshore direction. West of Iberostar the flow is eastward as expected, but to the east the flow is westward directed. These two flows merge at Hotel Sandals Royal Hicacos, left of Iberostar, which can be observed in reality because the beach is much wider here. For the Iberostar section this means that the erosion caused by waves coming from the north east is therefore not compensated by waves from the northwest. In fact, the occurring flow patterns can even result in erosion during these conditions. When modelling the full year wave climate in Delft3D, with a wave input reduction method, this pattern is confirmed. In front of Iberostar there is structural erosion, while in western direction sedimentation occurs.

D. *What is the best solution to the erosion problem?*

To come up with an optimal solution for the previous explained structural erosion, multiple solutions are investigated. In the end only two possible solutions remained, making a large nourishment or building a submerged breakwater with an additional nourishment. After a Multi Criteria Analysis, the nourishment solution was chosen because no additional complex flow patterns are created, the sustainability is higher and it is easier to construct and maintain. After modelling of the solution it seems that a nourishment of 100,000m^3 would be sufficient to provide a good beach width for a period of 5 years. When this is compared with the current executed solution, relocating the dunes in landward direction, it is in our opinion a better solution because the problem is not shifted. With as main goal the widening of the beach for tourists, relocating the dunes fulfils its requirements. However, the erosion problem is not solved for the long term with this solution as the yearly net erosion will still continue and the beach area will decrease again. Therefore it is advised not to relocate the dunes at the west part of the hotel, where it is still in original position, but reinforce the coastal system by means of a nourishment in front of the whole Iberostar section to compensate for the structural erosion. The proposed nourishment can also be easily combined with the currently executed solution, without having to relocate more dunes.

E. *How to construct the solution?*

The reason the currently applied solution does not consist of a nourishment is that during the first nourishment applied in the Tainos area in 2012, the effectiveness of the nourishment was only 64%. The reason this percentage is much lower than in other areas of the Hicacos peninsula, is that the timing and the execution of the nourishment was not optimal. The nourishment was performed in October and November, during these months there is still a chance of hurricanes (which happened with passing hurricane Sandy) and the cold front season had just started. Furthermore the sediment was not properly distributed over the area, which increases the amount of erosion.

To make sure that a new nourishment is more effective, the nourishment has to be executed in May and June. At that time there is no hurricane or tourist season and the occurrence of storm conditions is generally only 9%. In terms of execution, there has to be made use of bulldozers to distribute the sediment during the beach nourishment.

What is the cause of the erosion in front of the Iberostar Varadero Hotel, and what is the optimal solution to solve the problem?

When now all the sub questions are taken into account, the main research question can be answered. The causes of erosion are a combination of a general westward directed flow and the erosion this creates west of the headland, the complex flow patterns during northwest conditions which often also creates erosion and the influence of these on the recovery of the beach after storm and hurricane conditions.

The optimal solution for this problem is to apply a beach nourishment of 100,000 m^3 in front of the Iberostar hotel with a total cost of 1.1 million CUC for the first five years. This nourishment should be supplied during May and June using bulldozers to redistribute the sand. Furthermore the nourishment should not be seen as a single investment, but rather a nourishment program should be set up. Since the erosion problems are structural, after a couple of years there has to be nourished again. When making a maintenance program costs can be saved so for a period of 50 years the costs will be 12.8 million CUC, taking into account additional nourishments after possibly occurring hurricanes and extreme events.

When the behaviour of the nourishments is monitored, and the reshaping of the coastal profile after a nourishment is taken into account the structural erosion problems can be dealt with in a cost effective, visually attractive and flexible way.

9. Recommendations

Unibest

In the Unibest model the complex processes are not taken into account, which resulted in only a quantitative approximation of the longshore transport and no coastline evolution model. If we were able to put the more complex processes around the headland into Unibest, the Unibest model would give us the long-term coastline evolution. Furthermore, with a good working Unibest model it would also have been possible to calibrate the longshore sediment transports of the Delft3D model.

XBeach

XBeach has been validated with only minimal available data from profiles during cold fronts and hurricanes. Therefore the amount of transported sediments in reality may differ from the model output. This also has its influence on the computed amount of damage on the beach and dunes. Furthermore, there was hardly any data available for the wave set-up during the cold fronts. As these data are very important for the model input, this wave set-up should be definitely included in the model when further investigation is done. A final option to obtain more accurate results from the XBeach model is to use a different grid. This grid should have smaller grid sizes at the waterline and at the dunes. When using this grid, the erosion and sedimentation volumes and beach width retreat can be measured more precisely.

Delft3D

Due to the limited availability of data and the limited available time, it was not possible to extensively calibrate the Delft3D-model. The erosion and sedimentation areas seems to be quite good located, but the sedimentation/erosion rates seem to be quite exaggerated. This was clearly visible during the few 5 year runs. When further investigation is done with the Delft3D model, this behaviour should be fixed first. Another recommendation for the Delft3D model is that the nourishment is not simulated in a completely correct way. The nourished sand has different sediment characteristics than the original sand. Although there is an option to use different sediment characteristics for nourishment, this is not used due to the fact that testing different nourishment would become very complicated in this case. The third remark is the fact that the tides are only taken into account by the water levels.

Tidal flows are not included in the model, which in reality will be present. The last recommendation is about the solution designed by the Gamma office. For this solution, the bathymetry was not exactly known. Therefore the exact behaviour of the present solution could not be measured, which should be the case for the final solution.

Other

Besides the parameters for the calibration of the models, also other physical parameters are needed for the model input, as for instance viscosity and fall velocity. No values were available for these parameters, and therefore these parameters were computed with basic formulas and some assumptions. (Physical) tests need to be done in order to improve the accuracy of these parameters. The costs from the PRECON-catalogue is already quite outdated (2005). It should be checked whether updates have been published in order to get a more up-to-date cost estimation.

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A. Varadero Excursion

At the 14th of December, 2016, the project area was visited to get better insight in the measures which already have been taken and to ask questions to the people which are involved in this project.

The day started with an introduction at the CISAM office in Varadero, after which the Iberostar Hotel area was visited. Hereby, we would like to thank the CISAM office for their hospitality and all the explanations and answers on our questions at the project area.

Figure A- 1 Impression of the Iberostar Varadero Hotel

Iberostar Varadero area

The Iberostar Varadero hotel is located near the end of the Hicacos peninsula, on the northern side of the Autopista Sur, the main road which crosses the whole peninsula. Between the Iberostar hotel and the beach, a swimming pool, a green area of approximately 15 meters wide and a dune area are present. On top of the dunes, a small restaurant/cafeteria is located. From this cafeteria to the green area, a wooden bridge has been built over the dune row.

The Iberostar Varadero hotel has a capacity of approximately 1000 persons, of which, according to the hotel, a maximum of 45% visits the beach at the same time. For the project requirements, this results in a beach capacity of 450 persons.

Dune area

The dune area in front of Iberostar Varadero was originally divided into two parts. On the western side of the wooden bridge, the dunes existed of two dune rows. In the last years, the first dune row suffered under heavy erosion. Almost half of the dune was washed away in the last few years, after which an artificial slope was made on the sea side of the remaining dune body. On top of the remaining of this first dune row, the cafeteria is located.

On the eastern side of the bridge, originally only one dune row was present, which was in line with the first dune row on the western side. This dune row is removed in the spring of 2016 and relocated in landward direction in line with the second dune row.

Figure A- 2 On the eastern side the first dune row is removed and the artificial slope is visible

Measures spring 2016

In the spring of 2016, a measure has been taken to solve the erosion problem. The first dune row has been removed on the eastern side of the beach over a longshore range of approximately 400 meters, and has been rebuilt on a more landward location. Afterwards, sand is placed in the newly created area with a (cross-shore) width of 20 to 30 meters to create an artificial beach.

Vegetation and fences (Figure A- 3) are placed on the new dune to increase the sand retaining capability of the dune. In the near future, also the western part of the (remaining of) the first dune row will be removed and an artificial beach will be created at this location.

Plans are also made to remove the wooden bridge and connect the remaining dunes in order to create a continuous dune row. The main goals of the landward relocations of the beach are increasing the capacity and increasing the attractiveness of the beach. The difference between the eastern and western side of the beach in December 2016 is visible in Figure A- 4 and Figure A- 5. However, the problem is not permanently solved with this measure as the erosion will still continue. A more detailed description and evaluation of these measures can be found in section 6.1.5.

Figure A- 3 The backside of the new dune on the eastern side, with fences on top.

Figure A- 4 The beach on the western side, with only place for one row of stretchers and umbrellas.

Figure A- 5 The beach on the eastern side, with place for multiple rows of stretchers and umbrellas, and a wider beach.

Figure A- 6 Beach in front of Iberostar Varadero after a heavy storm (Gamma [3])

An important note which has to be made is that Figure A- 4 and Figure A- 5 are taken during the calm season in December 2016. In storm season, after many cold fronts or even hurricanes, the water reaches the first dune row and only a couple of meters wide beach is remaining. An impression of the beach during storm conditions is shown in Figure A- 6.

B. Nautical Charts

The nautical charts in this appendix are obtained from Navionics [4].

They're mainly used in order to improve the given bathymetry (see Appendix C). The bathymetry consists of multiple measurements, which do not fit perfectly. The reason behind this can be a difference in time between the measurements, different reference levels or coordinates or simply errors in the measurements themselves.

Therefore, to get the bathymetry as realistic as possible, some parts of the bathymetry data are shifted or deleted. These decisions are in accordance with the nautical charts in this appendix.

Figure B- 1 Nautical chart obtained by Navionics, larger area [4]

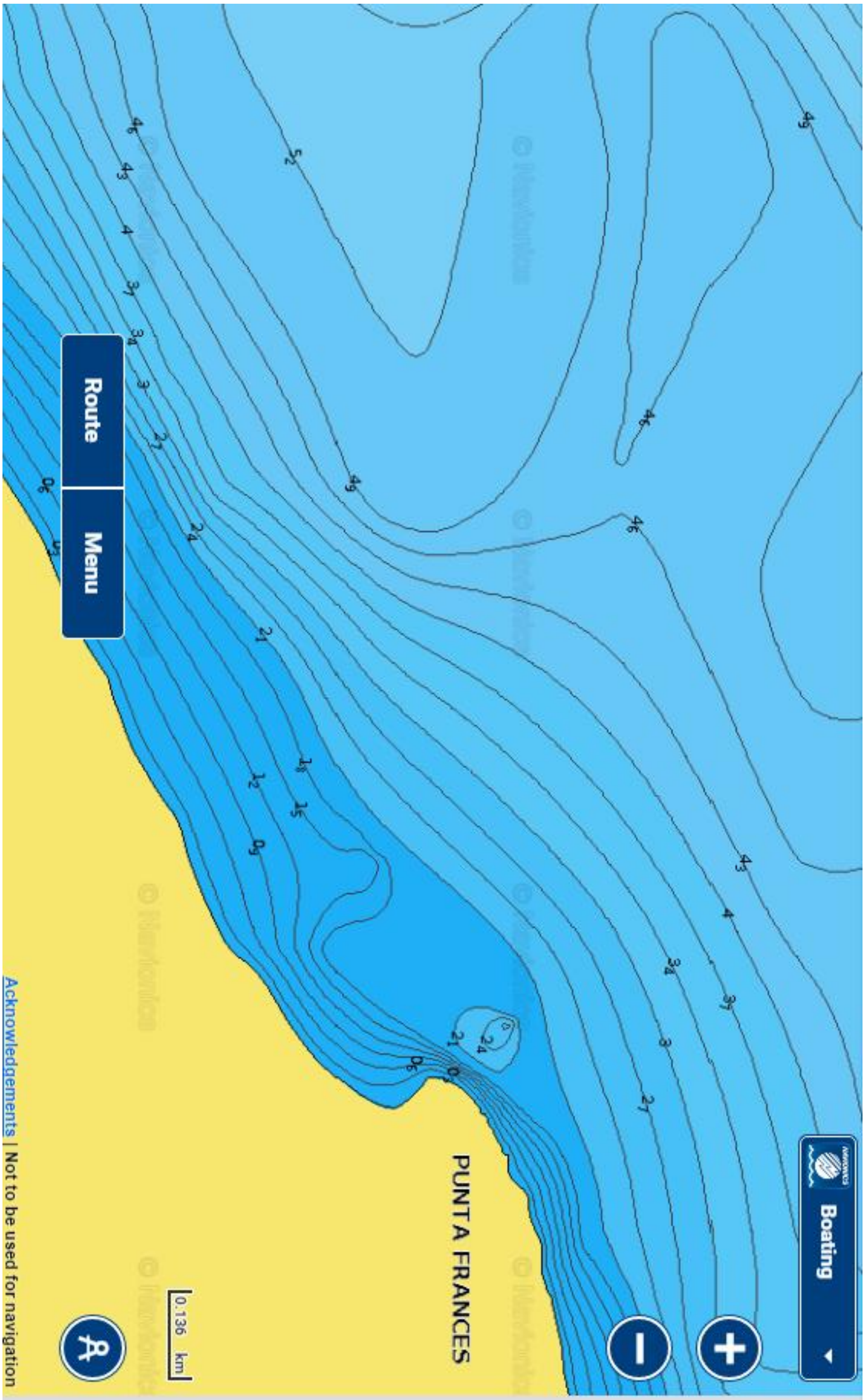


Figure B- 2 Nautical chart obtained by Navionics, smaller area [4]

C. Bathymetry and cross-sections

The bathymetry in this appendix is obtained by GeoCuba [5]. As said in Appendix B the bathymetry contained some errors and therefore some adjustments had to be done in order to get a realistic bathymetry. The cross-sections later shown in this appendix are also added to the total bathymetry file, in order to obtain a more accurate depth profile around the beach in front of the Iberostar hotel.

See Figure C- 1 for the resulting bathymetry file, plotted with QUICKIN.

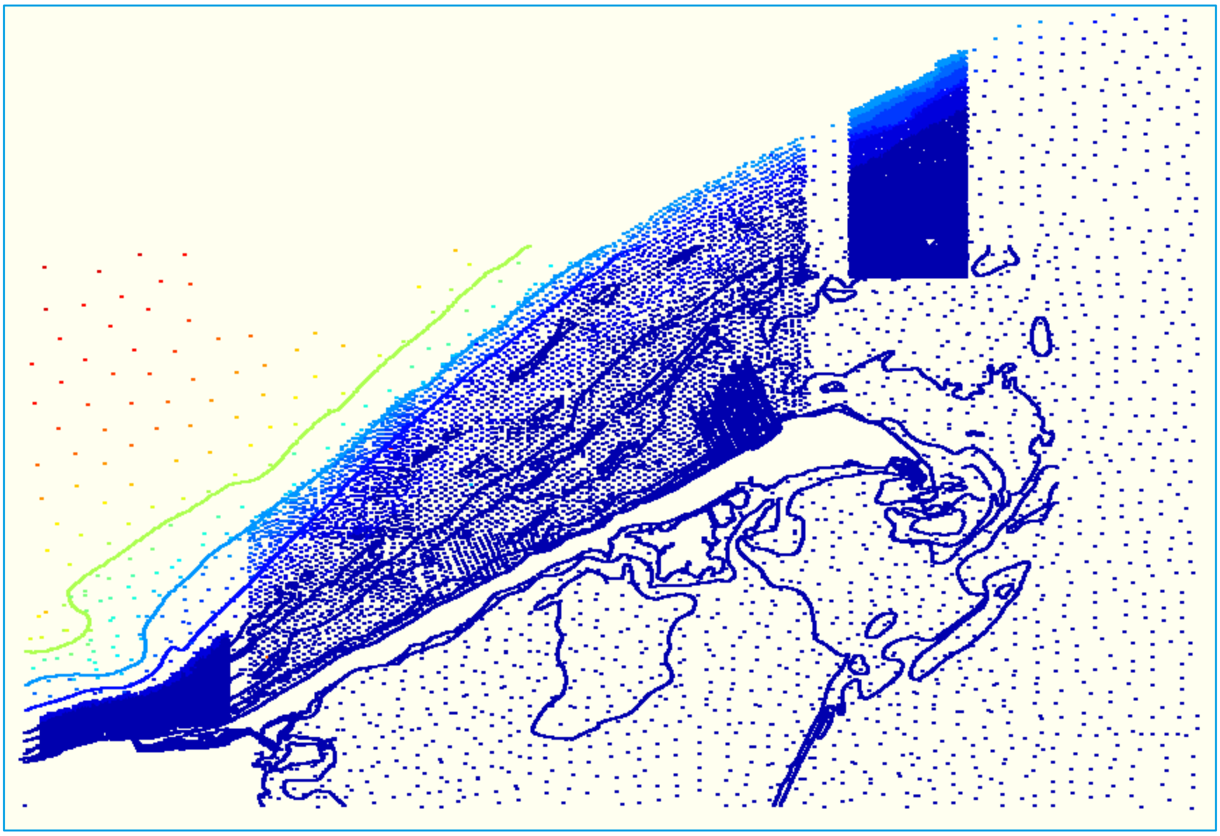


Figure C- 1 Total adjusted bathymetry data set (including cross-sections)

The cross-sections are obtained from Gamma [3]. The locations are shown in Figure C- 2 and the profiles in Figure C- 3.

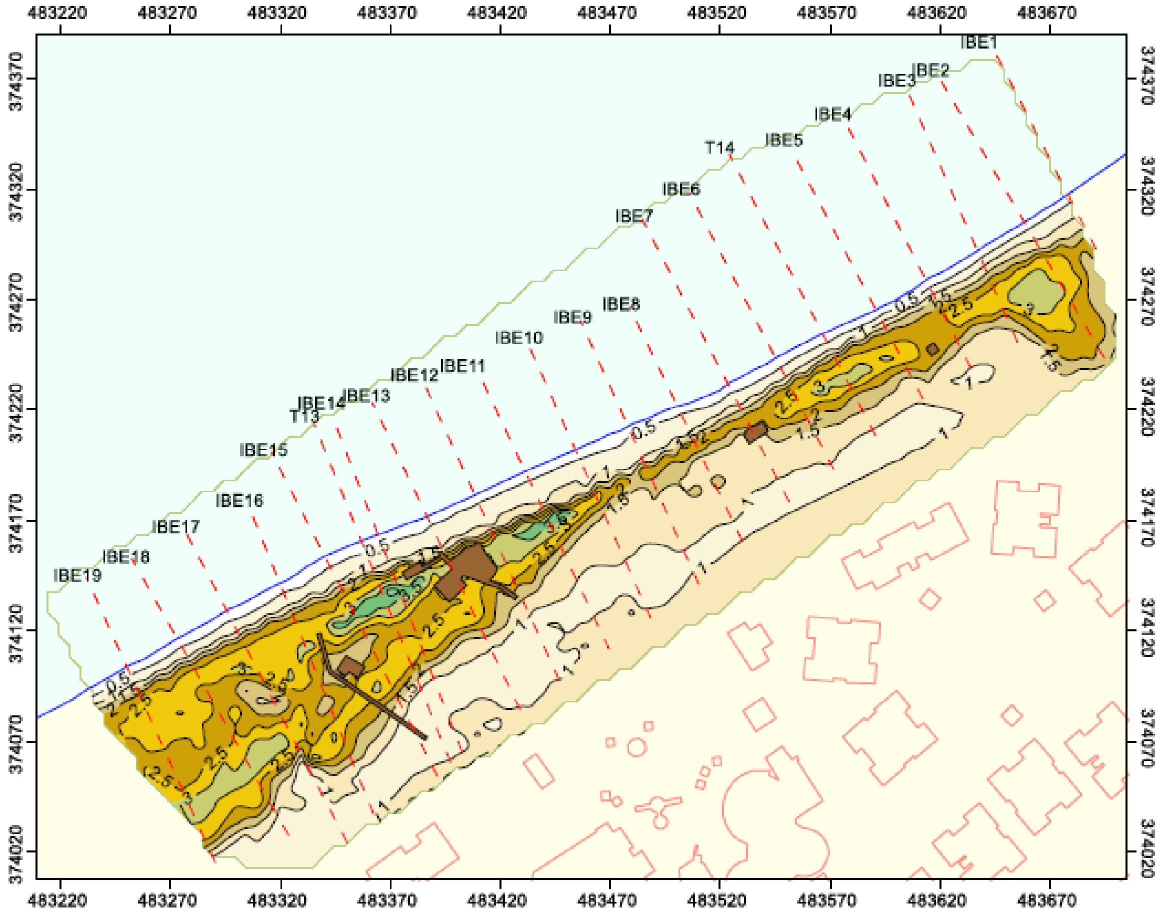
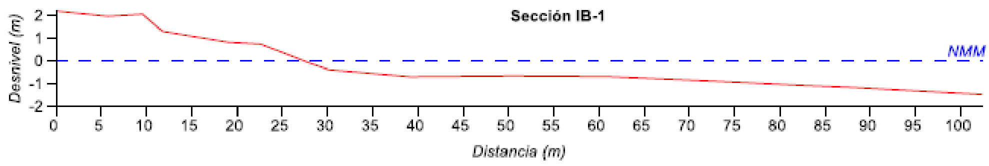
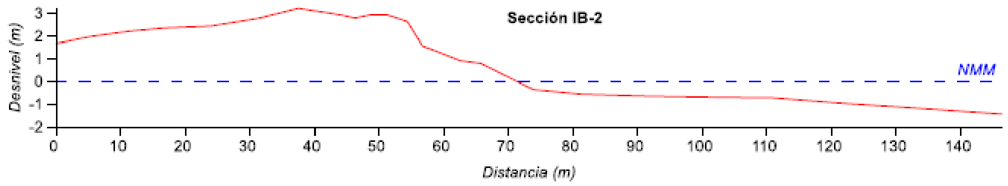
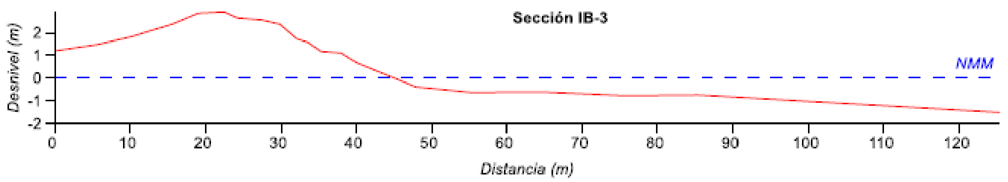


Figure C- 2 Locations of the cross-section measurements in front of the Iberostar hotel, Varadero


Sección IB-1
Desnivel (m)
Distancia (m)
NMM


Sección IB-2
Desnivel (m)
Distancia (m)
NMM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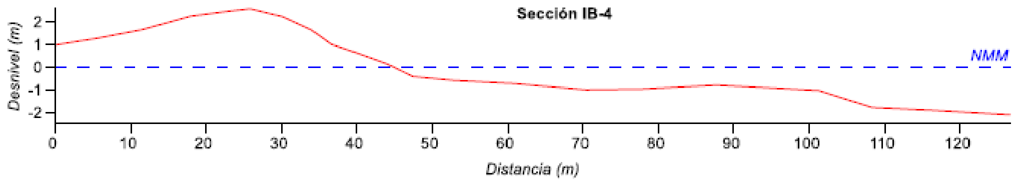
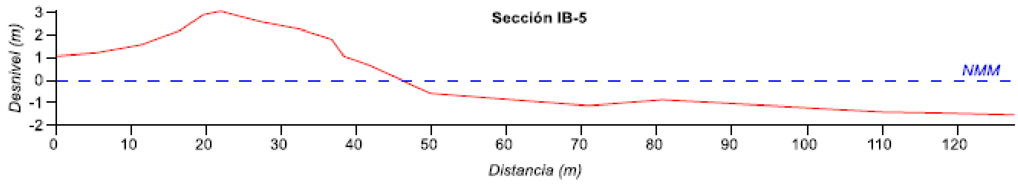
Desnivel (m)
Distancia (m)
NMM


Sección IB-4
Desnivel (m)
Distancia (m)
NMM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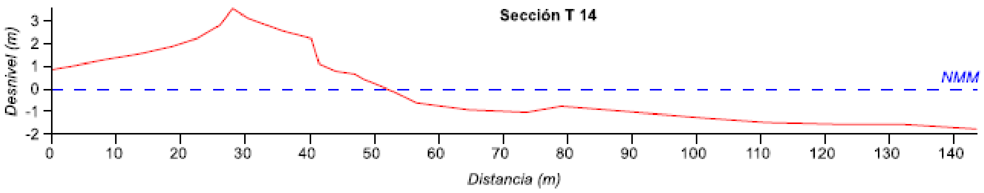
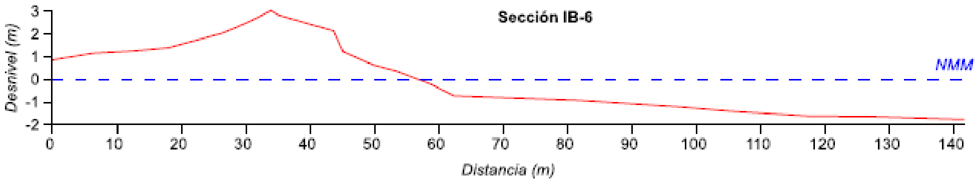
Desnivel (m)
Distancia (m)
NMM


Sección T 14
Desnivel (m)
Distancia (m)
NMM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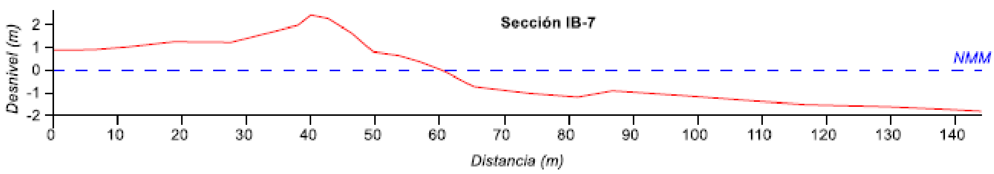
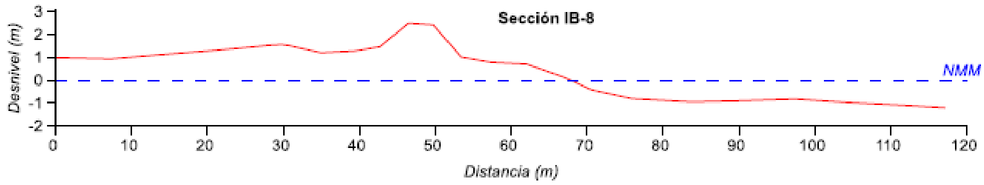
Desnivel (m)
Distancia (m)
NMM


Sección IB-7
Desnivel (m)
Distancia (m)
NMM


Sección IB-8
Desnivel (m)
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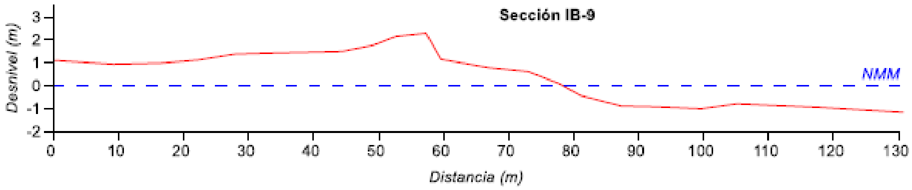
NMM
0 10 20 30 40 50 60 70 80 90 100 110 120
Distancia (m)


Sección IB-9
Desnivel (m)
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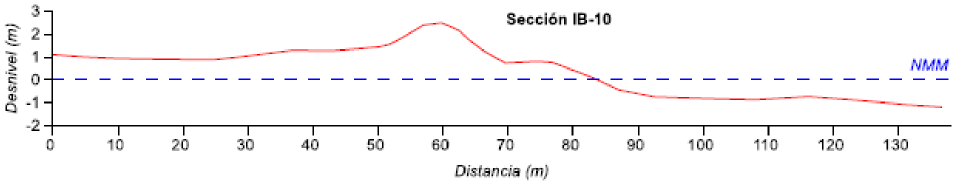
NMM
0 10 20 30 40 50 60 70 80 90 100 110 120 130
Distancia (m)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NMM
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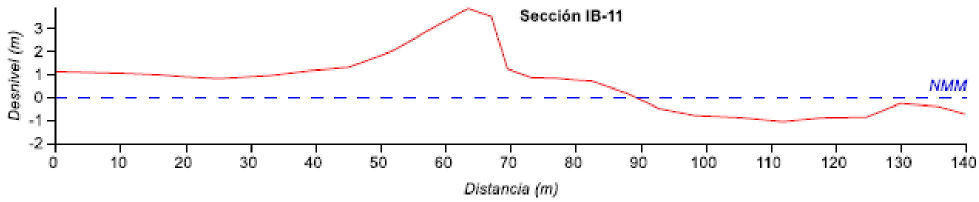
Distancia (m)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Desnivel (m)
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NMM
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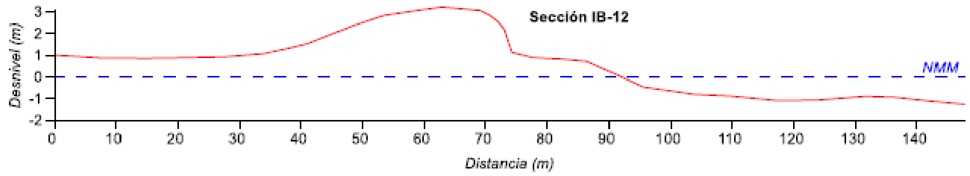
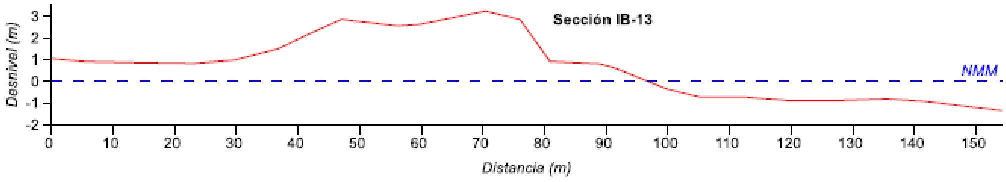
Distancia (m)


Sección IB-12
Desnivel (m)
3 2 1 0 -1 -2
NMM
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140
Distancia (m)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Desnivel (m)
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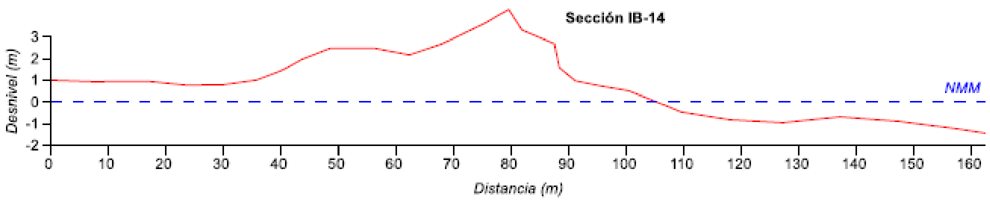
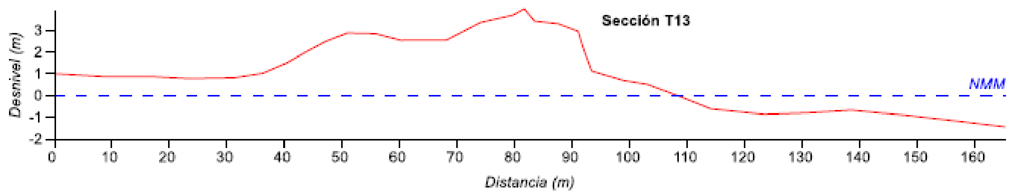
NMM
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150
Distancia (m)


Sección IB-14
Desnivel (m)
3 2 1 0 -1 -2
NMM
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160
Distancia (m)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Desnivel (m)
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NMM
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Distancia (m)

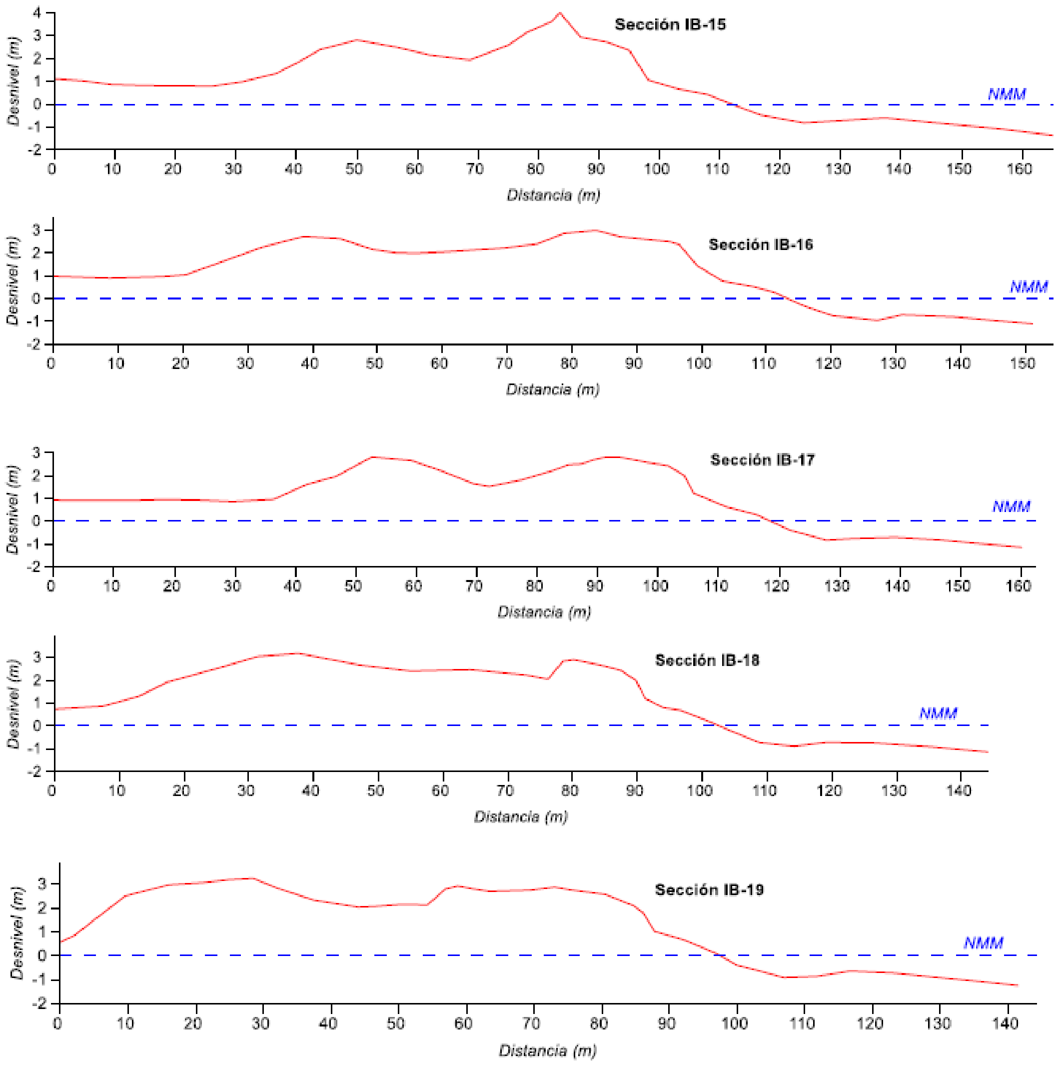

Figure C- 3 Cross-shore profiles in front of the Iberostar hotel

D. Wave Analysis

In this appendix three different wave analyses are described and executed. The differences between the analyses originate from the different objectives of each model. First, the main working method of each analysis will be explained. For more information about the type of wave analysis are used by which model, see Figure 4-1 in the main report.

The analyses will use the wave data set obtained from Argoss [11].

"Weather-condition-analysis"

The weather data set is divided into different conditions, which occur more often, representing a large part of the year or have a relatively large morphological effect. This division is not to represent reality as good as possible, but to represent some often occurring situations. These conditions can be modelled separately in order to be able to analyse those different situations. The division of the weather data is mostly done visually in order to eventually execute a simple, clear and mainly qualitatively analysis.

"Wave-reduction-analysis"

The most realistic results would be obtained by using the total wave data set as the final input. However, because some of the models are computationally very intensive, the large amount of wave conditions would make the computational run time unworkable. By doing a "Wave-reduction-analysis", for each wave the relative effect on the sediment transport can be calculated and by using these results the data can be divided in multiple wave conditions, which is still representative for the whole year.

"Hurricane-analysis"

The wave conditions occurring during hurricanes are not measured correctly in the Argoss data set. Therefore a separate hurricane analysis has to be made. Several hurricanes, with different tracks, wind speeds and diameters, will be compared and analysed.

D.1 Weather Condition Analysis

The weather condition analysis is executed in several steps. In this section each step is explained and the obtained data is shown.

Step 1 – Filtering the data set

The Varadero Peninsula is a straight coastline with a certain angle, which holds that not all waves from every direction can reach the coast. Therefore all the data with angles outside the range 247.5°-67.5° are not taken into account. The chosen range is based on the angle of the coastline (± 330°) and the size of the bins (22.5°/bin), which is used more commonly in this report.

Step 2 – Extracting weak and strong storms from the data

To extract storms from the data set, first a definition about storms should be given:

A weak storm starts from the moment that the significant wave height is higher than 1.6 meter and continues for every measurement this requirement holds. The weak storm ends when the significant wave height is lower than 1.6 meter. The time difference between the moment the storm starts and it ends is the duration of the storm. The same definition holds for a heavy storm but then the lower value for the significant wave height is 3.8 meter.

<u>Weak storm</u>

Start: $H_s > 1.6$ m ($t = t_0$)

End: $H_s < 1.6$ m ($t = t_{end}$)

Duration: $D = t_0 - t_{end}$

<u>Heavy storm</u>

Start: $H_s > 3.8$ m ($t = t_0$)

End: $H_s < 3.8$ m ($t = t_{end}$)

Duration: $D = t_0 - t_{end}$

These values are iteratively determined based on the wind speeds occurring during these conditions. The average wind speed occurring during the storm, according to the given definition, is 35 m/s during a weak storm and 55 m/s for a heavy storm. This corresponds with the values from section 3.3.3.

According to this definition there are 22.8 weak storms and 0.7 heavy storms on average per year. The average duration of a weak storm is 29 hours and 17 hours for a heavy storm.

	Weak storm	Heavy storm
Start storm	$H_s > 1.6$ m	$H_s > 3.8$ m
End storm	$H_s < 1.6$ m	$H_s < 3.8$ m
Average occurrence / year	22.8	0.7
Occurring average wind speed during condition	35 m/s	55 m/s
Average duration	29 hours	17 hours

Table D- 1 Overview of properties weak and heavy storms

Step 3 – Dividing the storms based on direction

To come up with several different conditions usable for the computations, the storms should also be divided on their angle. For the occurrence of weak and heavy storms over the past 22 years plotted over direction, see respectively Figure D- 1 and Figure D- 2. The numbers are shown in Table D- 2.

It can be clearly seen that for both weak and heavy storms there are two dominating directions. From these different directions the wave conditions will be formed, so in total four wave conditions will be created for storms. The angles taken into account in the wave conditions are marked blue in Table D- 2. For each generated wave condition, the average wave height and direction are calculated based on the average during the included storms. Also the occurring wind speeds and direction are calculated. An overview of the resulting wave conditions is given in Table D- 3.

It must be noted that the bins in which the storms are divided do not have similar directions and are not evenly large. As said this analysis is mainly for qualitative purposes and therefore it's assumed to be a correct method for this situation. Besides that also the names of the different wave conditions are not entirely corresponding with their actual properties, so they can be confusing. The names of the wave conditions are given for practical purposes.

Finally, in Table D- 3, it can be seen that the heavy storms from the northwest are stronger than storms from the north east. The reason behind this is that the storms from the northwest (also weak), are mainly caused by cold fronts coming from the Gulf of Mexico. These cold fronts are a well-known phenomenon in Cuba, which cause the most damage on the coastal area.

Angle (nautical)	Occurrences in Argoss data set (weak)	Occurrences in Argoss data set (heavy)
250	1	0
260	4	0
270	3	1
280	6	4
290	22	3
300	37	1
310	31	0
320	28	0
330	22	0
340	26	0
350	19	0
360	5	0
10	27	0
20	15	0
30	23	1
40	32	3
50	68	1
60	85	3
70	41	0

Table D- 2 Occurrences in Argoss data set of weak and heavy storms

	H_s (m)	H_{dir} (°)	T_p (s)	U_s (m/s)	U_{dir} (°)	Occurrence (%)
Weak storm NE	2.17	43.9	5.97	10.60	51.0	3.47
Weak storm NW	2.16	265.1	7.60	8.75	350.2	2.82
Heavy storm NE	4.30	52.8	8.11	16.29	48.0	0.04
Heavy storm NW	4.90	280.8	9.68	13.83	287.5	0.05

Table D- 3 Overview of generated wave conditions based on storms

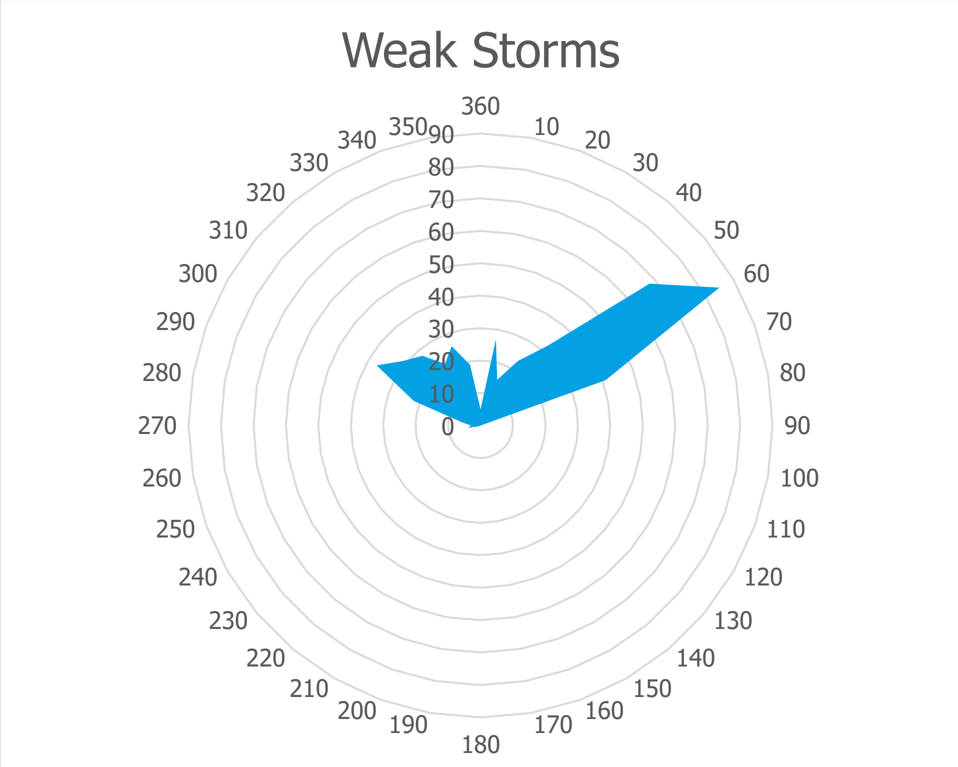

Figure D- 1 Weak storm, occurrence over direction

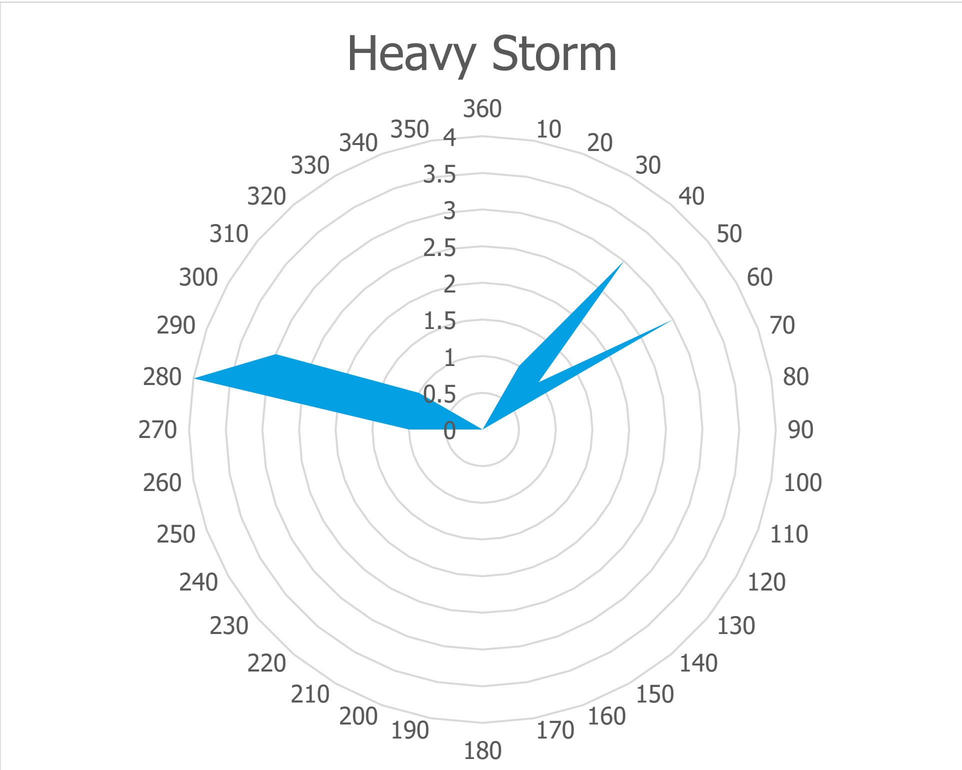

Figure D- 2 Heavy storm, occurrence over direction

Step 4 – Dividing normal conditions based on direction

In step 2, the storms were extracted from the data set. It should be noticed that hurricanes are not measured correctly in the Argoss data set, therefore only the normal conditions are still useful from the data. In order to obtain usable data, also these normal conditions should be divided based on their direction.

So in accordance with the definition stated in step 2, we speak of a normal condition when there is no storm or hurricane. Therefore it is not logical to express the normal conditions in number of occurrences (like storms), but in percentage of occurrence.

For the normal conditions there are some dominant wave directions, but not as clearly as for the storms. Therefore the data set is divided into three bins, all with a width of 40° and symmetrical around the nautical 0° point. So, finally there are three new wave conditions generated for the normal conditions. Again, for each wave condition the average wave height, wave direction, wind speed, wind direction and period are computed. An overview of the newly generated wave conditions and the wave conditions generated from the cold fronts are shown in Table D- 4.

The notes made in step 3, also apply for the wave conditions generated from the normal weather conditions.

	H_s (m)	H_{dir} (°)	T_p (s)	U_s (m/s)	U_{dir} (°)	Occurrence (%)
Weak storm NE	2.17	43.9	5.97	10.60	51.0	3.47
Weak storm NW	2.16	265.1	7.60	8.75	350.2	2.82
Heavy storm NE	4.30	52.8	8.11	16.29	48.0	0.04
Heavy storm NW	4.90	280.8	9.68	13.83	287.5	0.05
Normal condition NE	0.81	42.4	6.33	5.52	45.2	25.5
Normal condition N	0.85	320.3	5.86	4.89	6.0	19.1
Normal condition NW	0.85	359.9	6.08	5.57	25.6	17.1

Table D- 4 Overview of generated wave conditions

Step 4b – Generating conditions for extreme events

In reality, an extreme event does not have a constant significant wave height. In the beginning, when for example a cold front moves towards the coast, the significant wave height is still low. The wave height will then increase and from the moment the peak of the storm has passed, the wave height will decrease again.

For a modelling software like XBeach, this process of increasing and decreasing wave height is important, as sudden extreme waves can influence the results. Therefore the generated wave conditions from Table D- 4 are used to generated some realistic storm conditions as input for XBeach. The results are shown in Figure D- 3.

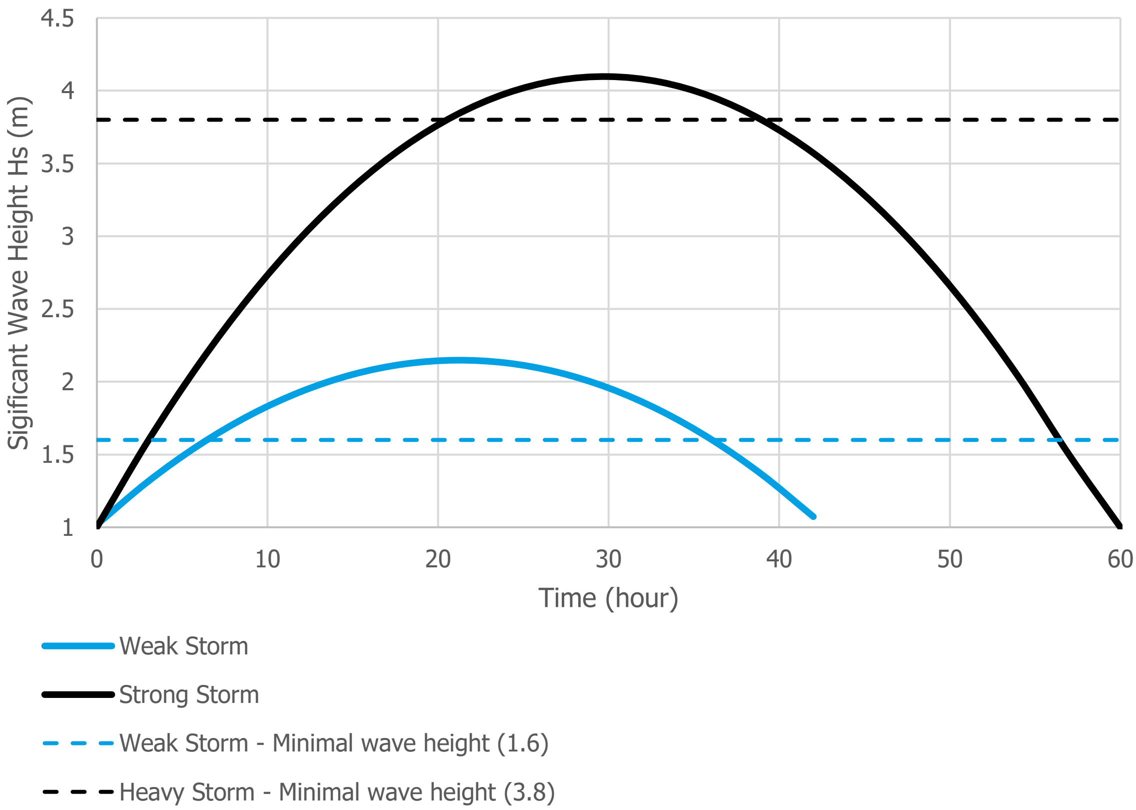

Figure D- 3 Weak and heavy storms as input for XBeach

These (fictional) storms are created by searching for weak and heavy storms in the Argoss data set, according to the given definition of weak and heavy storms. The behaviour of these periods is analysed and characteristics like duration, maximum wave height and the rate of increase and decrease of the wave height were determined. The result is a (fictional) storm that can be used as a realistic wave input for XBeach.

D.2 Wave reduction analysis

Similar to the weather condition analysis, also the wave reduction analysis is executed in multiple steps. The result of these steps and the working method are explained below [24].

Step 1 – Filtering the dataset

As a consequence of the orientation of the Varadero coastline and our area of interest, also in this analysis only the waves with a direction between 247.5 and 67.5 degrees north are taken into account. This range is divided in sections of 22.5 degrees, which results in 8 directional bins, representing directions from west south west to east north east. The coastline orientation is perpendicular to 330 degrees north. The dataset is further filtered by dividing each directional bin in 20 wave height bins of 0.5 meter each, reaching from 0 meter to 10 meter wave height.

The end result is a table with 160 different wave conditions with a directional spreading of 22.5 degrees and a wave height spreading of 0.5 meter. For each box the number of waves occurring in the 14 years of measurements is counted, depending on wave height and direction. Dividing the total number of waves in each box by the total amount of wave conditions (over 40,000) gives the percentage of occurrence of this wave condition. The result is presented in Table D- 5. It can be seen that only 82 wave conditions have a percentage of occurrence higher than zero.

Wave Height (m)		Direction (-)								Total
Min		247.5	270	292.5	315	337.5	0	22.5	45	
	Max	270	292.5	315	337.5	360	22.5	45	67.5	
0	0.5	0.108	0.163	0.474	0.824	0.715	0.880	1.077	1.510	5.755
0.5	1	0.340	0.499	1.436	1.680	1.463	1.436	1.756	2.840	11.451
1	1.5	0.164	0.296	0.955	1.195	0.918	0.872	1.094	2.171	7.664
1.5	2	0.051	0.167	0.625	0.687	0.478	0.409	0.652	1.469	4.537
2	2.5	0.025	0.124	0.427	0.243	0.186	0.232	0.307	0.787	2.330
2.5	3	0.006	0.060	0.229	0.100	0.057	0.068	0.147	0.323	0.990
3	3.5	0.005	0.046	0.071	0.022	0.016	0.006	0.034	0.155	0.356
3.5	4	0.002	0.018	0.028	0.002			0.022	0.049	0.121
4	4.5	0.001	0.018	0.012				0.006	0.030	0.067
4.5	5	0.006	0.012	0.003				0.001	0.001	0.024
5	5.5		0.004	0.003					0.001	0.009
5.5	6		0.004					0.001	0.001	0.007
6	6.5							0.001		0.001
6.5	7		0.001							0.001
7	7.5									0.000
7.5	8									0.000
8	8.5		0.001							0.001
8.5	9									0.000
9	9.5									0.000
9.5	10	0.001								0.001

Table D- 5 Wave conditions in percentage of occurrence

Step 2- Converting to nearshore wave conditions

In step 2, every wave condition belonging to a certain box is converted to near shore conditions with SwanOne. SwanOne computes the nearshore characteristics of an incoming offshore wave at a given location, only for waves which come in with an angle lower than 70 degrees to the shore normal. The direction of the wave conditions on the outer bins on both sides of the range have an angle larger than 70 degrees.

To be able to compute the nearshore characteristics of these waves, the transformation of the waves is modelled with a stationary Delft3D-WAVE model, which runs on SWAN (the 2D-version of SwanOne). The transformation to nearshore conditions is mainly done in order to be able to compute the sediment transports due to these waves in Unibest.

The transport computed with nearshore waves is needed because the Unibest LT model gives no reliable results if the input is transport computed with offshore wave conditions. The result of this wave analysis step gives the input of our Unibest LT model and also forms the starting point of the next step of the wave reduction analysis.

Step 3 – Wave reduction

A complex model like Delft3D works most efficient if only a small amount of different wave conditions is used as input. After step 1 and 2, the large dataset is reduced to 82 wave conditions, which is sufficient for a program like Unibest, but still too high to work efficiently with Delft3D.

The idea of a wave reduction is to pick a small amount of wave conditions, for instance eight, and scale them in such a way that the transport curve belonging to the combination of these wave conditions is more or less equal to the transport curve obtained with all (82) wave conditions.

First, the occurrences from Table D- 5 are multiplied by the longshore sediment transport that they induce. The result is a relative importance to the total erosion problem. This is shown in Table D- 6. The table shows that wave conditions with a high occurrence and a high effect on the sediment transport have the highest influence on the total sediment transport.

$$S_{p,i} = P(H_{s,i}, Dir_i) * S(H_{s,i}, Dir_i)$$

Where:

S_p	Weighted sediment contribution	$[m^3]$
S	Sediment from wave condition (Unibest LT)	$[m^3]$
P	Percentage of occurrence (Table D- 5)	[-]
i	Index of wave condition	[-]

Wave Height (m)		Direction							
Min		247.5	270	292.5	315	337.5	0	22.5	45
	Max	270	292.5	315	337.5	360	22.5	45	67.5
0	0.5	0	0	0	0	0.001	0.001	0	0
0.5	1	0.018	0.036	0.08	0.01	0.059	0.089	0.086	0.065
1	1.5	0.03	0.079	0.247	0.038	0.187	0.267	0.257	0.206
1.5	2	0.026	0.144	0.457	0.055	0.263	0.686	0.39	0.344
2	2.5	0.031	0.246	0.667	0.043	0.199	0.448	0.415	0.449
2.5	3	0.018	0.205	0.636	0.033	0.114	0.307	0.389	0.389
3	3.5	0.021	0.25	0.316	0.009	0.056	0.038	0.188	0.328
3.5	4	0.009	0.143	0.16				0.179	0.148
4	4.5	0.012	0.182	0.069				0.081	0.115
4.5	5	0.065	0.132	0.016				0.024	0.007
5	5.5		0.053	0.014					0.007
5.5	6		0.053					0.032	0.008
6	6.5							0.043	
6.5	7		0.015						
7	7.5								
7.5	8								
8	8.5		0.012						
8.5	9								
9	9.5								
9.5	10	0.022							

Table D- 6 Relative importance to total longshore sediment transport for each wave condition (S*P)

The next task is to determine which wave conditions are best capable of representing the whole wave condition data set. There are different techniques available to do this.

Highest contribution

The simplest technique is a wave reduction based on the waves with highest transport contribution. In this case, a certain amount of wave conditions with the highest transport contribution are picked and scaled by multiplying the duration of these conditions by a scale factor. The scale factor in this case is equal to the total transport (due to all wave conditions), divided by the sum of the transport caused by the chosen highest wave conditions.

Manual grouping of classes

Another technique is to manually group the wave conditions. Within each of the groups, the centre of gravity (based on transport) has to be found. The selected groups and their centre of gravities can be found in Table D- 7. The centre of gravity is going to be the representative wave condition of its group.

The original occurrence of the representative wave condition then will be multiplied with an upscaling factor to make the contribution of the representative wave condition equally large as the sum of the group.

The scale factor is equal to the transport contribution of the entire group, divided by the transport contribution of the wave condition at the centre of gravity. For that case, the scale factor is different for every group of wave conditions and therefore every wave condition at the appointed centre of gravity.

$$S_{p,j} = \sum_{i=1}^{n_j} P\left(H_{s,i}, Dir_i\right) * S\left(H_{s,i}, Dir_i\right)$$

Where:

S_p	Weighted sediment contribution	[m^3]
S	Sediment from wave condition (Unibest LT)	[m^3]
P	Percentage of occurrence (Table D- 5)	[-]
i	Index of wave condition	[-]
j	Index of drawn box	[-]

$$F_{up,j} = \frac{S_{p,j}}{P\left(H_{s,rep,j}, Dir_{rep,j}\right) * S\left(H_{s,rep,j}, Dir_{rep,j}\right)}$$

Where:

F_{up}	Weighted sediment contribution	[-]
S_p	Weighted sediment contribution	[m^3]
S	Sediment from wave condition (Unibest LT)	[m^3]
P	Percentage of occurrence (Table D- 5)	[-]
i	Index of wave condition	[-]
j	Index of drawn box	[-]

$$P_{rep,new} = P_{rep,0} * F_{up}$$

Where:

F_{up}	Weighted sediment contribution	[-]
P_{rep}	Percentage of occurrence of representative [-]	

The final result is a certain amount of wave conditions, of which all characteristics are equal to the characteristics of the original wave conditions, except the duration. In Figure D- 4 the comparison of the results for the different wave reductions are presented.

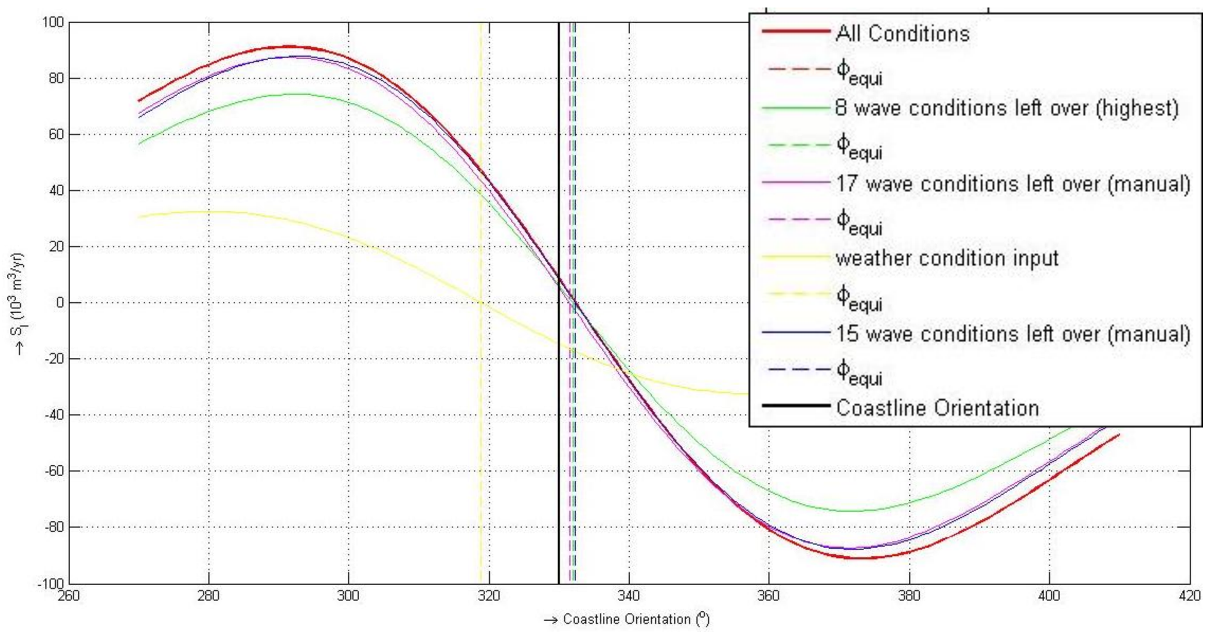

Figure D- 4 Comparison of different wave reduction techniques

Clearly visible is that the method with the manually selected wave groups gives the best result. The computed equilibrium coastline in this case is more or less equal to the equilibrium coastline in case of using all conditions and also the sediment transport at different coastal orientations lies close to the value for the transport in case of imposing all wave conditions.

The yellow line shows the sediment transport curve in case of using a different method for the wave height, period and duration for normal conditions and during cold fronts. The characteristics used are from the 'Weather condition analysis' derived in Appendix D.1, summarized in section 3.3.5 and presented in Table 3-7.

The difference in results is caused by the fact that the 'Weather conditions analysis' is based on wave height and duration only, while the 'Wave reduction analysis' is based on sediment transport quantities directly.

Between wave height and sediment transport, a certain power law exists, in our case for Delft3D this is a law by Van Rijn. Clearly visible is that the transport curve in case of assumptions based on wave height and duration does not give a representative sediment transport curve. Conditions based on wave height and duration therefore are only useful for analysing the flow and transport during a certain condition, but not for representing a whole year of wave conditions and the resulting transport.
In the region around the present coastline orientation (330°), the transport in the reduced case is even equal to the original transport. This is favourable for our case, because most coastline angles at the Hicacos peninsula are in this range. In Figure D- 5, a close view of the range between 320° and 340° is presented.

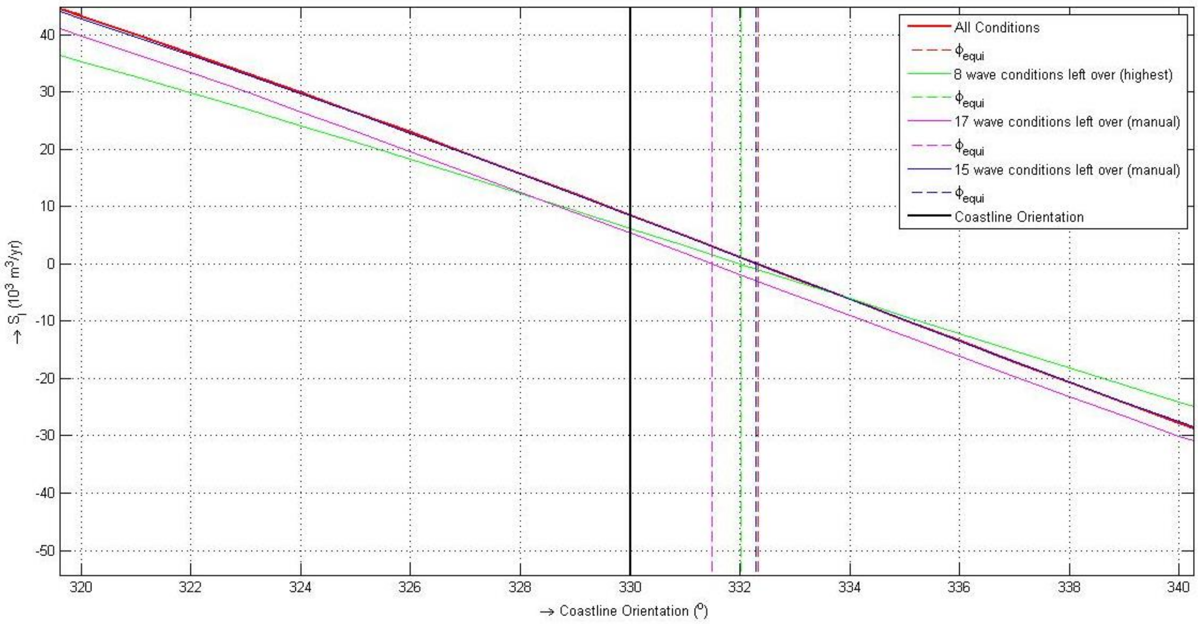

Figure D- 5 Comparison of the wave reduction techniques between 320 and 340 (-)

Finally, to come up with good reduced wave input, the manual selection method is chosen. The result of the technique is shown in Table D- 7. The manually chosen groups are given by the thick rectangles. In the rectangles, the blue value represents the yearly transport contribution of the wave at the centre of gravity. The values in all other boxes are the transport contribution of the offshore wave condition belonging to this box.

Finally, for each manually drawn box (15), the total longshore sediment transport of that box is divided by the longshore sediment transport of the representing wave condition (centre of gravity). The resulting factor is the upscaling factor. By multiplying the original occurrence (%) of the representative wave condition by the upscaling factor, the wave conditions represent its box. By doing this for all boxes, 15 wave conditions remain which are capable of accurately representing the whole data set.

Often higher wave heights (for example 1.75 m) are the representatives, which occur less often. Because of this, the total time of the wave input is reduced.

The results are shown in Table D- 8.

Wave Height (m)		Direction							
Min		247.5	270	292.5	315	337.5	0	22.5	45
	Max	270	292.5	315	337.5	360	22.5	45	67.5
0	0.5	0	0	0	0	0.001	0.001	0	0
0.5	1	0.018	0.036	0.08	0.01	0.059	0.089	0.086	0.065
1	1.5	0.03	0.079	0.247	0.038	0.187	0.267	0.257	0.206
1.5	2	0.026	0.144	0.457	0.055	0.263	0.686	0.390	0.344
2	2.5	0.031	0.246	0.667	0.043	0.199	0.448	0.415	0.449
2.5	3	0.018	0.205	0.636	0.033	0.114	0.307	0.389	0.389
3	3.5	0.021	0.25	0.316	0.009	0.056	0.038	0.188	0.328
3.5	4	0.009	0.143	0.16				0.179	0.148
4	4.5	0.012	0.182	0.069				0.081	0.115
4.5	5	0.065	0.132	0.016				0.024	0.007
5	5.5		0.053	0.014					0.007
5.5	6		0.053					0.032	0.008
6	6.5							0.043	
6.5	7		0.015						
7	7.5								
7.5	8								
8	8.5		0.012						
8.5	9								
9	9.5								
9.5	10	0.022							

Table D- 7 Manual selected groups with gravity points

Box id (-)	H_s (m)	Dir (deg)	T_p (s)	S*P block (m^3)	S*P rep. (m^3)	F (-)	P_0 (%)	P_{new} (%)	P_{new} (days/year)
1	2.75	258.75	6.5	0.231	0.018	12.77	0.006	0.077	0.282
2	2.75	281.25	8.4	1.418	0.204	6.93	0.060	0.412	1.505
3	5.75	281.25	10.2	0.168	0.053	3.18	0.004	0.014	0.052
4	1.75	303.75	7.8	1.452	0.457	3.18	0.625	1.987	7.251
5	3.25	303.75	9.2	1.197	0.316	3.79	0.071	0.271	0.987
6	1.75	11.25	5.7	0.953	0.686	1.39	0.409	0.568	2.074
7	2.25	11.25	6.3	0.793	0.448	1.77	0.232	0.411	1.500
8	0.75	11.25	6.7	0.241	0.086	2.80	1.756	4.924	17.972
9	1.75	33.75	5.5	1.062	0.390	2.72	0.652	1.774	6.474
10	2.75	33.75	6.7	0.757	0.388	1.95	0.147	0.287	1.046
11	4.75	33.75	7.8	0.317	0.081	3.90	0.006	0.023	0.087
12	1.75	33.75	5.5	0.999	0.344	2.91	1.469	4.267	15.575
13	3.25	56.25	7.1	0.865	0.382	2.64	0.155	0.408	1.489
14	1.75	56.25	6.3	0.878	0.262	3.34	0.478	1.597	5.829
15	1.75	348.75	6.8	0.189	0.055	3.43	0.687	2.361	8.616
Total				11.52	4.17	-	6.757	19.38	**70.7**

Table D- 8 Overview results wave reduction analysis

As seen from the table, the total duration for the calculated wave conditions is 70.7 days/year. This duration represents a whole year in morphological change. To finally determine if the wave input reduction is accurate enough, the results are also simulated with Delft3D and compared with the full wave set. The results of this comparison can be found in Appendix H, Figure H- 7.

D.3 Hurricane analysis

Because hurricanes are not correctly represented in the Argoss wave data, additional sources were needed to model the behaviour of the coast under hurricane conditions in XBeach. Hurricanes are complex phenomena so in order to convert a track, wind speeds and pressures into wave input for a model like XBeach, separate studies have to be made. This study was available for the hurricanes Michelle and Wilma, which are known to have caused serious damage at Varadero. The characteristics of the two hurricanes are shown in Figure D- 6 and Figure D- 7, according to Havana (2006) [25].

The studies used a large SWAN model to convert general data from the hurricane into nearshore conditions. In both cases the data output was made for the beach of Varadero which therefore could easily be used. This data could not be verified but seems plausible for offshore locations near Varadero, as showed in Figure D- 8 and Figure D- 9.

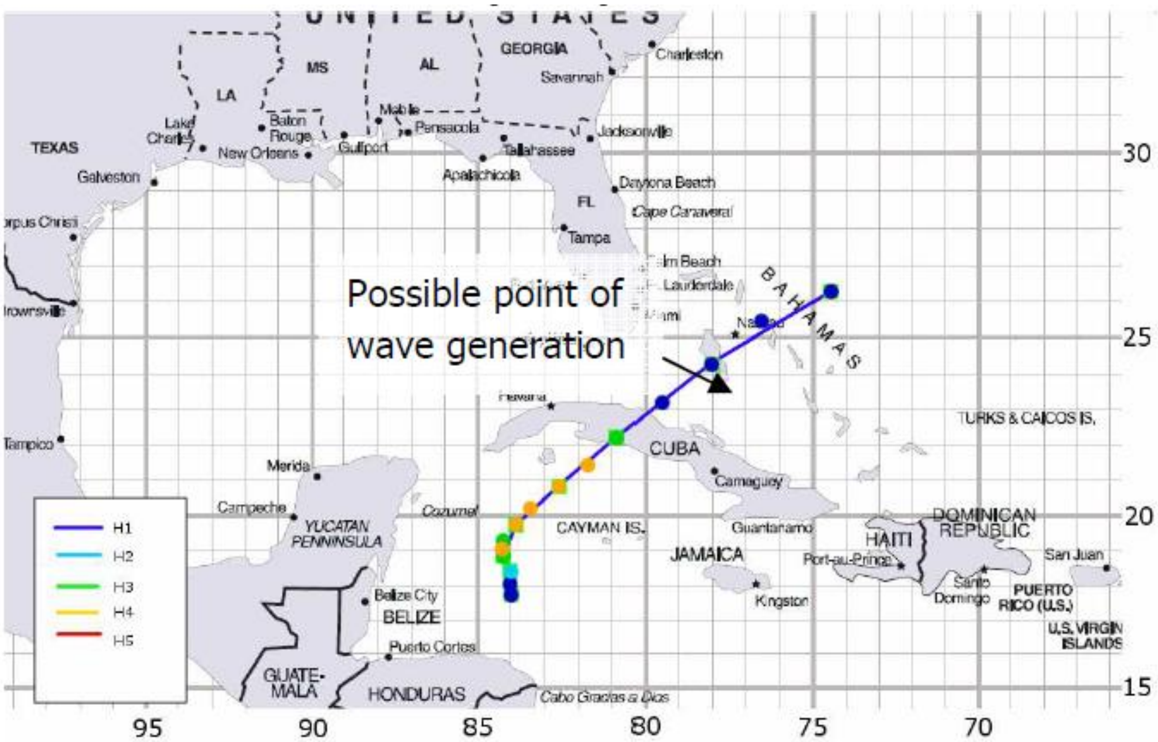

Figure D- 6 Characteristics of hurricane Michelle (2001), from (Havana 2006)

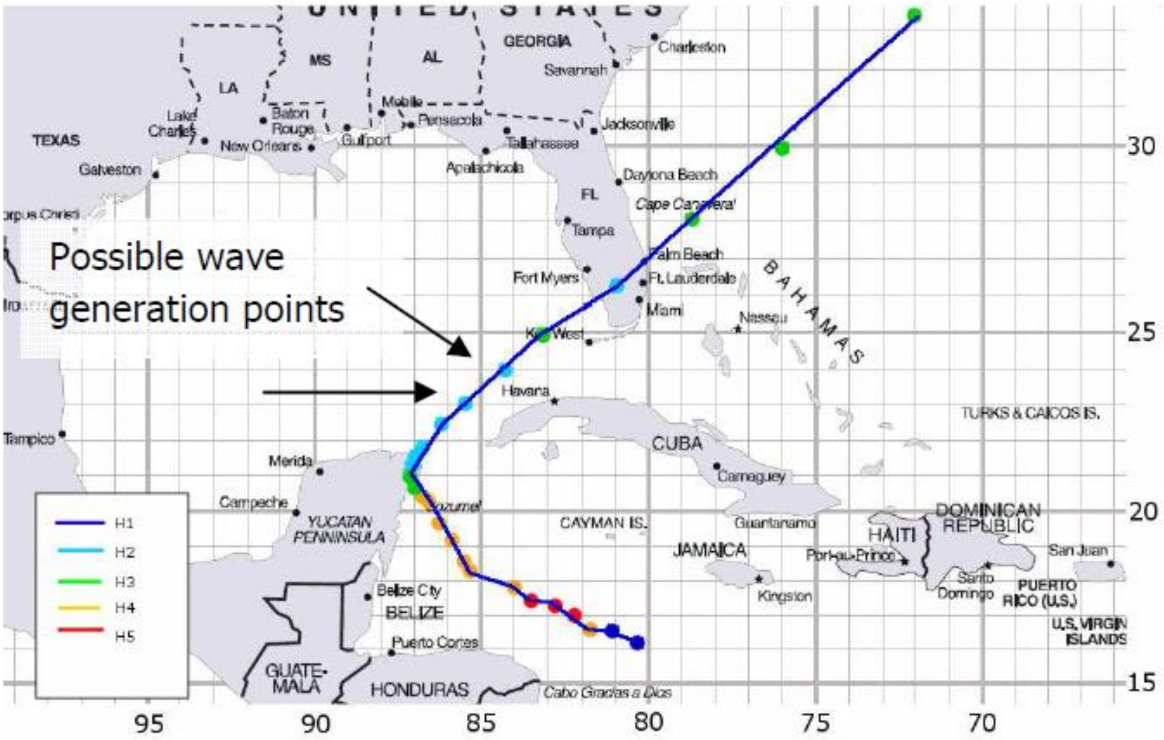

Figure D- 7 Characteristics of Hurricane Wilma (2005), from (Havana 2006)

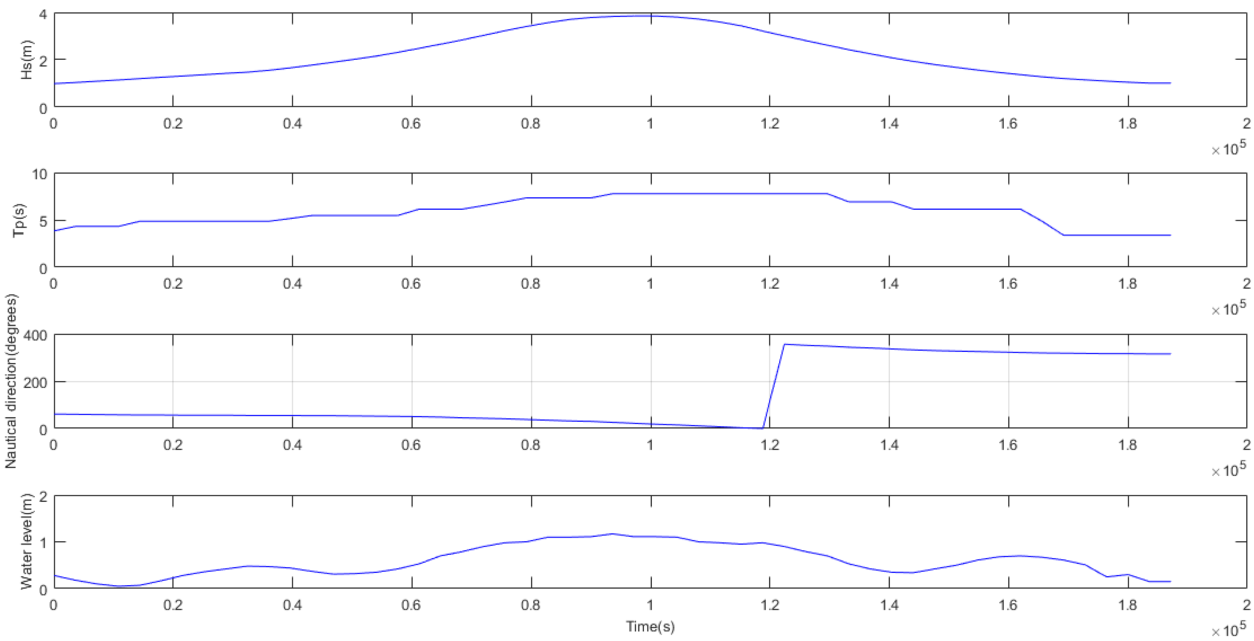

Figure D- 8 Conditions for Hurricane Michelle

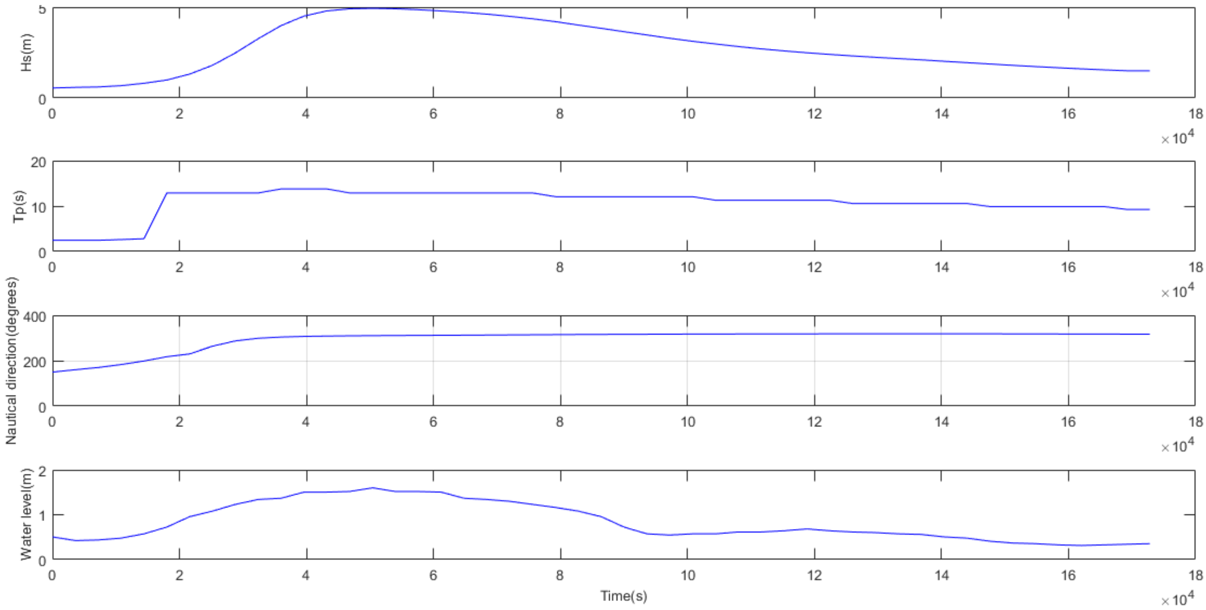

Figure D- 9 Conditions for Hurricane Wilma

For Wilma only a graph was available for the water levels, so the corresponding data was estimated. The rest of the data was presented as hourly data which could be inserted in Delft3D-WAVE to let SWAN convert the offshore conditions into nearshore conditions for XBeach. In this way a good representation of hurricane conditions to impose on the coast is obtained.

E. Modelling Software

In this report different modelling software is used to compute the erosion, find out the causes and come up with a solution. In this appendix an overview of the software, an explanation of their computation methods, the objectives of each model for this particular report and the coupling between the models is given.

The following software is used in this report:
- Unibest (Software: Appendix E.1, Modelling: Appendix F)
- SWAN (Software: Appendix E.2, Modelling: Appendix G)
- XBeach (Software: Appendix 0, Modelling: Appendix G)
- Delft3D (Software: Appendix E.4, Modelling: Appendix H)

E.1 Unibest

UNIBEST CL+ is designed to calculate longshore sediment transport and compute coastline changes as a function of time. These coastline changes are a consequence of gradients and therefore changes in longshore transport over the longshore distance. The UNIBEST LT tool calculates the longshore sediment transport and its distribution over the cross shore. UNIBEST CL predicts the changes in coastline and also takes into account the effect of the coastline changes on the longshore transport. In case of the Iberostar Varadero project, only UNIBEST LT is used to get insight in the contribution of longshore processes to the erosion problem. The coastline evolution is predicted with the help of more complex and advanced Delft3D and XBeach models.

UNIBEST LT

As stated before, UNIBEST LT is used to calculate the distribution of the longshore sediment transport over the cross-shore profile. The result of this calculation is a transport ray. To compute the transport ray, the following input can be specified:

- Orientation of the coastline.
- Profile height.
- Cross shore profile with characteristics.
- Transport parameters, the transport parameters which have to be specified depend on the chosen formula.
- Wave parameters.
- Wave and current conditions.

The output of UNIBEST LT consists of the transport ray, which is the distribution of longshore transport over the cross-shore profile as a function of the coastline angle, and optional, different graphs of for instance the evolution of the significant wave height, wave angle or sediment transport over the cross-shore profile. These plots can be made both for all wave conditions together, or for separate wave conditions. In terms of numbers, the main output is the sediment transport at the present coastline, per meter per year, and the shift of the coastline angle which is needed to reach equilibrium coastline angle.

E.2 SWAN

SwanOne is an easy to use software to transform offshore wave conditions to nearshore using the 1D- mode of the full SWAN model. It uses a Graphical User Interface to simplify the use of the SWAN model. The 1D-mode assumes that the offshore bathymetry can be represented by parallel bottom contours such that the bottom profile can be specified along one transect normal to the (average) coastline.

The SWAN model represents the wave field in terms of the 2D-frequency-direction wave spectrum which then evolves towards the coast including effects of wind, current, water level, depth, shoaling and refraction effects [29].

E.3 XBeach

XBeach is an open-source numerical model which is originally developed to simulate hydrodynamic and morphodynamic processes and impacts on sandy coasts with a domain size of kilometres and on the time scale of storms [16]. The model includes the hydrodynamic processes of short wave transformation (refraction, shoaling and breaking), long wave (infragravity wave) transformation (generation, propagation and dissipation), wave-induced setup and unsteady currents, as well as overwash and inundation.

The morphodynamic processes include bed load and suspended sediment transport, dune face avalanching, bed update and breaching [16]. Therefore it is perfectly suitable to simulate erosion during storm conditions (cold fronts) and extreme conditions (hurricanes).

In this project XBeach is mainly used to investigate the cross-shore processes. The wave input of XBeach must contain of nearshore wave spectra. To convert our offshore wave data into the needed nearshore data, SwanOne and Delft3D-WAVE (standalone) are used.

SwanOne (1D) and Delft3D-WAVE (2D) are able to convert the deep-water wave spectrum into a nearshore wave spectrum that can be directly use as boundary input for XBeach. The model hereby accounts for relevant processes as refraction, dissipation and shoaling. For more information about Swan, see Appendix E.2.

E.4 Delft3D

Delft3D is a modelling framework for 3D computations developed by Deltares. It can carry out numerical modelling of flows, sediment transport, waves, water quality, morphological developments and ecology. The Delft3D framework is composed of several modules which can interact with each other [26]. The properties of the modules used during this project are described below.

Delft3D-FLOW

The two main modules are Delft3D-FLOW (hydrodynamic) and Delft3D-WAVE (waves).
Delft3D-FLOW is a multi-dimensional hydrodynamic simulation program that is capable of calculating non-steady flow and transport phenomena. These flows and transport result from tidal and meteorological input given by the user. The full Navier-Stokes equations with the shallow water approximation are the base of the Delft3D-FLOW calculation. The computational grid used for Delft3D-FLOW is boundary-fitted and can be curvilinear.

During the computation Delft3D-FLOW will generate communication files. These files allow Delft3D-FLOW to communicate with the other Delft3D modules. The time-interval of the generation of this communication file is a variable and can be adjusted by the user. This way there is a dynamical exchange of the results between the modules, which help to make the model as realistic as possible.

Delft3D-WAVE

The Delft3D-WAVE module is capable of simulating the evolution of random, short-crested wind-generated waves in coastal waters. The module computes wave propagation, wave generation by wind, non-linear wave-wave interactions and dissipation.

At present the wave model SWAN is available in the wave module of Delft3D, see Appendix C.3 for more information about SWAN. Deltares has integrated the SWAN model into Delft3D and is applying SWAN in its research and consultancy projects.

Other Modules

RGFGRID is a program to generate grids suitable for Delft3D. In this project a curvilinear grid will be used, because curvilinear grids are better capable of varying in accuracy for certain areas than rectangular grids.

The generated grid can be imported to QUICKIN, a program capable of interpolating scattered data to depth-values at the grid points in the model.

For more accuracy around certain areas in the model, it is possible to generate boundary conditions from a course Delft3D model and use them for the open boundaries of a detailed Delft3D model. This offline generation of boundary conditions can be done by Delft3D-NESTHD.

E.5 Comparison between XBeach and Delft3D

Delft3D and XBeach are both mathematical models that can be used for hydrodynamic and morphological computations. However, there are differences between the calculation methods and included processes, so the models can be used for total different purposes.

The main differences can be best explained by Figure E- 1. During storm conditions, the high waves can damage the dunes and in that case avalanching will occur. The beach slope under the water line will change into a more gentle slope and eventually a new profile will be developed. These cross-shore changes will recover during normal conditions and if the time period between the extreme conditions is large enough, no net sediment losses are present.

For this project Delft3D is mainly used to compute the average sediment losses over longer periods of time, while XBeach is mainly used to simulate these short-term profile changes.

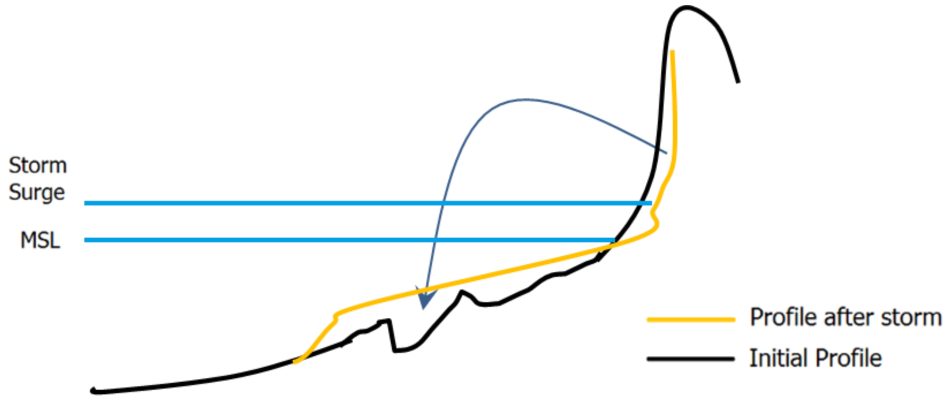

Figure E- 1 Beach profile after storm conditions

The differences in general computation methods are summarized in Table E- 1, according to Delgado (2012) [27]. The differences in cross-shore processes are described in Table E- 2. Additional to these differences, the relative importance for each process is expressed in a number (1: relatively not import, 4: relatively very important) for respectively onshore, offshore and bar behaviour.

XBeach	Delft3D
Wave envelope and long waves modelled in time domain.	Short waves modelled in frequency domain.
Not suitable for wind input	Wind input can be given
Non-stationary	Stationary
Formulation for longshore transport are similar	
Differences in formulation for cross-shore transport are shown in Table E- 2	

Table E- 1 General comparison XBeach and Delft3D

Process	Relative Importance			Delft3D	XBeach
	Onshore	Offshore	Bars		
Stokes' drift	1	-	1	No	Yes
Return flow	-	4	4	No (hydrodynamics only)	Yes
Streaming	1	-	1	Yes (in bed load)	No
Wave asymmetry	3	-	3	No	Yes (in suspended load)
Wave skewness	4	-	4	Yes (in bed load)	Yes (in suspended load)
In- and Exfiltration	1	1	1	No	No (hydrodynamics only)
Gravity	-	2	3	Yes (correction of bed load transport)	Yes (correction of equilibrium concentration)
Turbulence	2	2	3	No	No
Wind stress	1	1	1	No*	No*
Setting velocity	1	1	1	No**	No**
Bed forms	1	1	2	Yes (predictor)	Limited (initial conditions only)
Long waves	1	4	4	No	Yes
Wave roller	-	-	3	Limited (not convenient)	Yes
3D effects	-	-	2	Limited (longshore current and wind only)	Yes
* A wind field can be added but a 3D model would be required to model the cross-shore recirculation; longshore flow forcing possible					
** No intra-wave lag effects, only underloading / overloading of suspended sediment					

Table E- 2 Differences in cross-shore processes for XBeach and Delft3D [27]

From Table E- 2 it can be seen that XBeach is better capable of representing the bar behaviour due to cross-shore processes. To show this in a more practical way, two identical heavy storms are simulated with respectively XBeach and Delft3D, see respectively Figure E- 2 and Figure E- 3.

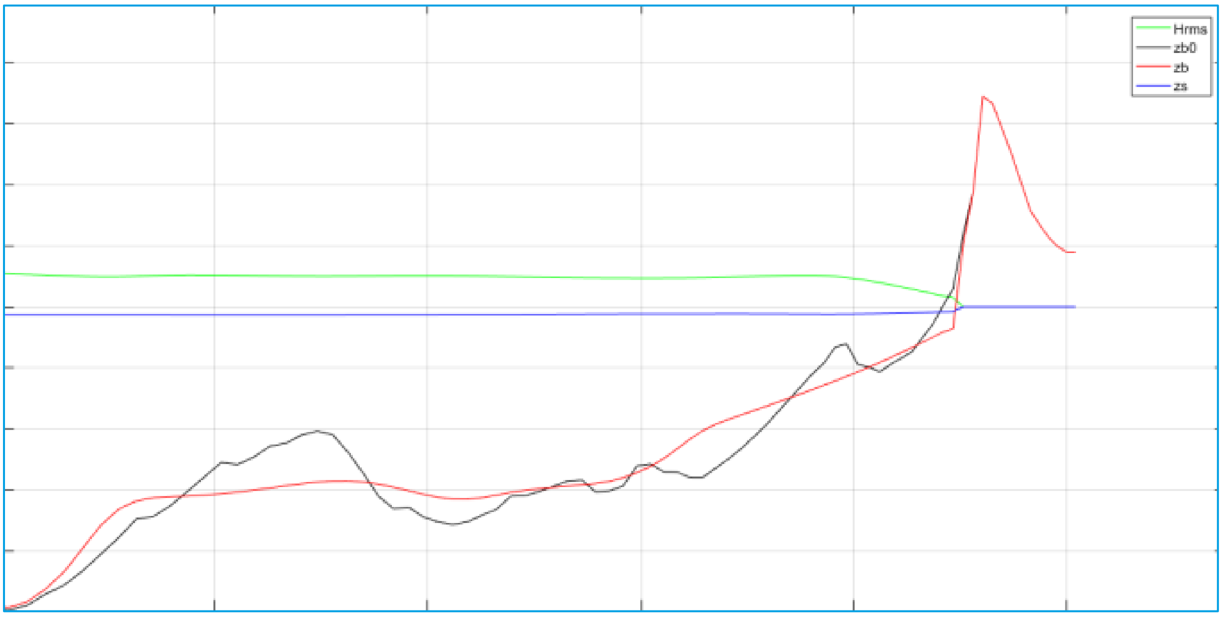

Figure E- 2 Heavy storm modelled with XBeach

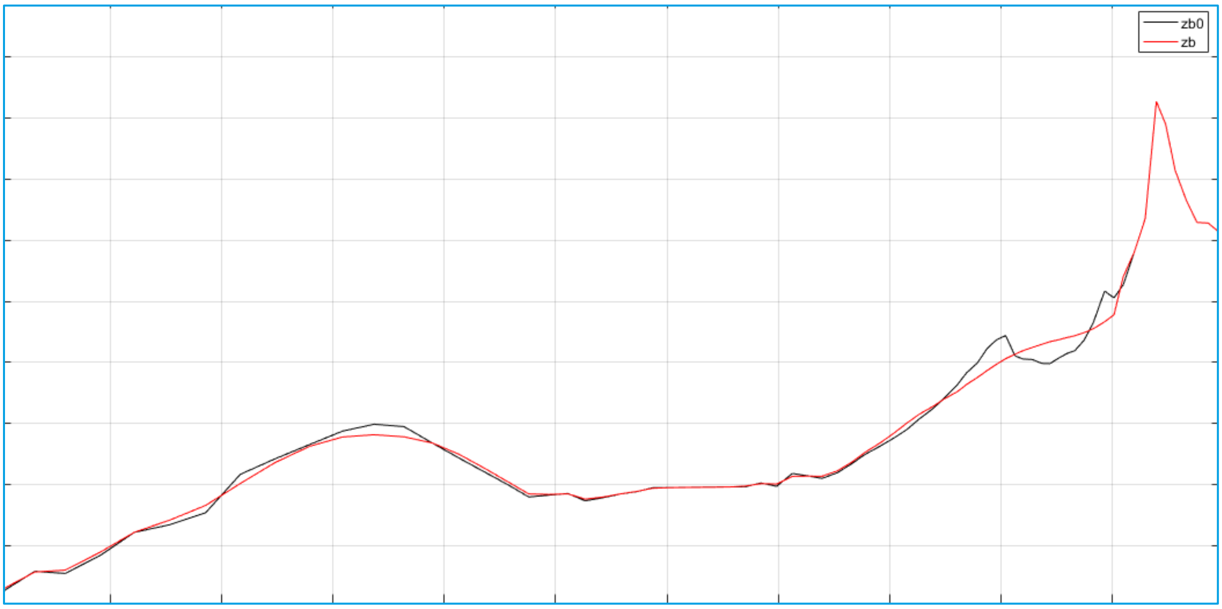

Figure E- 3 Heavy storm modelled with Delft3D

In comparison with Figure E- 1 it can be observed that XBeach is indeed better of simulation the short-term processes. Dune avalanching is taken into account, while the Delft3D model is not totally capable of capturing that. Also, the bar behaviour differs between the two models, which was already concluded from Table E- 2.

F. Modelling with Unibest

In Appendix E.1 the characteristics of the Unibest LT software are described. In this appendix, all the characteristics of the Unibest LT set-up are further specified. Also, a sensitivity analysis is made to evaluate the model results and check the performance of the model.

F.1 Set up

Coastline orientation and profile height

The first things that have to be specified are the coastline orientation and profile height. In our case, the profile height is set on 10 meter, which means that an erodible layer of 10 meters depth is present at the beach. It turns out that results do not change whether the profile height is equal to 1 meter or to 10 meters. The coastline orientation is set on 330° N for the western boundary or 334° N for the eastern boundary, which are the mean orientations of the coastline east and west of the Iberostar hotel section.

Cross shore profile

In order to make the beach profile, a cross section of the bathymetry in front of the Iberostar hotel is made (see Appendix C). This profile is averaged for the Unibest LT model, because the goal of the model is to get insight in the basis longshore transport and not to see the evolution of the cross-shore profile as a consequence of for instance waves. For that last purpose, the XBeach model is used with non-averaged cross shore profiles.

In Figure F- 1, the cross-shore profile used in Unibest LT is presented. The grid size is set on 4 meter. The dynamic boundary and truncation transport line are both set at the end of the profile. The location of the truncation transport line is in model practice often equal to location of the dynamic boundary, and so it is in this case. The location of the dynamic boundary depends on the significant wave height of the incoming waves according to the following relation (Hallermeier, 1981). The computed d_c is the critical depth, after which the waves no longer have significant influence on the bottom profile.

$$d_c = 1.6 * H_s$$

With the largest H_s in the wave input equal to approximately 3 meter, d_c is equal to 4.8 meter. For the computations, the dynamic boundary is set on the final data point, which is at a depth of 5.5 meter.

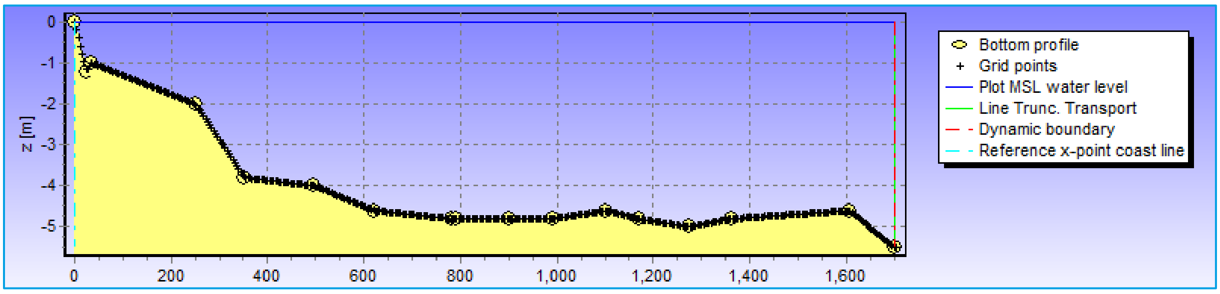

Figure F- 1 Bottom profile Unibest

Transport parameters

Based on the chosen transport formula, several transport parameters have to be specified. The comparison of the different transport formulae can be found in Appendix F.3. For the computation, the Bijker (1967, 1971) and Van Rijn (1992) formulae are used. In Table F- 1, all specified transport parameters for both formulae are presented, together with the source.

Transport parameter	-	Value	Source
Sediment diameter (D_{50})	(μm)	270	3.3.6
Sediment diameter (D_{90})	(μm)	740	3.3.6
Sediment density	(kg/m^3)	2700	3.3.6
Seawater density	(kg/m^3)	1022	3.3.6
Porosity	(-)	0.35	3.3.6
Sediment's fall velocity	(m/s)	0.041	3.3.6
Viscosity	(m^2/s)	0.866*10^6	3.3.4
Van Rijn correction factor	(-)	1	Default
Relative bottom transport layer thickness	(m)	0.03	Default
Bottom roughness, wave related	(m)	0.05	Default
Bottom roughness, current related	(m)	0.05	Default
Criterion deep water H_s/h	(-)	0.07	Default
Coefficient b deep water	(-)	2.0	Default
Criterion shallow water H_s/h	(-)	0.6	Default
Coefficient b shallow water	(-)	5.0	Default

Table F- 1 Overview transport parameters Unibest

Wave parameters

Besides the transport parameters, also wave parameters have to be specified. For the wave parameters, the default file is used with the bottom friction f_w (-) set on 0.01 instead of zero.

This value for bottom friction was also used in earlier reports, in which Unibest was used to compute erosion around the Hicacos peninsula, for instance Varadero (2003) [28].

Wave parameter	-	Value	Source
Coefficient for wave breaking γ	(-)	0.8	Default
Coefficient for wave breaking α	(-)	1.0	Default
Coefficient for bottom friction f_w	(-)	0.01	Varadero (2003) [28]
Value of bottom roughness k_b	(m)	0.1	Default

Table F- 2 Overview wave parameters Unibest

Wave current

In this part of the Unibest LT model, the wave scenario has to be specified. As explained in the wave reduction analysis (Appendix D.2), as starting point an offshore wave climate divided in directional bins of 22.5 degrees and wave height bins of 0.5 meter is used. This offshore wave climate is transformed into nearshore conditions and used as input for the Unibest LT model. The scenario duration of this wave scenario is 121.6 days (total year duration is 365 days).

Next to the wave scenario, also a wave current interaction model has to be specified. The default wave current interaction model is used, which is the Linear Interaction formula. Tidal information is not specified, because for sediment transport, tidal velocities are negligible compared to the flow velocities due to the waves. Wind driven currents are not used in the model.

F.2 Sensitivity analysis

To check the influence of all different specified parameters, a sensitivity analysis is performed for both transport formulae. For each parameter, a model run is executed in which the value of the relevant parameter is changed.

The results of these runs are compared with the main result to investigate the sensitivity of the model for this parameter. All results are presented in Table F- 3 for the Bijker formula, and in Table F- 4 for the Van Rijn formula. If the model turns out to be very sensitive for a certain parameter, the performance of the model is insufficient.

Bijker Parameter	-	Initial value	New value	Transport 330° k(m³)/year/m	Equilibrium angle shift (°)
Reference situation	**-**	**-**	**-**	**-18.777**	**-4.259**
Grid size	(m)	4	2	-19.260	-4.3027
Dynamic and truncation transport boundary	(m)	1700	1300	-20.161	-5.4673
Truncation transport boundary	(m)	1700	1300	-20.118	-5.8590
Wave current interaction	(-)	Linear interaction	Bijker	-6.496	-3.5858
Sediment density	(kg/m³)	2700	2600	-19.377	-4.295
Seawater density	(kg/m³)	1022	1025	-18.821	-4.2618
Shallow water coefficient b	(-)	5.0	4.0	-15.704	-4.3039
Shallow water criterion	(-)	0.6	0.8	-16.656	-4.3561
Deep water coefficient b	(-)	2.0	1.0	-17.159	-4.1597
Deep water criterion	(-)	0.07	0.1	-18.471	-4.2424
Sediment's fall velocity	(m/s)	0.041	0.02	-51.423	-3.4194
Sediment's fall velocity	(m/s)	0.041	0.038	-20.705	-4.1261
Bottom roughness (transport related)	(m)	0.05	0.025	-12.433	-4.0385
D_{50}	(μm)	270	310	-20.067	-4.1712
D_{90}	(μm)	740	600	-18.488	-4.2382
Porosity	(-)	0.35	0.4	-18.777	-4.2590
Bottom friction f_w	(-)	0.01	0.0	-20.966	-4.4177
Bottom roughness (wave related)	(m)	0.1	0.05	-24.274	-4.3721
Bottom friction f_w	(-)	0.01	0.03	-15.577	-4.0203

Table F- 3 Sensitivity analysis Bijker

Especially the behaviour of the model in case of increasing the grain size diameter is very surprising. For increasing grain sizes, the transport increases while one would expect a decrease in transport. Unfortunately, we are not able to explain this behaviour, however, in all reference models the behaviour of the model is in the same way. Therefore we assume that this behaviour has no negative impact on the model results.

Next to the influence of the grain sizes, also the large influence on the wave current interaction model is remarkable. However, the results are closer to reality in case of using the default linear interaction model, therefore this model is used in the main computation.

Van Rijn Parameter	-	Initial value	New value	Transport 330° k(m^3)/year/m	Equilibrium angle shift (°)
Reference situation		**-**	**-**	**-8.509**	**-2.3204**
Grid size	(m)	4	2	-8.981	-2.3945
Dynamic and truncation transport boundary	(m)	1700	1300	-11.006	-4.0069
Truncation transport boundary	(m)	1700	1300	-10.854	-4.2791
Wave current interaction model	(-)	Linear interaction	Fredsoe	-2.472	-1.9075
Sediment density	(kg/m^3)	2700	2600	-8.933	-2.3252
Seawater density	(kg/m^3)	1022	1025	-8.574	-2.3212
Sediment's fall velocity	(m/s)	0.041	0.038	-9.496	-2.3462
Bottom roughness (transport & current related)	(m)	0.05	0.1	-8.625	-2.3322
Bottom roughness (transport & wave related)	(m)	0.05	0.1	-17.959	-2.7312
Relative bottom transport layer thickness	(-)	0.03	0.025	-8.432	-2.2189
Viscosity	(*10^6)	0.866	1.0	-8.126	-2.3034
D_{50}	(μm)	270	310	-8.178	-2.3242
D_{90}	(μm)	740	600	-8.376	-2.3092
Porosity	(-)	0.35	0.4	-9.218	-2.3204
Bottom friction f_w	(-)	0.01	0.0	-13.119	-2.8840
Bottom roughness (wave related)	(m)	0.1	0.05	-12.982	-2.5301
Bottom friction f_w	(-)	0.01	0.03	-3.366	-1.2043

Table F- 4 Sensitivity analysis Van Rijn

Again the most remarkable result is the result in case of using a different wave current interaction model, in this case Fredsoe. The same reasoning as with the Bijker formula is made, from which is concluded that the linear wave interaction formula has to be used. The influence of friction parameters is larger in case of the van Rijn formula than in case of the Bijker formula, but still the results are according to the expectations. Decreasing the bottom friction increases the amount of longshore sediment transport, while increasing the influence of wave related roughness, increases the amount of sediment transport.

Conclusion sensitivity analysis

Except for the influence of the grain size diameter in case of using the Bijker formula, no surprising deviations in results are present in the tables, from which can be concluded that the model performs well for both the van Rijn as well as the Bijker transport formula.

F.3 Unibest transport formulae

When modelling sediment transport in Unibest LT, many different transport formulae can be used. To check which transport formula is best to use in this project situation, the four transport formulae which may be suitable for the project situation are compared. Only a simple comparison is made because the goal of the Unibest model is only to give insight in the causes of the erosion problem and not to quantitatively predict the evolution of the coastline.

For modelling the longshore sediment transport to get insight in the contribution of longshore sediment transport to the erosion problem, a lot of formulae can be used. The formulae are compared by comparing the longshore sediment transports at the relevant coastline angles (330° N and 334° N) and the sediment transport curve. All parameters are equal for each computation and the same as the parameters used in the final computations (see section F.1).

The formula with results closest to the reference value, a total loss at the Iberostar section of 19,890 m^3 per year, is used and evaluated in the final Unibest LT model. The results for the following five formulae are presented and discussed on the next pages.

- Soulsby and van Rijn
- Kamphuis
- Bijker
- CERC
- Van Rijn

It turns out that for both the van Rijn and the Bijker transport formulae, the computed erosional losses at the Iberostar Varadero section are in the right order of magnitude. Bijker is most often used in previous projects, while van Rijn is used in Unibest for the wave input reduction for the Delft3D model (see Appendix D.2). Therefore it is decided that both formulae will be used to investigate the contribution of erosion due to gradients in longshore transport as part of the total erosion.

Soulsby and van Rijn

In Figure F-2 it is clearly visible that the results with the Soulsby and van Rijn transport formula are not in line with the reference values. A net transport in eastern direction is expected, while a transport in western direction is computed. Next to the well-known parameters, also a calibration factor has to be specified. However, changing this calibration factor still not gives good results as it has no influence on the direction of the sediment transport, only on the quantities (see Figure F- 3 with calibration factor 0.6). Therefore, with only these test results, it already is clear that the Soulsby and van Rijn formula is not suitable for this project.

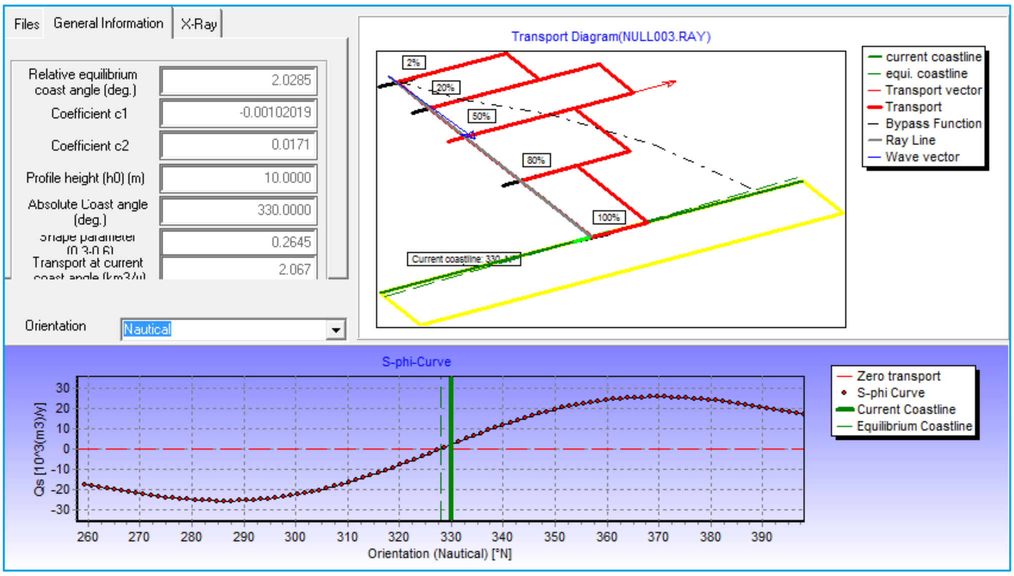

Figure F- 2 Longshore transport computed with Soulsby and van Rijn, for a calibration factor of 1.0

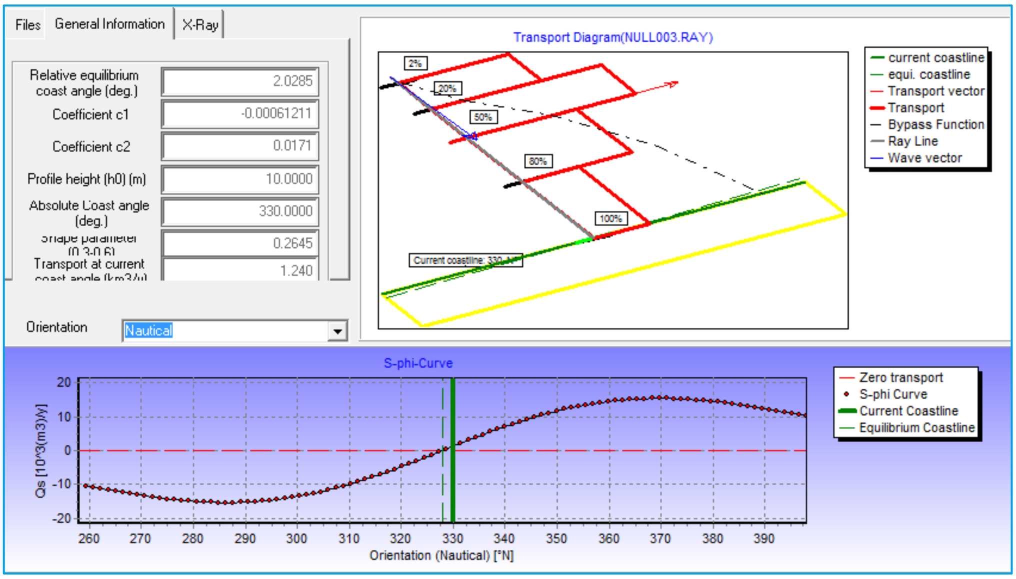

Figure F- 3 Longshore transport computed with Soulsby and van Rijn, for a calibration factor of 0.6

Kamphuis

Remarkable in the case of computing sediment transport with the Kamphuis formula is that the transport is located very close to the shore compared to the other formulas. This can be seen in Figure F-4 and Figure F-5. When the transports at the different coastline angles (330° N and 334° N) are compared, it turns out that according to Kamphuis, 2,000 m^3 would be gained per year. In reality the estimated volume change in the section is equal to a loss of approximately 20,000 m^3. With this difference in mind, it is concluded that the Kamphuis formula is not suitable for this situation.

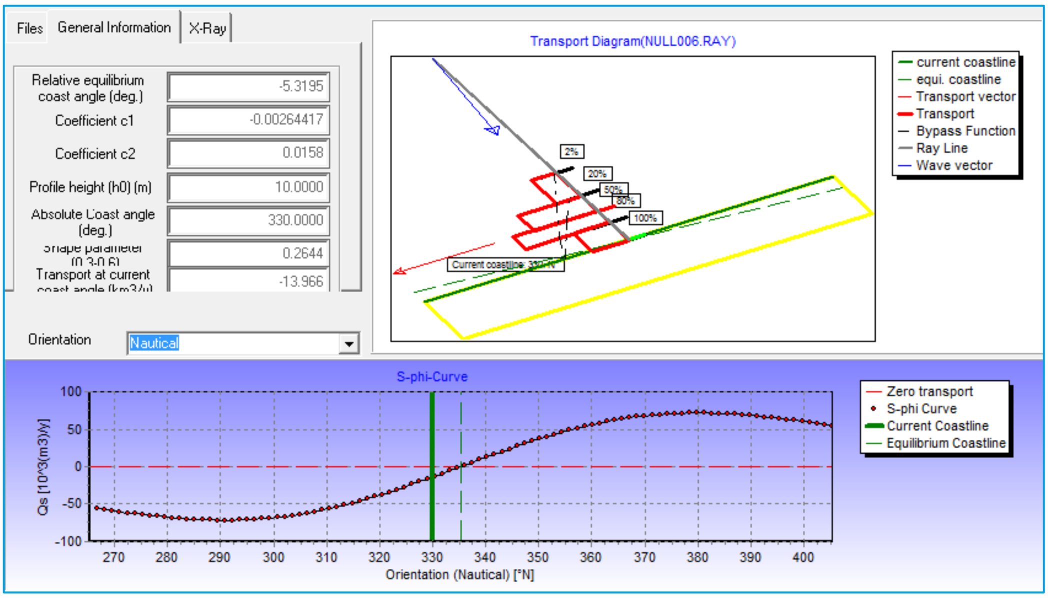

Figure F- 4 Longshore sediment transport for the Kamphuis formula, at a coastline angle of 330° N

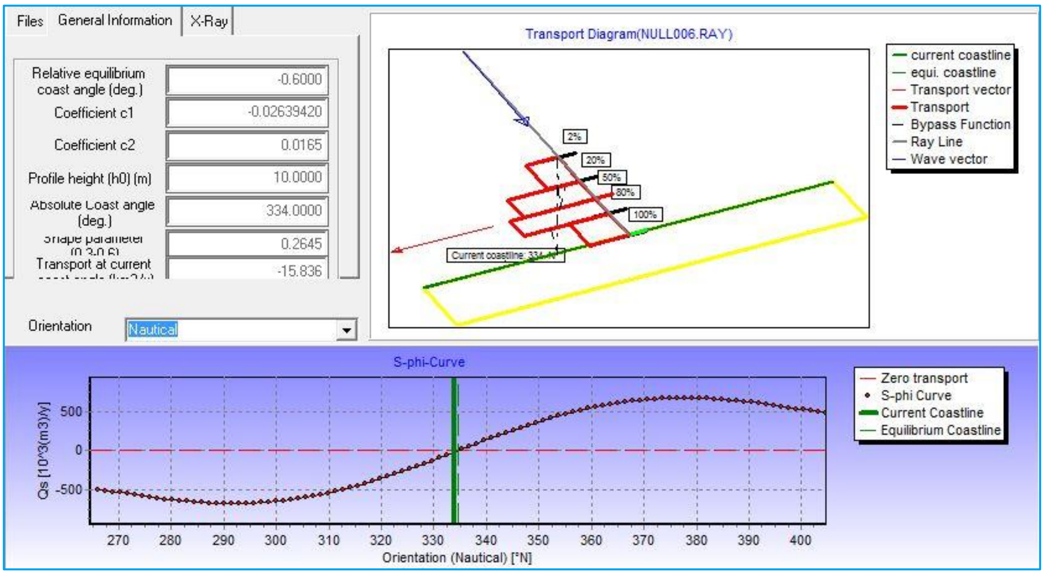

Figure F- 5 Longshore sediment transport for the Kamphuis formula, at a coastline angle of 334° N

Bijker

In case of transport computed with the Bijker (1967, 1971) formula, the value erosional loss in the section between the boundaries is very close to the reference value, namely 17,643 m^3/year where 20,000 m^3/year is expected. The results can be found in Figure F-6 and Figure F-7. This is according to the expectations, as in all available previous research, the Bijker formula is used. For a coastline angle of 334° N, the sediment transport curve shows that nearly a shift from westward to eastward sediment transport is made. For a coastline angle of 335° N, for instance the sediment transport will be in western direction.

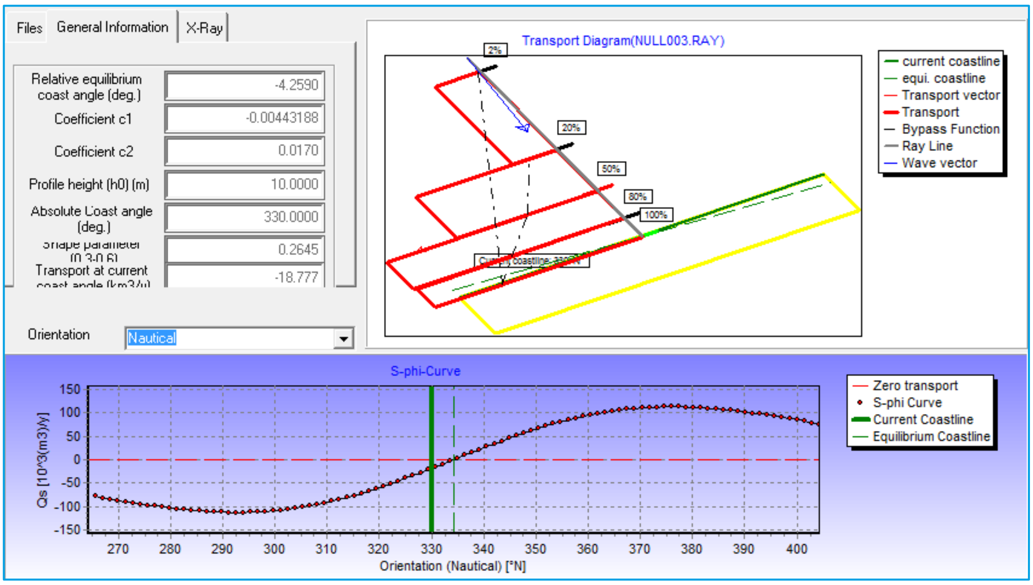

Figure F- 6 Longshore sediment transport for the Bijker formula, at a coastline angle of 330° N

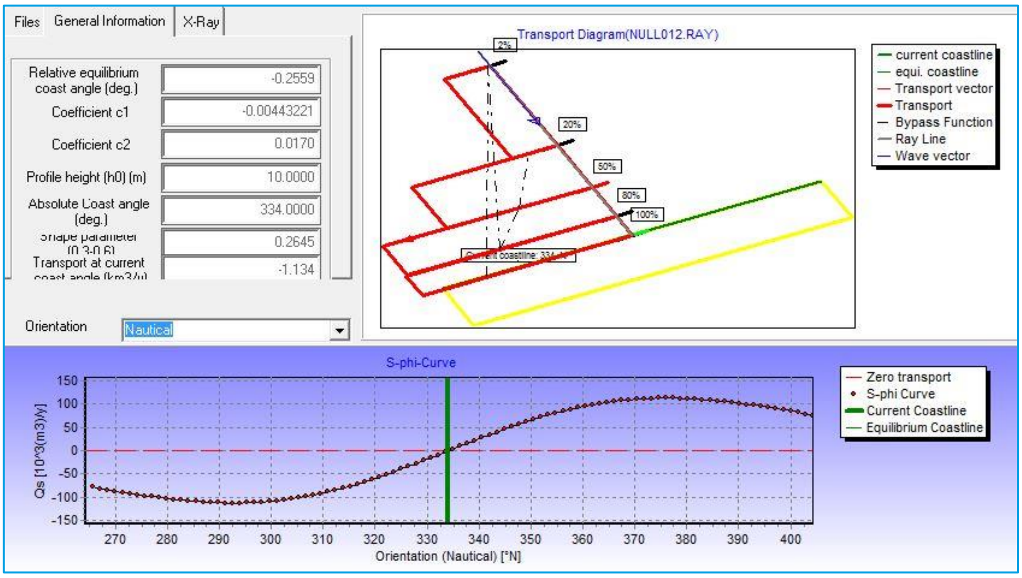

Figure F- 7 Longshore sediment transport for the Bijker formula, at a coastline angle of 334° N

CERC

The CERC formula (1984) is a basic formula for sediment transport, developed by the US Army Corps of Engineers. This formula is especially suitable for quick computations, but gives very different results for different values of the calibration factor which is in the formula. Therefore, for reliable results, this parameter has to be calibrated very extensively. For the figures below, the factor is set on default, which is 0.025. For the coastline angle of 330° N the computed longshore sediment transport is equal to -120,738 m^3/year, while the transport for the coastline angle of 334° N is equal to -15,836 m^3/year.

Together, this would lead to an erosional loss at the Iberostar section of 104,902 m^3/year, which is more than 5 times the reference value. Changing the calibration factor will lead to a loss closer to the reference value, but gives no insight in what happens in reality. Therefore it is preferred to work with a formula which gives comparable results without the use of a calibration factor. The results can be found in Figure F-8 and Figure F-9.

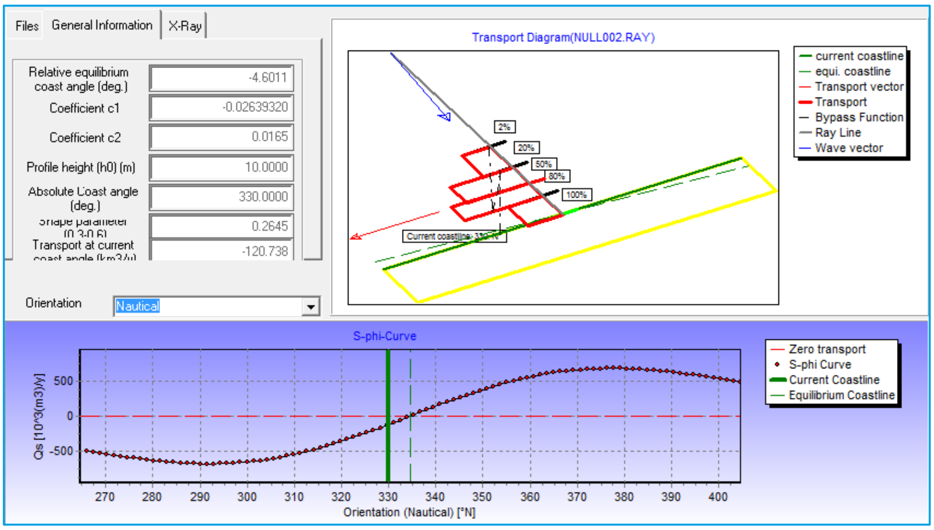

Figure F- 8 Longshore sediment transport for the CERC formula, at a coastline angle of 330° N

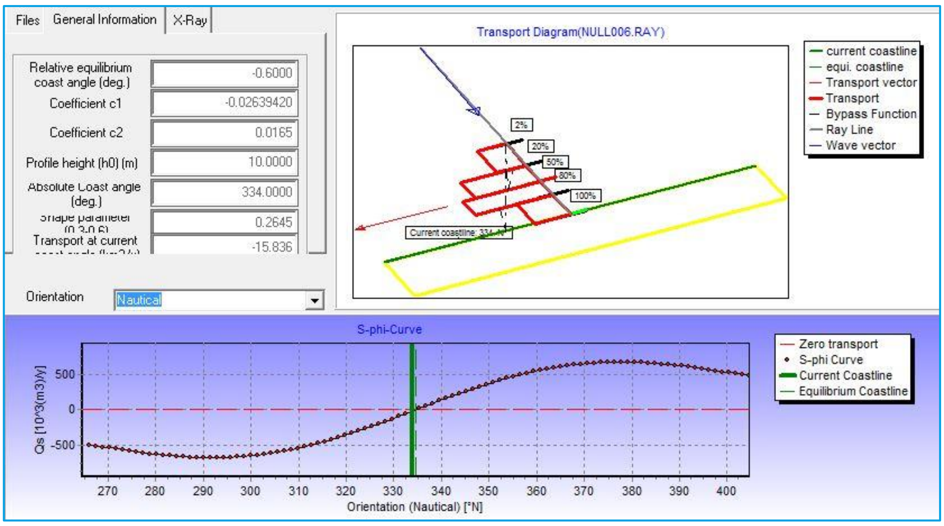

Figure F- 9 Longshore sediment transport for the CERC formula, at a coastline angle of 334° N

Van Rijn

Transport computed with the Van Rijn formula (1992) is relatively low compared to the transport computed with the other formulas. However, if the difference between the transport at 330° N and 334° N is investigated, it turns out the erosional loss at the Iberostar section in case of van Rijn would be estimated on 14,540 m^3/year, which is in the same order of magnitude as the reference value. At a coastline angle of 334° N, the transport is eastward directed, which at first sight seems to be strange. However, close to the headland, transport in eastern direction is expected as accretion can be found in the area close to the headland. The shift from westward to eastward transport is for the computations with the formula of van Rijn located around 334° N.

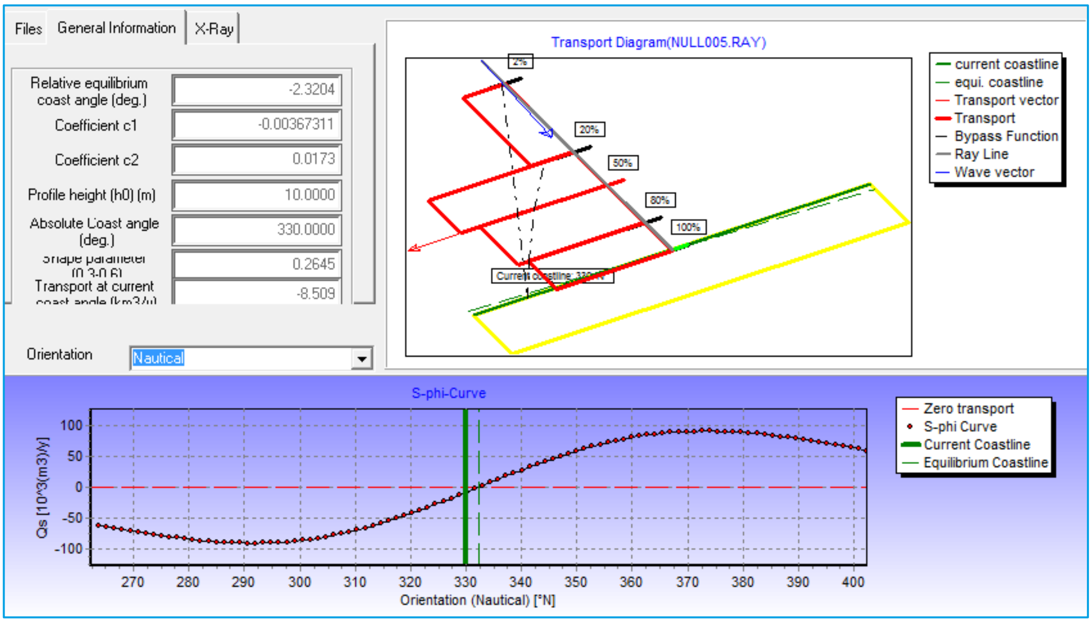

Figure F- 10 Longshore sediment transport for van Rijn formula, at a coastline angle of 330° N

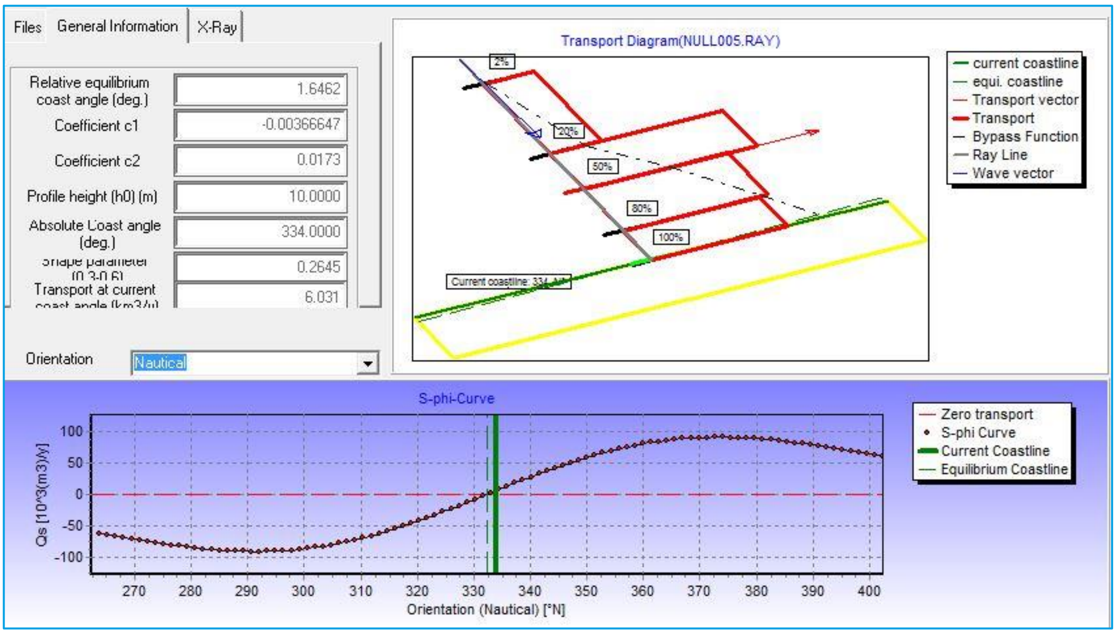

Figure F- 11 Longshore sediment transport for van Rijn formula, at a coastline angle of 334° N

G. Modelling with SWAN & XBeach

In this appendix extra information about the modelling with SwanOne, SWAN, XBeach1D and XBeach2D will be given, to complement the text in the main report.

G.1 SwanOne

For this project SwanOne is used to convert deep water wave conditions into nearshore wave conditions, as input for the XBeach1D model. In the following section the setup of the model is explained.

Bottom profile

To make an x,z-bottom profile some data is obtained from the general bathymetry data file (see Appendix C). At the location of the Iberostar hotel a perpendicular line with a certain band width is made in Excel to select useable data points. After removing false data points and points on the wrong side of the peninsula, a profile is obtained (see Figure G- 1). When inserting this generated profile in SwanOne it gave the profile shown in Figure 4-4, in the main report.

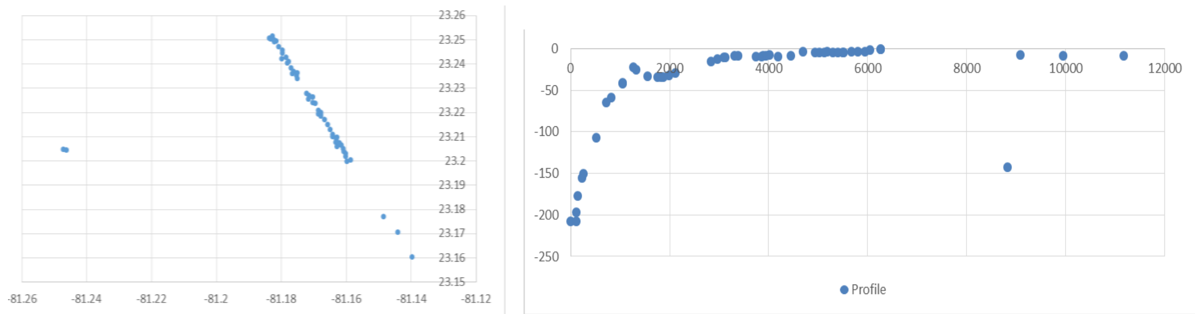

Figure G- 1 Selected points from data set for profile (left) and generated beach profile (right)

Wind- and wave parameters

To have some values for wind- and wave parameters (before the wave analysis was finished), the Master Thesis of Miguel Izquierdo Álvarez (2004) [17] is used to choose reasonable values for normal, storm and hurricane conditions in deep water in front of the Varadero coast. The input for SwanOne can be found in Table G-1.

Name	Wind speed (m/s)	Wind direction (°)	Hs (m)	Tp (s)	Wave angle (°)	Water level (m wrt MSL)
Normal condition 1	7	25	1.5	8	25	0.35
Normal condition 2	7	25	0.5	8	25	0.35
Storm 1	13	0	3	8	0	0.35
Storm 2	13	0	3	8	315	0.35
Hurricane	25	25	4.5	11	25	1.35

Table G- 1 SwanOne wind- and wave input conditions

Example of results

The wave output at 10m water depth is as follows:

Name	Hs (m)	Tp (s)	Wave angle (°)
Normal condition 1	1.188	8.035	3.45
Normal condition 2	0.552	8.035	21
Storm 1	2.674	8.035	349.263
Storm 2	2.716	8.035	323.421
Hurricane	3.808	11.157	358.185

Table G- 2 SwanOne wave output at 10m water depth

G.2 XBeach1D

XBeach setup

To show the setup of the XBeach1D model, an example file of params.txt is added; the input file of XBeach which specifies all adjustable parameters (see Appendix L.1). Note that the lateral boundaries are by default specified as Neumann boundaries and the offshore and landside boundaries as weakly reflective absorbing-generating boundaries, also as default. There are much more parameters than specified here but they are run in default [16].

Post-processing

The Matlab file used for post-processing the results of the Kingsday version XBeach simulations is fairly similar to the one described in Appendix G.3 and showed in Appendix L.3. Instead of creating a cross-shore profile from the 2D grid, the input was already in 1D. The file creates two time-varying figures consisting H, z_{b0}, z_b and z_s in the first and sediment/erosion in the second figure. Furthermore it calculates the amount of erosion/sedimentation in m^3/m in the profile and what the advance/retreat of the shoreline is with respect to mean sea level.

Calibration

The calibration phase consists of a first look at the general behaviour, a sensitivity analysis on various parameters and a comparison of V21 and Kingsday version.

General behaviour

First there has been looked if the general behaviour of the model and the results were as expected. When running for 24 hours with the SwanOne conditions storm 1 and hurricane the following was obtained:

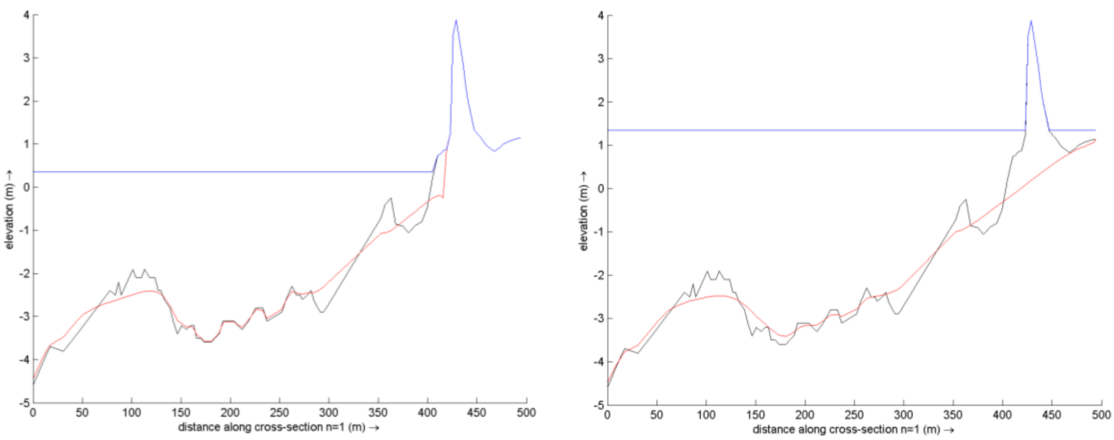

Figure G- 2 Results for Storm 1 and Hurricane

It can be seen during the storm quite some erosion occurs at the beach and at the first bar, in seems to be a realistic pattern. For the case of the hurricane, the water level is set much higher and the wave conditions are a lot stronger. The effect is that so much avalanching and over wash occurs that in the end the whole system is inundated. This seems to be a response to the conditions, but there has to be noticed that the coastal system is subjected to a wave field as strong as the maximum of hurricane Michelle but then for 24 hrs long. In a real hurricane the waves will not be this high for this long and normally no full inundation will happen. After full calibration this is not the case anymore as will be showed in the validation phase.

Also a lot of attention has been given to see if the final results of 24 hour modelling would correlate with the expected coastal response after that time. When specifying everything in morphological time this was the case, otherwise the forcing was 10 times shorter and the response much too low for a passing hurricane.

Sensitivity analysis
Hereafter various parameters were varied to see how sensitive the model was to changes in the parameters. This analysis was performed with the Storm 1 conditions with 24 hour simulation and as standard a morphological scale of 10, D_{50}=0.00027 meter, D_{90}=0.00074 meter, rt=7200 second, density=2650 kg/m^3, tidal water level = 0.35 meter and Chézy=55 $m^{1/2}$/s. Every time only one parameter in a time was changed.

Parameters that did not have a large effect were morstart, taper and random, so they are used on default. Furthermore the D_{90}, density, Coriolis latitude had little effect. So, the D90 is kept at 0.00074 meter, the density is changed to 2700 kg/m^3 for uniformity with the rest of the project and the latitude is set to 23 degrees.

Parameters that did have significant effect or are important were the D50, Chezy, rt, morfac and water level:

- D_{50}; no really different patterns occur but increasing the D50 reduced the erosion a bit and vice versa. Therefore the D50 is not changed, but it shows that nourishing with a different D50 can give a different coastal response.
- Chézy; the value for the bed friction has a considerable effect on the coastal response, not on the amount of erosion but more on where the most erosion occurs. Because a Chézy value of 68 is calculated, this value will be used instead of the default value of 55.
- rt; the value of rt is the time after which the generated time series is re-used and turned out to be rather sensitive. After correspondence with a developer of XBeach (Robert McCall) it was advised to specify a time series of jonswap spectra (using instat=jons_table) instead of just specifying just one spectrum. When using jons_table the parameter rt is bypassed so the sensitivity is no longer a problem, so this is done while validating.

- Morfac; the value of the morphological scale factor (varied between 1, 5 and 10) did not have a large effect in this storm 1 simulation, which is favourable for using morfac 10 to speed up the computations. But when simulating longer periods or stronger wave conditions the morfac parameters should be supervised.
- Waterlevel; the magnitude of the water level and/or tide can have a significant result on the coastal response. Therefore there has to be taken care specifying this parameter.

Finally the effect of the used XBeach version has been investigated. When switching from Quickplot to Matlab post-processing the output specification should be changed from 'netcdf' to the default 'fortran'. When testing this the written Matlab files gave no difference in outcome of the figures compared to Quickplot. When using all the final parameter values mentioned above and a realistic cold front (for characteristics see validation) the difference between the V21 and Kingsday version was significant, see Figure G- 3 and Figure G- 4.

The occurring difference is assumed to occur because of a better modelling close to the shore in the Kingsday version. Below 1m water depth there is hardly any difference, in contrast to around and at the beach. When modelling a realistic hurricane (for characteristics see validation) the difference around the waterline is hard to see. So, for a good modelling of cold fronts it seems to be important to use the more advanced Kingsday version of XBeach.

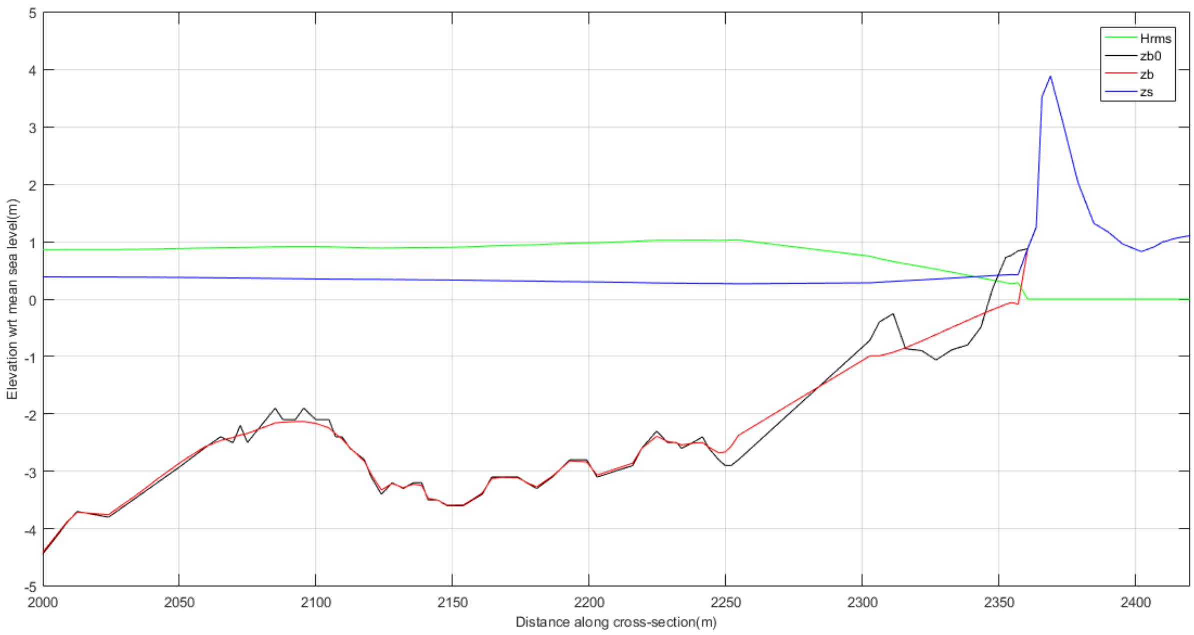

Figure G- 3 Storm result in V21 version

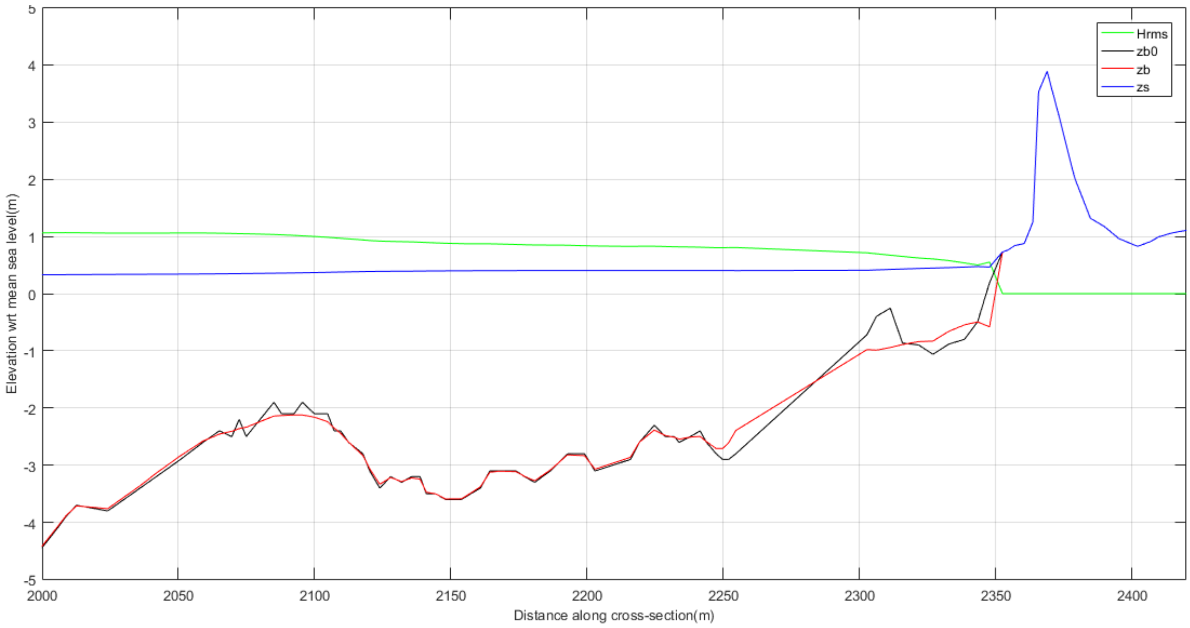

Figure G- 4 Storm result in Kingsday version

Validating

In Table G-3, Table G-4 and Table G-5 the input parameters for the validation phase are shown. Figure G-5, Figure G-6 and Figure G-7 show the results of the validation.

Hs (m)	Tp (s)	Wave angle (°)	Duration (s)
1.02	3.91	325	10800
1.19	4.3	315	10800
1.44	4.3	307	10800
1.7	5.21	306	10800
1.9	5.21	304	10800
1.99	5.73	303	10800
2.04	6.3	302	10800
2.09	6.3	301	10800
2.06	6.3	303	10800
1.97	6.93	306	10800
1.82	7.62	309	10800
1.67	7.62	311	10800
1.51	7.62	312	10800
1.38	7.62	312	10800
1.25	6.93	311	21600

Table G- 3 Real moderate storm from 04-01-1992

Hs (m)	Tp (s)	Wave angle (°)	Duration (s)		Hs (m)	Tp (s)	Wave angle (°)	Duration (s)
0.9922	3.8334	61	3600		3.82853	7.7616	26	3600
1.03842	4.3117	60	3600		3.84958	7.7616	22	3600
1.09275	4.3117	59	3600		3.84779	7.7616	18	3600
1.14441	4.3117	58	3600		3.80302	7.7616	15	3600
1.20337	4.8496	57	3600		3.7169	7.7616	11	3600
1.26111	4.8496	57	3600		3.5935	7.7616	7	3600
1.3137	4.8496	56	3600		3.43109	7.7616	3	3600
1.36867	4.8496	56	3600		3.20952	7.7616	0	3600
1.42477	4.8496	56	3600		3.00598	7.7616	356	3600
1.47335	4.8496	55	3600		2.80809	7.7616	351	3600
1.55346	4.8496	55	3600		2.61417	7.7616	348	3600
1.65724	5.1433	55	3600		2.42452	6.9007	343	3600
1.77251	5.4547	54	3600		2.25014	6.9007	340	3600
1.89446	5.4547	54	3600		2.08344	6.9007	336	3600
2.02145	5.4547	53	3600		1.93232	6.1352	332	3600
2.15231	5.4547	52	3600		1.79532	6.1352	329	3600
2.31167	5.4547	51	3600		1.67802	6.1352	327	3600
2.48105	6.1352	50	3600		1.56499	6.1352	325	3600
2.65714	6.1352	48	3600		1.46065	6.1352	323	3600
2.83571	6.1352	45	3600		1.36871	6.1352	321	3600
3.02859	6.5067	43	3600		1.27894	4.8496	319	3600
3.22582	6.9007	41	3600		1.20768	3.3727	318	3600
3.40456	7.3185	38	3600		1.15002	3.3727	317	3600
3.56646	7.3185	35	3600		1.09767	3.3727	316	3600
3.69985	7.3185	32	3600		1.0503	3.3727	316	3600
3.78444	7.3185	30	3600		1.01286	3.3727	315	3600

Table G- 4 Real hurricane Michelle wave conditions

Time	Water level	Time	Water level
0	0.28	93600	1.17
3600	0.18	97200	1.11
7200	0.1	100800	1.11
10800	0.05	104400	1.1
14400	0.07	108000	1
18000	0.17	111600	0.98
21600	0.28	115200	0.95
25200	0.36	118800	0.98

28800	0.42	122400	0.9
32400	0.48	126000	0.79
36000	0.47	129600	0.7
39600	0.44	133200	0.53
43200	0.37	136800	0.42
46800	0.31	140400	0.35
50400	0.32	144000	0.34
54000	0.35	147600	0.42
57600	0.42	151200	0.5
61200	0.53	154800	0.61
64800	0.7	158400	0.68
68400	0.79	162000	0.7
72000	0.9	165600	0.67
75600	0.98	169200	0.61
79200	1	172800	0.51
82800	1.1	176400	0.25
86400	1.1	180000	0.3
90000	1.11	183600	0.15

Table G- 5 Real hurricane Michelle water levels

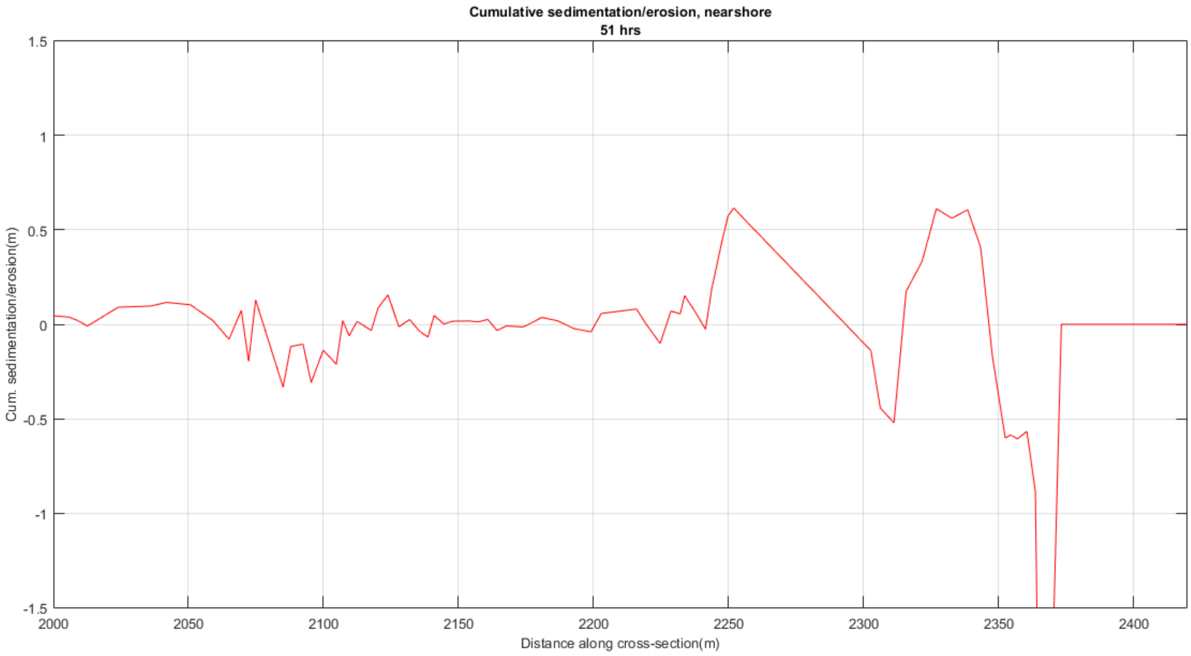

Figure G- 5 Cumulative sedimentation/erosion of hurricane Michelle. The peak at the dune: -3.2 m

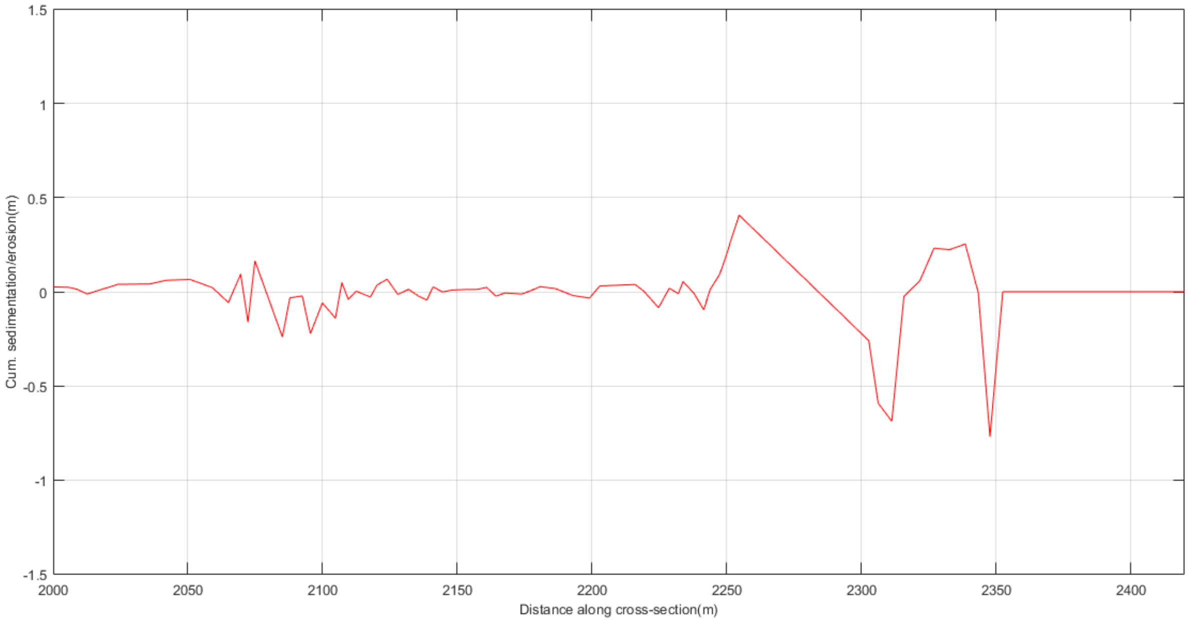

Figure G- 6 Cumulative sedimentation/erosion of the real storm conditions

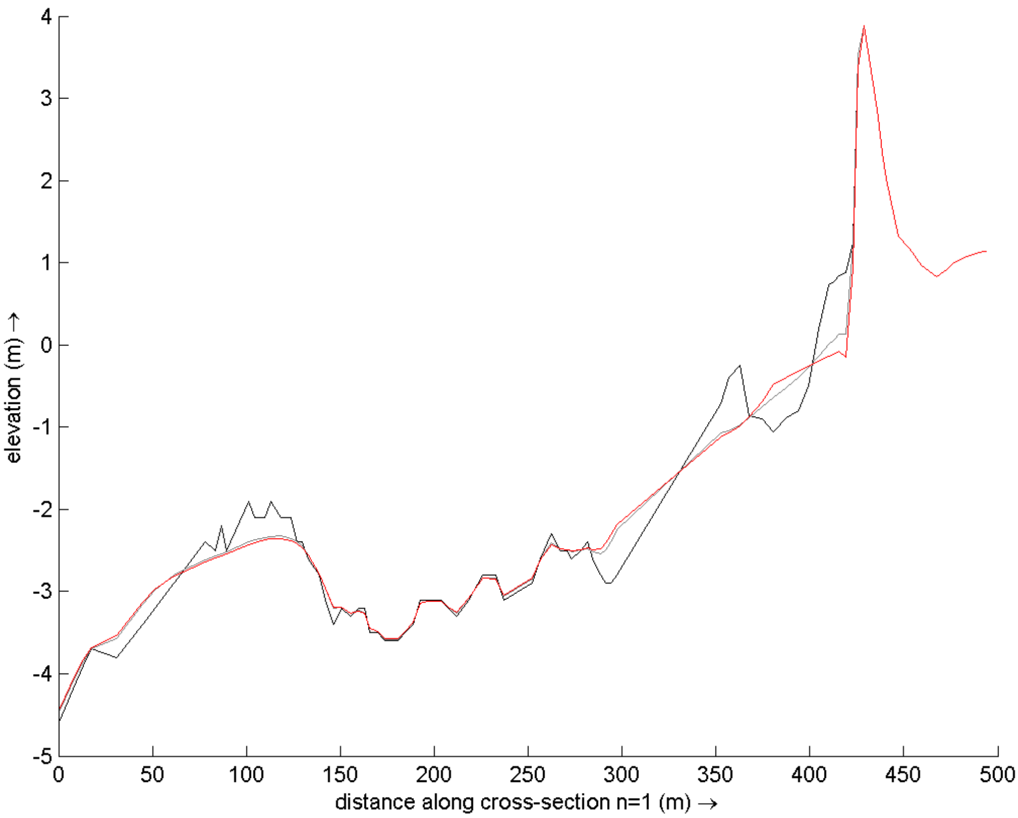

Figure G- 7 Modelling of cold front and normal conditions. Black is the original profile, grey the profile after 2 days of storm and red the profile at the end of the simulation

G.3 XBeach2D

XBeach setup

Same for the XBeach1D model, also the for the XBeach2D the params.txt file is added, see Appendix L.2. Changed parameters will be explained.

Post-processing

The MATLAB file (2016 version) used for post-processing the results of the XBeach 2D model is presented in Appendix L.3. Using this, future investigations can use the effort being put in post-processing our results. The code can be used for plotting cross-sections and sedimentation/erosion patterns as well as calculating sediment budgets, shoreline movements and beach widths. A similar code is also used for post-processing XBeach 1D and Delft3D results. Also other MATLAB codes are used for making the other plots presented in this report, but because they are more straight forward they are not presented here.

Validating 2D model

The results of the XBeach1D and XBeach2D model are shown in respectively Figure G- 8 and Figure G- 9.

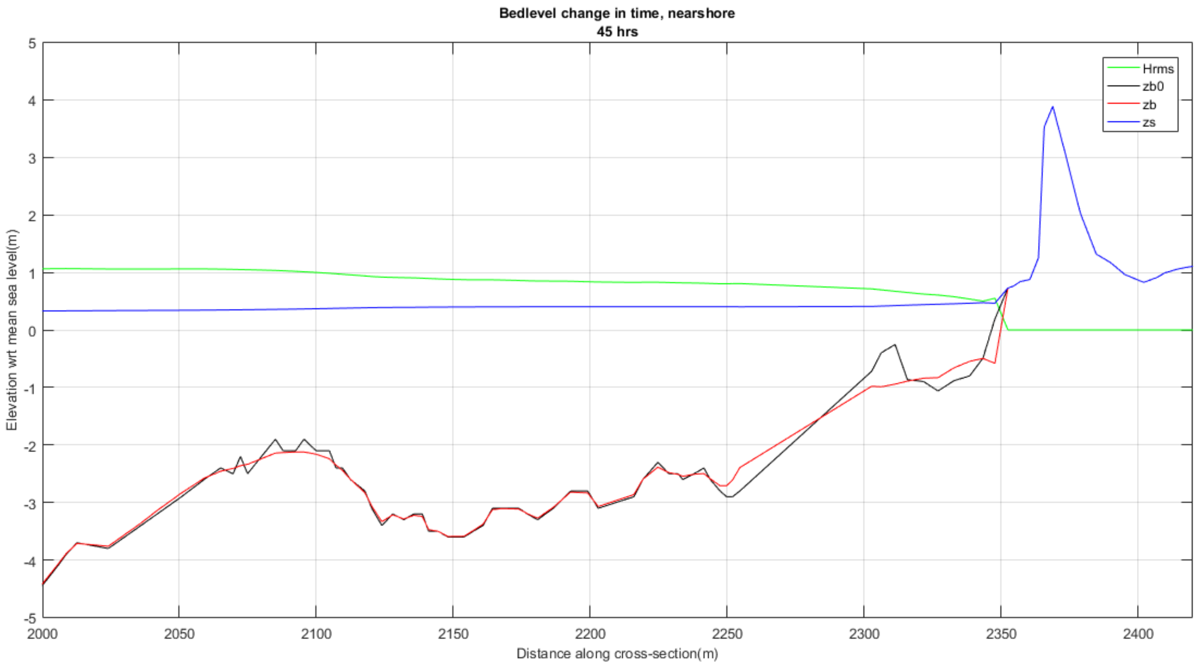

Figure G- 8 Realistic storm result in 1D

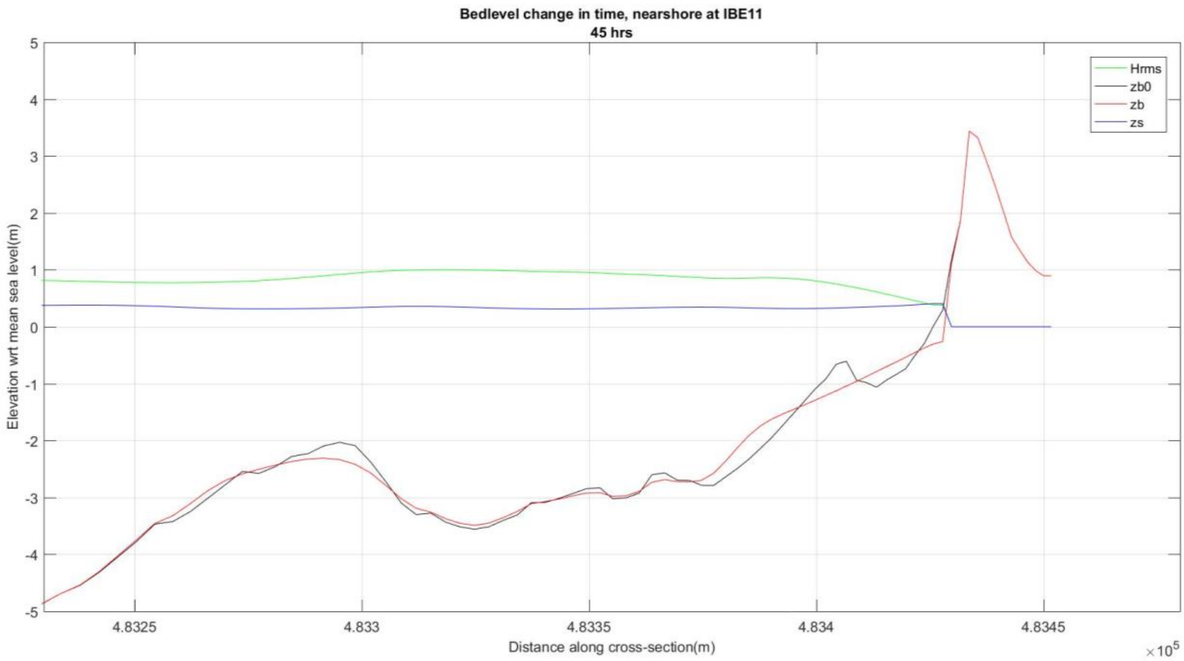

Figure G- 9 Realistic storm result in 2D, cross-section at IBE11 location

When the results are compared, the behaviour looks the same. The erosion at the beach and of both bars is captured. Also the amount of erosion and sedimentation looks the same. It should be noticed that the bottom file is not exactly the same because the interpolation of the bottom measurements into a bathymetry file by QUICKIN of Delft3D. Therefore the results of the models will also never be completely the same.

	Sedimentation (m^3/m)	Erosion (m^3/m)	Balance (m^3/m)
1D model	7.499	7.502	-0.0024
2D model	11.8375	11.1465	0.69093

Table G- 6 Validation results XBeach2D

A part of the extra erosion can be explained because of the slightly larger wave conditions. Furthermore looking at the 2D sedimentation/erosion in Figure 4-9 gives the idea that there is more erosion in front of the Iberostar hotel than in the rest of the modelled area. So because 2D effects occur, the erosion can be higher at a certain location than when modelling with a longshore uniform bathymetry as in the 1D case.

Zero state results

The cumulative sedimentation/erosion and cross-section figures of the various zero state runs are shown in the figures below. Specific calculated values for the zero state runs are given below in Table G- 7.

Storm from north west (cold front)

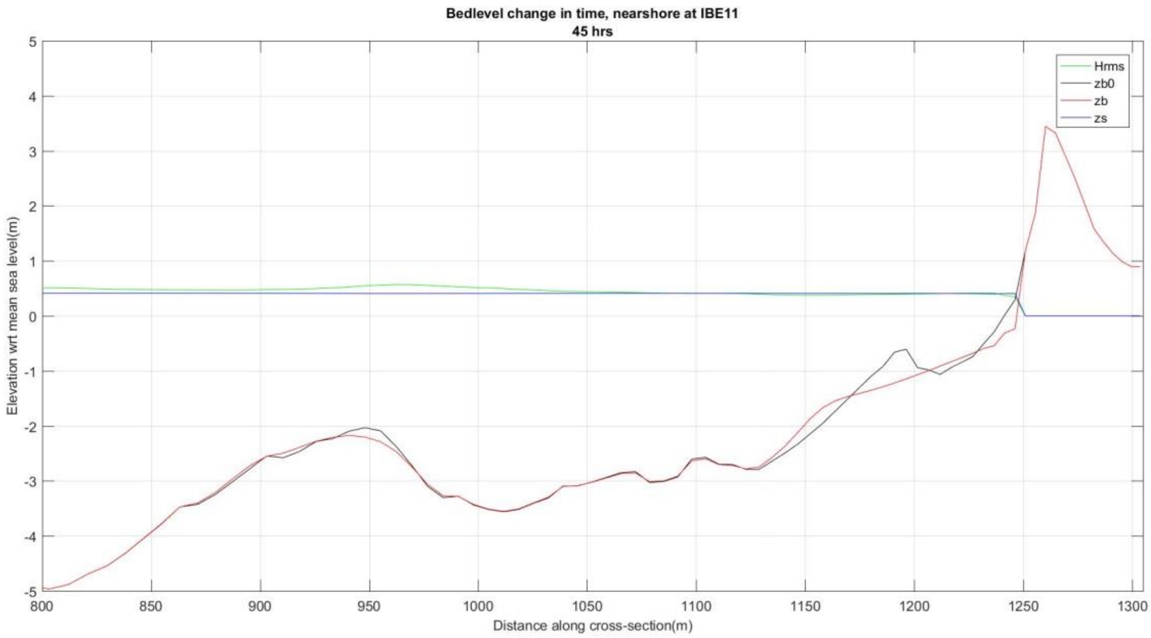

Figure G- 10 Weak Storm NW

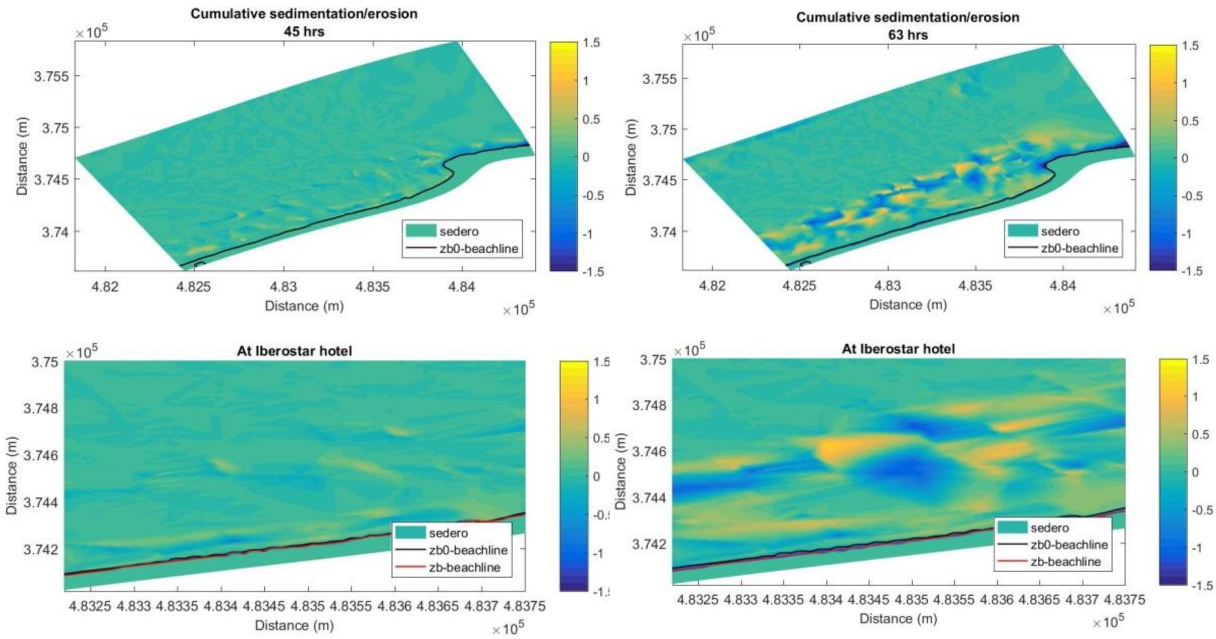

Figure G- 11 Storm NW, weak (left) and heavy (right)

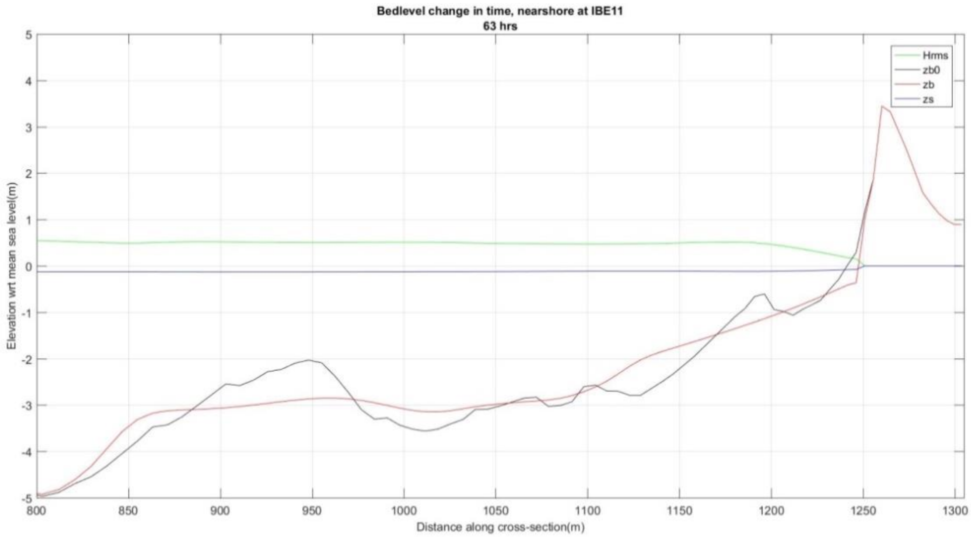

Figure G- 12 Heavy storm NW IBE11

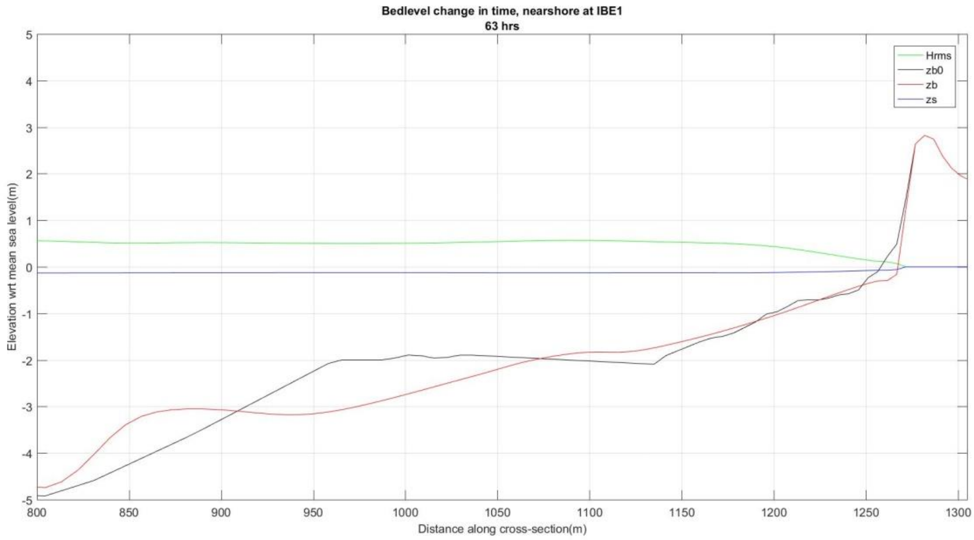

Figure G- 13 Heavy Storm NW IBE1

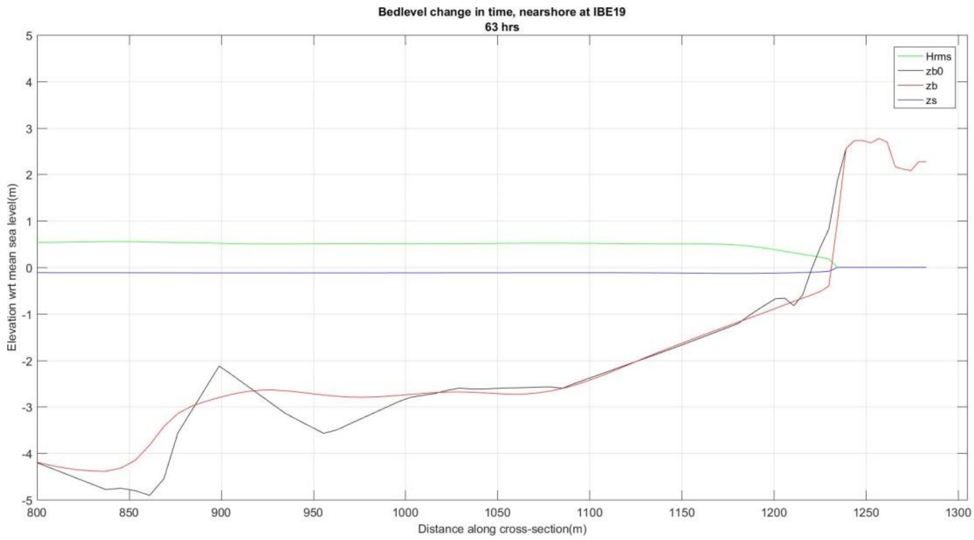

Figure G- 14 Heavy Storm NW IBE19

The locations IBE1, 11 and 19 are on the left, middle and right end of the Iberostar section, see Appendix C, Figure C- 2.

Storm from the North East

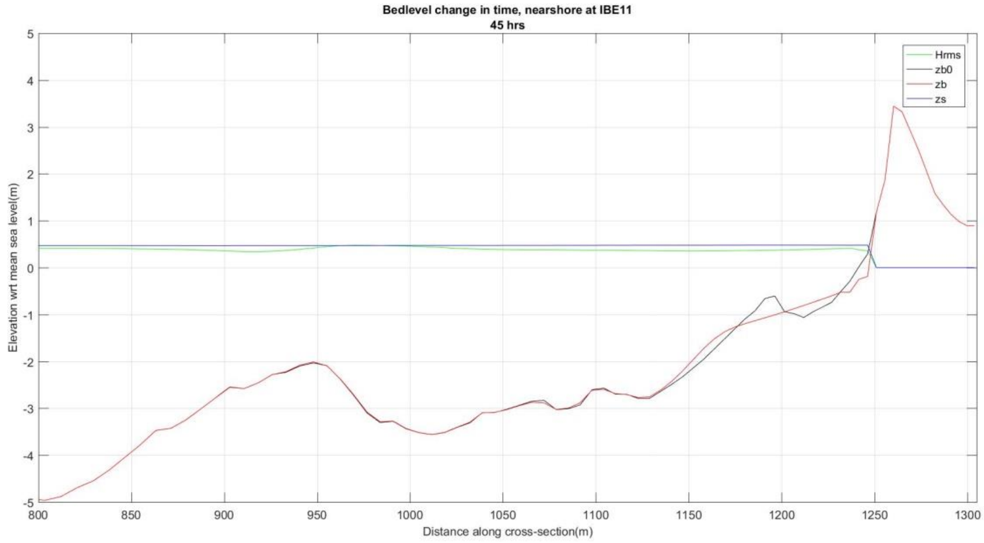

Figure G- 15 Weak Storm NE IBE11

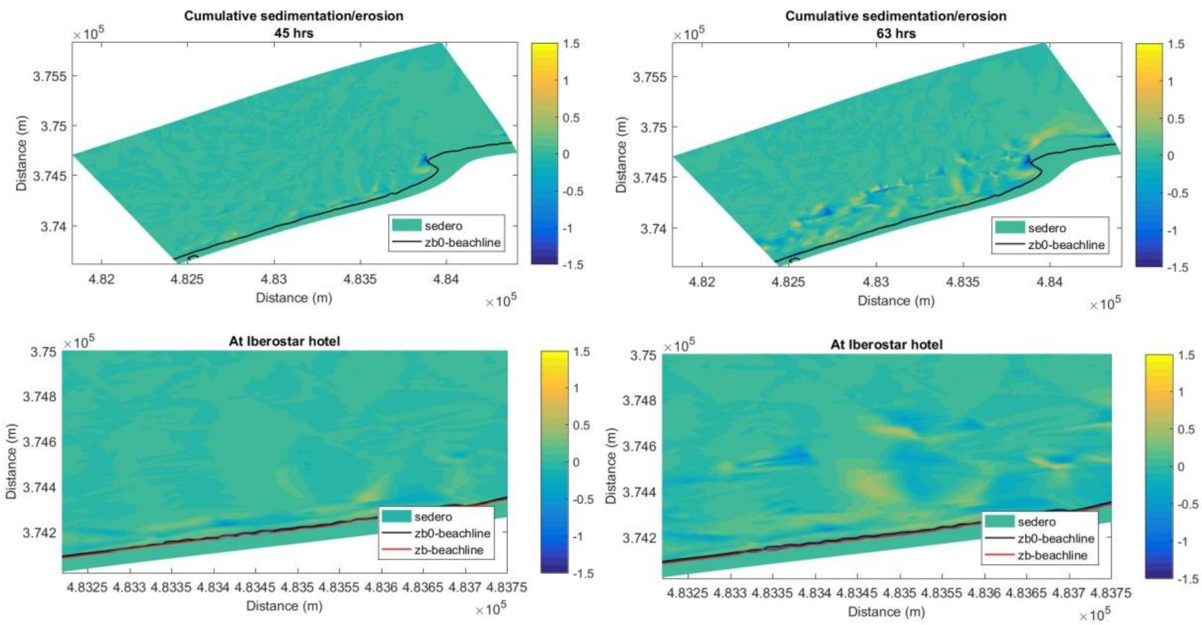

Figure G- 16 Storm north east, weak (left) and heavy (right)

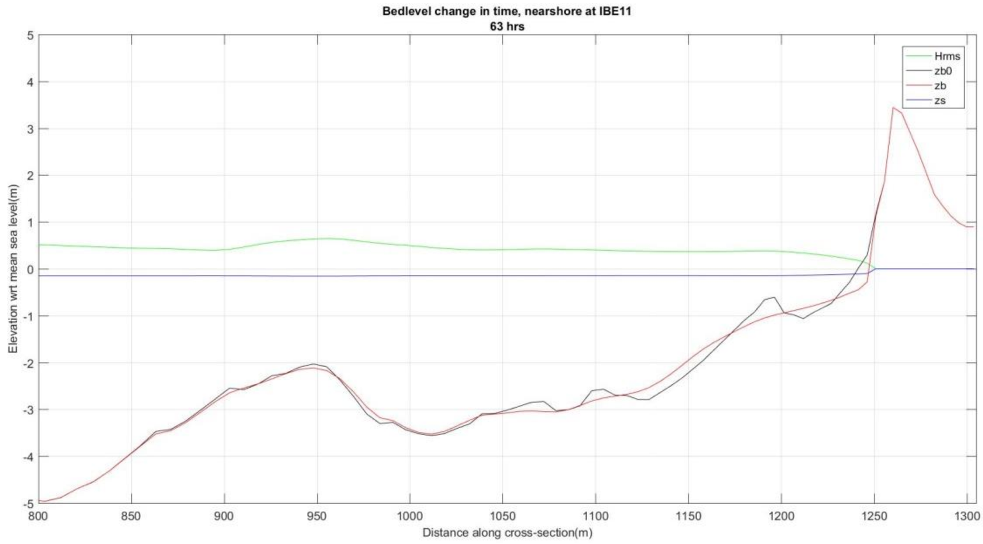

Figure G- 17 Heavy Storm NE IBE11

Hurricanes

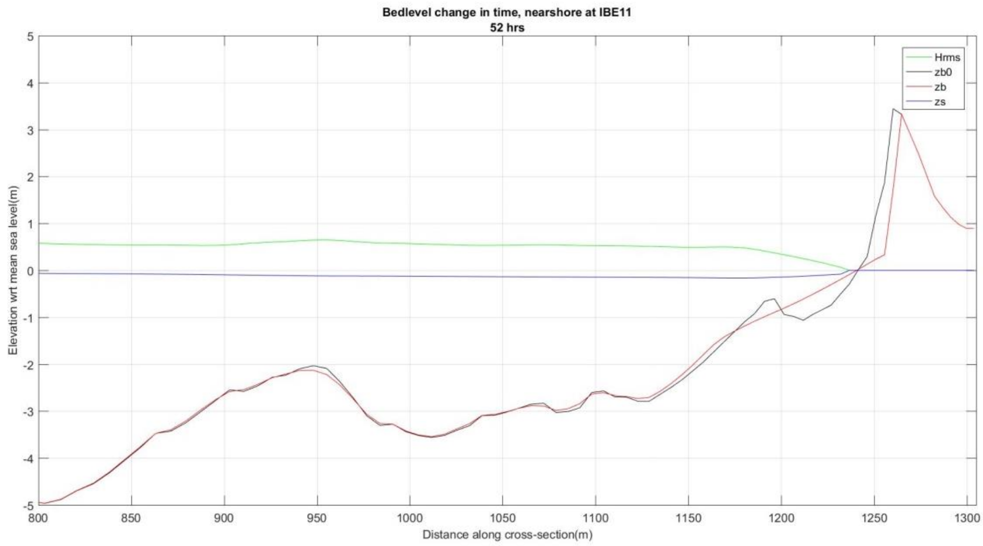

Figure G- 18 Hurricane Michelle IBE11

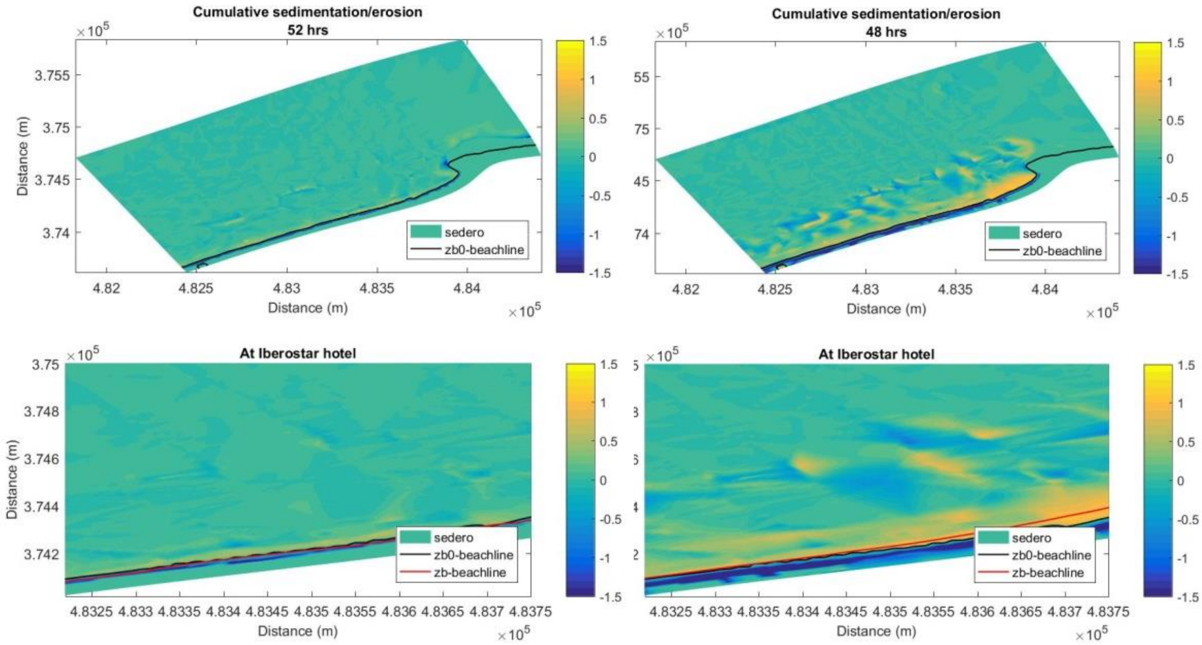

Figure G- 19 Hurricane Michelle (left) and Wilma (right)

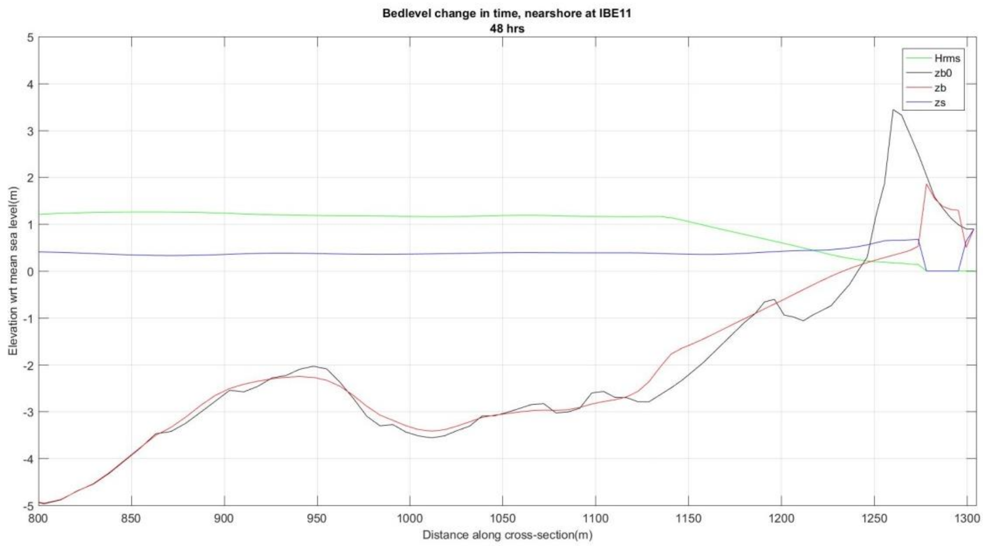

Figure G- 20 Hurricane Wilma IBE11

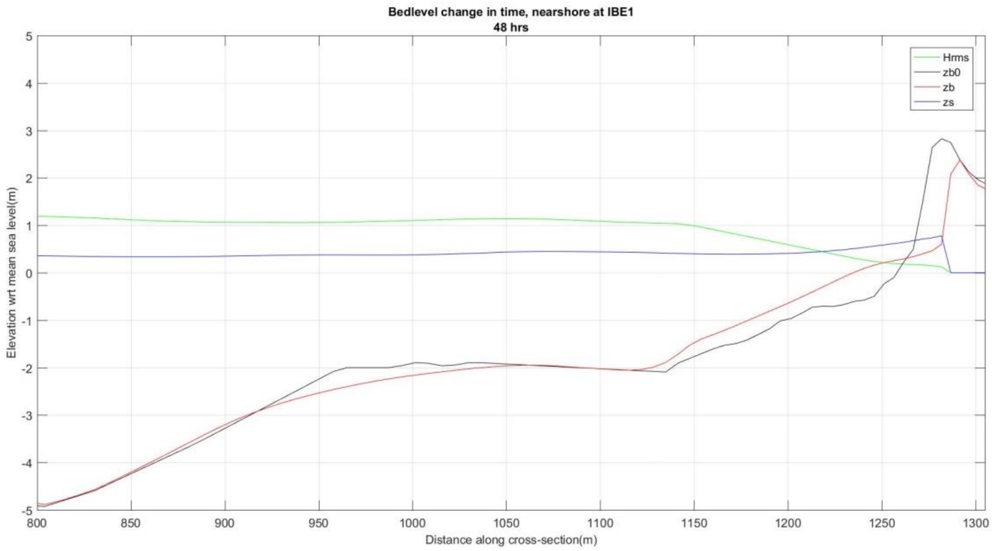

Figure G- 21 Hurricane Wilma IBE1

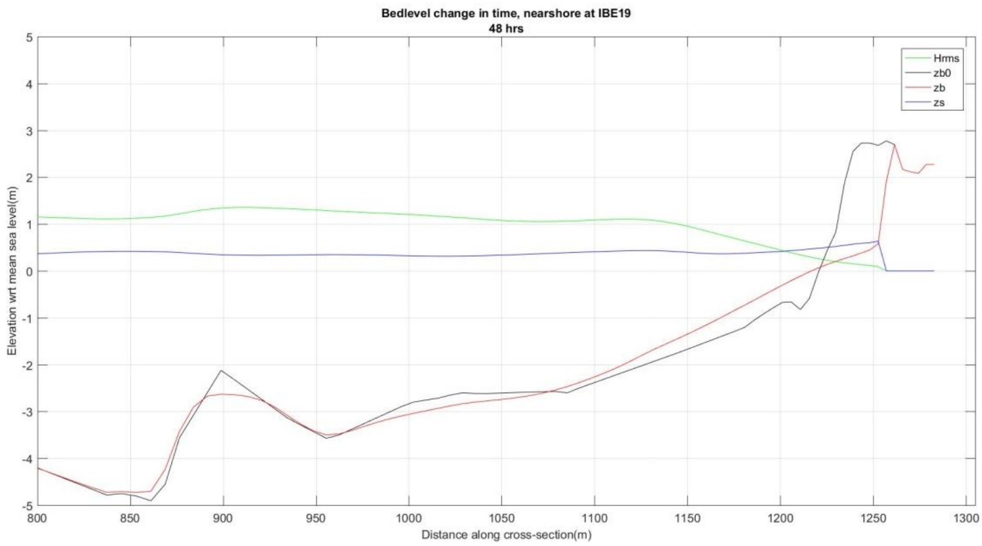

Figure G- 22 Hurricane Wilma IBE19

In the table below for every zero-state run and for three cross-sections multiple values are calculated. Per cross-section the amount of sedimentation, erosion and balance in m^3/m is calculated for that specific section. To look if there is sediment lost in offshore direction, the distance from the shoreline and the corresponding depth is calculated. In general, if there is sediment transport offshore out of the grid at all, the amount is very small. Next the shoreline retreat/advance is calculated, with the shoreline defined as the location where the water depth is zero meters with respect to Mean Sea Level. There after this calculation is extended to also calculate the width of the beach, hereby the end of the beach is defined to be at 1 meter above MSL. Using this, something can be said about the extension or shortage of the beach per zero state.

	Sedimentation(m3/m)	Erosion(m3/m)	Balance(m3/m)	No bed level change		Shoreline(m)	Beach_0 (m)	Beach_end (m)	Beach_dif (m)
ZS_CF_WE_NW				distance	depth				
IBE19	14.82	-10.63	4.19	1160.90	-4.76	-5.73	9.87	4.21	-5.66
IBE11	10.76	-19.08	-8.32	1211.24	-4.80	-5.77	8.82	3.48	-5.34
IBE1	2.67	-19.37	-16.71	1228.01	-5.29	-8.74	11.33	3.51	-7.82
Averaged	9.42	-16.36	-6.94	1200.05	-4.95	-6.75	10.01	3.73	-6.28
ZS_CF_ST_NW									
IBE19	78.32	-40.44	37.88	1190.81	-4.90	-10.38	9.87	3.47	-6.40
IBE11	73.29	-67.00	6.29	1211.24	-4.91	-6.23	8.82	3.56	-5.26
IBE1	87.34	-110.70	-23.35	1228.01	-5.23	-9.25	11.33	3.65	-7.68
Averaged	79.65	-72.71	6.94	1210.02	-5.01	-8.62	10.01	3.56	-6.45
ZS_CF_WE_NE									
IBE19	11.11	-6.73	4.38	1190.81	-4.78	-5.87	9.87	4.07	-5.80
IBE11	9.75	-9.57	0.18	378.24	-3.47	-5.63	8.82	3.59	-5.23
IBE1	6.60	-20.53	-13.93	377.06	-3.66	-3.80	11.33	8.16	-3.17
Averaged	9.15	-12.28	-3.12	648.70	-3.97	-5.10	10.01	5.27	-4.74
ZS_CF_ST_NE									
IBE19	16.23	-18.30	-2.06	1190.81	-4.79	-6.32	9.87	3.68	-6.20
IBE11	17.63	-22.51	-4.88	1211.24	-4.81	-5.91	8.82	3.47	-5.36
IBE1	11.24	-56.69	-45.45	1228.01	-5.30	-9.26	11.33	3.46	-7.87
Averaged	15.04	-32.50	-17.46	1210.02	-4.97	-7.16	10.01	3.54	-6.47
Michelle_ZS									
IBE19	27.12	-19.96	7.16	1190.81	-4.79	-9.33	9.87	3.48	-6.39
IBE11	18.24	-23.71	-5.47	1211.24	-4.81	0.65	8.82	17.33	8.51
IBE1	11.90	-10.35	1.56	1228.01	-5.30	-8.73	11.33	3.51	-7.82
Averaged	19.09	-18.01	1.08	1210.02	-4.97	-5.80	10.01	8.11	-1.90
Wilma_ZS									
IBE19	53.09	-79.70	-26.62	1190.81	-4.82	4.00	9.87	37.32	27.45
IBE11	64.21	-74.53	-10.31	1211.24	-4.89	7.74	8.82	41.88	33.05
IBE1	59.18	-59.18	0.00	1288.01	-5.25	23.21	11.33	48.39	37.06
Averaged	58.83	-71.14	-12.31	1230.02	-4.99	11.65	10.01	42.53	32.52

Table G- 7 Calculated values per cross-section for the zero state runs

H. Modelling with Delft3D

In this appendix the set-up of Delft3D will be explained and the results will be shown. More information about the background of Delft3D software is given in Appendix E.4.

The Delft3D models have two main objectives to fulfil, which are described in section 4.1:

- Determining the causes of erosion.
- Checking if the alternatives fulfil the project requirements.

To fulfil these objectives, the first task is to ensure that the models have a good predictive skill. This is done by calibrating the model, comparing it with measurements and observations known from the project area.

When the models have a good predictive skill, the causes of erosion can be determined by computing values for the different sediment transports. In combination with the XBeach results, conclusions can be made about the contribution of the different coastal processes to the total amount of erosion.

At last, the models are used to simulate the different alternatives. These simulations help with determining the effect of some measures taken and with further optimizing the design.

So eventually the total modelling process can be divided into three steps:

- Calibration
- Determining cause of erosion
- Simulating alternatives

H.1 Approach

For each mentioned step before, the main approach is described in this section.

Calibration

The calibration of a mathematical model is an important part of the modelling process, because without a good calibration, the final results are worthless. Calibration is performed by comparing the modelling results with the known coastal behaviour (from measurements and observations) and adjust the model in order to fit to this behaviour.

To ensure that the models have some predictive skill, the results should match the measurements and observations. However, a large limitation of this project is the lack of measurements. Especially morphological time measurements are not widely available for this area. Therefore the calibration is mainly based on visual observations of the GAMMA office. Besides, one table with sedimentation measurement data is available, see Table H- 1. This table is already used in section 3.5 to describe the nourishment done in 2012.

For locations hotels, See Figure 1-3	**November 2012 – February 2015**	**Mayo 2013 – February 2015**
Tainos	Monthly: -0.49 m^3/m Annual: -5.94 m^3/m Total: -22,869 m^3/year Tendency of erosion	Monthly: -0.22 m^3/m Annual: -2.59 m^3/m Total: -9,971.5 m^3/year Tendency of erosion
Brisas del Caribe - Royalton Hicacos	Monthly: 0.11 m^3/m Annual: 1.35 m^3/m Total: 3,847.5 m^3/year Tendency of accretion	Monthly: 0.25 m^3/m Annual: 3.02 m^3/m Total: 8,807 m^3/year Tendency of accretion
Iberostar Varadero – Paradisus	Monthly: -2.31 m^3/m Annual: -27.71 m^3/m Total: -27,710 m^3/year Tendency of erosion	Monthly: -1.66 m^3/m Annual: -19.89 m^3/m Total: -19,890 m^3/year Tendency of erosion

Table H- 1 Overview erosion after nourishment

It has to be noticed that these measurements are influenced by the performed nourishment. Combining these numbers with the visual observations from the GAMMA office, the available information for the calibration process can be summarized by:

- Structural erosion east and in front of the Iberostar hotel (relatively large).
- Accretion west of the Iberostar hotel (relatively small).

Another limitation that has to be dealt with, is that the exact time of the performed bathymetry measurements are unknown. This can be problematic if, for example, the bathymetry is measured during winter conditions. So, if the calibration is executed with normal (summer) wave conditions, some erosion would be expected. However it is possible that accretion is observed, because the profile will adjust towards its equilibrium (summer) state. In this way the calibration is more difficult, because it's harder to know what the expected results should be.

Calibrating the output is done by adjusting some of the input parameters. However, not all input parameters can be used in this calibration process. The input can be divided in:

- Project-related input (examples: wave climate, tides, wind, sediments, bathymetry)
- Computational-related input (examples: grid cells, cell sizes, time step sizes)
- Output-related input (examples: location grid, simulation time, *Morfac*)

The remaining parameters (not listed above) can be used to calibrate the model. These parameters can be straightforward linear multiplication factors, but can also have a more physical background.

With all the limitations and the types of input parameters listed, it's possible to determine the right approach for the calibration. Before the actual calibration is performed, a stable and correctly working model should be created. In order to achieve this, the first model only contained the bathymetry, a rough grid and some simple boundary conditions. After checking if the results are reasonable, the model input is extended several times. Eventually a (more advanced) stable model is created, with reasonable hydrodynamical and wave-related results. The actual calibration is mainly based on sediment transports and morphological changes. The following approach is used during the calibration:

- Checking and calibrating morphological changes during certain weather conditions (from weather condition analysis, see Appendix D.1). Final goal is to qualitatively check if model has predictive skills.

- Checking and calibrating morphological changes during full wave conditions set for one morphological year (Argoss [11] data set divided in bins). Final goal is to quantitively check if model has predictive skills.

- Checking wave reduction input to the result from full wave condition set (from wave reduction analysis, see Appendix D.2). Goal is to determine if wave reduction analysis is accurate enough.

If eventually the model is calibrated and the results are as expected, the next step in de Delft3D modelling process can be taken. The final calibrated model will be called the zero-state model, as it is the current situation without new human interventions yet.

Determining cause of erosion

By simulating different weather condition, the morphological changes can be determined quantitively for each weather condition. Because the occurrence of these conditions is known and the results can be compared to the results from XBeach and the relative contribution to the total erosion problem can be computed. The zero-state model is used and the boundary conditions will be obtained from the weather condition analysis.

Simulating alternatives

Finally the alternatives will be simulated. The solution (nourishment and/or breakwater) will be added to the zero-state model. This simulation will have three main purposes:

- Observing the effect of some possible measures;
- Checking if every alternative can fulfil the project requirements;
- Optimizing the design;

So for example, first the submerged breakwater will be tested to see if there are any negative influences on the coastal area. If not, the breakwater will be added to the design. The initial nourishment will also be added to the design and the next simulation must show if the total solution will fulfil the requirements after five years of morphological time. Finally, the design is optimized in such way that the coastline will be perfectly according to the requirements after five years.

H.2 Input

In order to keep a good overview of the setup, the input parameters are divided in the same categories used by the Delft3D software. The input is explained for each relevant category during this model set-up.

Domain

The bathymetry used for this project is obtained from GeoCuba [5]. Because some irregularities were observed, a couple of adjustments had to be made. For more information about the bathymetry and the necessary adjustments, see Appendix C.

In order to make the computation more efficient, two different grids are used. The smaller grid is nested into the larger one, as shown in Figure H- 1.

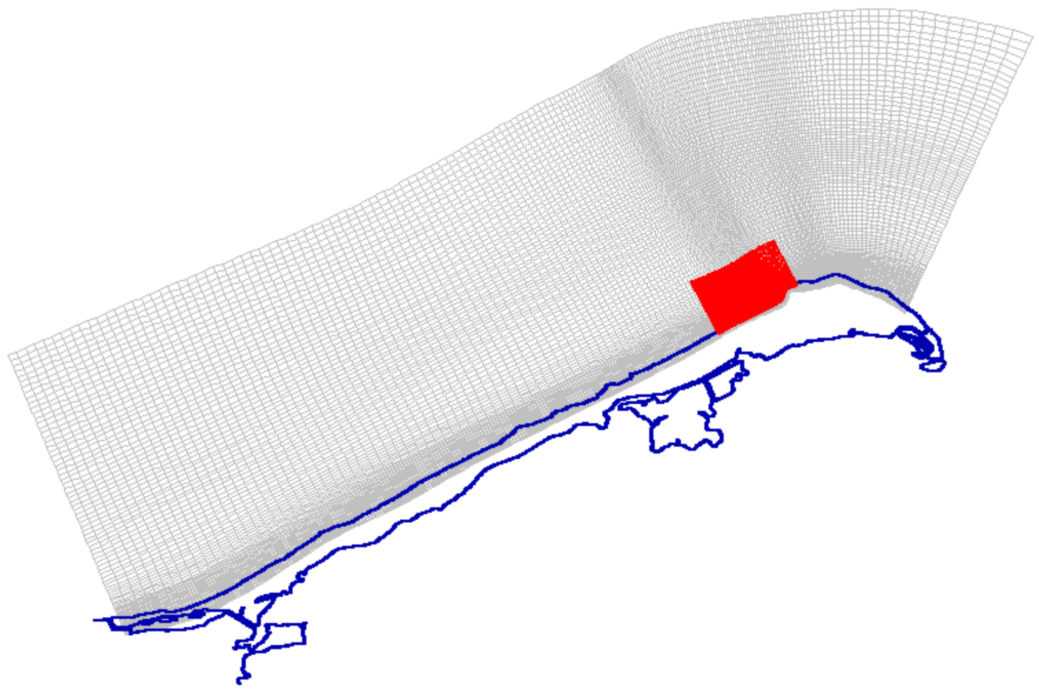

Figure H- 1 Large grid (grey), small grid (red) and Varadero coastline (blue)

The grids are both curvilinear. The first advantage of curvilinear grids is that they are capable of containing finer grid cells in the area of interest (Iberostar hotel) and secondly that it can bend along with the coastline.

The large grid has 180 cells in longshore direction and 100 cells in cross-shore direction and overlaps the whole peninsula, which is 22 kilometre long. Its outer edge is directed 7 kilometres into the sea, where the maximum depth is 600 meter. The sizes of the larger cells in this area are in the order of 150 meter in cross-shore direction and 250 meter longshore. In the area of interest, the grid sizes are approximately 35 meter in longshore direction and 10 meter in cross-shore direction.

The small grid has 135 cells in longshore direction and 120 cells cross-shore. The longshore length of the small grid is 2200 meter and 1440 meter cross-shore, where the maximum depth is 8 meter. Around the area of interest the grid cells are 10 meter long in longshore direction and 5 meter in cross-shore.

An overview of the grid properties is given in Figure H- 2, Figure H- 3, Figure H- 4 and Figure H- 5.

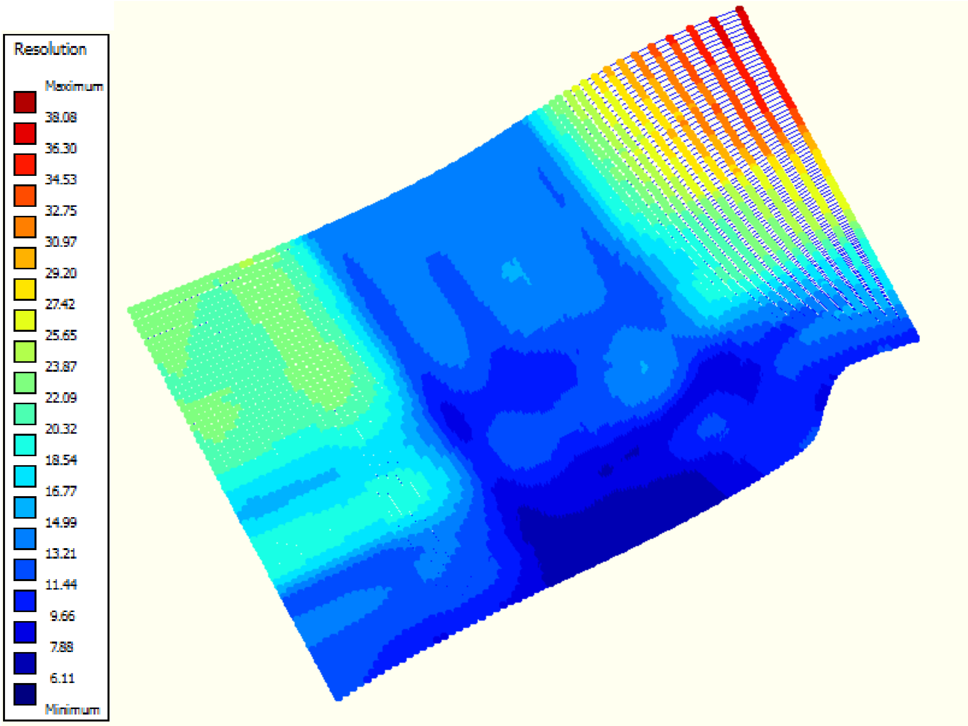

Figure H- 2 Resolution of the small grid

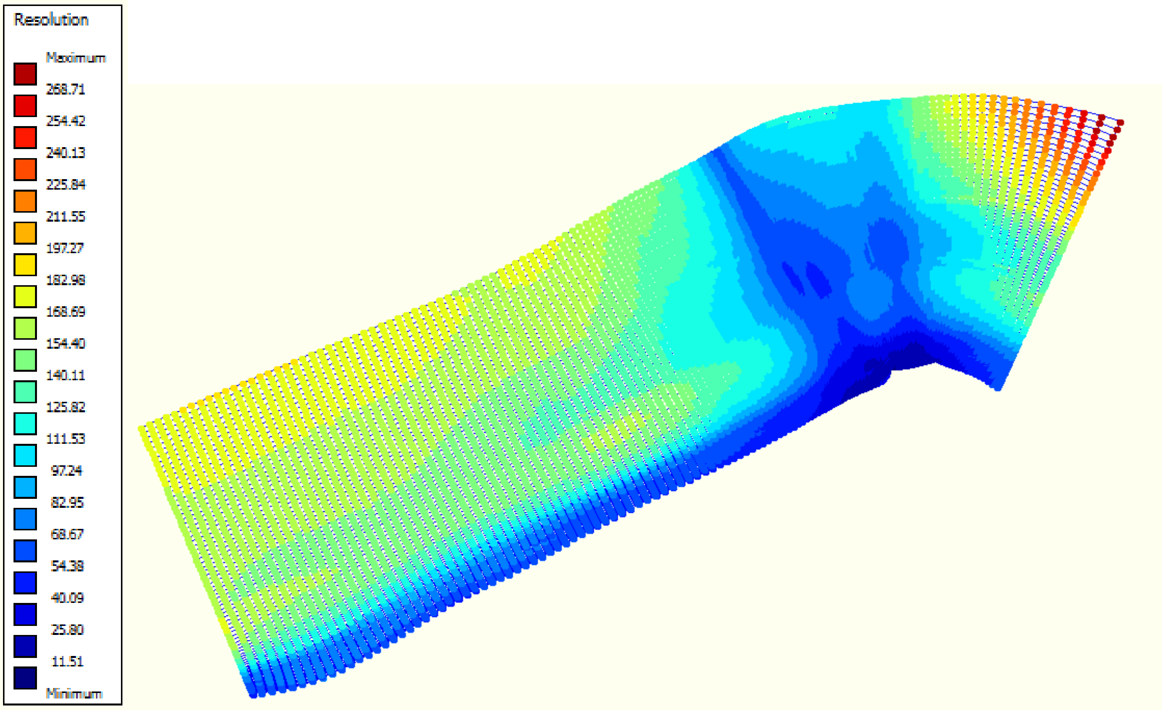

Figure H- 3 Resolution of the large grid

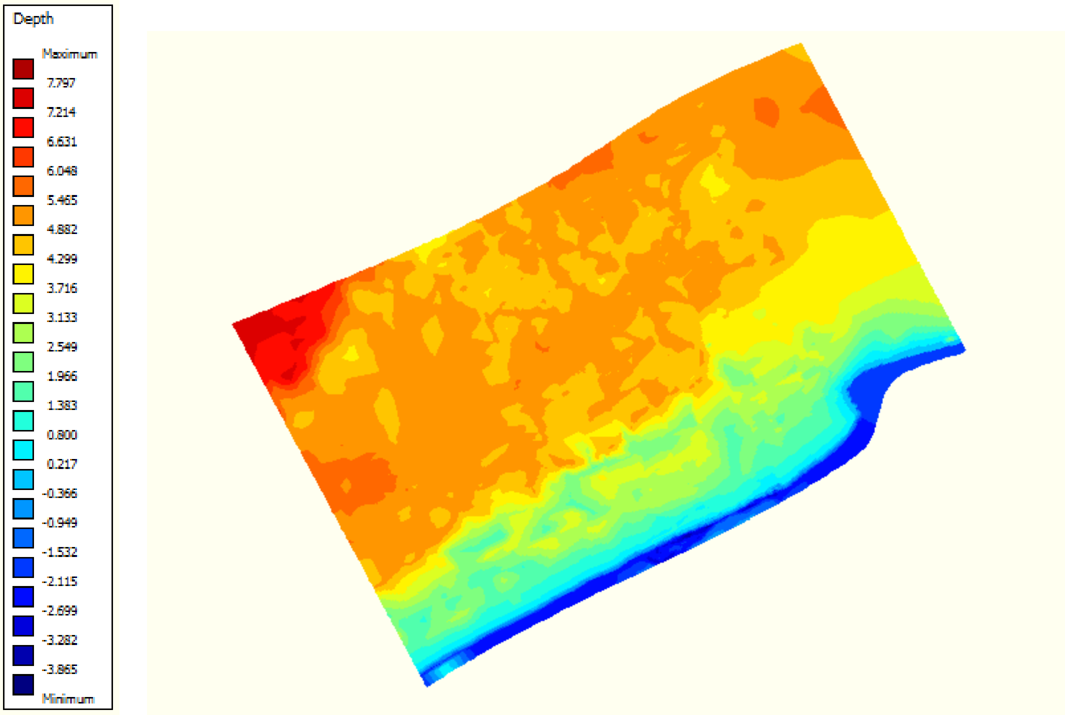

Figure H- 4 Depth for small grid

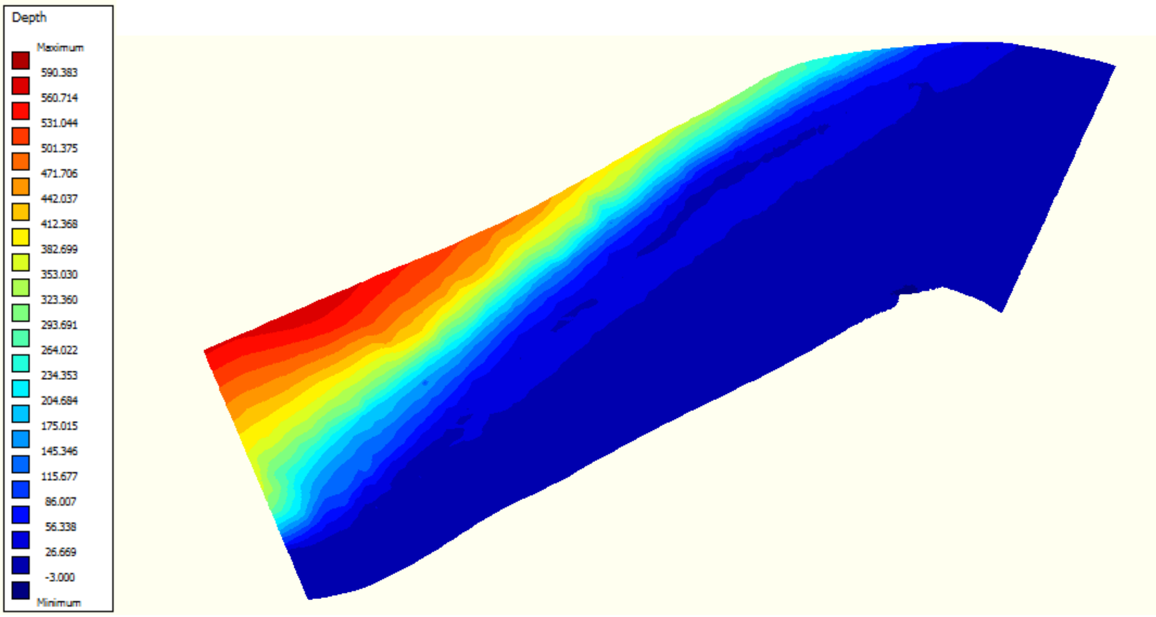

Figure H- 5 Depth for large grid

Time frame

The size of time steps has an effect on the accuracy of the calculation. Smaller time steps give a more accurate result, but do also increase the computational time. So it is favourable to keep the time steps as large as possible, without getting an inaccurate model. This upper boundary is given by the so-called Courant number. The idea behind this number is that the relation between the flow velocity and grid size should not be too large, because in that case the current could "skip" a cell. Partly based on the calibration and partly because of the Courant number, the time step is chosen to be 0.05 minutes for each Delft3D model.

The total simulation time of the model is relying mainly on the wished output. If a certain morphological time is wished, the simulation time of the model is dependent on that morphological time, the morphological scale factor, the used wave data and the morphological spin-up interval. The chosen simulation times are given in Table H- 4.

Boundary Conditions

The boundary conditions are the input of the edges of the computational grid. For the type of boundary in Delft3D-FLOW module several options are available and for the Delft3D-WAVE module wave parameters are required.

Delft3D-FLOW

The boundary type of the Delft3D-FLOW module is set to be a water level. The tidal signal (given in section 3.3.5) is converted into several harmonics. These harmonics are used as the forcing type of the water level. The final input is shown in Table H- 2.

Harmonic	Frequency (deg/h)	Amplitude (m)	Phase (deg)
M2	28.99	0.127	45.9
O1	13.94	0.101	5.0
K1	15.05	0.094	8.5
S2	30.00	0.042	69.5

Table H- 2 Harmonics as boundary condition Delft3D-FLOW

Delft3D-WAVE

The wave input relies on the objective of the model. Therefore different wave input from different wave analyses is used for each model. The two types of wave analysis used with Delft3D are:

- Weather condition analysis (see Appendix D.1)
- Wave reduction analysis (see Appendix D.2)

The models used for determining the cause of erosion will use the weather condition analysis. For simulating a certain morphological period, it is then possible to quantify the morphological changes and sediment transports during a certain weather condition. In combination with the storms simulated with XBeach, the relative importance of different types of weather can be determined.

The models which will simulate the alternatives are required to represent and predict reality. For these models the wave reduction analysis is used in order to simulate the real wave conditions, but with a reduced required computational time. The computational time is approximately two times shorter than the time required with a full wave set.

Physical parameters

The physical parameters are divided into several sub-categories, which all contain multiple parameters. Some of the parameters are more project related and can be determined or computed. Other ones are more computational and model related and therefore need to be determined by own insight. This insight is based on some available reference projects, information in the manual [26] or own available knowledge. If information is missing and/or the parameter has no physical background, the value is determined in the calibration process.

In Table H- 3 an overview is given of the way all the physical parameters are obtained. For some physical parameters, a small description is given below about the way it is computed or determined.

- The Chezy coefficients are computed with project related parameters (section 3.3.6)
- For projects with a relatively small domain, the horizontal eddy viscosity and diffusivity are usually between 1 and 10. By calibrating these, the values chosen to be 5.
- The sediment properties are obtained from Gamma (2015) [3], see section 3.3.6.
- The sediment layer thickness is set to 5 meter over the whole grid, except around the headland area. There the layer thickness is 0 meter, to create a non-erodible layer.
- The morphological scale factor is chosen such that no inaccuracies arise because of this factor, but still is large enough to decrease the computational time. This point is found by calibrating the factor.
- The spin-up interval is chosen by looking at the water levels over time. In the first few hours of every run, the water levels are not completely stable. After approximately 6 hours the water level becomes more smooth. The spin-up interval is chosen according to this stabilization time.
- The morphological multiplication factors are fully calibrated values. Within a range of the default value and values from reference projects, the correct values for this project are obtained.

The values of all the physical parameters are given in Table H- 4.

Category	Physical Parameter	Computed Project related	Manual References	Calibrated
Constants (FLOW)	Gravity	■		
	Water density	■		
	Air density	■		
	Wind drag		■	
Roughness (FLOW)	Roughness form.		■	
	Chezy coeff.	■		
	Stress formulation due to wave forces		■	■
Viscosity (FLOW)	Hor. ed. viscosity		■	■
	Hor. Ed. diffusivity		■	■
Sediment (FLOW)	Reference density hindered settling		■	
	Specific density	■		
	Dry bed density	■		
	Diameter (D_{50})	■		
	Layer thickness	■		
Morphology (FLOW)	Morphological scale factor	■	■	■
	Spin-up interval morphology	■	■	■
	Minimum depth sediment		■	
	Van Rijn's reference height		■	
	Threshold sediment thickness		■	
	Estimated ripple height factor		■	
	Other multiplication factors		■	■
Wind (FLOW)	Wind speed	■		
	Wind direction	■		
(WAVE)	Constants (ALL)	(From FLOW)		
	Processes (ALL)		■	
	Various (ALL)		■	

Table H- 3 Overview of the way the physical parameters are obtained

Numerical parameters

The numerical parameters mainly determine which numerical schemes are used and their computational properties. Because the lack of knowledge about the numerical part of the models, most of the values are kept default. It has to be remarked that all the available reference projects used the same default values. An overview of the numerical values is given in Table H- 4.

Output

The output consists of all kind of files which store the results generated during the computation. For this project, the interval between the storage of these results is set to be 30 minutes. That means that the time interval between the morphological output is approximately one day (with a morphological scale factor of 50).

Delft3D-FLOW also generates communication files. These communication files are used to let Delft3D-FLOW interact with Delft3D-WAVE. The interval between the generation of the communication files is again a consideration between accuracy and computational run time. For this project, this interval is set to be 20 minutes.

Overview

In Table H- 4 an overview is given of all the input parameters for the different types of Delft3D models. The types of models are divided on their objective; calibration, determining cause of erosion or simulation the alternatives.

Because the wave input differs in each model, Table H- 5 and Table H- 6 are present.

Input	Unit	Objective of model: Calibration	Objective of model: Cause of erosion	Objective of model: Simulating alternatives
Domain				
Grid	-	See description *Domain*		
Bathymetry	-	See Appendix C		
Time frame				
Simulation time	days	-	Normal: 2.00 Storm: 1.75	1 year: 3.00 5 year: 8.00
Time step	min	0.05	0.05	0.05
Initial Conditions				
Water level	m	0.0	0.0	0.0
Sediment sand concentration	kg/m^3	0.0	0.0	0.0
Boundaries				
FLOW: Water level (tides)	-	Harmonics (see Table H- 2)		
WAVE: Wave analyses	-	-	Weather conditions Appendix D.1 Table H- 5	Wave reduction Appendix D.2 Table H- 6
Physical parameters - Constants				
Gravity	m/s^2	9.81	9.81	9.81
Water density	kg/m^3	1022	1022	1022
Air density	kg/m^3	1	1	1
Wind drag coefficient (A)	-	0.00063	0.00063	0.00063
Wind drag coefficient (B)	-	0.00723	0.00723	0.00723
Wind drag coefficient (C)	-	0.00723	0.00723	0.00723
Wind drag coefficient – speed (A)	m/s	0	0	0
Wind drag coefficient – speed (B)	m/s	100	100	100
Wind drag coefficient – speed (C)	m/s	100	100	100
Physical parameters - Roughness				
Roughness formula	-	Chezy	Chezy	Chezy
Chezy coefficients (U, V)	-	68.6	68.6	68.6
Stress formulation due to wave forces	-	Van Rijn	Van Rijn	Van Rijn
Physical parameters - Viscosity				
Horizontal eddy viscosity	m^2/s	1 / 5 / 10	5	5
Horizontal eddy diffusivity	m^2/s	1 / 5 / 10	5	5
Physical parameters - Sediment				
Reference density for hindered settling	kg/m^3	1600	1600	1600
Specific density	kg/m^3	2700	2700	2700

Dry bed density	kg/m^3	1675	1675	1675
Median sediment diameter (D_{50})	µm	270	270	270
Initial sediment layer thickness	m	5 m (except for headland: 0 m)		
Physical parameters - Morphology				
Morphological scale factor	-	50	50	50
Spin-up interval before morphology	min	720	720	720
Minimum depth for sediment calculation	m	0.1	0.1	0.1
Van Rijn's reference height factor	-	1	1	1
Threshold sediment thickness	m	0.05	0.05	0.05
Estimated ripple height factor	-	1 / 2	1	1
Factor for erosion of adjacent dry cells	-	1	1	1
Current-rel. reference concentration fac.	-	0.5 / 1 / 1.2 / 1.5	1.75	1.75
Current-rel. transport vector magnitude	-	0.5 / 1 / 1.2 / 1.5	1.75	1.75
Wave-rel. suspended transport factor	-	0.2 / 1.0	0.15	0.15
Wave-rel. transport factor	-	0.2 / 1.0	0.15	0.15
Physical parameters - Wind				
Wind speed	m/s deg	-	Appendix D.1	4.78 22.5
Numerical parameters				
Threshold depth	m	0.002	0.002	0.002
Marginal depth	m	-999	-999	-999
Smoothing time	min	720	720	720
Interval communication file	min	20	20	20

Table H- 4 Overview of input parameters Delft3D

	H_s (m)	Dir (deg)	T_p (s)	U_s (m/s)	U_{dir} (°)	P (%)
Weak storm NE	2.17	43.9	5.97	10.60	51.0	3.47
Weak storm NW	2.16	265.1	7.60	8.75	350.2	2.82
Heavy storm NE	4.30	52.8	8.11	16.29	48.0	0.04
Heavy storm NW	4.90	280.8	9.68	13.83	287.5	0.05
Normal condition NE	0.81	42.4	6.33	5.52	45.2	25.5
Normal condition N	0.85	320.3	5.86	4.89	6.0	19.1
Normal condition NW	0.85	359.9	6.08	5.57	25.6	17.1

Table H- 5 Summary input from weather condition analysis

Box id (-)	H_s (m)	Dir (deg)	T_p (s)	P_{tot} (%)	P_{tot} (days/ year)
1	2.75	258.75	6.5	0.077	0.282
2	2.75	281.25	8.4	0.412	1.505
3	5.75	281.25	10.2	0.014	0.052
4	1.75	303.75	7.8	1.987	7.251
5	3.25	303.75	9.2	0.271	0.987
6	1.75	11.25	5.7	0.568	2.074
7	2.25	11.25	6.3	0.411	1.500
8	0.75	11.25	6.7	4.924	17.972
9	1.75	33.75	5.5	1.774	6.474
10	2.75	33.75	6.7	0.287	1.046
11	4.75	33.75	7.8	0.023	0.087
12	1.75	33.75	5.5	4.267	15.575
13	3.25	56.25	7.1	0.408	1.489
14	1.75	56.25	6.3	1.597	5.829
15	1.75	348.75	6.8	2.361	8.616
Total				19.38	70.7

Table H- 6 Summary input from wave reduction analysis

H.3 Results

In this section, the results are shown from the Delft3D model runs. The results are divided in the same categories as for the approach and set-up is done.

Calibration

The calibration results show the process of finding the correct zero-state model. Sometimes it seemed that the right values were determined, but when small adjustments were made to the bathymetry (nourishment, breakwater) the results were not as expected. Therefore the calibration had to be restarted multiple times. This is also the reason that the models sometimes differ in the calibration process, because the calibration is done during different parts of the whole modelling process. The process is shown below for several parameters. For every parameter also the final chosen value is given. Not every calibration step is shown, but only the results which can clarify the choices made.

This calibration is performed on the zero-state model, with a morphological time of one year.

Horizontal eddy viscosity and horizontal eddy diffusivity (decision: 5 m^2/s both)

The usual values for horizontal eddy viscosity and horizontal eddy diffusivity for a smaller domain are between 1 m^2/s and 10 m^2/s. From Figure H- 6 it can be seen that all the complex eddy formations are almost disappeared for a value of 5 m^2/s. In reality the eddies are not observed in such heavy way and therefor the value of 5 m^2/s is kept in the models.

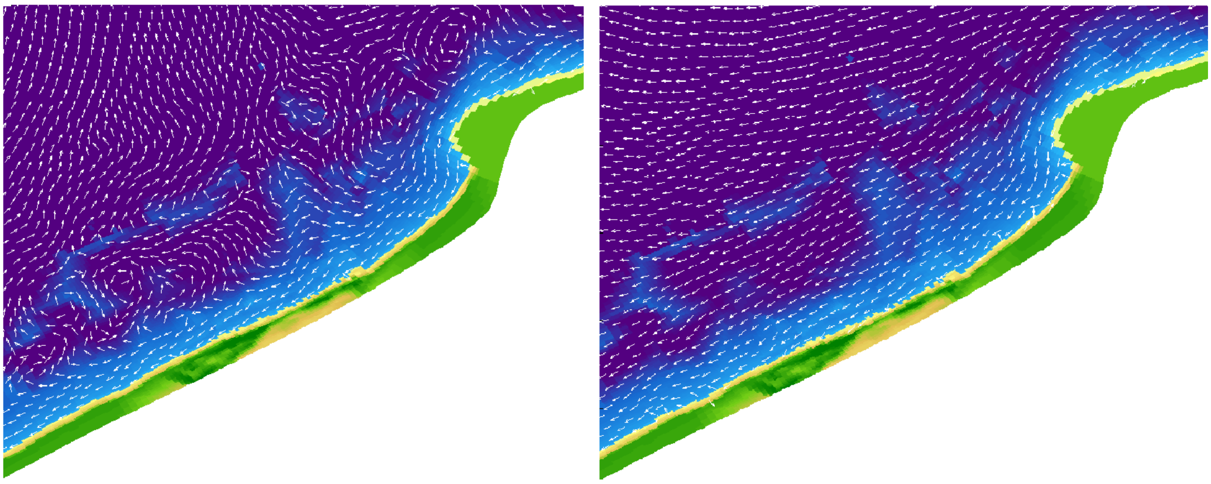

Figure H- 6 Calibration results - Normalized flow vectors, left: 1 m^2/s, right: 5 m^2/s

Calibration wave reduction analysis (decision: wave reduction analysis is accurate)
The wave reduction analysis is performed by using the same transport formula as Delft3D does: Van Rijn see Appendix D.2. However, this computation is performed by Unibest which is less advanced than Delft3D and therefore the wave reduction analysis must also be checked in the Delft3D software.

In Figure H- 7 the comparison between the full wave input and the reduced wave input is shown. The differences between the two final results (cumulative erosion/sedimentation after one morphological year) are very small and therefore the wave reduction analysis is used for the Delft3D models.

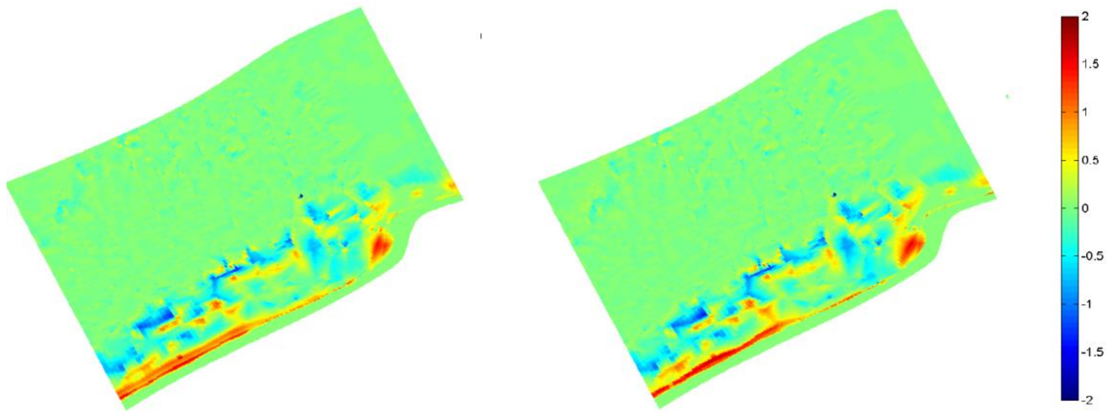

Figure H- 7 Wave input calibration: left: Full wave data set, right: Reduced wave data

Multiplication (calibration) factors for morphology
After the model setup of Delft3D, the general behaviour of the simulated coastal area was as expected. The last calibration step is to improve the general similarities between reality and the simulation to a more accurate quantitative result.

The multiplication factors are:

- Current-related reference concentration factor
- Current-related transport vector magnitude factor
- Wave-related suspended transport factor
- Wave-related bed-load transport factor

The model has been running with values for the current-related factors of 1, 0.5, 1.2, 1.5, 2.0 and 1.75, in that order. The tested wave-related factors are 1, 0.2, 0.02, 0.08, 0.12 and 0.15.

The main influence of the current-related factors is that a higher factor induces in general more erosion. So an increasing current-related factor, decreases the accretion in western direction and increases the erosion in front of Iberostar hotel (see Figure H- 8). Finally, the chosen value is 1.75 (-).

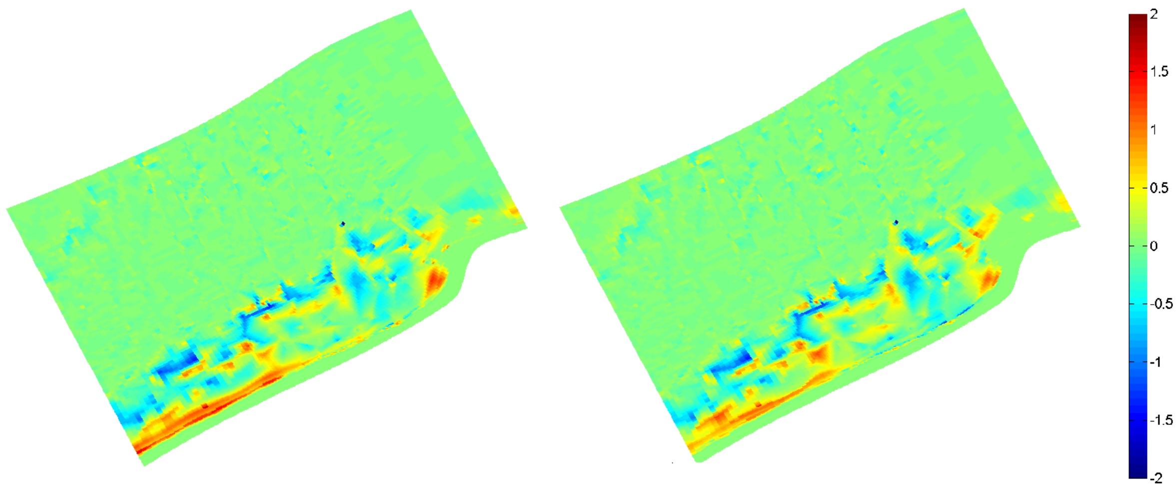

Figure H- 8 Cumulative erosion patterns for current-related factors. 1.2 (left) and 1.5 (right)

A higher wave-related factor seems to induce more cross-shore changes in the profile, so mainly the beach profiles were adjusted. The chosen value is 0.15 (-).

Determining cause of erosion

Now the model has been calibrated, usable result can be obtained. In this part, first the different weather conditions from the weather condition analysis (see Appendix D.1) are simulated and a qualitative analysis is performed on the results. After that, the wave reduction analysis (see Appendix D.2) is used, in order obtain certain quantities about the problem.

To determine longshore related causes of erosion with Delft3D, first there is looked at large scale flow patterns with the large grid. Thereafter there will be zoomed in on the small grid to see the very local flow patterns causing erosion.

Large scale flow patterns

For the large-scale flow patterns for every wave condition, two figures are given. The first (upper left corner) is the whole peninsula with normalized flow vectors and the second (lower right corner) is zoomed in on in the Iberostar area showing none-normalized flow vectors. Besides, some arrows are added manually to indicate the main flow directions, which may be a little bit exaggerated to clarify some patterns.

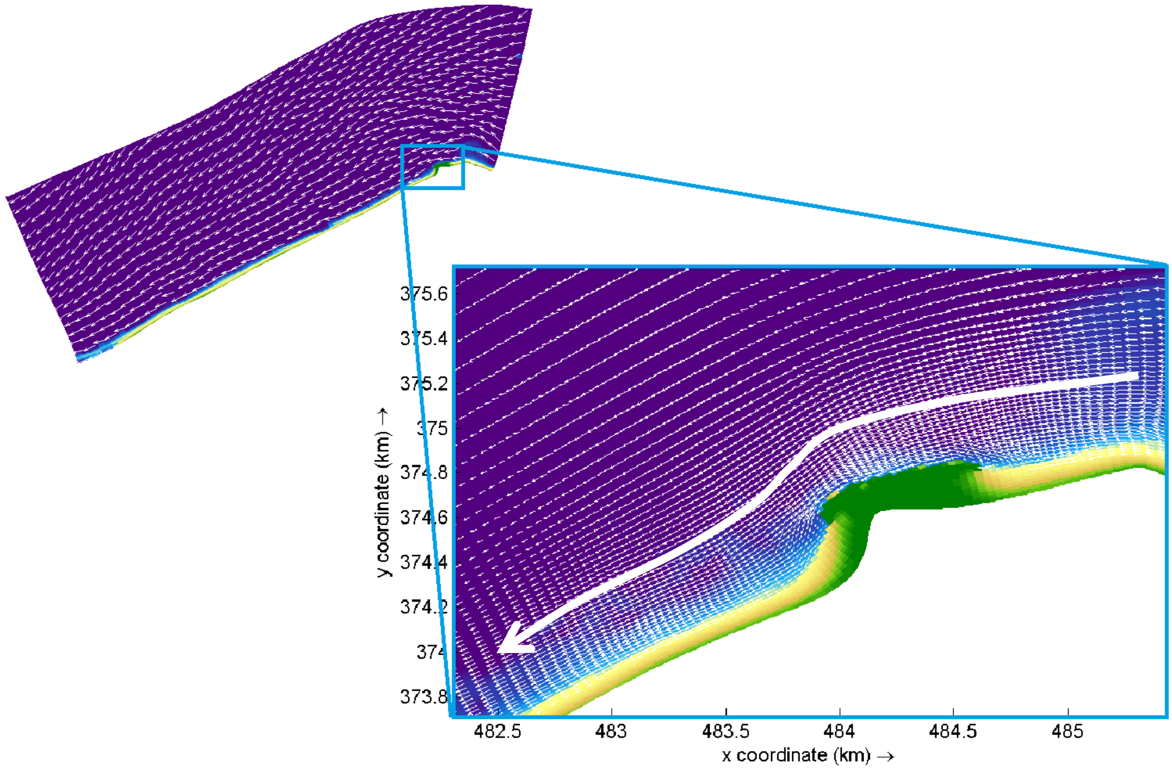

Figure H- 9 Weak storm NE, H_s=2.17 m, H_{dir}=44°

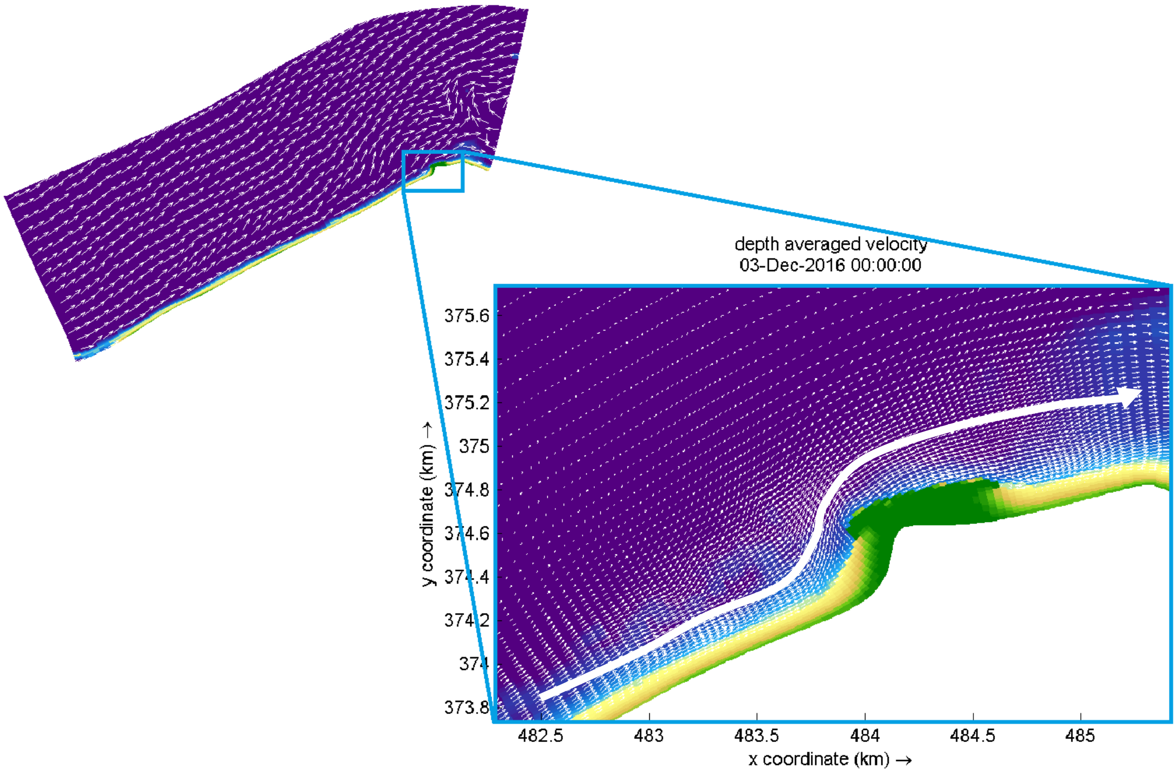

Figure H- 10 Weak cold front NW, H_s=2.16 m, H_{dir}=265°

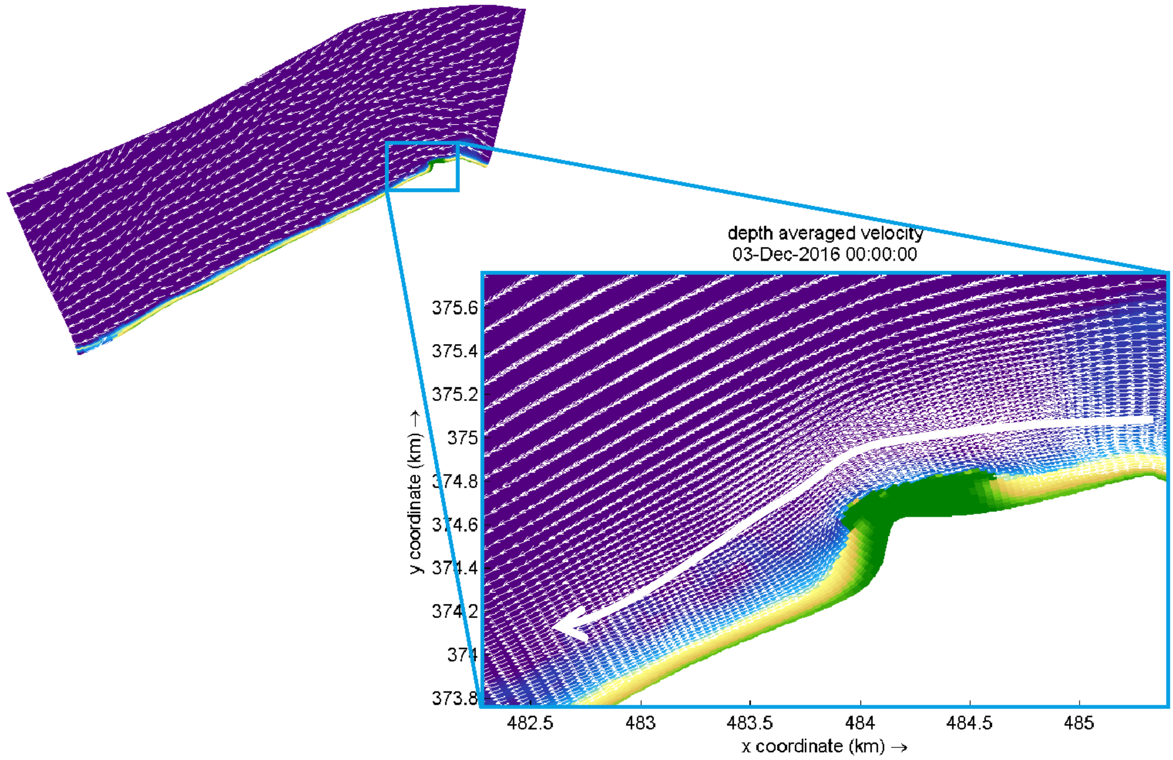

Figure H- 11 Strong storm NE, H_s=4.3 m, H_{dir}=52.8°

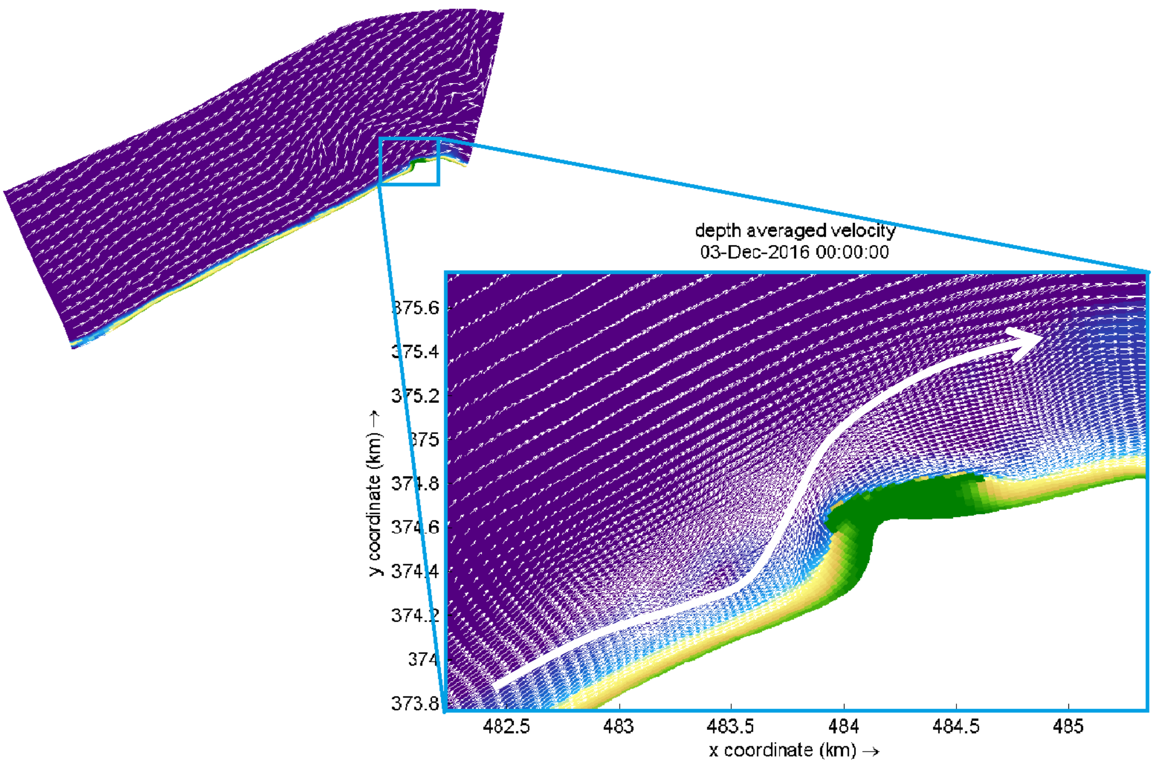

Figure H- 12 Strong cold front NW, H_s=4.9 m, H_{dir}=281°

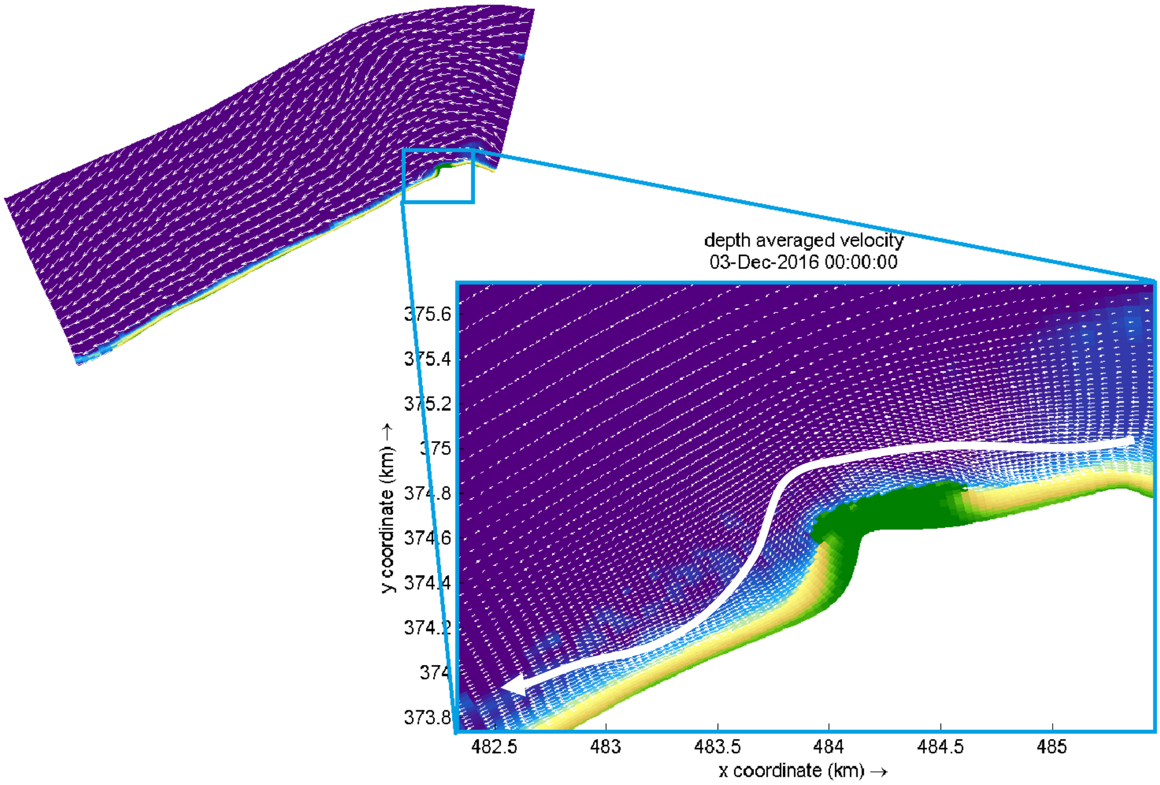

Figure H- 13 Normal conditions NE, H_s=0.81 m, H_{dir}=42°

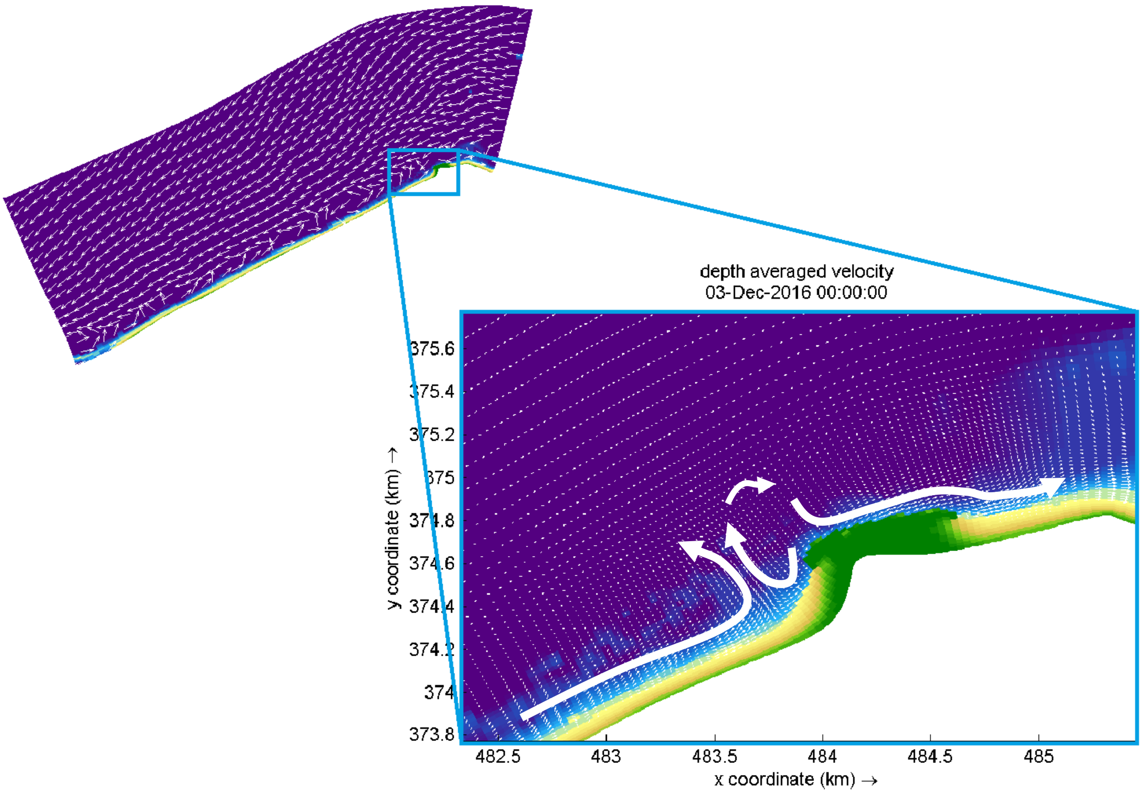

Figure H- 14 Normal conditions NW, H_s=0.85 m, H_{dir}=320°

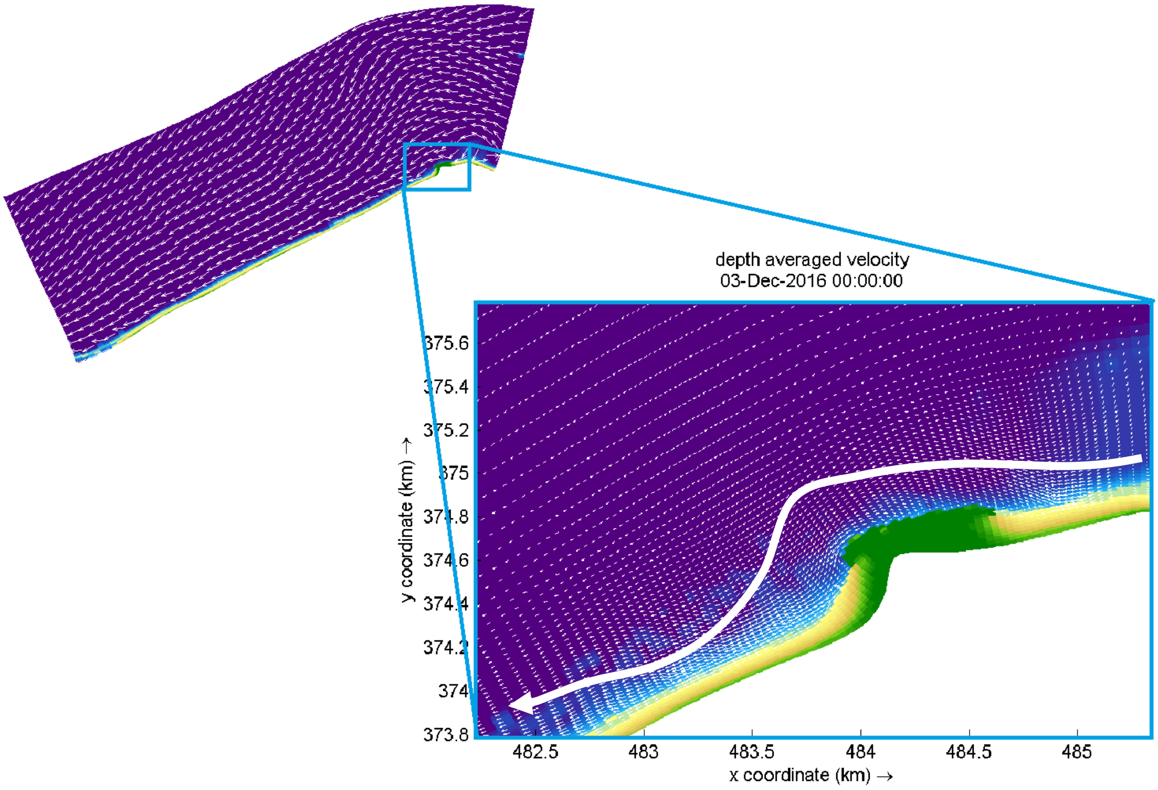

Figure H- 15 Normal conditions N, H_s=0.85 m, H_{dir}=0°

The results mainly confirm the expected hydrodynamic reaction on the wave input. Waves from the north east and the north induce a flow directed in westward direction, while waves from the north west induce a flow directed in eastward direction. However some remarks can be made, about some less common symptoms.

In case of waves coming in from the north east, the flow is directed westwards. Around the headland diffraction takes place. For stronger weather conditions (storms) this diffraction is relatively lower and therefore the flow is "less bended". For the normal conditions, the waves bend relatively fast back towards the coast. Once the flow reached the coast again, it bends a little bit offshore again. This happens around the location of the Iberostar hotel beach.

For the normal conditions directed from the north west, some more "complex" flow patterns are observed. The flow velocities are relatively low, but an eddy is generated around the headland.

Small scale flow patterns

For the small-scale flow patterns first the coastal response during north west, north and north east conditions with normal waves is investigated. Thereafter there is looked at a one year and a multiple year simulation with a full wave spectrum. This results is an analysis of patterns causing erosion, the amount of beach width in the zero state and a reflection on the Delft3D performance.

North east

The normal condition runs represent 25 days of a constant wave condition and leads to the following results.

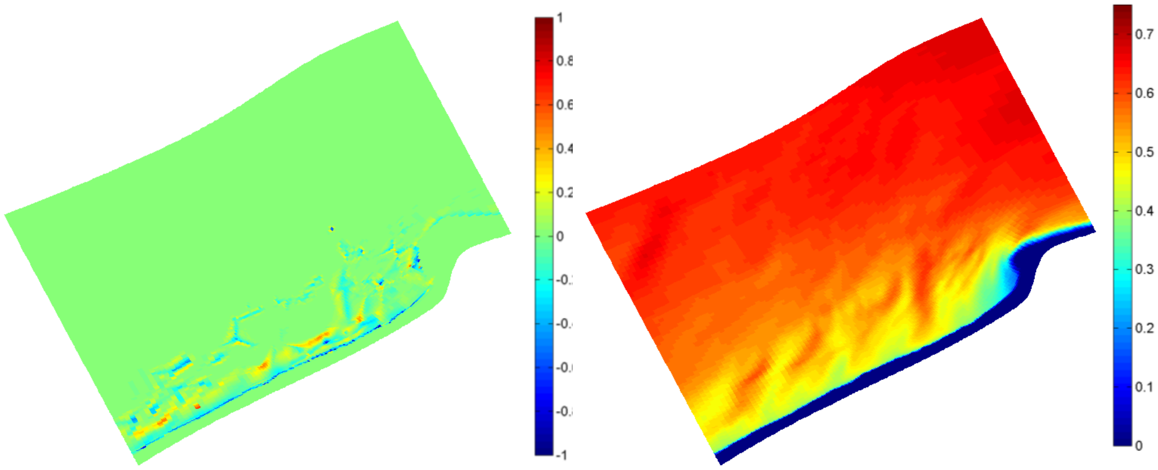

Figure H- 16 North east conditions, cumulative sedimentation/erosion (left) and Hs (right)

For these regular north east conditions it can be seen that the waves break relatively far from the coast and that there is a shadow zone west of the breakwater. The cumulative sedimentation /erosion figure shows that the pattern is quite longshore uniform. Close to the coast there is erosion and around the bars there is sedimentation, this behaviour is as expected and nicely captured.

North

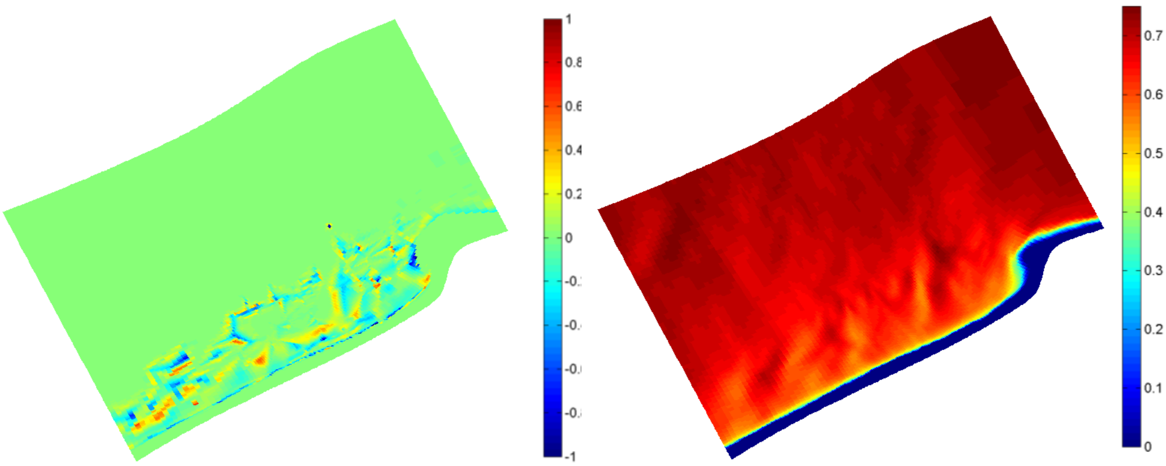

Figure H- 17 North conditions, cumulative sedimentation/erosion (left) and Hs (right)

For these regular north conditions it can be seen that the waves break much closer to the coast and that this does not happen longshore uniform, few waves already break earlier on the bars and so have less energy when reaching the coast. Also the incoming wave energy at the offshore boundary is a little bit higher because there is less dissipation offshore, because the bathymetry in this direction is steeper and less shallow.

When looking at the left figure it can be seen that there generally still is erosion at the coast. But when looking more in closely it can be seen that the erosion at the coast is not longshore uniform anymore, which can be explained by the right figure. Furthermore the amount of sedimentation and erosion is larger because more wave energy reaches the coast. Finally some sedimentation can be seen behind the headland.

North west

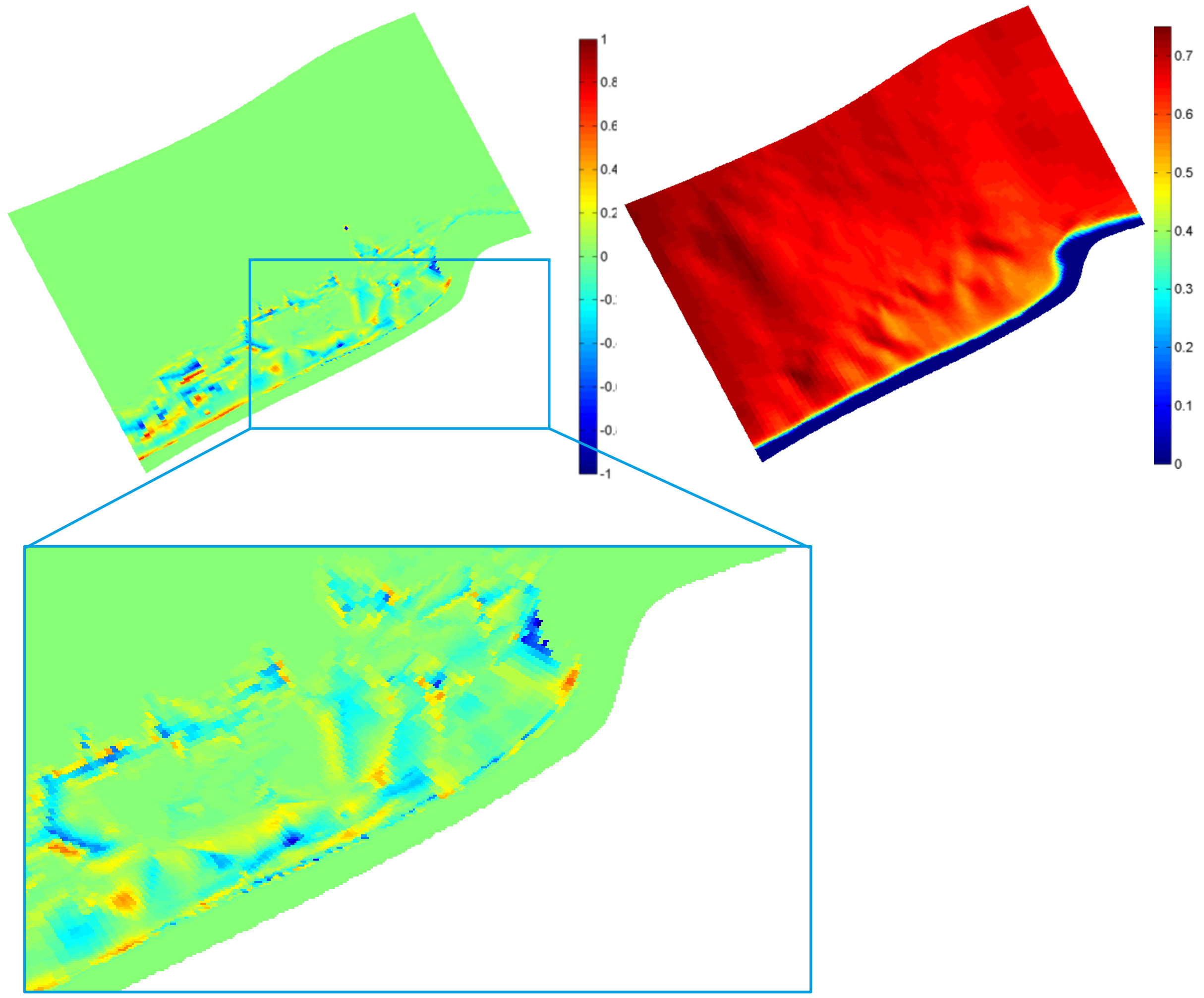

Figure H- 18 North west conditions, cumulative sedimentation/erosion (left) and Hs (right)

For these north west conditions it can be seen that the waves also break closer to the coast and that the pattern is not spatially uniform and induced by wave breaking over bars. Left of the Iberostar section more wave energy penetrates close to the coast. This behaviour can also be seen in the left figure, generally speaking there is sedimentation at the coast which seems to correspond with local observations.

When zooming in on the Iberostar section surprisingly it can be seen that close to the coast some erosion occurs. The sediment that is transported longshore during normal north east wave conditions, gets transported back to the section less easy.

When now depth averaged flow velocities are observed the same interesting pattern as in Figure H- 14 can be observed.

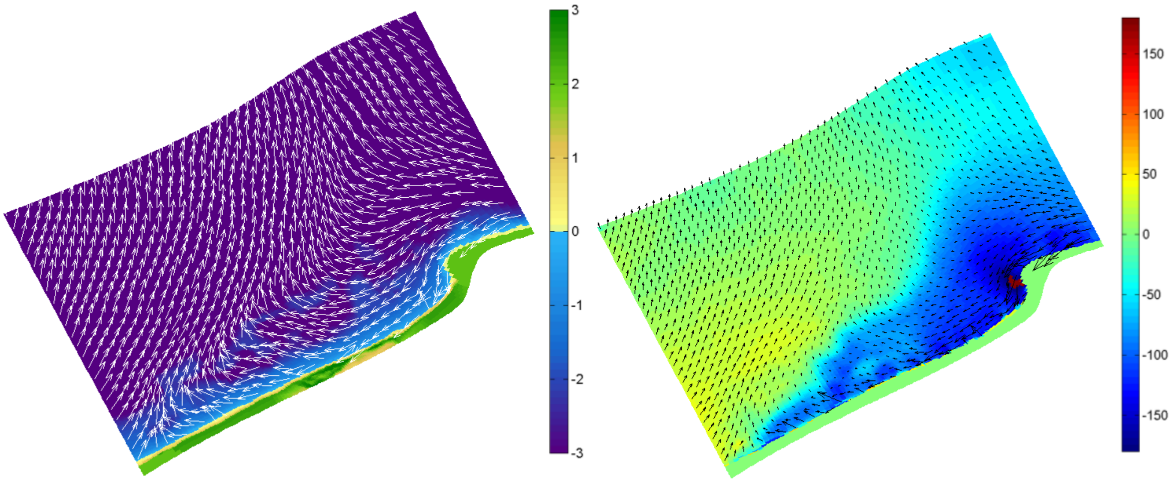

Figure H- 19 Normal conditions NW; bed level and depth averaged velocity as normalised arrows (left), depth averaged velocity as nautical flow direction angles in colour and real vectors in black (right)

Despite the fact that the wave direction is north west, the flow at the coast is in south west direction. As in Figure H- 14 a large circulation pattern develops, which is remarkably constant in time.

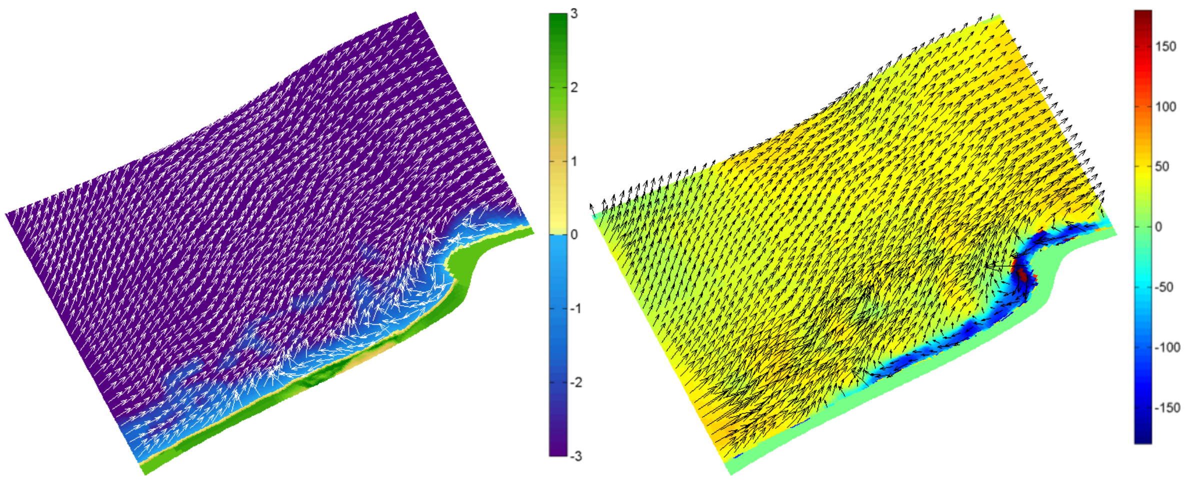

Figure H- 20 Cold front NW; bed level and depth averaged velocity vectors (left), depth averaged velocity as nautical flow direction angles in colour and vectors in black (right)

The main explanation behind these patterns is described in the main report, see section 4.4.3.

<u>One year simulation</u>

With these observed patterns, erosion around certain areas can be expected. However, before anything can be said about this, all wave conditions should be combined to be able to represent reality. The following simulations are performed by using the wave reduction analysis (see Appendix D.2) for runs of one morphological year. The result is the following:

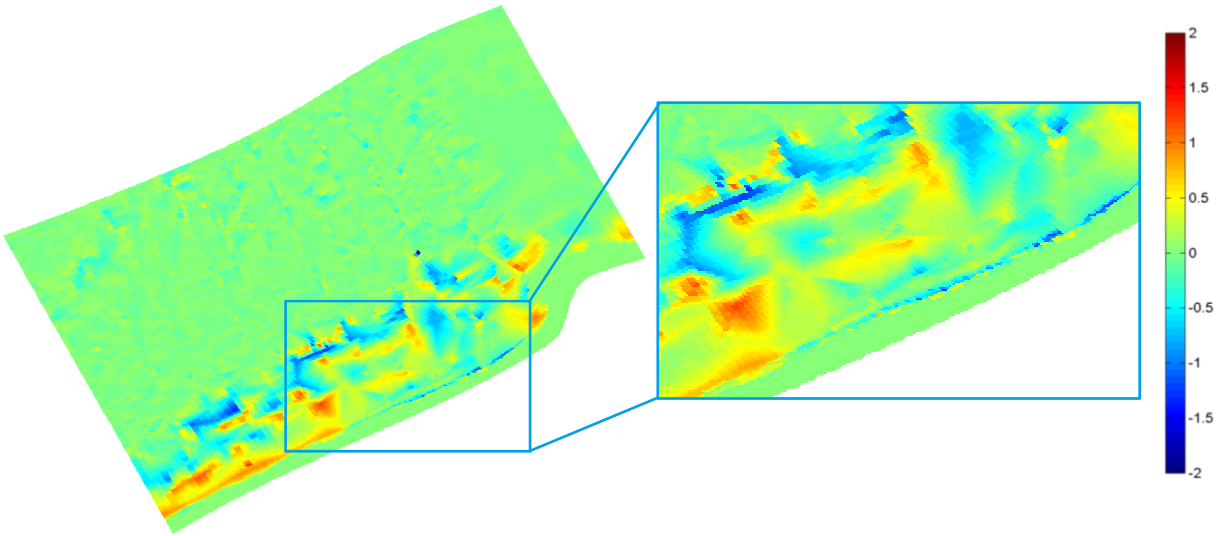

Figure H- 21 Cumulative sedimentation/erosion after 1 year

The figure shows that after a year of simulation with using all wave directions, there is erosion at the Iberostar section. More westward, there is serious sedimentation, as well as around the headland. This general response corresponds with reality, as the beach in front of the Iberostar is much smaller compared to the west and east.

More offshore it can be said that some strong sedimentation/erosion occurs at the bars and this can be explained by the fact that these partly get levelled out. There has to be noticed that even more offshore, at the 'second bars', there is less smoothing visible because only stronger waves have effect here. But the smoothing closer to the shore is good visible when looking at the bed levels.

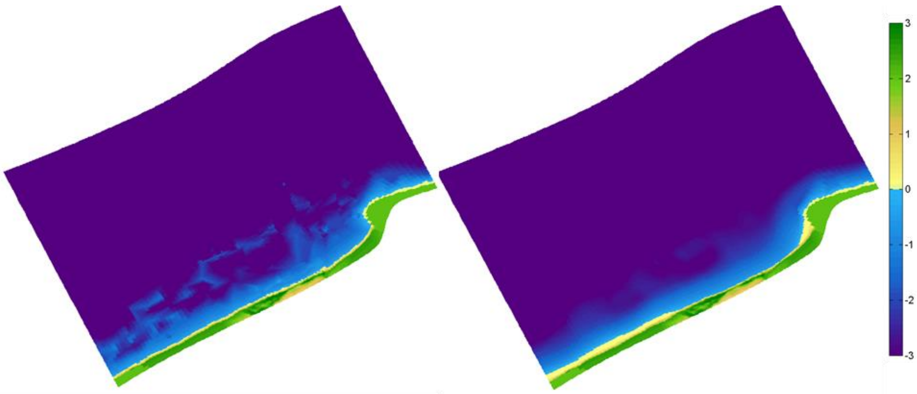

Figure H- 22 Initial bed level (left) and the bed level after 1 year (right)

This indicates that when no measures are taken, the beach width in front of Iberostar will decrease even more.

Multiple year simulation

The next step is to extend the one year morphological runs to multiple year runs.

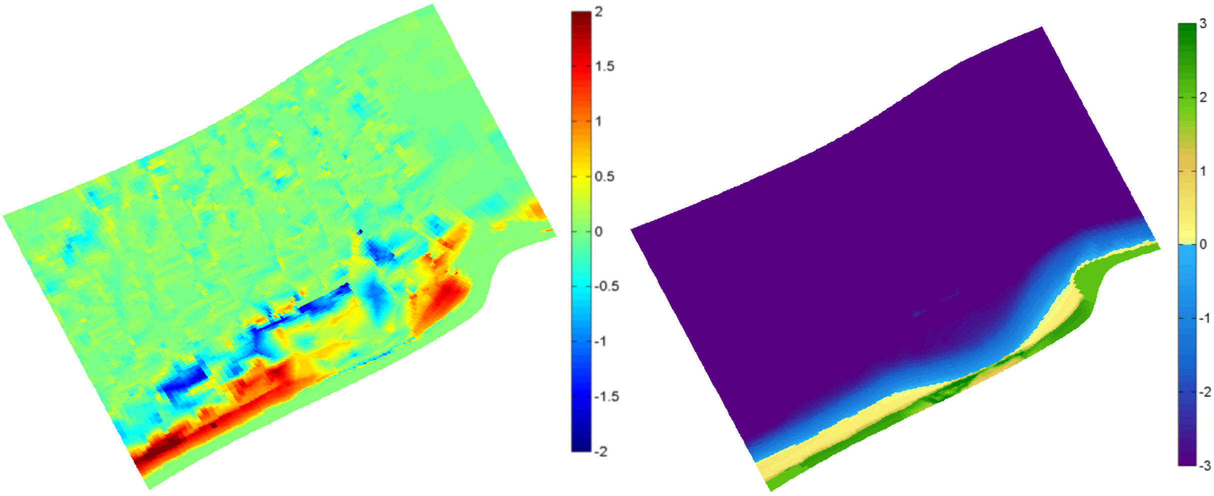

Figure H- 23 Sedimentation/erosion (left) and bed levels (right) after 3 years

The first remark that has to be made is that the amount of sedimentation east- and westwards of the Iberostar hotel are too large. The resulting coastline is not realistic and the results cannot be taken into account quantitively.

However, although there is way too much sedimentation, in front of the Iberostar hotel still erosion occurs. These figures show that the amount of erosion along the Iberostar section is severe, not much beach will remain after three years as can be seen in this graph:

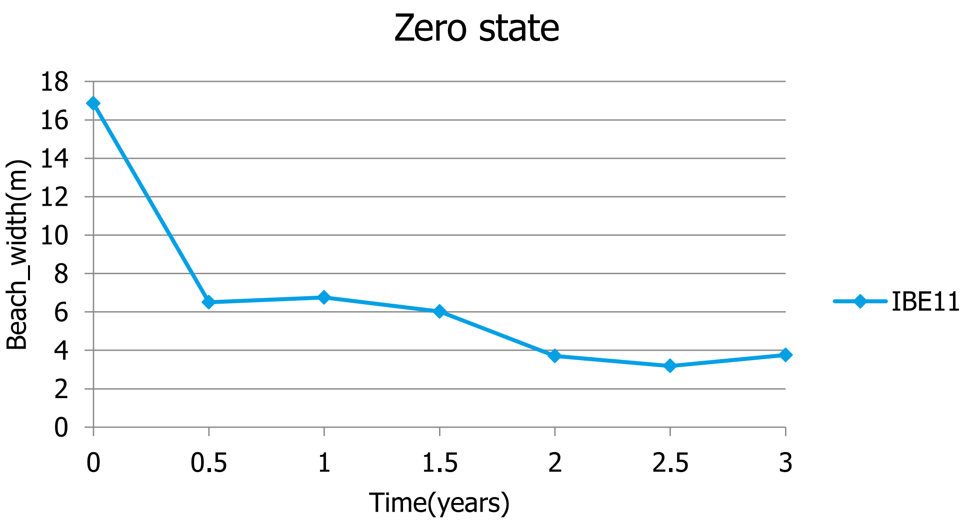

Figure H- 24 Beach widths in time for the zero state, profile IBE11

It is interesting that the amount of erosion is so strong in the first half year of the run. Physically this could be explained by the adjusting of the profile to a winter profile (also called storm profile). It is not known when the measurements were performed during the year, so measuring during the summer could explain (a part of) the adjustment and erosion of the profile.

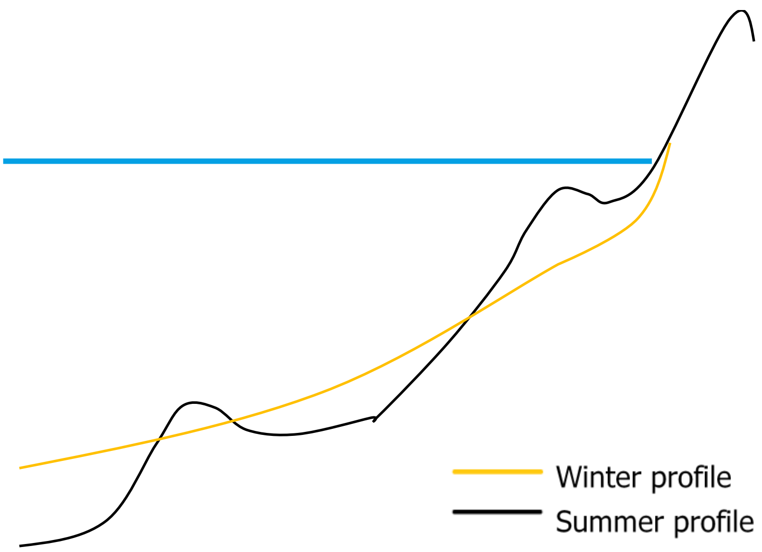

Figure H- 25 Summer and winter (storm) profile

During weaker conditions, often during the summer, bars develop and move towards the shore. During stronger storm conditions, often during the winter, the higher waves break earlier on the bars and because of the larger wave energy the whole profile gets levelled out to some extent. The beach width decreases, which could be what is happening in our model. The adjustment is good visible when plotting cross-sections at various time steps:

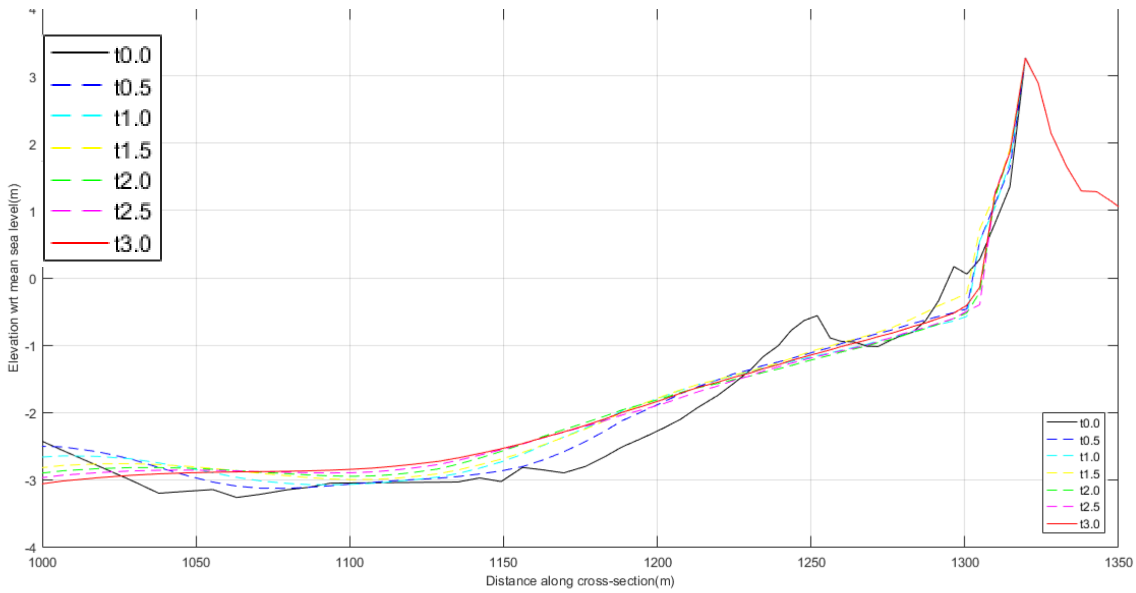

Figure H- 26 Cross-section IBE 11 in time, zero state

The wave input reduction mainly contains strong wave conditions. These conditions are selected based on their longshore contribution, but the cross-shore contribution is not taken into account. This can result that annually the coastal changes are correct for the wave reduction analysis, but that the beach profile will permanently change into a winter profile due to the high wave conditions. This process is visible from Figure H- 25 and Figure H- 26.

Numerically the adjustment could also partly be subscripted to the fact that Delft3D does not contain all processes relevant for bar movement, see Appendix E.5 for more information.

When taking all this into account it could be remarked that the amount sedimentation in the model is too strong. The fact that the Delft3D was hard to calibrate without data, as well as the performed visual observation calibration after only one year can explain this. The last means that small differences in parameters in the one year calibration can lead to large differences after multiple years. Unfortunately this cannot be solved because of the lack of data, time and computational power.

Because of this, the Delft3D model results should be treated as qualitative results from where differences and percentages can be used to compare solutions. At last there has to be noticed that the calibration problem seems to be in morphology part, not in the wave and flow parts. The simulated patterns of sedimentation coincide with observations, only the quantity of sedimentation does not.

Simulation

The zero-state model is used to design alternatives and test the solutions. The parameters remain the same, but by changing the bathymetry, some solutions can be represented. The results of these simulations are used and handled in the main report.

I. Multi Criteria Analysis

I.1 Explanation of the (sub)criteria

In this part of the Appendix, the criteria for the multi criteria analysis will be shortly explained by their sub criteria. These criteria and their sub criteria have been shown in Table 6-4.

Functionality

(Sub criteria: beach width, stabilisation of the coastline, swimmer safety and reliability)
The main function of the solution is to prevent the beach in front of the Iberostar Varadero hotel from structural erosion. This functionality can be verified by the beach width and the stabilisation of the coastline. On the other hand, a safe sea for the tourist should also be the result of the solution. The flows should not be too fast and offshore directed flows should be avoided in order to preserve the swimmer safety. The reliability of the solution should also be verified for its functionality. The solution should be stable, also for most unforeseen conditions.

Constructability

(Sub criteria: presence of materials, presence of equipment, experience and complexity)
In Cuba, materials and (special) equipment are not always available. It is preferred to have a solution which does not need special equipment in order to avoid that expensive contractors should be hired for the construction. Also the local experience with the construction method and the design should be taken into account. The newest construction methods cannot be used due to the lack of experience. Therefore the already proven construction methods should be used. It can be concluded that the complexity of the construction should not be too difficult.

Maintainability

(Sub criteria: lifetime, durability and maintenance complexity)
The lifetime of the solution is of importance. When the lifetime is short, the solution should be executed several times, which is not preferred. The number of monitoring operations and regular checks on the proposed solution are taken into account in these criteria as the sub criterion durability. When less monitoring and less checks need to be executed, this will be preferred. The complexity of the monitoring operations of the solution is also taken into

account in these criteria. These operations should not be complex for the same reasons as for the criteria constructability.

Sustainability

(Sub criteria: influence on ecology during construction, operational time and removal)

This criterion is about the effects of the proposed solutions on the environment. The whole lifetime of the solution is taken into account, so this holds also for the construction and demolishing phase. The effects of the solution on the environment should be as low as possible and it will be even preferred to avoid this at all.

Spatial quality

(Sub criterion: visibility)

The tourists at Varadero are basing their holiday destination on the beautiful tropical beaches with full sight on the blue beaches. When this sight is blocked, this can be considered as pollution of the landscape. This is a form of hindrance which can result in the choice of the tourist for another destination. It can be concluded that the most preferred solution should not be seen from the beach.

I.2 Scores

In the second part of the Appendix, the scores per solution for each criterion will be explained. These scores should be between 1 and 5. A score of 1 means that it is a bad solution for that specific criterion, while a score of 5 stands for a perfect solution for the criterion.

In the scoring process all sub criteria are taken into account, which can be seen in the explanation in the tables below. The final results of the multi criteria analysis can be found Table 6-6 of the main report.

Functionality

(Sub criteria: beach width, stabilisation of the coastline, swimmer safety and reliability)

Solution	Score	Explanation
Breakwater	1	The currents behind the breakwater are changing the sediment transports and do result in some little accretion at the beach. On the other hand, this leads to erosion at the adjacent coastline, which should be avoided. The currents are also unfavourable for the swimmer safety and the reliability of the solution.
Nourishment	4	The nourishment results in a wider beach in front of the Iberostar hotel. As the erosion will not be stopped, the coastline will not be stable. The swimmer safety and reliability will be quite good as the currents can be predicted quite accurate.
Combination	4	In the combination solution, the beach will have a sufficient width. Due to the breakwater, the coastline can be more maintained than the solution with only a nourishment. Due to the offshore breakwaters, the current will be more unpredictable which decreases the reliability and the swimmer safety. The surrounding coasts will also suffer from more erosion.

Table I- 1 MCA: Functionality

Constructability

(Sub criteria: presence of materials, presence of equipment, experience and complexity)

Solution	Score	Explanation
Breakwater	3	The construction of an offshore breakwater can be considered as being quite difficult. First the surface needs to be flattened, which is under the water surface. Thereafter the core of the breakwater should be constructed after which the different layers consisting of different grain size layers can be constructed. This is quite a complex work and it is not sure that the equipment in Cuba is available for this specific construction works.
Nourishment	5	Nourishments cannot be considered as complex operations, but you need the right equipment for it. Luckily, the Cuban government owns the equipment to execute a good nourishment. The sand can be extracted from an area nearby. Finally, also some successful nourishments have been executed in the past, so there is enough experience for the construction of this solution.
Combination	2	The combination of the two different construction works makes the process more complex. It should be kept in mind that the construction of the nourishment will be relatively easy, but construction of the breakwater will be quite difficult. The reasons for this difference has been explained above. It can also be stated that the construction of both methods is more complex.

Table I- 2 MCA: Constructability

Maintainability

(Sub criteria: lifetime, durability and maintenance complexity)

Solution	Score	Explanation
Breakwater	4	When the breakwater is executed correctly, the lifetime of the breakwater should be quite long. Unfortunately, it will probably not resist against the heavy hurricanes in which it can be destroyed. The maintenance works on the offshore breakwater is quite complex and the breakwater should be checked quite often.
Nourishment	4	The lifetime of the total nourishment solution last for the full 50 years, but the lifetime of just one nourishment is not long. Normally, it is considered that nourishments have to take place every 5 to 10 years. Also after severe storms, it can be assumed that a maintenance nourishment has to take place to be sure that the beach width is still sufficient. Therefore the nourishments should be checked regularly and also occasionally after the storms. This checks are not very complex and can be executed quite easily.
Combination	3	The combination solution is a partly durable solution. It can be stated that the breakwater will stay for a long time (unless a very heavy storm passes) and that the nourishment will be vanished within a few years (and then a new nourishment should be executed). For this solution, the maintenance should be done for both parts of the solutions, which is quite complex.

Table I- 3 MCA: Maintainability

Sustainability

(Sub criteria: influence on ecology during construction, operational time and removal)

Solution	Score	Explanation
Breakwater	2	The construction of the breakwater will not result in a lot of environmental problems as the area needed for the construction is not very big. During the lifetime the environmental damage can be very big as the flow patterns and wave heights will be transformed. It can be decided to demolish the breakwater after the lifetime, which again results in some environmental damage
Nourishment	5	The nourishment only gives some environmental damage during construction. During this period the sand should be nourished and the water level and bed level changes significantly. As it is a soft solution, the influence on the environment during the lifetime will be low. Nature can change the morphology and on the land it is possible to grow vegetation. As it is not needed to demolish the nourishment, there will be no environmental damage during removal.
Combination	2	The combination between a hard and soft solution also has an influence on the environment. During the construction this is especially caused by the nourishment. The breakwater is the major influencing factor during the lifetime and the demolishing time.

Table I- 4 MCA: Sustainability

Spatial quality

(Sub criterion: visibility)

Solution	Score	Explanation
Breakwater	3	When only a submerged breakwater is constructed, it will not be seen from the beach. On the other hand, the beach is not very wide, so the beach will not be visible attractive.
Nourishment	5	The nourishment is also not a structure that blocks the ocean view. The beach width has been increased, which results in a better visibly attractive beach.
Combination	4	The combination nourishment has less volume needed for the nourishment than the solution with only a nourishment. This results in a smaller beach than the nourishment, which is visibly less attractive. The breakwater, however, will still be below the waterline, which is not a bad thing for the ocean views.

Table I- 5 Spatial quality

J. Construction planning

In this appendix, the construction planning for the four types of nourishments is explained. Although these nourishments method seems like the same, these time schedules do differ (apart from the differences in volume). These differences will be covered as much as possible in this section.

J.1 Initial nourishment

The initial nourishment has a volume of 120,000 m^3 (120% of 100,000 m^3). For the design phase a total of 26 days have been taken into consideration. During these 26 days, the design of the nourishment has to be started, which takes about 1 day. After the design phase a more conceptual design has to be designed. For the detailed technical design of the nourishment 20 days has been taken into account, in which also a general design of the regular nourishment should be designed for the future.

This phase is followed by the preparation phase, in which the permits have to be obtained. During this period the different companies or (governmental) organisations have to be contracted in order to execute the nourishment. During this period it is already possible to execute a geological survey. During this survey the present situation has to be measured.
After this period, it could take some time before the actual nourishment takes place, but in our case we assumed that it can immediately start. Therefore the contracting and obtaining of permits will be directly followed by the building of the small construction site, which takes 1 day. This can be built on a small beach area, which will be unavailable for recreational purposes for the project time. This will be followed by the assembling of equipment, which also includes the construction of the pipeline between the dredging vessel and the construction site.

The next 12 days were taken into account for nourishing (as calculated in chapter 7). Simultaneously detailed measurements should be executed to check whether the nourishment is executed correctly. On the beach the sand has to be spread out by several machines, which takes about 7 days in total. This can already be started when a part of the nourishment at a specific location has already been finished.

The finishing phase has been started by the removal of the pipeline and the small construction site, which both takes about 1 day. This is followed by the cleaning of the beach. For the whole nourishment area the beach should be checked whether all dangerous material is removed and tourist can safely enter the sea at the project area. The process should be followed by an intense inspection. This is included to be sure that the nourishment is executed in a good way. When it seems that the nourishment is a disaster, the contractor can be called to redo the nourishment before something disastrous happens. Although two days have been planned for this activity, the inspection continues (in a less intense way) after this period.

As the last point also a buffer day has been included. This day can be included somewhere in the project when an unforeseen event (e.g. broken equipment) takes place.

In Table J- 1 the processes and duration of the activities are scheduled. It also contains a start and end date. The nourishment itself will take place in the months May and June, in which there are less tourists and the wave conditions are calm. The relation column shows which activity should be finished before the activity can be executed.

INITIAL NOURISHMENT				
Activity	**Days**	**Relation**	**Start date**	**End date**
Design phase				
1 Initiation	1	-	1-4-2017	1-4-2017
2 Concept design	5	1	2-4-2017	6-4-2017
3 Technical design	20	2	7-4-2017	26-4-2017
Preparation phase				
4 Obtaining permits	20	3	27-4-2017	16-5-2017
5 Contracting	10	3	2-5-2017	11-5-2017
6 Geological survey	5	2	9-5-2017	13-5-2017
7 Building small construction site	1	4	17-5-2017	17-5-2017
8 Assembling equipment	1	7	18-5-2017	18-5-2017
Construction phase				
9 Nourishing	12	8	19-5-2017	30-5-2017
10 Detailed measuring	12	8	19-5-2017	30-5-2017
11 Smoothening beach	7	8	26-5-2017	1-6-2017
Finishing phase				
12 Removing pipeline	1	9	31-5-2017	31-5-2017
13 Removing construction site	1	11, 12	2-6-2017	2-6-2017
14 Cleaning of the beach	2	13	3-6-2017	4-6-2017
15 Inspection	2	14	5-6-2017	6-6-2017
Other				
16 Buffer	1	-	7-6-2017	7-6-2017
Total				**68 days**

Table J- 1 Duration of activities during the initial nourishment

From the table it can be seen that the total duration of the activities takes approximately 68 days. The hindrance for tourists has been minimised as it takes just 19 days (between the 17th of May and the 4th of June.

In Figure J- 1 the construction method has been showed in a Gantt chart for this initial nourishment. The blue coloured bars represent the critical path, which directly influence the duration of the construction. These activities can only be started when the previous activity has been finished. It can be concluded that when one of these activities are delayed, all later activities will be also delayed. For the project manager it is of high importance that these activities do not get delayed.

The grey colour bars represent the activities which are not on the critical path. During the initial nourishment there are just four activities on the critical path. During the obtaining of the permits, the contracting and the geological survey can be executed. During the nourishment time, the detailed measuring should be executed. As this activity should always be executed simultaneously to nourishment, this activity will never be on the critical path.

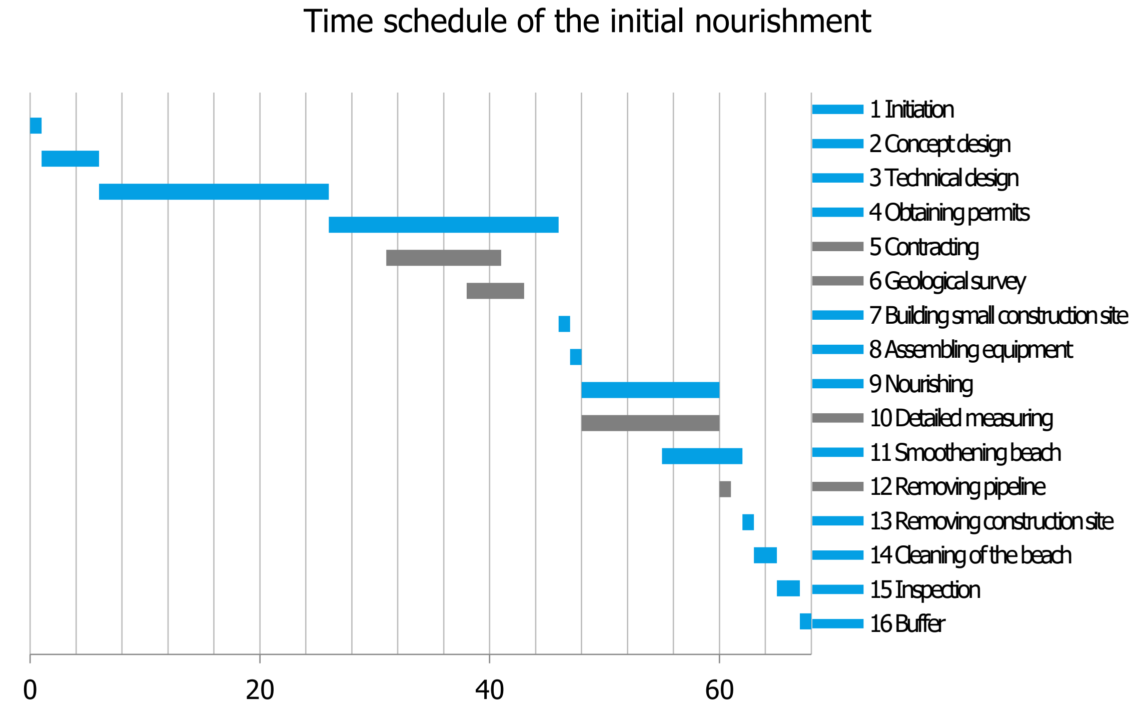

Figure J- 1 Gantt chart for the initial nourishment

J.2 The regular nourishment

The regular nourishment has a smaller sediment volume. This volume consists of 102,000 m^3 as 20% of the regular nourishment (85,000 m^3) will be directly gone during the nourishment procedure. During the initial nourishment already a concept of the regular nourishment has been made, which decreases the time needed for the conceptual design.
The duration for the technical design has also been decreased as the nourishment can be done in the same way as the initial or the previous regular nourishment.

The preparation time for the regular nourishments is also shorter as the permits can be obtained much faster as it is already known for a long time that the area should be nourished. The contracting phase can also be much shorter as this will be probably the same company or organisation as before. This reduces the duration of the preparation phase from 22 days to 12 days.

The duration of construction phase has been decreased from 14 to 13 days as the regular nourishment is smaller than the initial nourishment. For that reason the dredging vessel needs less time for the nourishing activity.

The finishing phase and buffer time are the same as they have not been changed by the smaller nourishment.

The duration of the activities, its relation to the other activities and the start and end date per activity are presented in the table below. It should be noted that the start and end dates are in the year 2022 as it is 5 years after the first nourishment. This could also be 2027, 2032 or any other year that is 5 years after a previous regular nourishment.

REGULAR NOURISHMENT				
Activity	**Duration**	**Relation**	**Start date**	**End date**
Design phase				
1 Initiation	1	-	30-4-2022	30-4-2022
2 Concept design	2	1	1-5-2022	2-5-2022
3 Technical design	5	2	3-5-2022	7-5-2022
Preparation phase				
4 Obtaining permits	10	3	8-5-2022	17-5-2022
5 Contracting	1	3	15-5-2022	15-5-2022
6 Geological survey	5	2	11-5-2022	15-5-2022
7 Building small construction site	1	4	18-5-2022	18-5-2022
8 Assembling equipment	1	7	19-5-2022	19-5-2022
Construction phase				
9 Nourishing	11	8	20-5-2022	31-5-2022
10 Detailed measuring	11	8	20-5-2022	31-5-2022
11 Smoothening beach	6	8	27-5-2022	1-6-2022
Finishing phase				
12 Removing pipeline	1	9	1-6-2022	1-6-2022
13 Removing construction site	1	11, 12	2-6-2022	2-6-2022
14 Cleaning of the beach	2	13	3-6-2022	4-6-2022
15 Inspection	2	14	5-6-2022	6-6-2022
Other				
16 Buffer	1	-	7-6-2022	7-6-2022
Total				**39 days**

Table J- 2 Duration of activities during the regular nourishment

From the table it can be seen that the total time needed for this nourishment is 39 days. It is almost half of the number of days needed for the initial nourishment. The tourists are hindered for 18 days, which is one day shorter than the initial nourishment. When the nourishment is executed in the off-season (May and June), then this hindrance will be minimised.

In Figure J- 2 the Gantt chart for the regular nourishment is presented. Like in the previous Gantt chart, the blue bars represent the critical path. There are still four grey colour bars, which do not directly influence the duration of the construction.

Compared with the previous Gantt chart, the proportional duration of the nourishment activity has been significantly grown. This is mainly caused by the reduced design and preparation phase, which could make use of the designs and actions from the previous nourishment.

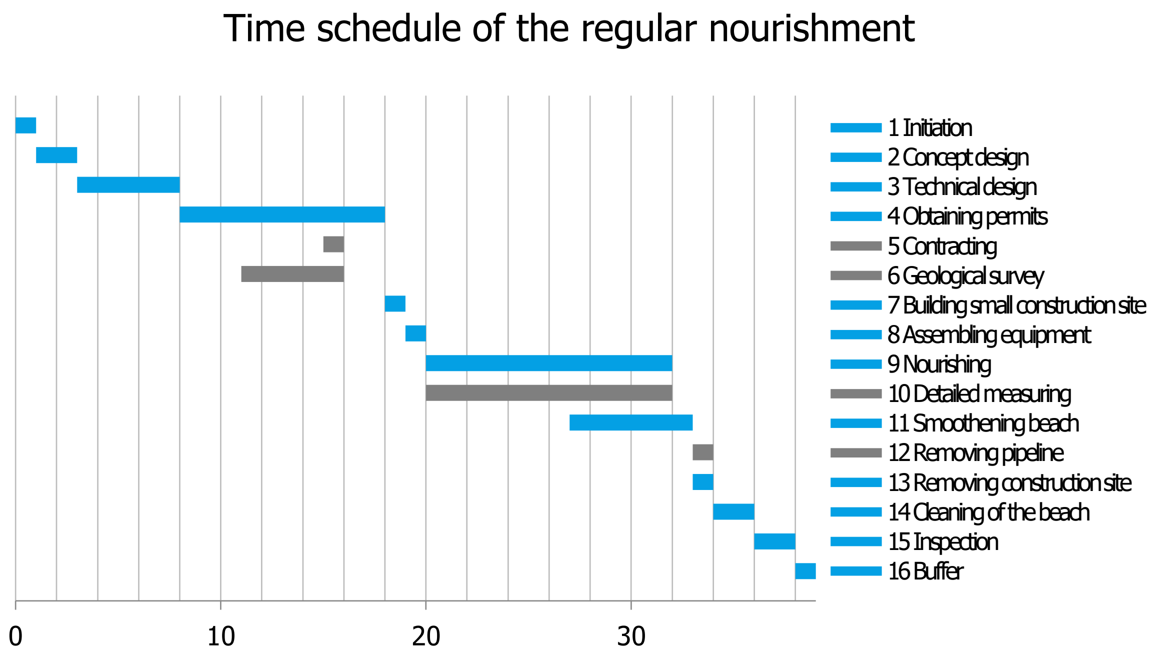

Figure J- 2 Gant chart for the regular nourishment

J.3 Additional nourishment

The additional nourishment has a quite small volume. This nourishment will be only executed when there is a severe damage of the nourishment by extreme conditions. As the total loss due to an extreme event cannot be more than 20,000 m^3, the additional nourishment consists should be minimal 20,000 m^3. As there will be 20% of the sediment lost, a total nourishment volume of 24,000 m^3 will be nourished.

Due to the severe damage, there is not a lot of time to lose before the nourishment has to take place. Therefore several plans for these additional nourishments have to be made beforehand, which can be easily adjusted on the specific situation.

The preparation time should be reduced by reducing the contracting time and the geological survey. The obtaining time for permits should also be reduced by an arrangement that an additional nourishment is allowed to be executed when there is severe damage to a previous nourishment.

The construction phase is mostly reduced by the volume which should be nourished during this additional nourishment. This will take only three days, while it was for both other nourishments more than 10 days. The duration of the spreading out of the sand is also reduced as there is less sediment to spread out.

The finishing phase is somewhat shortened due to the smaller construction site.

The buffer time has been kept similar with the other nourishments as the conditions can be slightly heavier. As extreme events can take place year-round, the nourishment can also take place year-round and thus also in a period with heavier wave conditions.

In the Table J- 3 the duration of the activities, its relation to the other activities and the day of the activity are presented. It is chosen not to use dates as an extreme event (and thus an additional nourishment) can happen in every moment in the year.

ADDITIONAL NOURISHMENT				
Activity	**Duration**	**Relation**	**Start date**	**End date**
Design phase				
1 Initiation	1	-	day 1	day 1
2 Concept design	2	1	day 2	day 3
3 Technical design	3	2	day 4	day 6
Preparation phase				
4 Obtaining permits	1	3	day 7	day 7
5 Contracting	1	3	day 7	day 7
6 Geological survey	2	2	day 4	day 5
7 Building small construction site	0.5	4	day 8	day 8
8 Assembling equipment	1	4	day 8	day 8
Construction phase				
9 Nourishing	2.5	8	day 9	day 11
10 Detailed measuring	2.5	8	day 9	day 11
11 Smoothening beach	2	8	day 10	day 11
Finishing phase				
12 Removing pipeline	1	9	day 12	day 12
13 Removing construction site	0.5	11, 12	day 12	day 12
14 Cleaning of the beach	1	13	day 13	day 13
15 Inspection	2	14	day 14	day 14
Other				
16 Buffer	1	-	day 15	day 15
Total				**15 days**

Table J- 3 Duration of activities during the additional nourishment

It can be seen that the total time needed for the additional nourishment is only 15 days. This low number of days can be crucial to encounter the damage given by the extreme event. During this additional nourishment the beach has to be closed for 5 days, which is very short.

On the other hand, this could happen during the busy season with a lot of tourist in the hotel, but you have to take into account that this will happen approximately 10 times in 50 years.

In Figure J- 3 Gantt chart for the additional nourishment also a Gantt chart for the additional nourishment is presented. Like in the previous Gantt charts, the blue coloured bars are the critical path. In this nourishment there are five grey coloured bars, which are not part of the critical path.
Compared with the previous Gantt charts, the proportional duration of all activities has been quite normalised. This is mainly caused by the reduced design, preparation and construction phase, due to the great urgency and smaller volume of the additional nourishment.

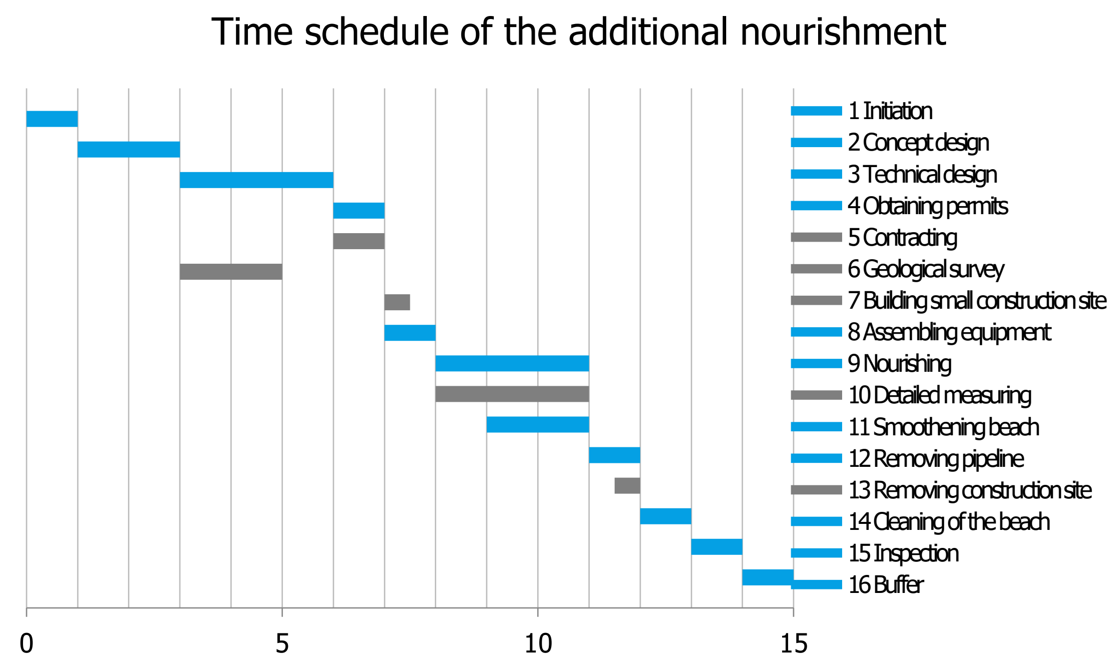

Figure J- 3 Gantt chart for the additional nourishment

J.4 Reshaping nourishment

The reshaping nourishment has the smallest overall volume of all nourishments (=10,000 m^3). This volume should be dredged from the foreshore and be dumped on the upper shore face in which way no sediment should be added to the active zone.

This nourishment will be only executed when there is a severe damage to the shape of the nourishment by extreme bad conditions, but no sediment is lost in the active zone in front of the Iberostar Varadero hotel. When this reshaping will not take place soon after the damage has been done, the nourishment could be easily destroyed during the next worse wave conditions.
Therefore the reshaping nourishment may not take too much time, so a short time planning will be preferred. This can be achieved when several plans for the reshaping nourishments should be made beforehand, when it already can be seen from the measurements that a reshaping nourishment could be needed.

In the design phase, preparation phase, finishing phase and buffer time the duration of the activities will be equal to the ones in the additional nourishment. This can be explained as both nourishments should be executed in a short time period, deal with relatively low sediment volumes and they both can take place year-round.

The duration of construction phase has been reduced due to the less required time for the reshaping nourishment. The smaller nourishment volume and time saving of the dredging vessel on sailing times to the borrowing zone is more effective than the smaller pumping capacity of the small dredging vessel. This results in a construction phase of just two days, the duration of the spreading out of the sand is also reduced to two days as less sediment has to be spread out.

In Table J- 4, the final table about the duration of the activities is shown. It also contains the relation to the other activities and the start and end day of the activity. Like in the table of the additional nourishment, it is chosen not to use dates as an extreme event can happen in every moment in the year. Therefore the reshaping nourishment is not fixed to a certain date.

RESHAPING NOURISHMENT				
Activity	**Duration**	**Relation**	**Start date**	**End date**
Design phase				
1 Initiation	1	-	day 1	day 1
2 Concept design	2	1	day 2	day 3
3 Technical design	3	2	day 4	day 6
Preparation phase				
4 Obtaining permits	1	3	day 7	day 7
5 Contracting	1	3	day 7	day 7
6 Geological survey	2	2	day 4	day 5
7 Building small construction site	0.5	4	day 8	day 8
8 Assembling equipment	1	4	day 8	day 8
Construction phase				
9 Nourishing	2	8	day 9	day 11
10 Detailed measuring	2	8	day 9	day 11
11 Smoothening beach	2	8	day 10	day 11
Finishing phase				
12 Removing pipeline	1	9	day 12	day 12
13 Removing construction site	0.5	11, 12	day 12	day 12
14 Cleaning of the beach	1	13	day 13	day 13
15 Inspection	2	14	day 14	day 14
Other				
16 Buffer	1	-	day 15	day 15
Total				**15 days**

Table J- 4 Gantt chart for the additional nourishment

It can be seen that the total time needed for the additional nourishment is equal to the additional nourishment (15 days). As the nourishment can be very urgent, it is a good thing that this period is relatively short. Like the additional nourishment, part of the beach of the Iberostar Varadero hotel should be closed 20 times during its lifetime for approximately 5 days.

In Figure J- 4 the last Gantt chart is presented. This Gantt chart shows the planning for the different activities of the reshaping nourishment. In this nourishment there are five grey colour bars, which are not part of the critical path.

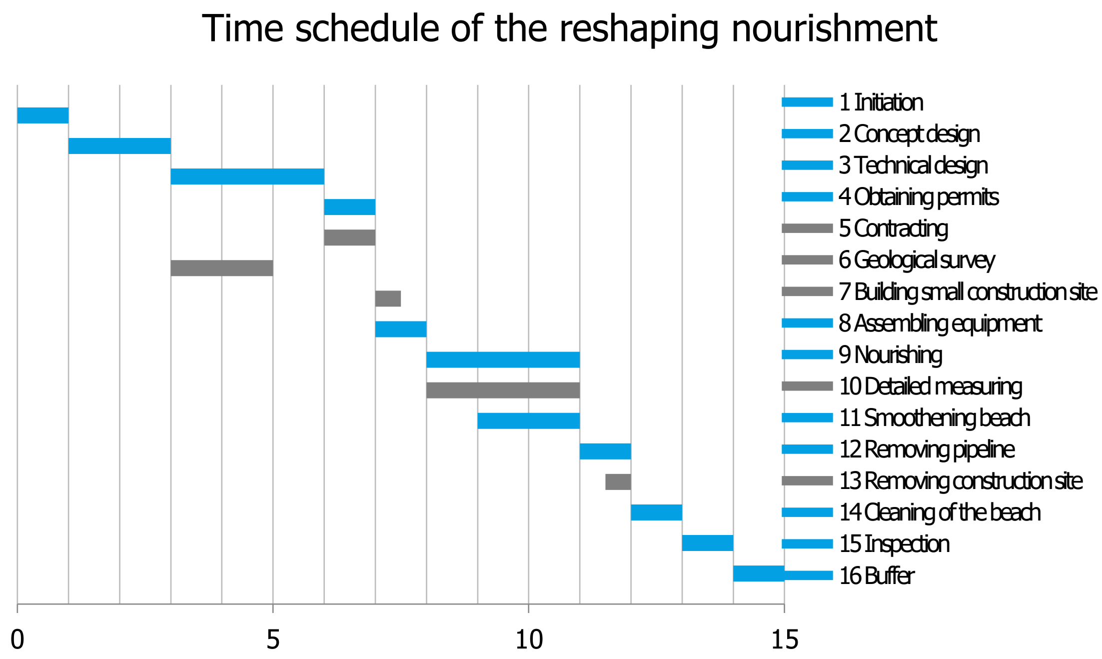

Figure J- 4 Gantt chart for the reshaping nourishment

J.5 Trailing Suction Hopper Dredger

In this section, all characteristics from the Trailing Suction Hopper Dredger (TSHD) owned by the Cuban government are presented.

Name	Quality Star
Year of construction	1981
Vessel type	TSHD
Length Over All	88.19 m
Width	16.62 m
Depth	7.01 m
Maximum draught	6.29 m
Dredging depth	22.3 m
Hopper volume	2,500 m^3
Pumping capacity mixture	5,000 m^3/hour
Sailing speed	6.6 m/s
Crew capacity	22 people, working 24/7 in three shifts

K. Financial

K.1 General costs

General costs of the initial nourishment

For the initial nourishment the global costs are calculated, which is done with help from the PRECONS [23]. It seemed that the total nourishment was equal to $ 1,2 million CUC. With a nourishment volume of 100,000 m^3 the cost per cubic meter sand will be set on 12 CUC/m^3. It is assumed that the borrowing zone is 16 nautical miles away from the nourishment area.

Activity	Unit	Quantity	Unit costs	Total costs
Dredging	100 m^3	1000	563.83	$ 563,830.00
Transporting	100 m^3 / NM	160000	13.54	$ 216,640.00
Nourishing	100 m^3	1000	387.08	$ 387,080.00
Spreading out	m^3	75000	0.59	$ 44,250.00
Total				$ 1,211,800.00

Table K- 1 General costs of the initial nourishment

General costs of the breakwater

The general costs of the breakwater will be showed in Table K- 2. It is assumed that the breakwater volume is 19837 m^3. The distance between the construction site and the breakwater location is assumed to be half a nautical mile, which results in a total distance of 1 nautical mile for the total cycle of the pontoon. The quarry is located at 60 kilometres distance from the project area nearby Cardenas. This results in a total distance of 120 kilometres. It is also assumed that the rocks have to be 4 times loaded (quarry -> truck, truck -> storage, storage -> pontoon and pontoon -> placement on breakwater). The total costs for the breakwater will be approximately $ 840,000 CUC.

Activity	Unit	Quantity	Unit costs	Total costs
Excavation from quarry	m^3	19837.00	6.43	$ 127,551.91
Transportation (first km)	100 m^3	198.37	80.52	$ 15,972.75
Transportation (> 1 km)	100 m^3 / km	23804.40	19.36	$ 460,853.18
Mechanically loading	m^3	79348.00	0.98	$ 77,761.04
Transporting on pontoon	100 m^3 / NM	198.37	770.75	$ 152,893.68
Total				$ 835,032.56

Table K- 2 General cost of the breakwater

K.2 Detailed cost of the nourishments

In the second part of the Appendix the cost estimation for the optimised nourishment will be presented. To be able to compute the total costs of the solution, the local costs should be known. The PRECONS II (2005) catalogue [23] will be used for all rules and values for the design costs and procedure costs.

First some additional information will be given about some specific financial aspects. This will be followed by the determination of the number of working hours per nourishment type. The information from PRECONS II will be summarised in the third part of this appendix. This will be concluded by the detailed cost estimation of the solution for the whole lifetime.

Additional information

This part contains some extra information about financial aspects in Cuba.

Inflation rate

The PRECONS II catalogue dates back to 2005. In the mean it is very likely that the prices have been raised by the inflation process. The inflation in Cuba can be averaged on 4% over the last 11 year, which leads to a modification factor due to inflation of 1.04.

Discount rate

The discount rate is a factor which is used to calculate the value of the money spent in the future. This can be calculated by dividing the interest rate by the inflation rate. The interest rate is also around 4%, but fluctuates a lot in Cuba. This heavily fluctuating interest rate will also result in a heavily fluctuating discount rate. As this is not useful, it is chosen not to use both discount and inflation rates.

Currency

Cuba has two different currencies. The Cuban pesos (CUP) is the national currency, while the Cuban dollar (CUC) is mainly used by tourist and is directly linked to the US Dollar. In the cost estimation it is chosen to use the Cuban Dollar, with the following rates:

- $ 1.00 CUC = $ 24.00 CUP
- $ 1.00 US Dollar = $ 1.03 CUP

Risks

Projects can take longer than estimated or can be costlier as previously calculated due to unforeseen events. This can be delays or wrong estimations. These risks can be reduced by reducing the probability or by reducing the consequences.

The probability can be reduced by obtaining buffers in the estimation. This could be done for the planning, but also for the costs. These unforeseen costs can be seen in the cost overview in Table K- 7 as element P6. Element 6.1 has been used for the wrong cost estimation.

The consequences can be reduced by having a good insurance (element P5 in Table K- 7). This protects the constructor and owner from very high costs due to an accident. It should also be considered that the project time can be estimated in a wrong way, which increases the costs for labour and equipment (element P6.2 in the overview of the costs in Table K- 7).

Working hours per nourishment

Before using the PRECON II-catalogue, the number of workers and working hours should be determined during every construction phase mentioned in the time planning. This is of importance to compute the labour costs in a later stage. The number of labour costs will be presented in the four tables below, representing the four types of nourishments.

Phase	Number of days	Working hours per day	Number of workers	Total number of working hours
Design	26	12	5	1,560
Preparation	22	12	20	5,280
Construction	14	24	35	11,760
Finishing	7	12	15	1,260
Total				19,860

Table K- 3 Number of working hours for initial nourishment

Phase	Number of days	Working hours per day	Number of workers	Total number of working hours
Design	8	12	5	480
Preparation	12	12	20	2,880
Construction	13	24	35	10,920
Finishing	6	12	15	1,080
Total				**15,360**

Table K- 4 Number of working hours for the regular nourishment

Phase	Number of days	Working hours per day	Number of workers	Total number of working hours
Design	6	12	5	360
Preparation	5	12	20	480
Construction	3	24	35	2,520
Finishing	3	12	15	540
Total				**3,900**

Table K- 5 Number of working hours for the additional nourishment

Phase	Number of days	Working hours per day	Number of workers	Total number of working hours
Design	6	12	5	360
Preparation	2	12	20	480
Construction	3	24	25	1,800
Finishing	3	12	15	540
Total				**3,180**

Table K- 6 Number of working hours for the reshaping nourishment

From the tables it can be clearly seen that most working hours are related to the initial nourishment as this is the biggest nourishment. The reshaping nourishment is the smallest one and therefore has the smallest number of working hours. It can also be seen that the number of workers is smaller during the construction phase in the reshaping nourishment. This is caused by the use of the smaller dredging vessel, which needs less crew on board.

PRECON procedure

According to PRECONS II (2005) [23], the total costs can be divided into two categories. These are the primary costs and the secondary costs. The primary costs are the costs which are directly related to the construction of the project. This includes the costs for material, equipment and labour. The secondary costs are specified as the costs for organisation and management of the project. This can be the construction site, material storage and transport of the material.

These two main groups in costs can be divided into several components. These are all kind of elements on which the total costs can be calculated. The components for the primary and secondary costs will be shown in Table K- 7. These costs also include risks, which is already explained earlier in this appendix.

Primary costs	
C1 Direct cost of material	Sum of all elements in C1
C2 Direct cost of labour	Sum of all elements in C2
C3 Direct cost of equipment	Sum of all elements in C3
C4 Direct cost of means of support and small materials	3% of (C1 + C2 + C3)
C5 Total direct costs	C1 + C2 + C3 + C4
C6 Indirect costs	29% of C5
C7 Total costs	C5 + C6
C8 Profit	20% of processing costs = 20% of (1.3 * (C2 + C3))
C9 Total primary cost	**C7 + C8**
Secondary costs	
P1 Temporary facilities	Sum of all elements in P1
P2 Transport	Sum of all elements in P2
P3 Other additional costs	Sum of all elements in P3
P4 Banking P 4.1 Interest salaries P 4.2 Interest investment	P 4.1 + P 4.2 10% of C2 2% of (C8 - C1)
P5 Insurance	10% of C5
P6 Unforeseen costs P 6.1 Wrong cost estimation P 6.2 Wrong time estimation	P 6.1 + P 6.2 2% of (C9 + P1 + P2 + P3) 2% of (C2 + C3)
P7 Total secondary costs	**P1 + P2 + P3 + P4 + P5 + P6**
T Total capital costs	**C9 + P7**

Table K- 7 Cost estimation procedure

This scheme will now be filled in for all four nourishment types. This results in a total cost estimation for all four of these nourishments.

Detailed cost per nourishment type

INITIAL NOURISHMENT	**Quantity**	**Price/unit**	**Costs**
Primary costs			
C1 Direct cost of material C 1.1 Sand	120.000 m^3	$ 5.00 / m^3	$ 600,000.00
			Total: $ 600,000.00
C2 Direct cost of labour C 2.1 Design phase C 2.2 Preparation phase C 2.3 Construction phase C 2.4 Finishing phase	1,560 hr 5,280 hr 11,760 hr 1,260 hr	$ 4.00 / hr $ 3.50 / hr $ 2.00 / hr $ 3.50 / hr	$ 6,240.00 $ 18,480.00 $ 23,520.00 $ 4,410.00
			Total: $ 52,650.00
C3 Direct cost of equipment C 3.1 Dredging vessel C 3.2 Pipeline C 3.3 Bulldozer (2x) C 3.4 Fuel (for 3 machines)	288 hr 1,000 m 336 hr 1,500 L	$ 17.62 / hr $ 2.00 / m $ 30.96 / hr / bulldozer $ 20.00 / L	$ 5,074.56 $ 2,000.00 $ 10,402.56 $ 30,000.00
			Total: $ 47,477.12
C4 Direct cost of means of support and small materials			Total: $ 21,003.81
C5 Total direct costs			Total: $ 721,130.93
C6 Indirect costs			Total: $ 209,127.97
C7 Total costs			Total: $ 930,258.90
C8 Profit			Total: $ 26,033.05
C9 Total primary cost			**Total: $ 956,291.95**
Secondary costs			
P1 Temporary facilities P 1.1 Toilets, warehouses, etc.	14 days	$ 480.00 / day	$ 6,720.00
			Total: $ 6,720.00
P2 Transport			Total: $ 0
P3 Other additional costs P 3.1 Cleaning, 10 persons	480 hr	$ 3.00 / hr / person	$ 1,440.00
			Total: $ 1,440.00
P4 Banking P 4.1 Interest salaries P 4.2 Interest investment			$ 5,255.00 $ 18,072.84
			Total: $ 23,337.84
P5 Insurance			Total: $ 72,113.09
P6 Unforeseen costs P 6.1 Wrong cost estimation P 6.2 Wrong time estimation			$ 19,289,04 $ 2,002.54
			Total: $ 21,291.58
P7 Total secondary costs			**Total: $ 124,902.51**
T Total capital costs			**Total: $ 1,091,294.47**

Table K- 8 Total cost of the initial nourishment

REGULAR NOURISHMENT	**Quantity**	**Price/unit**	**Costs**
Primary costs			
C1 Direct cost of material C 1.1 Sand	102.000 m^3	\$ 5.00 / m^3	\$ 510,000.00
			Total: \$ 510,000.00
C2 Direct cost of labour C 2.1 Design phase C 2.2 Preparation phase C 2.3 Construction phase C 2.4 Finishing phase	 480 hr 2,880 hr 10,920 hr 1,080 hr	 \$ 4.00 / hr \$ 3.50 / hr \$ 2.00 / hr \$ 3.50 / hr	 \$ 1,920.00 \$ 10,080.00 \$ 21,840.00 \$ 3,780.00
			Total: \$ 37,620.00
C3 Direct cost of equipment C 3.1 Dredging vessel C 3.2 Pipeline C 3.3 Bulldozer (2x) C 3.4 Fuel (for 3 machines)	 264 hr 1,000 m 288 hr 1,300 L	 \$ 17.62 / hr \$ 2.00 / m \$ 30.96 / hr / bulldozer \$ 20.00 / L	 \$ 4,651.68 \$ 2,000.00 \$ 8,916.48 \$ 26,000.00
			Total: \$ 41,568.16
C4 Direct cost of means of support and small materials			Total: \$ 17,675.64
C5 Total direct costs			Total: \$ 606,863.81
C6 Indirect costs			Total: \$ 175,990.50
C7 Total costs			Total: \$ 782,854.31
C8 Profit			Total: \$ 20,588.92
C9 Total primary cost			**Total: \$ 803,443.23**
Secondary costs			
P1 Temporary facilities P 1.1 Toilets, warehouses, etc.	13 days	\$ 480.00 / day	\$ 6,240.00
			Total: \$ 6,240.00
P2 Transport			Total: \$ 0
P3 Other additional costs P 3.1 Cleaning, 10 persons	480 hr	\$ 3.00 / hr / person	\$ 1,440.00
			Total: \$ 1,440.00
P4 Banking P 4.1 Interest salaries P 4.2 Interest investment			 \$ 3,762.00 \$ 15,316.46
			Total: \$ 19,078.46
P5 Insurance			Total: \$ 60,686.38
P6 Unforeseen costs P 6.1 Wrong cost estimation P 6.2 Wrong time estimation			 \$ 16,222,46 \$ 1,583.76
			Total: \$ 17,806.23
P7 Total secondary costs			**Total: \$ 105,251.07**
T Total capital costs			**Total: \$ 908,694.30**

Table K- 9 Total cost of the regular nourishment

ADDITIONAL NOURISHMENT	Quantity	Price/unit	Costs
Primary costs			
C1 Direct cost of material			
C 1.1 Sand	24.000 m^3	\$ 5.00 / m^3	\$ 120,000.00
			Total: \$ 120,000.00
C2 Direct cost of labour			
C 2.1 Design phase	360 hr	\$ 4.00 / hr	\$ 1,440.00
C 2.2 Preparation phase	480 hr	\$ 3.50 / hr	\$ 1,680.00
C 2.3 Construction phase	2,520 hr	\$ 2.00 / hr	\$ 5,040.00
C 2.4 Finishing phase	540 hr	\$ 3.50 / hr	\$ 1,890.00
			Total: \$ 10,050.00
C3 Direct cost of equipment			
C 3.1 Dredging vessel	60 hr	\$ 17.62 / hr	\$ 1,057.20
C 3.2 Pipeline	1,000 m	\$ 2.00 / m	\$ 2,000.00
C 3.3 Bulldozer (2x)	96 hr	\$ 30.96 / hr / bulldozer	\$ 2,972.16
C 3.4 Fuel (for 3 machines)	500 L	\$ 20.00 / L	\$ 10,000.00
			Total: \$ 16,029.36
C4 Direct cost of means of support and small materials			Total: \$ 4,382.38
C5 Total direct costs			Total: \$ 150,461.74
C6 Indirect costs			Total: \$ 43,633.90
C7 Total costs			Total: \$ 194,095.65
C8 Profit			Total: \$ 6,780.63
C9 Total primary cost			**Total: \$ 200,876.28**
	Quantity	**Price/unit**	**Costs**
Secondary costs			
P1 Temporary facilities			
P 1.1 Toilets, warehouses, etc.	3 days	\$ 480.00 / day	\$ 1,440.00
			Total: \$ 1,440.00
P2 Transport			Total: \$ 0
P3 Other additional costs			
P 3.1 Cleaning, 10 persons	240 hr	\$ 3.00 / hr / person	\$ 720.00
			Total: \$ 720.00
P4 Banking			
P 4.1 Interest salaries			\$ 1,005.00
P 4.2 Interest investment			\$ 3,816.53
			Total: \$ 4,821.53
P5 Insurance			Total: \$ 15,046.17
P6 Unforeseen costs			
P 6.1 Wrong cost estimation			\$ 4,060,73
P 6.2 Wrong time estimation			\$ 521.59
			Total: \$ 4,582.31
P7 Total secondary costs			**Total: \$ 26,610.01**
T Total capital costs			**Total: \$227,486.29**

Table K- 10 Total cost of the additional nourishment

RESHAPING NOURISHMENT	**Quantity**	**Price/unit**	**Costs**
Primary costs			
C1 Direct cost of material C 1.1 Sand	0 m³	$ 5.00 / m³	$ 0
			Total: $ 0
C2 Direct cost of labour C 2.1 Design phase C 2.2 Preparation phase C 2.3 Construction phase C 2.4 Finishing phase	 1,560 hr 5,280 hr 11,760 hr 1,260 hr	 $ 4.00 / hr $ 3.50 / hr $ 2.00 / hr $ 3.50 / hr	 $ 1,440.00 $ 1,680.00 $ 3,600.00 $ 1,890.00
			Total: $ 8,610
C3 Direct cost of equipment C 3.1 Dredging vessel C 3.2 Pipeline C 3.3 Bulldozer (2x) C 3.4 Fuel (for 3 machines)	 288 hr 1,000 m 336 hr 1,500 L	 $ 17.62 / hr $ 2.00 / m $ 30.96 / hr / bulldozer $ 20.00 / L	 $ 845.76 $ 2,000.00 $ 2,972.16 $ 6,000.00
			Total: $ 11,817.92
C4 Direct cost of means of support and small materials			Total: $ 612.84
C5 Total direct costs			Total: $ 21,040.76
C6 Indirect costs			Total: $ 6,101.82
C7 Total costs			Total: $ 27,142.58
C8 Profit			Total: $ 5,311.26
C9 Total primary cost			**Total: $ 32,453.84**
	Quantity	**Price/unit**	**Costs**
Secondary costs			
P1 Temporary facilities P 1.1 Toilets, warehouses, etc.	3 days	$ 480.00 / day	$ 1,440.00
			Total: $ 1,440.00
P2 Transport			Total: $ 0
P3 Other additional costs P 3.1 Cleaning, 10 persons	240 hr	$ 3.00 / hr / person	$ 720.00
			Total: $ 720.00
P4 Banking P 4.1 Interest salaries P 4.2 Interest investment			 $ 861.00 $ 476.88
			Total: $ 1,337.87
P5 Insurance			Total: $ 2,104.08
P6 Unforeseen costs P 6.1 Wrong cost estimation P 6.2 Wrong time estimation			 $ 692.28 $ 408.56
			Total: $ 1,100.84
P7 Total secondary costs			**Total: $ 6,702.79**
T Total capital costs			**Total: $ 39.156,62**

Table K- 11 Total cost of the reshaping nourishment

Total cost estimation for the entire lifetime

At this point all four nourishments have been calculated in detail. With the help from the formula from section 6.6, the costs for the total lifetime can be calculated. This formula has been adjusted as the detailed costs are now known. The new formula for the total costs are presented below.

$$C_{N_{50}} = C_0 * N_0 + C_R * N_R + C_A * N_A + C_{RE} * N_{RE} + B$$

Where:

C_{N50}	Costs of final solution for 50 years	[\$]
C_0	Costs of one initial nourishment	[\$/m^3]
C_R	Costs of one regular nourishment	[\$/m^3]
C_A	Costs of one additional nourishment	[\$/m^3]
C_{RE}	Costs of one reshaping nourishment	[\$/m^3]
N_0	Amount of initial nourishments in 50 years	[-]
N_R	Amount of regular nourishments in 50 years	[-]
N_A	Amount of additional nourishments in 50 years	[-]
N_{RE}	Amount of reshaping nourishments in 50 years	[-]
B	Buffer costs for extra additional/reshaping nourishments	[-]

In chapter 6 it was already determined that the initial nourishment should only be executed once. The regular nourishment should be executed every 5 years after the initial nourishments, which results in 9 regular nourishments. The additional nourishments should on average also be executed every 5 years, which results in approximately 10 additional nourishments. The reshaping nourishment should be executed 2 times in every five years on average, which results is approximately 20 reshaping nourishments. The buffer costs are added in order to be able to pay extra additional or reshaping nourishments in case of bad conditions during the lifetime. For this purposes it is chosen on $500,000.

This will in the end lead to the following formula:

$$C_{N_{50}} = 1{,}091{,}294.47 * 1 + 908{,}694.30 * 9 + 227{,}486.29 * 10 + 39{,}156 * 20 + 500{,}000$$
$$= 12{,}827{,}538.47 \approx \$\ 12.8\ \text{million}$$

The final solution will cost approximately 12.8 million CUC. When divided by the lifetime, the maintenance of the beach costs $ 256,550.77 per year.

L. Scripts and Input files

L.1 XBeach1D: params.txt

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% XBeach parameter settings input file
%%%
%%% XBeach1D Input File MP210
%%% function: xb_write_params
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Flow boundary condition parameters
front        = abs_1d              >>1D grid so run in 1D mode
back         = abs_1d

%%% Grid parameters
depfile      = name_of_file.dep    >>File with the bed levels
posdwn       = -1                  >>Bed levels below MSL are negative values
nx           = 141
ny           = 0                   >>1D mode so specify ny=0
alfa         = 330
vardx        = 1
thetamin     = -150
thetamax     = 90
dtheta       = 10
thetanaut    = 1
gridform     = xbeach
xfile        = name_of_file.grd    >>File with the x-locations of the bed levels (nx+1)
yfile        = name_of_file.grd    >>File with (nx+1) zeroes

%%% Model time
tstop        = 86400               >>Morphological time in seconds, dependent on run
```

```
%%% Morphology parameters
morfacopt      = 1                    >>Specify times in morphological time (default)
morfac         = 10                   >>Morphological scale factor
D50            = 0.00027              >>D50 in m
D90            = 0.00074              >>D90 in m
rhos           = 2700                 >>Density of sediment in kg/m3

%%% Tide boundary conditions
zs0file        = name_of_file.txt     >>Text file with specified water level/tide
tideloc        = 1                    >>One input
%%% Wave boundary condition parameters
instat         = jons/jons_table      >> jons for 1 condition, jons_table for time-
varying

%%% Wave-spectrum boundary condition parameters
nspectrumloc  = 1                     >>Number of input spectrum locations
bcfile         = name_of_file.txt     >>Text file with Jonswap spectrum
random         = 0
rt                   = 7200           >>Is ignored when instat=jons_table
dtbc           = 1

%%% Friction Parameters
bedfriction    = chezy
bedfriccoef    = 68                   >> Chézy value in m1/2/s

%%% Coriolis parameters
lat=23                                >>Latitude of Cuba in degrees North

%%% Output variables
outputformat  = netcdf/fortran        >>netcdf for Quickplot, fortran for Matlab
processing
tintm          = 3600
tintp          = 30
tintg          = 300
tstart         = 0

nglobalvar   = 13
zb
zs
u
```

```
ue
v
ve
Fx
Fy
Susg
Svsg
sedero
dzav
H

nmeanvar     = 6
zs
u
ue
v
ve
H

npointvar    = 6
zs
u
ue
v
ve
H

npoints      = 3
2668.87523663402        0       %%% Surfzone
2419.65323167164        0       %%% Large bar
1491.69261796715        0       %%% 5m water depth
```

L.2 XBeach2D: params.txt

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%% XBeach parameter settings input file
%%%%
%%%% XBeach2D Input File MP210
%%%% function: xb_write_params
%%%% Flow boundary condition parameters
front          = abs_2d                >>2D grid so run in 2D mode
back           = abs_2d

%%%% Grid parameters
depfile        = name_of_file.dep      >>File with the bed levels, made by QUICKINN
posdwn         = 1                     >>Bed levels below MSL are positive values now
alfa           = 0
xori           = 4.81787470E+05        >>x-coordinate of the (0,0) gridpoint
yori           = 3.74866894E+05        >>y-coordinate of the (0,0) gridpoint
vardx          = 1
thetamin       = -150
thetamax       = 90
dtheta         = 10
thetanaut      = 1
gridform       = delft3d
xyfile         = name_of_file.grd      >>File containing the grid made by RGFGRID

%%%% Model time
tstop          = 86400

%%%% Morphology parameters
morfacopt      = 1
morfac         = 10
D50            = 0.00027
D90            = 0.00074
rhos           = 2700

%%%% Tide boundary conditions
zs0file        = name_of_file.txt      >>Text file with specified water level/tide
tideloc        = 1                     >>One input

%%%% Wave boundary condition parameters
```

instat = swan >>Wave conditions created by Delft3D_WAVE are read as .sp2 files

%%% Wave-spectrum boundary condition parameters
nspectrumloc = 3 >>Number of input spectrum locations
bcfile = loclist.txt >>Locations are specified in a separate file, multiple wave conditions per boundary location can be inserted by referencing to a separate 'filelist.txt' file containing the wave conditions
random = 0

%%% Friction Parameters
bedfriction = chezy
bedfriccoef = 68

%%% Coriolis parameters
lat=23 >>Latitude of Cuba in degrees North

%%% Output variables
outputformat = fortran >>only fortran is used now
tintm = 3600
tintp = 30
tintg = 600
tstart = 0

nglobalvar = 8
zb
zs
u
v
sedero
H
Svtot
Sutot

nmeanvar = 6
zs
u
v
H
Svtot
Sutot

L.3 MATLAB: Post-processing cross-sections

```
%%% Program for post-processing XBeach2D results
%%% Written by project group MP210 ('Varadero Beach Erosion Project')
%%%
%%% Code can be used for plotting cross-sections and sedimentation/erosion
%%% patterns as well as calculating sediment budgets, shoreline movements
and beach widths
%%%
%%% Legend of used XBeach fortran output files (.dat):
%%%     dims file:
%%%         nt= number of timesteps
%%%         nx= number of points in x-direction
%%%         ny= number of points in y-direction
%%%         xy= file consisting the used grid points
%%%     xy= grid file
%%%     H = wave height (Hrms)
%%%     zs= sea surface elevation wrt mean sea level
%%%     zb= bed level elevation wrt mean sea level
%%%     sedero = cumulative sedimentation/erosion
clear;
%zb=0 coordinate: IBE19(left)=(483250, 374100>> y=47, BE11(middle)=(483430,
374190)>>y=66, IBE1(right)=(483670, 374320)>> y=92
cross=66; %choose where you want to make the cross-section.

fid=fopen('dims.dat','r');
nt=fread(fid,(1),'double'); nx=fread(fid,(1),'double');
ny=fread(fid,(1),'double');
fclose(fid);
fixy=fopen('xy.dat','r');
ax=fread(fid,[nx+1,ny+1],'double');
xx=ax(:,cross);
ay=fread(fid,[nx+1,ny+1],'double');
y=ay(:,cross);
xx0=xx(1); y0=y(1);
x=sqrt( (xx(:)-xx0).^2 + (y(:)-y0).^2); %x now represents a path distance
from the offshore boundary point
fclose(fixy);

%%% Personal input
tintg=600; %timestep (seconds) in which XBeach produces output (tintg)
tstop=tintg*(nt-1);
xleft=800; %left boundary for plots
xright=1375; %right boundary for plots

%%%Creating the figure with time varying zs, zb, H and initial zb
figure(1);
fiH=fopen('H.dat','r'); fizb=fopen('zb.dat','r'); fizs=fopen('zs.dat','r');

 for i=1:nt;
    aH=fread(fiH,[nx+1,ny+1 ],'double');
    H=aH(:,cross);
    azb=fread(fizb,[nx+1,ny+1],'double');
    zb=azb(:,cross);
    azs=fread(fizs,[nx+1,ny+1],'double');
    zs=azs(:,cross);
    zs(find(H==0))=0;
```

```
    if i==1;
        zb0=zb;
    end
    if i==nt;
        zbend=zb;
    end
    plot(x, H, 'g');
    hold on
    plot(x, zb0, 'k');
    hold on
    plot(x,zb, 'r');
    hold on
    plot(x,zs, 'b');
    hold on
    axis([xleft xright -5 5])
    grid
    set(gca, 'PlotBoxAspectRatio', [2 1 1]);
    title({'Bedlevel change in time, nearshore at IBE11',[num2str((i-
1)*tintg/3600) ' hrs']},'fontsize',10);
    xlabel('Distance along cross-section(m)','fontsize',10)
    ylabel('Elevation wrt mean sea level(m)','fontsize',10)
    drawnow;
    hold off
    legend('Hrms','zb0', 'zb','zs');
 end
fname=strcat(num2str(116000+i),'.gif'); print('-djpeg',fname);
fname2=strcat(num2str(2116000+i),'.fig'); print('-djpeg',fname2);

%%%Creating the figure of cumulative sedimentation/erosion
figure(2);
fisedero=fopen('sedero.dat','r');

for m=1:nt;
    asedero=fread(fisedero,[nx+1,ny+1],'double');
    sedero=asedero(:,cross);
    plot(x, sedero, 'r');
    axis([xleft xright -3.5 2.5])
    grid
    set(gca, 'PlotBoxAspectRatio', [2 1 1]);
    title({'Cumulative sedimentation/erosion, nearshore at
IBE11',[num2str((m-1)*tintg/3600) ' hrs']},'fontsize',10);
    xlabel('Distance along cross-section(m)','fontsize',10)
    ylabel('Cum. sedimentation/erosion(m)','fontsize',10)
    drawnow;
    hold off
end
fname3=strcat(num2str(117000+i),'.gif'); print('-djpeg',fname3);
fname4=strcat(num2str(117000+i),'.fig'); print('-djpeg',fname4);
fclose(fiH); fclose(fizb); fclose(fizs); fclose(fisedero);

%%% Calculation of sediment budgets within cross-section
dx=zeros(length(zb0),1);
dif=zeros(length(zb0),1);
a=zeros(length(zb0),1);
area=zeros(length(zb0),1);
sed=0;
ero=0;

for j=1:(length(zb0));
```

```
    dif(j)=zbend(j)-zb0(j);
    if dif(j)>0;
        a(j)=1;
    elseif dif(j)<0;
        a(j)=-1;
    end
end

for k=1:(length(zb0)-1);
    dx(k+1)=x(k+1)-x(k);
    area(k+1)=0.5*(dif(k)+dif(k+1))*dx(k+1);
end

for l=1:(length(zb0));
    if a(l)>=0;
        sed=sed+area(l);
    elseif a(l)<0;
        ero=ero+area(l);
    end
    total=sed+ero;
end
display(['Total sedimentation (m3/m)= ',num2str(sed)])
display(['Total erosion (m3/m)= ',num2str(ero)])
display(['Total balance (m3/m)= ',num2str(total)])

%%%Determening shoreline(0m zb height) and beachline(1m zb height) movement
wrt mean sea level and corresponding beach widths
b=zeros(length(zb0),1); c=zeros(length(zbend),1); d=zeros(length(zb0),1);
e=zeros(length(zbend),1);
inter_0=0; inter_end=0;
beach_0=0; beach_end=0;
zb1_0=zeros(length(zb0),1); zb1_end=zeros(length(zbend),1);
waterline_0=0; waterline_end=0;
beachline_0=0; beachline_end=0;
n_water_0=0; n_water_end=0;
n_beach_0=0; n_beach_end=0;

for p=1:(length(zb1_0));
    zb1_0(p)=zb0(p)-1.01; % to find the intersection point with 1m beach
height
    zb1_end(p)=zbend(p)-1.01; %to find the intersection point with 1m beach
height
end

for n=1:(length(zb0)-7);% '7' has to be adapted to profile, it has to be
prevented that the +1m zb value is crossed twice
    b(n)=(zb0(n+1)/abs(zb0(n+1))) * (zb0(n)/abs(zb0(n)));
    c(n)=(zbend(n+1)/abs(zbend(n+1))) * (zbend(n)/abs(zbend(n)));
    d(n)=(zb1_0(n+1)/abs(zb1_0(n+1))) * (zb1_0(n)/abs(zb1_0(n)));
    e(n)=(zb1_end(n+1)/abs(zb1_end(n+1))) * (zb1_end(n)/abs(zb1_end(n)));

    if b(n)<0;
        waterline_0= x(n)+abs(zb0(n))*1/((zb0(n+1)-zb0(n)) / (x(n+1)-
x(n)));
        n_water_0=n;
    end
    if c(n)<0;
        waterline_end= x(n)+abs(zbend(n))*1/((zbend(n+1)-zbend(n)) /
(x(n+1)-x(n)));
```

```
        n_water_end=n;
    end
    if d(n)<0;
        beachline_0= x(n)+abs(zb1_0(n))*1/((zb0(n+1)-zb0(n)) / (x(n+1)-
x(n)));
        n_beach_0=n;
    end
    if e(n)<0;
        beachline_end= x(n)+abs(zb1_end(n))*1/((zbend(n+1)-zbend(n)) /
(x(n+1)-x(n)));
        n_beach_end=n;
    end
end

len_0=(n_beach_0 - n_water_0);
len_end=(n_beach_end - n_water_end);
f_0= sqrt( (x(n_water_0 +1) - waterline_0)^2 + (zb0(n_water_0 +1) -0 )^2 );
f_end= sqrt( (x(n_water_end +1) - waterline_end)^2 + (zbend(n_water_end +1)
-0 )^2);
g_0= sqrt( (beachline_0 - x(n_beach_0) )^2 + (1 - zb0(n_beach_0))^2);
g_end= sqrt( (beachline_end - x(n_beach_end))^2 + (1 - zbend(n_beach_end
))^2);

if  len_0>0;
    for q=1:(len_0 -1);
        inter_0= inter_0 + sqrt( (x(n_water_0 +q +1) - x(n_water_0 +q))^2 +
(zb0(n_water_0 +q +1) -zb0(n_water_0 +q))^2 );
    end
        beach_0=inter_0+f_0+g_0;
elseif  len_0 == 0;
        beach_0= sqrt( (beachline_0 - waterline_0)^2 + (1-0)^2 );
end

if  len_end>0;
    for r=1:(len_end -1);
        inter_end= inter_end + sqrt( (x(n_water_end +r +1) - x(n_water_end
+r))^2 + (zbend(n_water_end +r +1) - zbend(n_water_end +r))^2 );
    end
    beach_end=inter_end+f_end+g_end;
elseif  len_end==0;
    beach_end= sqrt( (beachline_end - waterline_end)^2 + (1-0)^2 );
end

for a=1:length(dif);
    if abs(dif(a))>0 ; %%% first location and depth of erosion
        display(['No bedlevel change offshore from x= ',num2str(x(a)),'m,
with water depth= ',num2str(zbend(a)),'m  >> no loss of sediment in cross-
shore direction from here'])
        break
    end
end
for a=1:length(dif);
    if abs(dif(a))>0.001 ; %%% location and depth of first real noticable
erosion when difference> 1mm
        display(['First real noticable erosion= ', num2str(waterline_0 -
x(a)),'m away from the coast, with water depth= ',num2str(zbend(a)),'m '])
        break
    end
end
```

```
waterline_balance=waterline_0-waterline_end; %%%(m) positive is advance of
shoreline
beachincrease=beach_end-beach_0;
display(['Advance of shoreline= ',num2str(waterline_balance), 'm (negative
is erosion)'])
display(['Initial beach width= ',num2str(beach_0), 'm '])
display(['Final beach width= ',num2str(beach_end), 'm '])
display(['Beach width increase= ',num2str(beachincrease), 'm '])
```

M. Additional empirical relations

In this report several times some simple empirical formulas are used in order to compute / estimate certain values. These formulas are explained in this appendix a little bit more.

A remark has to be made that these formulas are a first rough estimation and are only used to estimate certain values in order to be able to compare some results. It is a possibility that relatively large errors are induced by using these formulas.

M.1 Bruun and Dean

Bruun (1954) proposed an empirical formulation for an equilibrium beach profile:

$$h = A(x')^m$$

Where:

h	water depth	[m]
m	exponent (=2/3)	[-]
A	shape factor	[-]
x'	offshore distance (water line, x'=0)	[m]

A remark about the Bruun equation is that this profile leads to a vertical slope around the water line. This is not in accordance with reality. The shape factor A determines the steepness of the slope. A large shape factor, induces a steeper slope. The shape factor is empirical related by Moore (1982) to the D_{50}, coarser grains induce a larger shape factor and therefore a steeper slope. Dean (1987) translated this empirical relation into a relation using the fall velocity w_s.

$$A = 0.5 w_s^{0.44}$$

Where:

w_s	fall velocity	[m/s]

This formulation can be used for engineering purposes, for instance when for a nourishment a different grain size is used. The fall velocity of the new grainsize has to be determined and with that value a new equilibrium profile can be compared with the current one.

M.2 Hallermeier

The active zone is the coastal area which is influenced by waves. Hallermeier (1978) defined the active zone as the surf zone width for extreme conditions which only occur 12 hours per year. From the Argoss data set that extreme wave condition is determined to be 4.26 meter.

The edge of the active zone is the closure depth. From this depth on it is assumed that changes have no effect on the coastal dynamics. A rough first estimate of this closure depth is to see at what depth the extreme wave conditions still break.

The depth at which this waves are breaking can be determined with the breaker index:

$$\gamma = \frac{H_b}{hb} \approx 0.78$$

Where:

γ	Breaker index	[-]
H_b	Significant wave height for breaking	[m]
h_b	Water depth for breaking	[m]

By using this formula, the depth at which the extreme waves break is 5.5 meter and therefore also the closure depth is assumed to be 5.5 meter.

M.3 Shoreline retreat – Nourishment volume

To be able to compare values, units of these values have to be equal.

During these project the amount of erosion needs to be compared several times. Sometimes the erosion is determined in terms of retreat of the waterline (m) and others by erosion volumes (m^3/m) in a cross-section.

These values can be converted by taking the equilibrium profile into account to compute the new volume (see Figure M- 1).

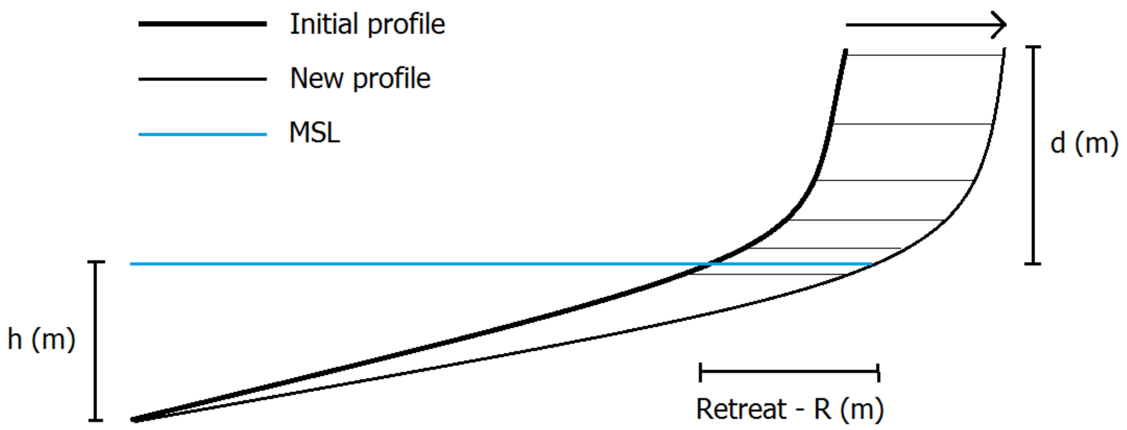

Figure M- 1 Converting shoreline retreat to erosion volumes

$$\Delta V = R * (d + h)$$

Where:

ΔV	Difference in equilibrium profile volume	[m^3/m]
R	Shoreline retreat	[m]
d	Dune height	[m]
h	Water depth at end active zone	[m]

The dune height d is known from the cross-shore measurements (see Appendix C): d ≈ 3 meter. For the underwater part, h is usually taken as the depth at the end active zone (Hallermeier). A rough first estimate for this value is obtained from the computation in Appendix **Fout! Verwijzingsbron niet gevonden.**. The water depth d is estimated on 5.5 meter.

By filling in the formula with the determined parameters, the relation between ΔV and R is eventually 8.5 (=5.5+3).

M.4 Sea Level Rise – Shoreline retreat

Sea level rise is a present problem and has an impact on the coastal area. To say something about this impact, it could be desired to express the Sea Level Rise in terms of shoreline retreat. The relative impact of the SLR is mainly dependent on the slope of the beach profile.

In Figure M- 2 all the relevant parameters are shown. The dune height d can be determined from measurements, which are relatively easy to measure. The underwater depth h is harder to determine. Usually this depth is taken as the active closure depth.

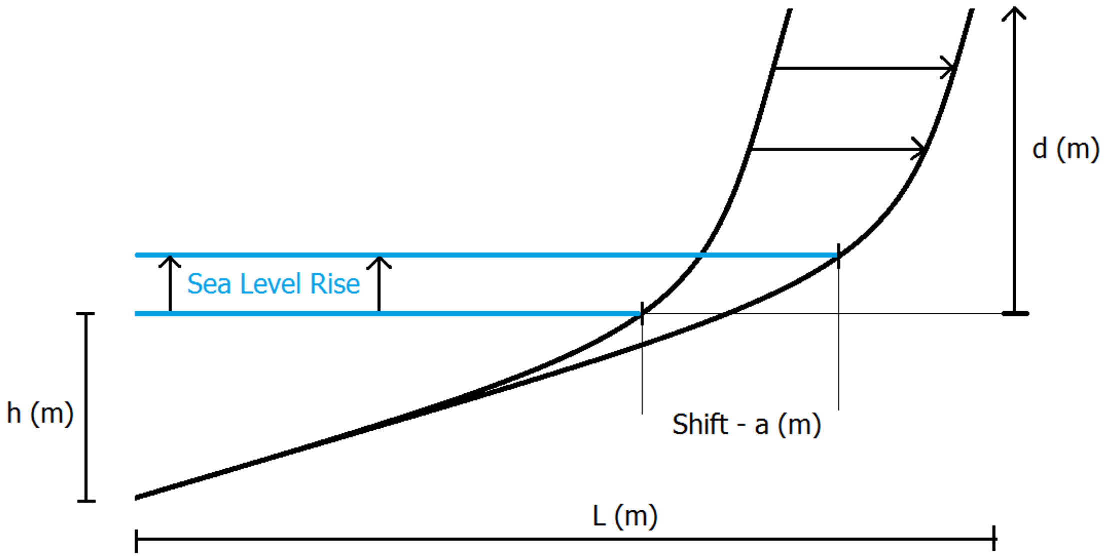

Figure M- 2 Sea Level Rise to shift of profile

The shifting a (m) of the profile due to the sea level rise can be calculated by:

$$a = \frac{SLR * L}{d + h}$$

Where:

a	Shifting of the profile	[m/y]
SLR	Sea Level Rise	[m/y]
L	Desired fill up length	[m]
d	Dune height	[m]
h	Water depth at end of fill up length L	[m]

N. XBeach modelling of the solution

In this appendix something will be said about the improved grid used in modelling the solutions and the results of modelling the current solution.

N.1 New XBeach grid

For uniformity and practicality reasons there has been chosen to use the same grid as for the Delft3D simulations for the solutions. In this way solutions can be directly modelled in both models without having to change anything. Details of the grid can be found in Appendix H.2, but the most important change is now that the curvilinear grid consists of 135 (longshore) by 120 (cross-shore) cells.

Furthermore the runtime is much shorter without losing resolution around the dunes and water line of Iberostar Hotel. Because the grid is changed, the calculated beach widths of Table G-7 are now slightly different. This can be explained by the fact that with a grid size of 4m, beaches of 10m width are more linearized than is the case in reality. In the figure below it can be seen that the beach length between 0 and 1 meter above MSL is captured by a few grid points. Because grid points are never exactly at 0 or 1m height, the beach length here is linearly interpolated. The result of this is that 100% exact calculations of beach widths are not possible, but that differences can be modelled adequately.

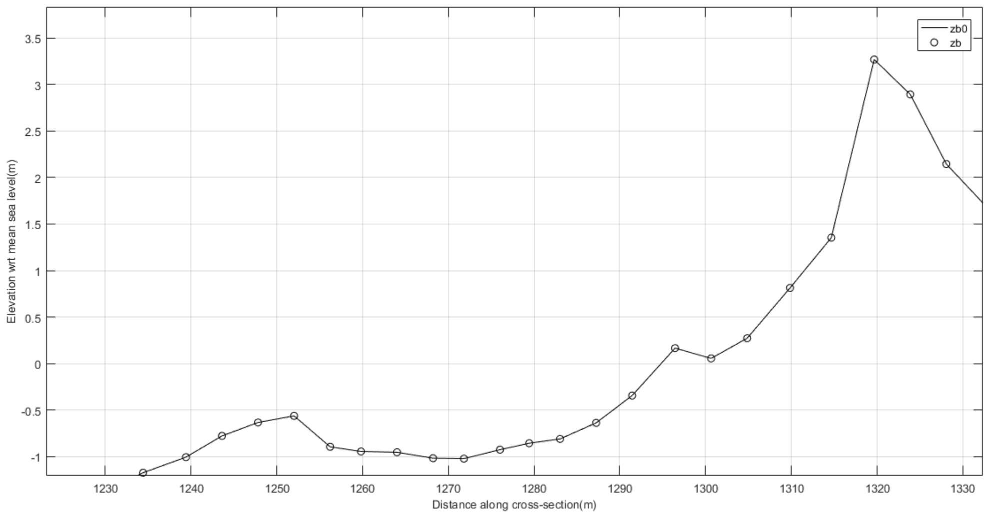

Figure N-1: grid resolution for IBE11 for Delft3D and XBeach small grid

Because the grid size for the new grid differs from the zero-state grid, the calculated beach width also differs. Because the new grid captures the beach area slightly better, the new calculated beach width is presented in Table N-1:

New beach widths in m:	
Left (IBE19)	6.1038
Middle (IBE11)	16.8513
Right (IBE1)	22.9621

Table N-1 New beach widths

N.2 Current solution under extreme events

Here the results for the current solution are given for the cold front north west and the hurricane Wilma.

Strong cold front north west

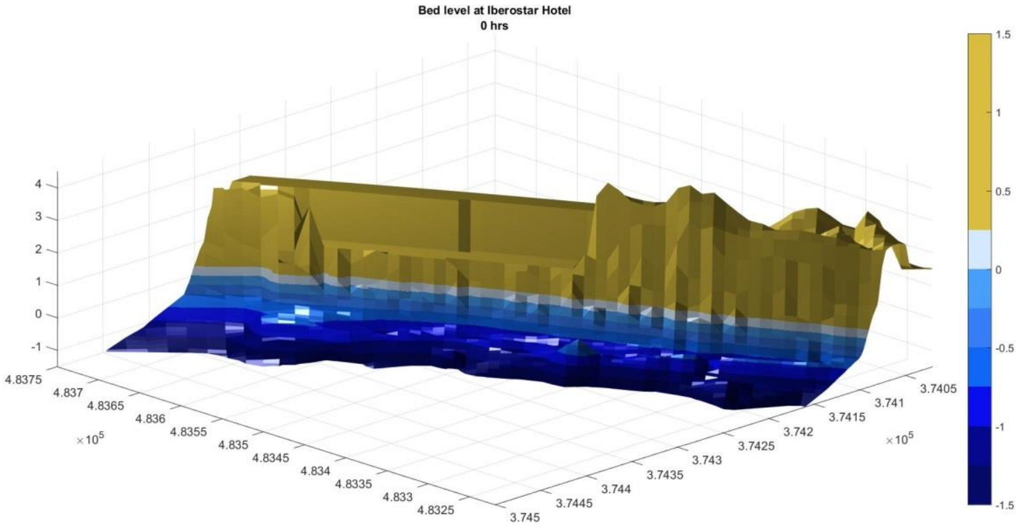

Figure N- 2 Bed levels current solution t=0 during a strong north west cold front

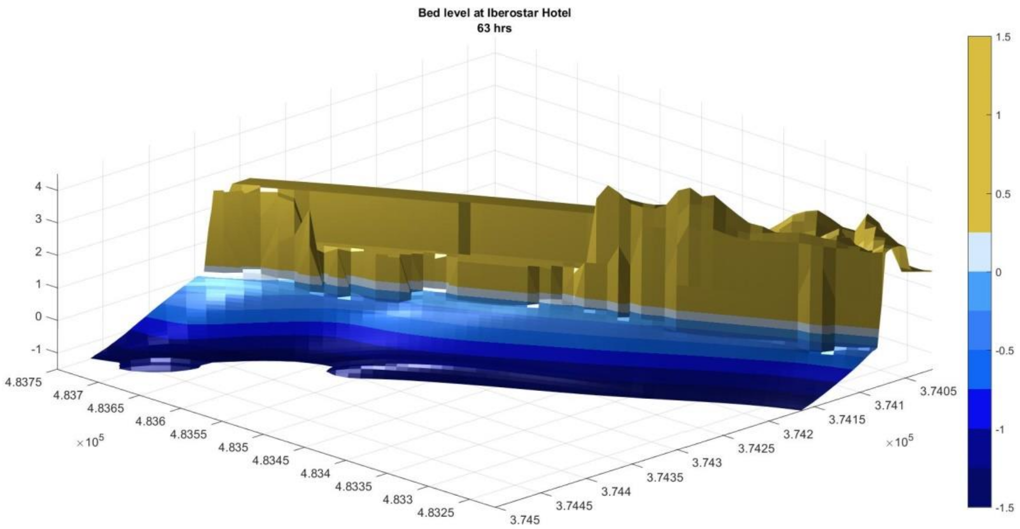

Figure N- 3 Bed levels current solution t=63 hrs during a strong north west cold front

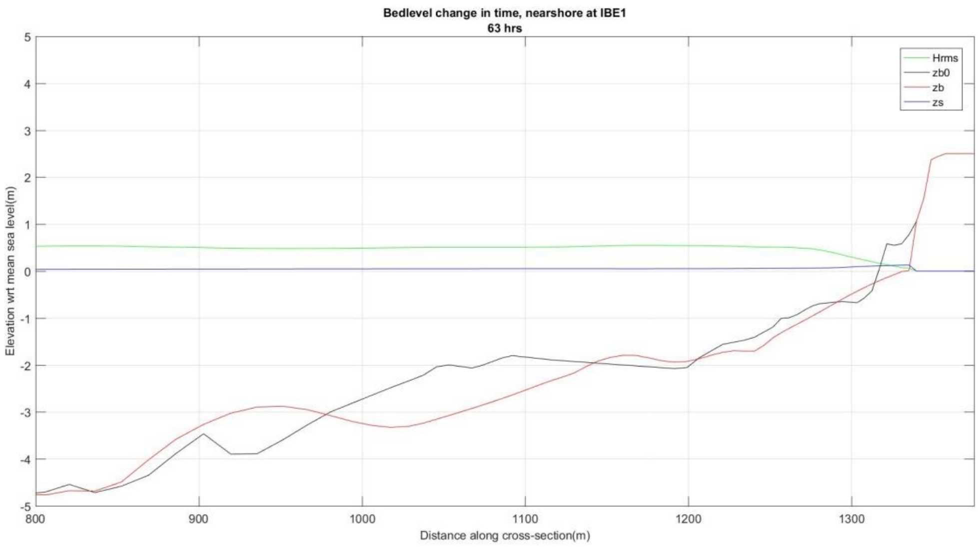

Figure N- 4 Bed levels current solution at IBE 1, t=63 hrs during a strong north west cold front

It can be seen that parts of the beach are almost completely eroded away. It has to be noticed that the made profile is not an exact representation of reality because no measurements are available. But it shows that the current solution is not optimal during strong conditions because the shape is far from equilibrium.

Hurricane Wilma

Note that the bathymetry is improved for this run compared to the cold front run.

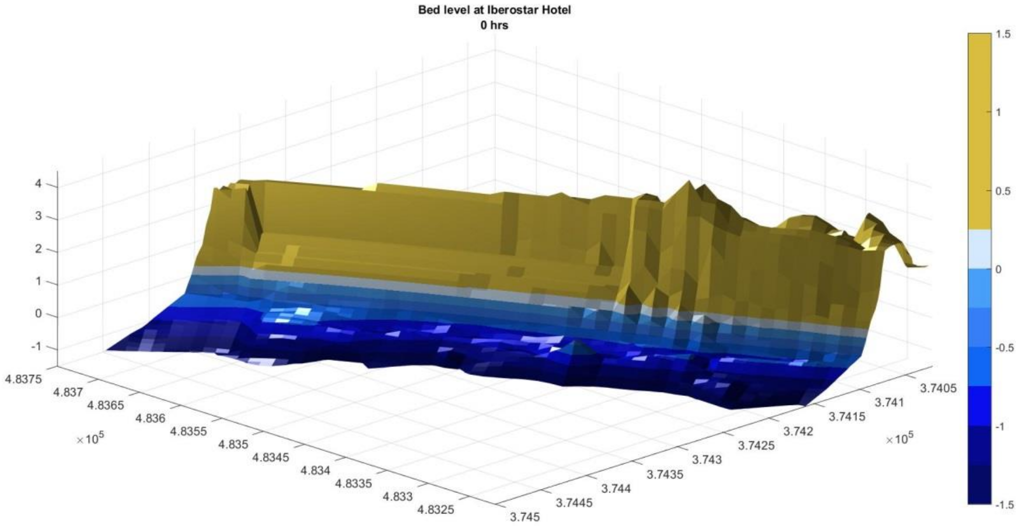

Figure N- 5 Bed levels current solution t=0 during hurricane Wilma

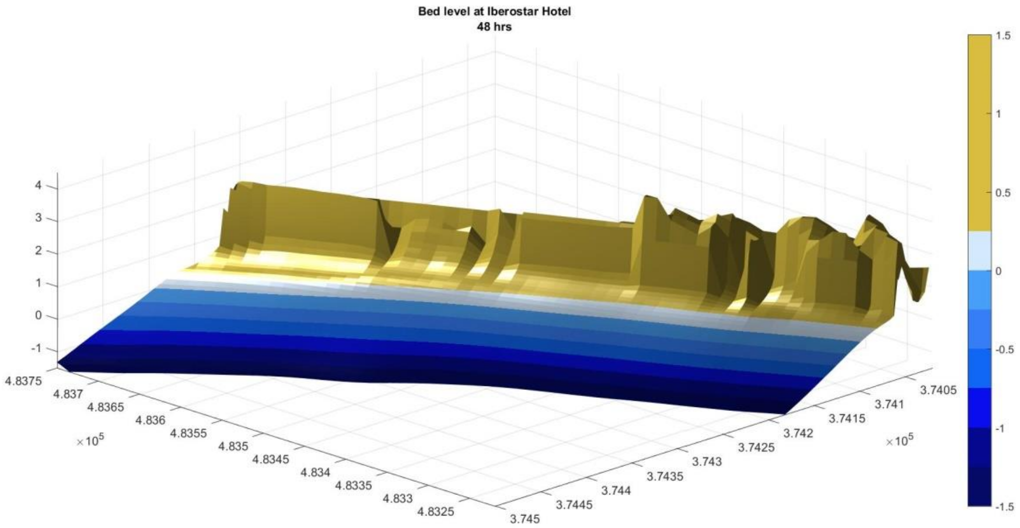

Figure N- 6 Bed levels current solution t=48hrs during Hurricane Wilma

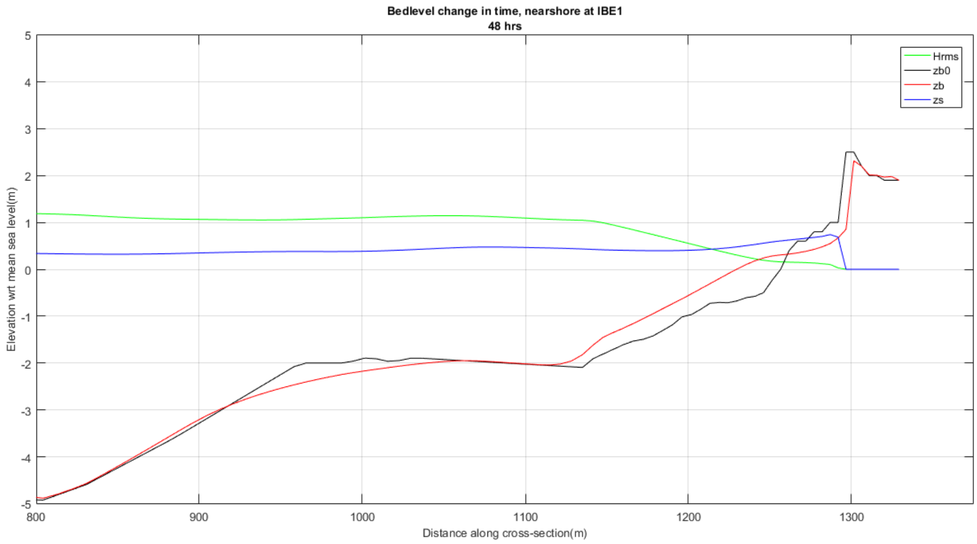

Figure N- 7 Bed levels current solution at IBE 1, t=48hrs during hurricane Wilma

It can be seen that a larger part of the dunes remains intact compared to the nourishment solution, but it has to be noticed that the dunes are represented wider than they are in reality. The result is that the dunes are wide enough to prevent real overwash, so less damage to the dunes, although this may not be completely correct. But because there is less damage, it seems to be good to have strong and wide dunes in front of the Iberostar hotel.