Preliminary study of river- and beach processes in the Matina region of Costa Rica






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With assistance of

Endangered Wildlife Trust

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Halcrow

Van Oord

DAMEN

DAMEN DREDGING EQUIPMENT

Preface

This research was initiated by the directors of Rainforest Concern Charity and The Endangered Wildlife Trust as one of their reserves, Pacuare Nature Reserve in Cost Rica, is suffering from severe erosion. The Rainforest Concern approached the engineering consultancy Halcrow Group Ltd to assist them with their problem. Due to the charities limited funds, Halcrow volunteered staff to help with an initial assessment on site and contacted the TU Delft in the hope to find volunteers to undertake further work. Professor Verhagen at the TU Delft kindly agreed to find students willing to assist and to co-ordinate this effort as part of a 4th year MSc Project. .

Hence, this study is the culmination of the effort by four Civil Engineering students as a part of a Multidisciplinary Project in the 4th year of their MSc course. The project group consists of three students reading for a Masters in Hydraulic Engineering and one in Structural Engineering. The project has been supervised by Ir. H.J. Verhagen and Dr. ir. E. Mosselman.

The scope of the study is to investigate the possible causes of erosion at Pacuare Reserve and to present possible solutions. Problem description and objectives are found in chapter 1. Chapter 2 elaborates on the project area. Chapter 3 discusses river processes and chapter 4 introduces beach processes. The results of the study are presented in chapter 5, where conclusions and recommendations are outlined.

We would like to thank Mr. J. Denham and Mr. C. Fernandez from the Endangered Wildlife Trust for offering this great opportunity for us. It was an interesting and useful project in our Masters programme. Further we would like to thank Anna, Arturo and Danilo for their help during our stay at the Reserve. We want to thank Julia Nammuni at Halcrow for her mediation and making this project possible. Further we want to thank her colleague, Simon Burchett for his help on our project. We also appreciated the help provided by the University of San Jose, in particular we would like to thank them for lending us their surveying equipment which enabled the gathering of useful data. Next we would like to thank Mr. C. Richter from the Dutch Embassy in Costa Rica for agreeing to distribute this report to the relevant authorities. We would like to give special thanks to Ir. J. Gravesteijn for his enthusiastic help in gathering the required equipment. From the University we would like to thank our supervisors Ir. H.J. Verhagen and Dr. ir. E. Mosselman. Finally we thank our sponsors Damen Dredging Equipment, Halcrow and Van Oord.

We hope that this preliminary study will be useful for the Pacuare Nature Reserve and the region of Matina. Furthermore we hope that this report can be of value to other regions experiencing similar problems in the Caribbean area or even in the world.

Project group Costa Rica

Executive summary

The starting point for this project are the severe erosion problems at the Pacuare Nature Reserve, situated on the Caribbean coast of Costa Rica. The Reserve's installations are situated next to a lagoon which is separated from the open sea by a barrier beach. The lagoon is connected on the landward side to local river- and channel system. During periods of high rainfall, the lagoon is susceptible to break through to the open sea. After such breaches, high flow velocities and waves have caused significant land-loss and subsequently endangered the continued existence of the buildings at the Reserve. Since 1989, recorded breaches occurred in 1994, 2005 and 2009.

It is believed that erosion of land is mainly caused by breaching events rather than continued coastal erosion by waves or currents. The breaching events may be caused by the increasing channelisation of river and drainage stretches and increasing water discharges by cultivated areas in former natural flood-plains. These interventions may be beneficial for some populated areas who are protected by channelised section and for the economy in certain regions as formerly unused land becomes productive (enabling banana plantations). However, the interventions increase the volume of water to be discharged in a confined space which reduces the capacity to discharge water safely towards open sea. The objective is to present recommendations for safely discharging water during extreme events towards the open sea, in which the 'small scale' breakthrough problem forms the criterion for damage for the reserve.

The project consists of two areas of interest: river- and beach processes. The river processes were analysed and solutions were sought to safely discharge water using a computer model which models the real life processes. These solutions focus on the macro scale problem, and interfere in the water system as a whole. Analyzing the beach processes involved identifying the key processes in the stretch of coast between the Río Matina and Río Pacuare and modelling these processes in a computer model. Possible small scale solutions were then tested in the computer models and assessed on their effectiveness. These small scale solutions have to be interpreted as interventions the Reserve staff can implement themselves to help prevent the continued erosion during extreme events.

According to the computer models used, the channelisation of river sections, the intensive cultivation of flood-plains and the tropical climate are the main causes of the increased water levels in the project area which cause the lagoon barrier to breach and subsequent erosion. Creating room for the river in the Río Matina and/or Río Pacuare results in decreasing the number of inundation events, but does not significantly lower water levels in the channels in between these two rivers. Further, it is stated that the drainage canals between the rivers are one of the main contributors of high water levels around the Reserve's lagoon.

A review of the solutions tested in the computer models indicated that the combination of artificially breaching the ‘Barrita barrier beach’ and extend drainage canal to Caribbean Sea is the preferred option. This study did not consider the possible ecological and economical impact of solutions and a separate environmental impact assessment should be undertaken prior to any works being implemented to evaluate the effects.

Further, during extreme storm events the beach system may erode during a single event as a whole. Mitigation measures to prevent the Reserve’s main Lodge from eroding during an extreme event may include the application of sandbags in combination with bamboo piles until an equilibrium profile of the beach is restored. However, it is unclear if also continued ‘structural erosion’ is present at the site. This would not be prevented by bagwork and would require more costly interventions such as beach nourishment etc. In order to gain exact insights in this loss of beach, a monitoring programme is highly recommended. A continued measured progression-/regression line over a number of years leads to more accurate erosion/accretion rates. Such a monitoring programme is critical to allow informed future decisions and provide measured data for further studies.

To prevent the barrier beach from breaching, applying a similar sandbag construction across the barrier beach could be sufficient to raise the level of the barrier. It is likely that this measure in itself will not be sufficient to prevent a breach at the reserve site and it is likely that the Barrita barrier beach would need to be breached artificially as well. For a full list of conclusions, please refer to Chapter 5.

Finally, a number of assumptions had to be made to enable computer modelling and analysis. It is recommended that measurements of normal and extreme water level and flow conditions are undertaken in the rivers, canals and lagoons where safe to do so as part of a monitoring campaign. This will be vital in validating computer models and undertaking future studies to enable mitigation works to be planned and executed.

Table of Contents

1 Introduction

1.1 Structure of report

This report involves finding structural solutions for the water related problems in the Matina region at the Caribbean coast of Costa Rica.

At the moment, the existing water system is not able to safely discharge all the excess water within the project area. This phenomenon can be appointed as being the macro-scale problem. The water related problems can be split up in macro- and small-scale proportions. The small-scale problem was the starting point for the research done. High discharges caused downstream erosion problems near the Pacuare Nature Reserve. Within this report, the macro-scale problem is expressed by treating this small-scale problem. This is because these problems are coherent and all causes can be related to the macro-scale problems.

This report first describes the problem definition and shortly after the objectives. Next, the system area is elaborated. Now a distinction is made between river- and beach processes. For each component, the project approach, models used and results are sketched. Finally, the results for both components are integrated and conclusions and recommendations are sketched.

This report should be interpreted as a starting point for future studies involving these waterborne troubles, and is therefore called "*Preliminary study of river- and beach processes in the Matina region of Costa Rica*".

1.2 Problem description

The Pacuare Nature Reserve is situated at the eastside of Costa Rica in the Matina region, see Figure 1.1. The Matina region in Costa Rica is a remote area with a lack of an infrastructural network. The region is important because of ecological values, rather than humane interests.

Figure 1.1: Location Project

The Reserve is founded by the Endangered Wildlife Trust in 1989 and protects 800 hectare of tropical rainforest and has six kilometres of deserted beach. The Reserve is especially focused on protecting the endangered sea turtles. The buildings and main installations of the Reserve are located directly next to the Mondonguillo lagoon, see Figure 1.2. This lagoon reaches periodically such high water levels that it might break through to open sea. This breakthrough transforms the lagoon in a rapid flowing river. Such a breakthrough has occurred in 1994, 2005 and 2009. The last breakthrough was worse then all previous ones and lasted for several weeks.

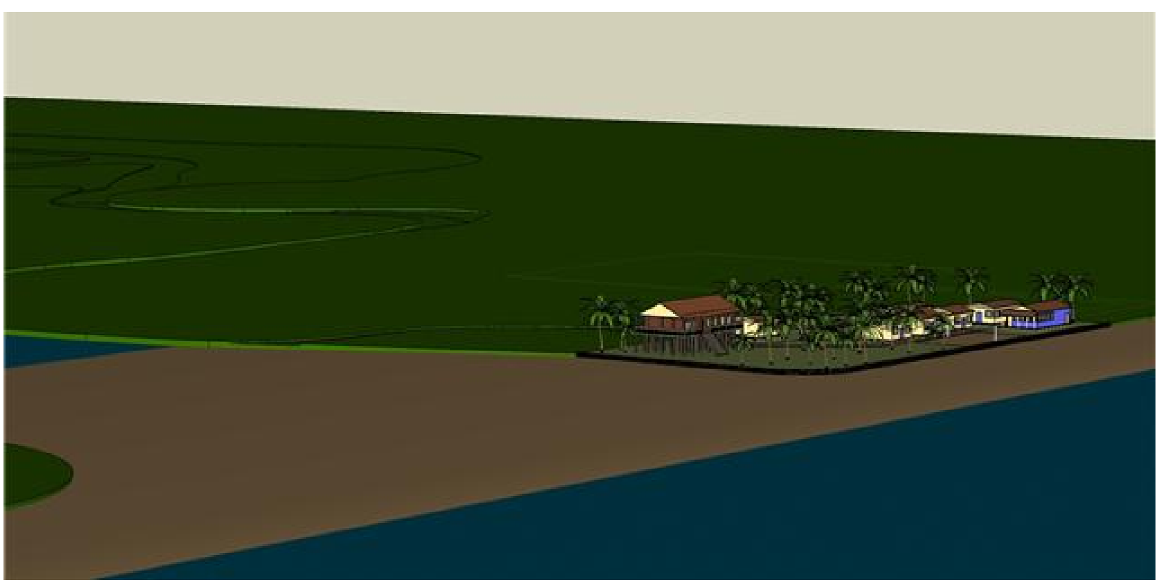

Figure 1.2: Overview of the Reserve

Breakthroughs are not exceptional for this lowland area with many rivers and channels. The rivers are typically rain-rivers and periods with massive rainfall are common in this area. Over the whole region from Costa Rica to Panama, breakthroughs of barrier beach strips and inundation of coastal plains occur. Natural processes like meandering and bend cut-offs play a major role and will change equilibrium situations constantly. This makes it hard to exactly predict where and when a breakthrough will occur.

Macro-scale problem

During wet periods in Costa Rica, the rivers which lead to the Caribbean Sea have to deal with much higher discharges. Sometimes the water system is not able to safely discharge all the excess water. The excess water is then stored in natural flood-plains.

In the Matina Region the rivers are channelised for flood protection of the towns Batán & Matina. Subsequently the banana plantations channelised further downstream. Large parts of the natural flood-plains upstream are now inaccessible because of this channelisation. The rivers are incapable of discharging all the extra run off through the mouth of these rivers; the water will find its way to the sea via alternative waterways downstream. Because of the channelisation this system of waterways and the downstream part of the natural flood-plains has to endure larger amounts of water. During severe conditions this system might flood and will put lives in danger.

The inability of safely discharging all the excess water to the sea within the project area is stated as the macro-scale problem.

Small-scale problem

Related to this macro-scale problem there exists a small-scale problem. In the initial situation, the barrier beach strip is intact and separates the sea from penetrating in the coastal plains (see Figure 1.3). The high discharges cause downstream erosion problems near the Pacuare Nature Reserve. These higher discharges cause increased water levels in the Mondonguillo lagoon. The water finds its way to the sea by overflowing and breaching the lagoon barrier beach after some time (see Figure 1.4). The lagoon changes in a river with high flow velocities.

The biggest problems start when this breach is a fact and the lagoon is not discharging to the sea any more. The lagoon barrier beach is washed away so waves will not break any more at this particular stretch. The waves eroded the lagoon area severely, with erosion rates of one metre a day. The situation is even more delicate because of the trade winds directed from the east which gives these waves a stimulating effect. The buildings and installations of the Reserve are threatened by this phenomenon.

The erosion of land of the Pacuare Nature Reserve is stated as the small-scale problem.

Figure 1.3: Reserve in initial situation; barrier beach strip intact

Figure 1.4: Reserve during breakthrough

1.3 Objective

1.3.1 Main objective

The main objective is presenting recommendations for an unconditional safe discharge of water within the project area, after studying probable causes.

1.3.2 Sub objectives

In addition to the main objective there are several sub objectives. These objectives are formulated to obtain a solution for the Pacuare Nature Reserve. The sub objectives are described below.

- Presenting solutions for safeguarding the Pacuare Nature Reserves' installations.
- Presenting approaches to realize long-term data. These data will give better knowledge of the dynamic beach- and river systems and will enable policy-makers to make informed recommendations regarding future land-use on the medium- to long-term.

1.4 Stakeholders

There are different parties involved in the project that have their own interest, which may conflict.

Endangered Wildlife Trust

The Endangered Wildlife Trust is the owner of the Pacuare Nature Reserve. The Trust would like to find a solution for the breakthrough of the lagoon. After a breakthrough the Trust has to face a loss of land. They also will need money for repairs and to build protection works for their buildings and installations. The Trust believes that most of the problems are caused by the channelisation of the rivers by the banana plantations. The social relation between the Trust and the banana plantations is therefore not always positive; even more because the banana-plantations are also one of the reasons of the disappearance of natural areas.

Banana plantations

The banana plantations channelised the rivers to protect the plantations of flooding. At the same time they made a lot of small channels between the banana plants for dewatering, because banana plants cannot stand in water for long periods. There is need to find out if the banana plantations are indeed a major cause of the problems. It has to be determined if the banana plantations are in fact a major cause of the problems. The plantations are still growing; this should be taken into account in the study.

Local population

In this low-lying area floods are common; the situation around January 2009 was the most severe so far. The local population would prefer to minimize floods. They also want better insights in where and when a flood/breakthrough might occur. The houses and cattle are at risk when the land is flooded, even more now flood-plains are disappearing. Most of the houses are already build on high piles, in times of flooding this is required to maintain dry feet. Living with floods is part of life in this area and discussion is open for living with the river instead of embanking rivers and canals.

Government

For the government it is of importance to gather insights in the processes and to know the causes of the problems. Accordingly, the government can make policies for the future land-use and can make plans for protection of the area. The Reserve is not the only location with these problems in Costa Rica, so insights in these processes and possible solutions might be useful for other locations as well.

Panama

The republic of Panama is not a direct stakeholder, but similar as Costa Rica, Panama has areas with the same problems as the Reserve. For them this study can be of importance to compare their own problems and implement possible solutions given in this study.

2. Description of the system

The project area is defined as the area between the Río Pacuare and Río Matina. It consists of natural flood-plains, cultivated land (banana plantations), two river branches and mouths, some drainage canals, two lagoons, an estuary, a partly artificial canal and beaches. Figure 2.1 shows the project area and its components. The hydraulic components together form a rather complex system.

Figure 2.1: Project components

Every hydraulic component is described individually below. Appendix I contains photo's of every component.

Río Matina
The rivers form the source of sediments one will find on the beaches. The Río Matina finds its origin in the Cordillera de Talamanaca, and gently slopes from a 3000 metres elevation to the Caribbean Sea. As mentioned, the river cross-sections are not capable of discharging all the water during peak discharges. As a result, parts of the Río Matina were channelised to prevent the cities of Batán and Matina from flooding. Subsequently, the more seaward lying banana plantations had to continue this channelisation to keep their bananas dry. Large quantities of flood-plains were lost and accordingly the system is not always capable of safely discharging water to the open sea.

Boca Río Matina
This river mouth can be described as being a combination of river- and wave dominated. It is an estuary, which is the part of the river that is (mildly) affected by tides. It is the region in the vicinity of the mouth of the river where fresh and salt water mix. Figure 2.1 shows that the Boca Río Matina is not significantly wider than the upstream part. This is because of the small tidal range. This implies the river mouth as being wave dominated.

Río Pacuare
The Río Pacuare also finds its origin in the Cordillera de Talamanaca. There are no low lying cities which might be flooded due to high discharges. Again, banana plantations are situated along this river. A big part of this river is channelised; this is beneficial for the banana plantations.

Boca del Río Pacuare
The river mouth of the Río Pacuare is also a combination of a river- and wave dominated system. Not only the Río Pacuare discharges through this gorge, the Madre de Dios also. Because of this 'duo discharge', standard textbook qualifications cannot be appointed to this river mouth. As this river mouth is subjected to the same conditions, the same qualification holds as for the Boca Río Matina.

Tortuguero Canal
The Tortuguero Canal is a combination of natural and artificial parts. It has been constructed for the sake of accessibility and tourism purposes. The hydrodynamics most definitely change in the system because of this (artificial) canal. Different components became in direct contact with each other.

Estero Madre de Dios
The Madre de Dios river finds its origin in the Cordillera de Talamanca. It is a relatively small river compared to the Río Pacuare and Río Matina. The Estero Madre de Dios is the natural estuary of this river. It is more or less parallel to the Caribbean coast. It now functions as a natural part of the Tortuguero Canal.

Caño Negro
This is the river which discharges on the Estero Madre de Dios (more upstream known as the Madre de Dios). It is small compared to the Río Pacuare and Río Matina.

Drainage Canal

This is a river shaped waterway which also discharges on the Tortuguero Canal. This small river used to discharge directly on the Caribbean Sea. Nowadays, after the implementation of the Tortuguero Canal, it discharges on the Tortuguero Canal. The natural part is more landward connected to a series of drainage canals, applied by the banana plantations. This old river has not got a specific name, and is therefore called 'Drainage Canal' within this report.

Mondonguillo Lagoon

The Mondonguillo Lagoon is situated next to the Pacuare Nature Reserve. The lagoon used to be an old river mouth of a relatively small river. The hydraulic related problems here have been explained in previous sections. Technically, one cannot call the Mondonguillo (and Barrita) Lagoon, lagoons. They can be qualified best by backwaters. For the sake of clarity, we continue to refer to this 'backwaters' as being lagoons. The lagoons are now, indirectly, connected to the system of rivers.

Barrita Lagoon

The Barrita Lagoon is situated about three kilometres south from the Mondonguillo Lagoon. The same qualification holds for this lagoon. During the wet season, the barrier beach strip of this lagoon is being breached (artificially). Without human interference, the Barrita barrier beach breaches before the one at the Mondonguillo Lagoon. To help preventing the Mondonguillo Lagoon from opening to the open sea, the Barrita barrier beach is sometimes breached artificially. Creating a new discharge opportunity may lower water levels in the Mondonguillo Lagoon.

Flood-plains

The flood-plain is the area which inundates when the river and channel sections cannot harbour the water. These flood-plains can be mangroves, swamps or low-lying rainforests. The cultivated plantations used to be natural flood-plains. The area mainly consists of low-lying rainforests, which can inundate rapidly during high water levels in the Tortuguero Canal or both of the rivers.

Barrier beach strip

The barrier beach is the strip of beach which separates a body of water (Mondonguillo and Barrita Lagoon) from the open sea. As mentioned, this beach strip can be washed away during periods of high stream flow. When a tidal inlet is formed after the breach, several morphological processes determine the stability of the inlet. Tidal conditions and sediment transports determine if this inlet will be naturally restored or not. It has been observed that the barrier beach will be restored quite rapidly after a breach. This would indicate that the inlet formed is poorly stable. Appendix II elaborates on the inlet morphology and inlet stability.

Beach

The Caribbean coast is not a uniform strip of beach. It partly consists of fine grained sediments finding their origin in the mountainous areas. It is dark of colour. The six kilometre strip of beach investigated erodes and accretes not uniform over its length. Broad and narrow strips follow each other up on short distances. The beach changes throughout the year, it can erode severely and then accrete again quickly. There is no clear pattern in this.

The beach profile is quite typical, at the end of the forest there is a clear land/beach interface visible. The backshore and foreshore are separated by the beach crest. The beach/sea interface is qualified by beach cusps[1]. Beach cusps are undulations in the beach face morphology characterized by distinctive alongshore periodicity. A beach cusp is usually defined as a sequence of a horn–bay–horn where the horns extend seaward, coupled with steeper slopes, and bays landward coupled with milder slopes (see Figure 2.2). Sequences of beach cusps can be highly regular in the alongshore direction with a spacing, defined as the distance between consecutive horns, ranging from centimetres to tens of metres. Beach cusps have been observed over a variety of beach-types but more commonly develop on beaches experiencing relatively low wave energy and with medium to coarse sediment size.

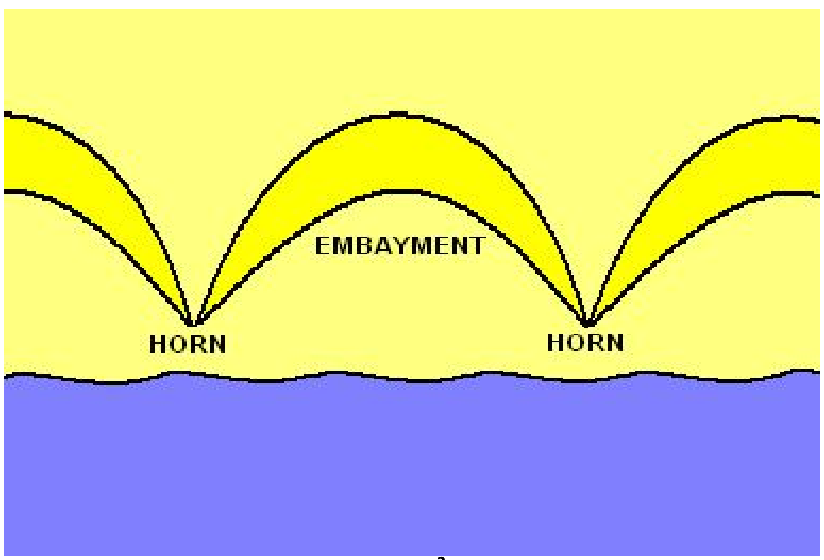

Figure 2.2: Schematization beach cusps[2]

Surf zone

As ocean surface waves come closer to shore they break, forming the foamy, bubbly surface one calls surf. The region of breaking waves defines the surf zone. The wave height is changing constantly and thus the surf zone is also changing in length constantly. In the surf zone some important coastal processes take place, which are explained in Appendix III.

1 Almar,R., Coco G., Bryan, K. R., Huntley, D.A., Short, A.D. and Senechal, N. (2000): Video observations of beach cusps morphodynamics, Elsevier Coastal Engineering.

2 http://en.wikipedia.org/wiki/Beach_cusps

3 Analysis of river system

3.1 Approach

In order to sufficiently reach the objectives, a clear approach was defined. The project is divided in phases; analysis, gathering data, fieldwork and modelling. Each phase is elaborated on further.

3.1.1 Analysis

The analysis of the problem is the first step in the project. Creating clear insights in the problems resulting in project objectives is necessary. The results of this analysis are described in Chapter 1.2.

3.1.2 Gathering data

In order to reach the objectives sketched in Chapter 1.3, several data is obligated. For the river system, this involves information about discharges, bed level slopes, river geometries et cetera. Table 3.1 states the data necessary and if this information is available. Appendix IV contains the available data.

Data	Availability
Discharge distributions	Available[3]
Bed level slopes	Available[3]
River geometries	Available[3]
Canal- Channel- and Lagoon geometries	Unavailable
Bed roughness	Unavailable
Topographical maps	Unavailable
Tidal information	Available[4]
Tidal penetration	Unavailable
General water system	Unavailable

Table 3.1: Availability necessary data

Because not all the necessary data is available or even exists, fieldwork is necessary. The obtained data is necessary input for our computational models.

3.1.3 Fieldwork

In order to draw conclusions with the help of computer models, the unavailable data has to be gathered in the project area. The fieldwork concerning the river system consists of measurements and observation. Measurements of river sections, velocities and tidal penetration were executed. General water system information was gathered by observing and interviewing locals. Appendix V sketches the measurement techniques followed by the results.

[3] Oreamuno Vega, R. and Serrano Pacheco, A. (2005): Estudio de Inundaciones en el Rio Matina. Costa Rica.

[4] http://www.imn.ac.cr

3.1.4 Modelling

The next step is to use all the gathered data and put this in a computer model. Causes and solutions can be validated within this model.

To properly simulate river flows, a numerical model for the river network and flood plain can be set up based on SOBEK Rural version 2.11[5]. SOBEK Rural is a numerical modelling package for a wide range of inland water problems. An advanced feature of this model is the integration of a 1D module to simulate flow in the river network and a 2D overflow module for the flood plain allowing the model to simulate river flow and flood problems in the river basin of the Matina region. The simulation of the region's inland hydrodynamics is carried out with the application of these two hydro-dynamically coupled modules (the 1D Channel Flow and the 2D Overland Flow modules).

3.2 Probable causes breakthrough

In this paragraph the probable causes are being elaborated. This explanation of the causes is based on common sense and observations. These causes are in fact hypothetical, purely based on common sense and the fieldwork done, and will be validated in the used computer models.

The problem at the Pacuare Nature Reserve can have several causes. Below, probable causes of this breakthrough are listed. All of the possible causes are related to high water levels, flow velocities and discharges. The causes all have in common that they can inundate the area in the vicinity of the rivers and canals. Subsequently, the water levels in the Tortuguero Canal will rise and discharges and flow velocities will increase.

3.2.1 Channelisation Río Matina

During the wet period in Costa Rica, the rivers which lead to the Caribbean Sea have to deal with much higher discharges. The Río Matina was channelised for flood protection of the towns of Batán & Matina. Subsequently the banana plantations had to channelise further downstream, because banana trees cannot grow in a layer of water. This means that the natural flood-plains are inaccessible because of this channelisation. This can result in increased flows in the Tortuguero Canal. The Río Pacuare and Río Matina cannot transport all the water to the sea, so it will find other ways to the sea. These higher discharges cause increased flows and high water levels in the Mondonguillo and Barrita lagoon. After eroding the top of the barrier beach, a new surface slope will be introduced. This might cause a shift in the equilibrium distribution of water at the Río Matina bifurcation.
This hypothesis is being validated in the SOBEK model. Applying different discharges on the upstream boundary should show a difference in discharges, flow velocities and water levels in the Tortuguero Canal and Lagoons to underline this hypothesis. The results are described in Chapter 3.5.1.1.

[5] © Deltares

3.2.2 Earthquake 1991

On April 22, 1991, an earthquake appeared in the Limon Province[6]. This was a severe one with 48 casualties. Limon Province lies in the eastern part of Costa Rica in a geologic province dominated by a broad plain that gently slopes from the Cordillera de Talamanaca to the Caribbean Sea. The area affected by the earthquake within Costa Rica is made up by low-lying coastal plains of soft alluvial soils. These soils are likely to amplify the seismic waves and are in addition subjected to liquefaction.

Among the geological effects of this event, the tectonic uplift of the upper continental crust was the most spectacular. The uplift raised the Caribbean coast between 0.3 and 1.9 metres, adding as much as 100 metres to the shore in some places and revealing large areas of coral reefs, see Figure 3.1.

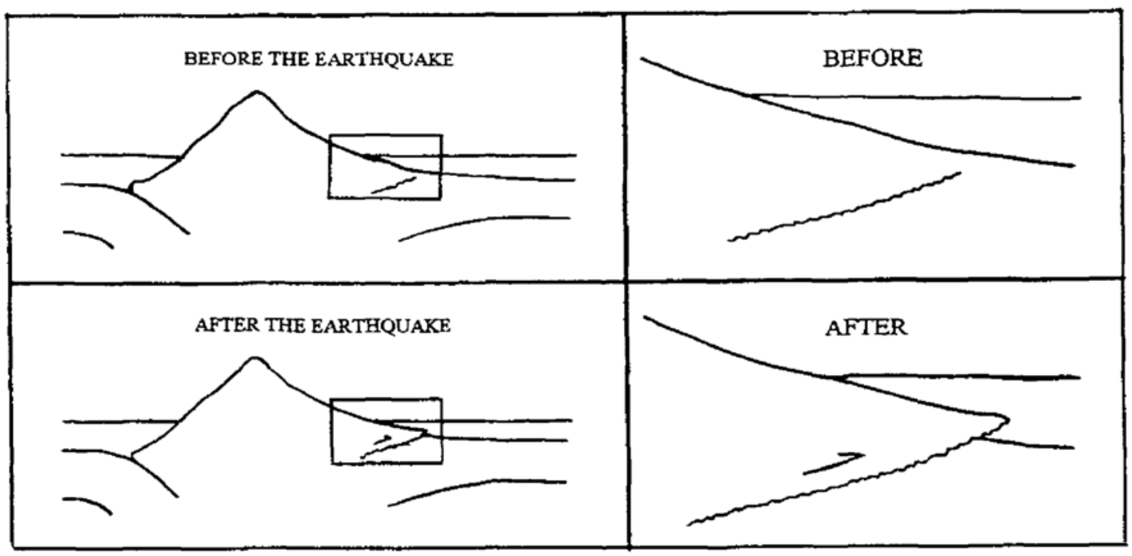

Figure 3.1: Tectonic uplift raised the Caribbean Sea coast and added about 100 metres to the shore

Docks in the port of Limon lost more than 1.5 metres in water depth and a part of the Tortuguero Canals in the north was drained. Another aspect of geological changes caused by the earthquake was the triggering of massive landslides on the eastern slopes of the Cordillera de Talamanca. This effect caused extensive destruction of rainforests and obstructions of river beds. Soil failure, particularly due to liquefaction and lateral spreading in low-lying and coastal areas, was the primary source of serious damage in this earthquake. Soil liquefaction caused severe damage to roads, bridges, railways, ports, water systems and banana plantations.

This event might have caused a shift in discharge equilibrium and subsequently endangers the safe discharging of water to the sea. The loss of flood-plains and the obstruction of river beds are the main initiators of these probable problems.

This hypothesis is elaborated on in Chapter 3.5.1.2. Because there is no information available on the precise coastal (-plains) deformations, a validation in SOBEK is not possible and therefore kept qualitative.

[6] http://www.cne.go.cr/CEDO-CRID/CEDO-CRID%20V4/pdf/eng/doc2974/doc2974-4.pdf

3.2.3 Drainage Canals

A significant part of the flood-plains in the vicinity of the Pacuare Nature Reserve are cultivated in the last decades for banana plantations. Banana trees cannot stay in water long, so ditches are made to drain off the rainfall. Large drainage canals drain off the total volume of water towards the Caribbean Sea via, in this case, the Tortuguero Canal. This can cause a breakthrough as well. Instead of using these flood plains for the storage of water, they run off all the water to the canals.
This hypothesis is being validated in the SOBEK model. Setting the discharges zero coming out of these canals might show lower water levels and flow velocities in the Tortuguero Canal. The results are described in Chapter 3.5.1.3.

3.2.4 High rainfall

The broad plain that slopes from the Cordillera de Talamanaca to the Caribbean Sea consist of several large and many small river valleys. In our area of interest, the Río Matina and Río Pacuare have the biggest catchment areas, hence the biggest run off. The mentioned channelisation made it impossible to use the valuable flood-plains for the storage of water. High rainfall causes high run offs and subsequently high river flows. At the bifurcation between the Río Matina and the Tortuguero Canal a distribution of water over the stretches takes place. About 10% of the water coming from upstream diverts into the Tortuguero Canal, in the case when the barrier beach strips are closed. This follows from our measurements, see Appendix V. This follows from the fact that the water levels in both stretches have to be equal, so there will be flowing water into the Tortuguero Canal. Because of bed and/or surface slopes the water flows towards the north.
This hypothesis is being validated in the SOBEK model. Varying the discharge at the upstream boundary should show differences in discharges, water levels and flow velocities in the Tortuguero Canal and the lagoons. The results are described in Chapter 3.5.1.4.

3.2.5 Artificial Tortuguero Canal

About 20% of the Tortuguero Canal, which leads from Puerto Limon up to Tortuguero, is artificial. This has been done in order to make this whole stretch of Caribbean coast accessible with a boat. Natural lagoons, like the Mondonguillo Lagoon, came in direct contact with the Tortuguero Canal. This new system is quite complex and made it possible to generate a breakthrough in the Barrita and Mondonguillo lagoon.
This hypothesis is elaborated on in Chapter 3.5.1.5.

3.3 Possible solutions

In this paragraph possible solutions to prevent the barrier beach strip from breaching will be presented. These solutions will be checked on their validity within the SOBEK model. One should understand that this relatively small-scale problem is used to validate the more global solutions for safely discharging the excess of water. The focus is on generating room for the rivers and canals. A decrease in inundation can be seen as the global benefits, whereas the lower risk of breaching the barrier beach is beneficial on the smaller scale. The solutions have in common that they interfere in the set of rivers and channels. Water levels, velocities and discharges will change.

3.3.1 Fully channelise Río Matina and/or Río Pacuare

The upstream embanking of both rivers will increase inundation of the coastal plains. To prevent this, the full channelisation of the Río Matina and/or Río Pacuare can be a good option. The red line in Figure 3.2 shows the embanked part. The blue line shows the stretch which is already embanked.

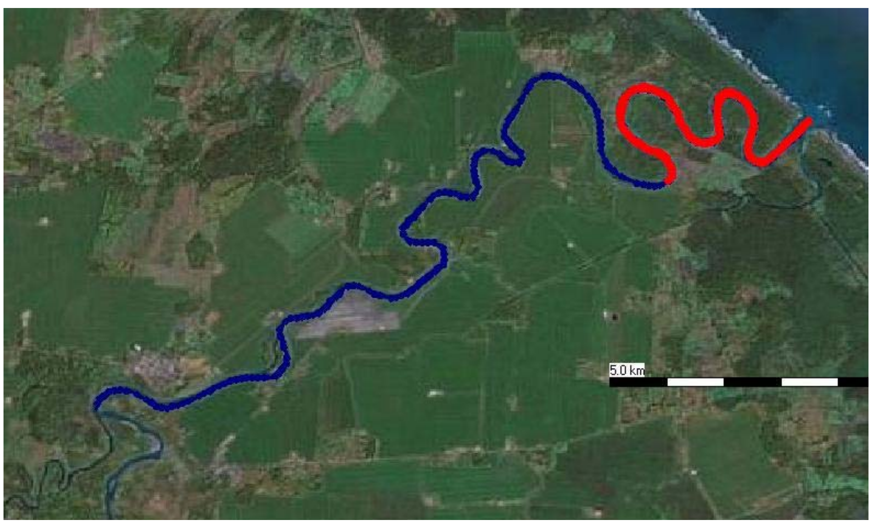

Figure 3.2: Fully channelise Río Matina and/or Río Pacuare

3.3.2 Broadening Boca Río Matina

This possible solution is in line with the notion of donating room for the river.

Figure 3.3 shows the area where the model input has been adjusted. The adjustment consists of wider cross-sections.


Figure 3.3: Broadening Boca Río Matina

3.3.3 Dredging Río Matina

This possible solution is in line with the notion of donating room for the river. The orange part in Figure 3.4 indicates the (periodically) dredged part of the Río Matina.

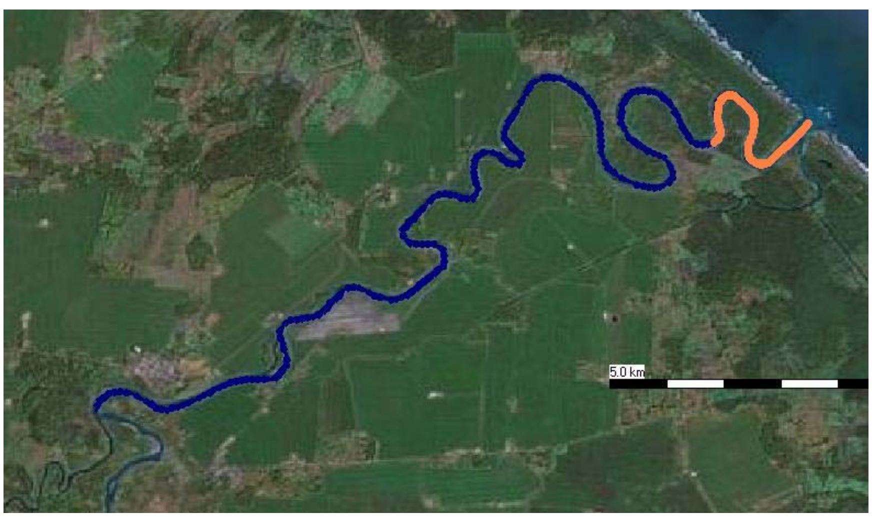

Figure 3.4: Dredging Río Matina

3.3.4 Artificially breaching of Barrita barrier beach

This is an existing solution. During wet periods, this lagoon is breached (artificially) to generate a new waterway to the sea. Figure 3.5 shows this solution.

Figure 3.5: Artificially breaching of Barrita barrier beach

3.3.5 Artificial channel to Caribbean Sea

This possible solution is in line with the notion of donating room for the river. Generating new ways to discharge the excess of water might be a good solution. The red line in Figure 3.6 shows this possible solution.

Figure 3.6: Artificial channel to Caribbean Sea

3.3.6 Extend drainage canals to Caribbean Sea

This possible solution is in line with the notion of donating room for the river. Generating new ways to discharge the excess of water might be a good solution. Figure 3.7 shows this possible solution.

Figure 3.7: Extended drainage canals to Caribbean Sea

3.3.7 Widen river mouth

This possible solution is in line with the notion of donating room for the river. Figure 3.8 shows the area where the model has been adjusted. This adjustment consists of wider cross-sections.

Note: This option differs from the one described in chapter 3.3.2 'Broadening Boca Río Matina' in terms of applied models. Chapter 3.5 elaborates on the two different used models.

Figure 3.8: Widen river mouth

3.3.8 Stop cultivating land for banana plantations

This solution involves donating cultivated land to nature. Flood-plains can store water; plantations discharge rainfall directly on the series of canals. Figure 3.9 shows the cultivated areas around the Río Matina.

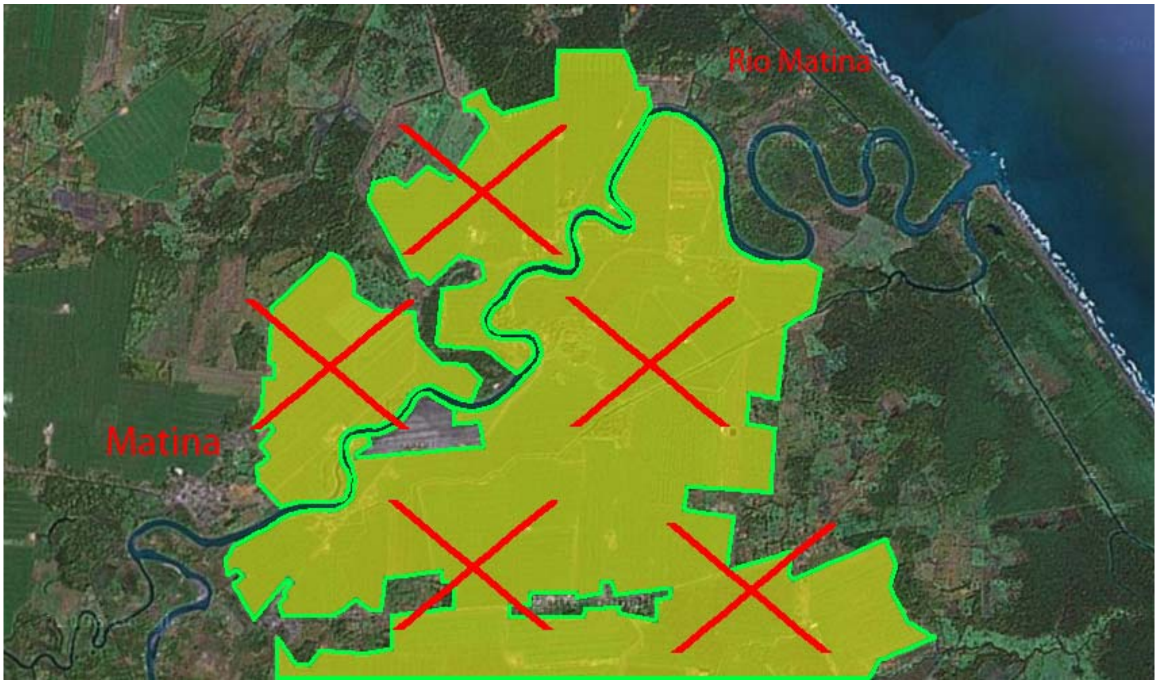

Figure 3.9: Stop cultivating land for banana plantations

3.4 Computational modelling

3.4.1 Model used

The tidal inlets of the Río Pacuare and Río Matina are located on a micro tidal wave-dominated coast in a tropical monsoon region. The tropical monsoon regime exerts its influence on the tidal inlet morphology through the seasonal variation of river flow and wave climate. In such an environment, river flow certainly has a significant role in maintenance of the inlets in compensation for weak tidal flushing.
River flow hydrodynamics are simulated by a numerical model for the river network and its flood plain.

To properly simulate river flows, a numerical model for the river network and flood plain can be set up based on SOBEK Rural version 2.11[7].
This project consists of two separate models. The 'Tortuguero model' covers the combination of river stretches, canals and lagoons. The 'Río Matina model' consists of the Río Matina river stretch only.

3.4.2 Basic equations and numerical scheme

3.4.2.1 1D Channel flow module

The 1D Channel Flow module of SOBEK Rural simulates hydrodynamics in a river network by solving the complete 'de Saint Venant'-equations (equations (1.1) and (1.2)) for long waves in shallow waters, with the wind friction term added in the momentum equation (equation (1.3)). The equations describing the water motion of long waves include the equation of continuity presenting the mass conservation law and the equation of motion presenting the momentum conservation law.

Conservation of mass:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{1.1}$$

Conservation of momentum:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial \eta}{\partial x} + g\frac{|Q|Q}{C^2AR} - B_w\frac{\tau_w}{\rho} = o \tag{1.2}$$

Wind stress:

$$\tau_w = C_d \rho_a V^2 \cos\varphi_w \tag{1.3}$$

[7] SOBEK Rural v2.11. Deltares (2009)

The equations are discretized and solved numerically using the implicit Preissmann box scheme for a staggered grid of the hydrodynamic states (water level and discharge). The model can also include hydraulic structures such as weirs, bridges, culverts, etc. The structures are modelled in the module by solving the discharge formula based on energy conservation law for each type of structures.

3.4.2.2 2D Overland flow module

The 2D Overland Flow module of SOBEK Rural solves a subset of the system of 2D shallow water equations. The momentum equations consist of acceleration, horizontal pressure gradient, advection, bottom friction, and wall friction terms. The 2D shallow water equations are solved numerically by the Delft-scheme for a staggered grid. In the staggered grid, water levels are defined at the connection nodes and calculation points, while discharges are defined at the intermediate reaches or reach segments. The scheme is robust, and can deal with the problems of drying/flooding and super-critical flow including hydraulic jumps.

3.4.3 Model domain

3.4.3.1 Río Matina model

The Río Matina is schematised originating from the Río Chirripo and the Río Barbilla. This model (see Figure 3.10) is made to check how water propagates through the Río Matina and to look how many water can enter the Tortuguero Canal. Overflow of the existing embankments in this particular river stretch will show more accurate input for the Tortuguero model.

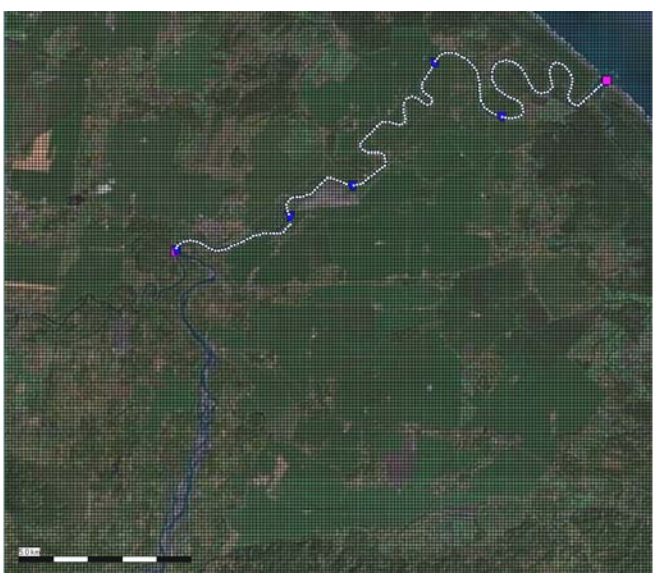

Figure 3.10: Río Matina model area including 1D network

3.4.3.2 Tortuguero Canal model

The 1D channel flow grid of the model includes the main rivers of the network, the channels, the lagoons and the tidal inlets. Figure 3.11 shows the model area with the 1D network.

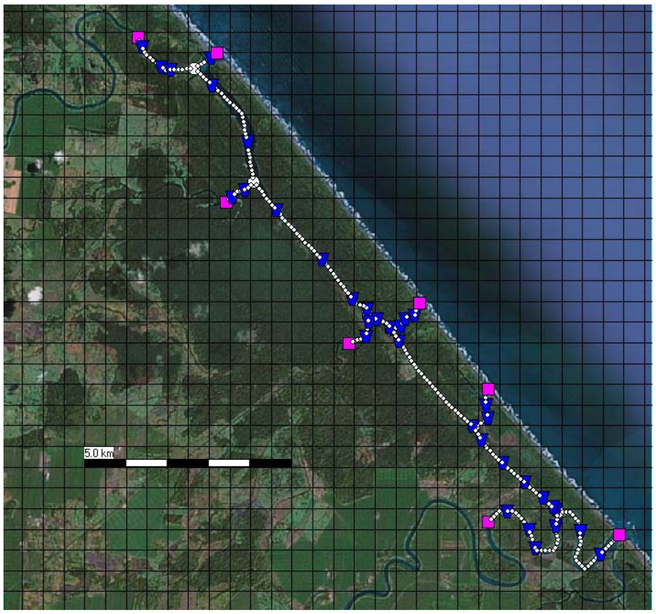

Figure 3.11: Tortuguero model area including 1D network

In the lowland and coastal areas, the 1D channel flow network is overlapping with the 2D overland flow grid. This is logical because the mountainous areas cannot really inundate, they directly discharge on the river. The 2D overland flow grid is manufactured using topographical maps, and sketched in Figure 3.12.
When only the 1D river flow module of SOBEK is used, the model cannot simulate the overflow on the flood-plain nor the flow in the river channels properly. Furthermore, if only the 1D model is used for the area where overland flow on the flood plain occurs, unrealistic results are obtained.

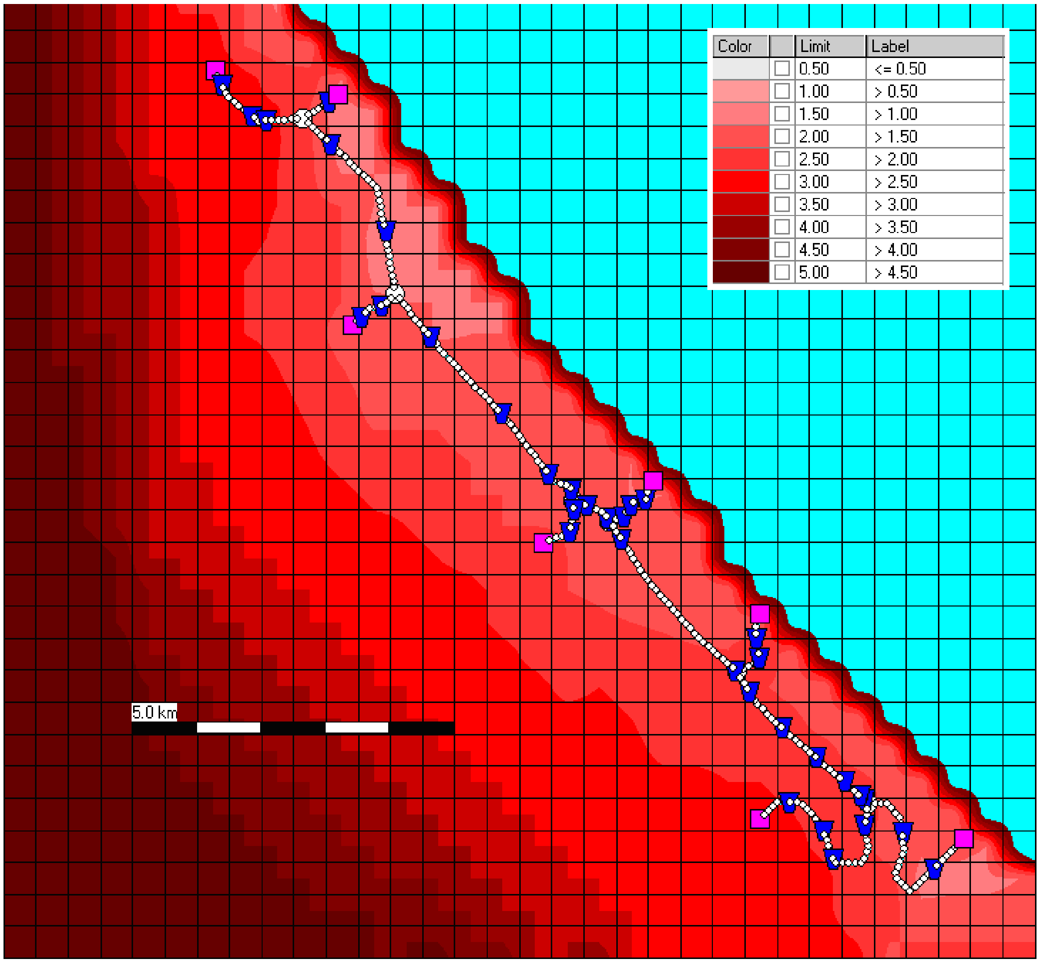

Figure 3.12: 2D Overland flow grid

The 1D network as shown in the 2D Overland flow grid in Figure 3.12 contains several elements, which are elaborated further below:

 = Cross-section

The blue buckets simulate the cross-section. Figure 3.12 shows several cross-sections, which have been measured during the fieldwork. SOBEK Rural interpolates these cross-sections over the reaches and generates a cross-section for every point in the 1D network.

 = Boundary condition

The pink rectangles simulate the boundaries. The modelled network consists of eight boundary conditions.

 = Linkage node

The white circles simulate the links for bifurcations or confluences.

3.4.4 Boundary conditions

3.4.4.1 Río Matina model

The upstream boundary location is situated at the confluence of the Río Chirripo and the Río Barbilla. The upstream boundary condition is a constant or varying discharge distribution.

The downstream boundary is the Boca Río Matina, and is set to a tidal elevation distribution.

3.4.4.2 Tortuguero Canal model

Upstream boundary locations for the model are selected at the positions until field measurements were executed. These boundary conditions are always discharges.

Downstream boundary conditions of the model are either tidal elevation when the barrier beach is open; otherwise the discharge is set to zero when it is closed. The Boca Río Matina and the Boca del Río Pacuare inlet are always open, so should be set to a tidal elevation.

3.5 Results

Two important criteria are checked upon in the validation process; Inundation of coastal plains and the water level in the Mondonguillo Lagoon. The inundation of coastal plains does not need elaboration. The other criterion is the water level in the Mondonguillo Lagoon.

The barrier beach strip can breach when the water level in the lagoon is higher than the crest of this beach. If the high water level exceeds this critical level for an extended period of time, the chance of a breakthrough is bigger. The crest of the barrier beach strip is 1.25 metres above MSL (see Figure 3.13). This fact is important when checking possible solutions on their use.

Note: The mean sea level (MSL) is chosen to be the datum and is set to zero throughout the modelling stage.

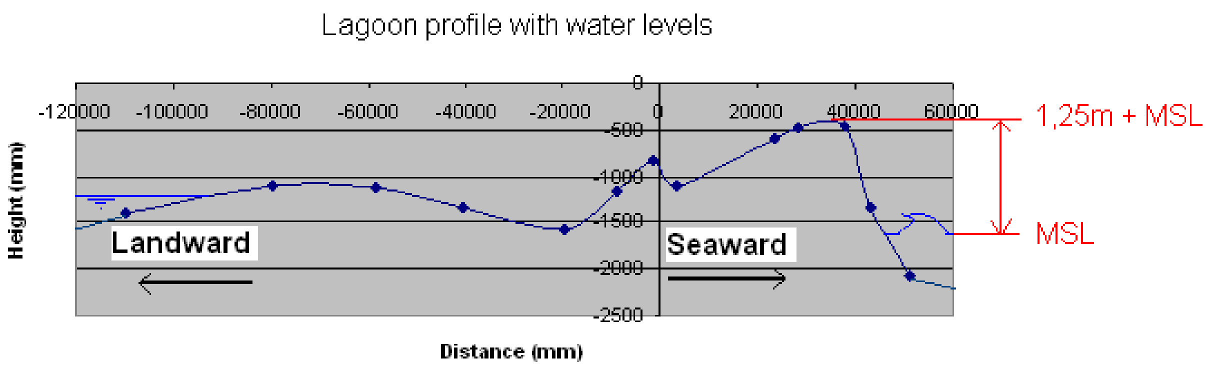

Figure 3.13: Mondonguillo Lagoon barrier beach profile

3.5.1 Validating probable causes breakthrough

Chapter 3.2 listed a number of probable causes of the insufficient discharging of water to the Caribbean Sea. Within the SOBEK Rural model, these different hypotheses are being validated. Below, the different causes are listed and results are sketched. Appendix VIII will elaborate on the model settings.

3.5.1.1 Channelisation Río Matina and/or Río Pacuare

This hypothesis is being validated in the SOBEK model. Applying different discharges on the upstream boundary should show a difference in discharges, flow velocities and water levels in the Tortuguero Canal (and Lagoons) to underline this hypothesis.
Related studies showed peak discharge distributions for the Río Matina. Figure 3.14 shows the peak discharge distribution for the Río Matina (return period of five years). The assumption is made that this peak discharge does not decrease in height throughout the Río Matina stretch (no overflow of the embankments). These discharges over time are used as upstream boundary conditions for the Río Matina

and Río Pacuare in the Tortuguero model. The assumption means a rather conservative approach when validating the probable causes.

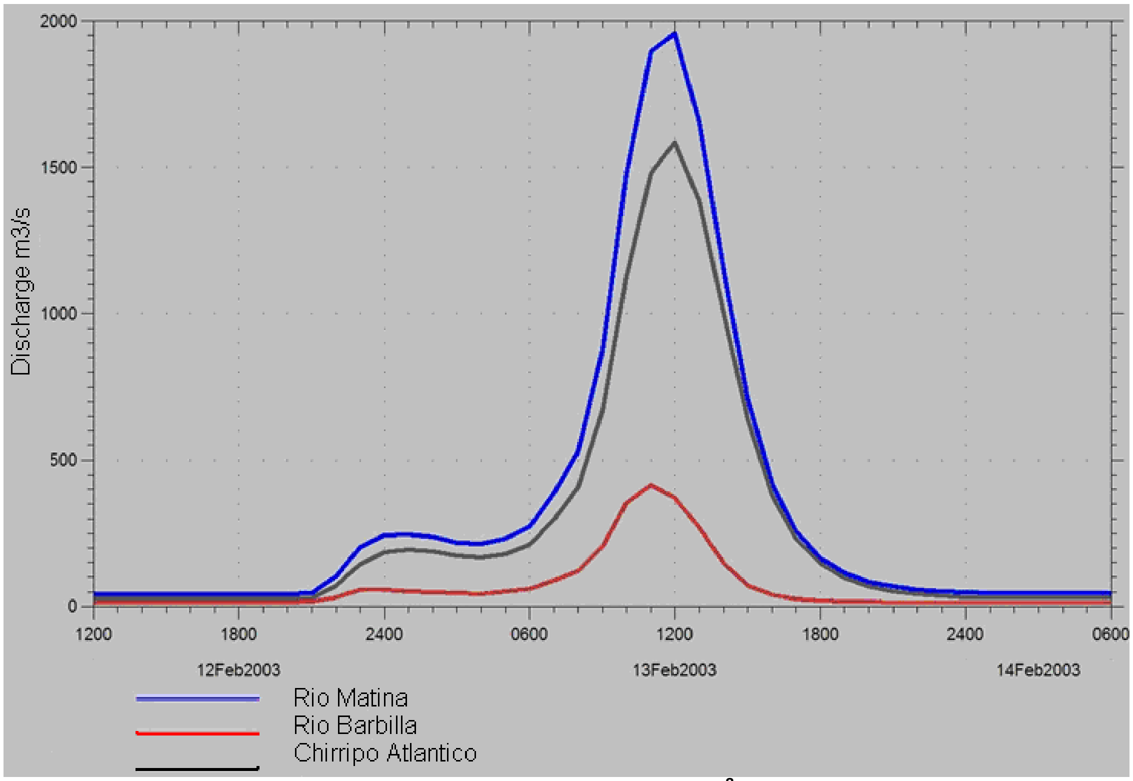

Figure 3.14: Hydrograph Río Matina for a return period of 5 years[8]

Figure 3.15, Figure 3.16 and Figure 3.17 shows that these high discharge distributions cause an overflow of the coastal flood-plains. The blue line exceeds the green line (embankments), this implies an overflow of the flood-plains. There will be an excess of water which cannot leave the low-lying coastal plain directly via the rivers and channels.

[8] Oreamuno Vega, R. and Serrano Pacheco, A. (2005): Estudio de Inundaciones en el Rio Matina. Costa Rica.

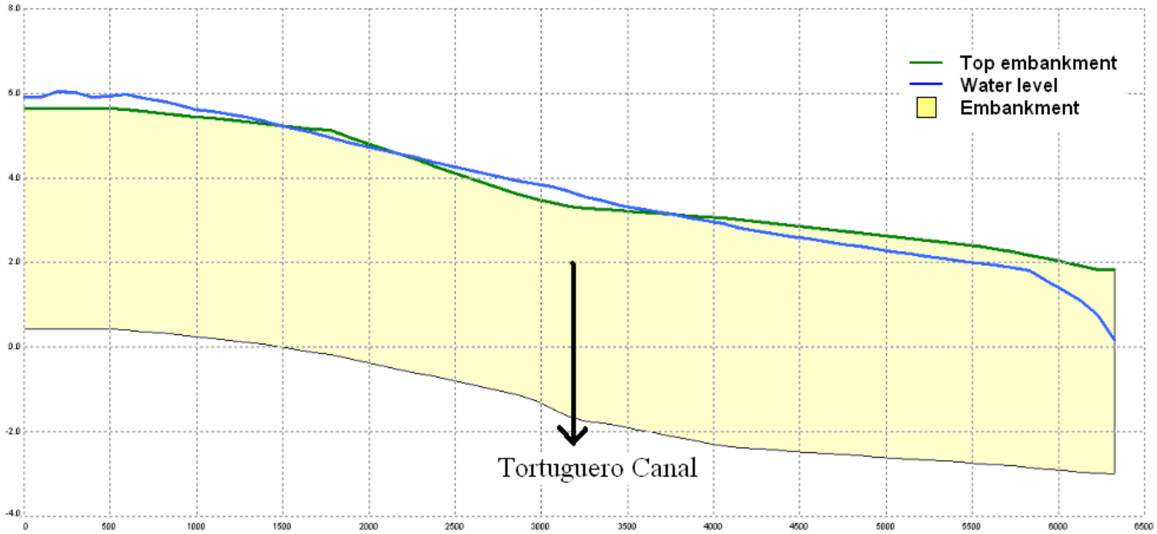

Figure 3.15: Overflow embankments Río Matina during peak water discharge distribution of 2000 m^3/s

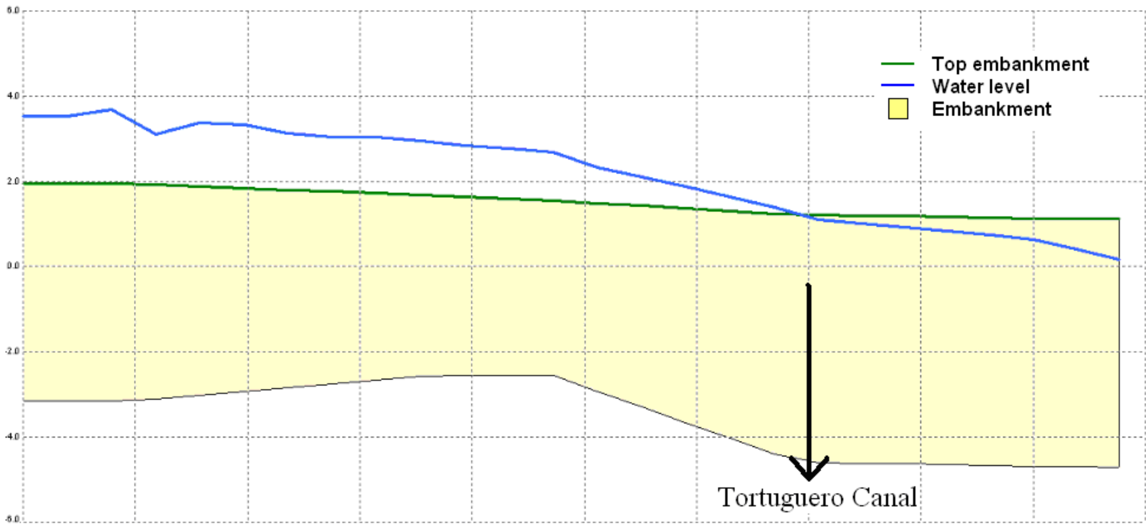

Figure 3.16: Overflow embankments Río Pacuare during peak water discharge distribution of 2000 m^3/s

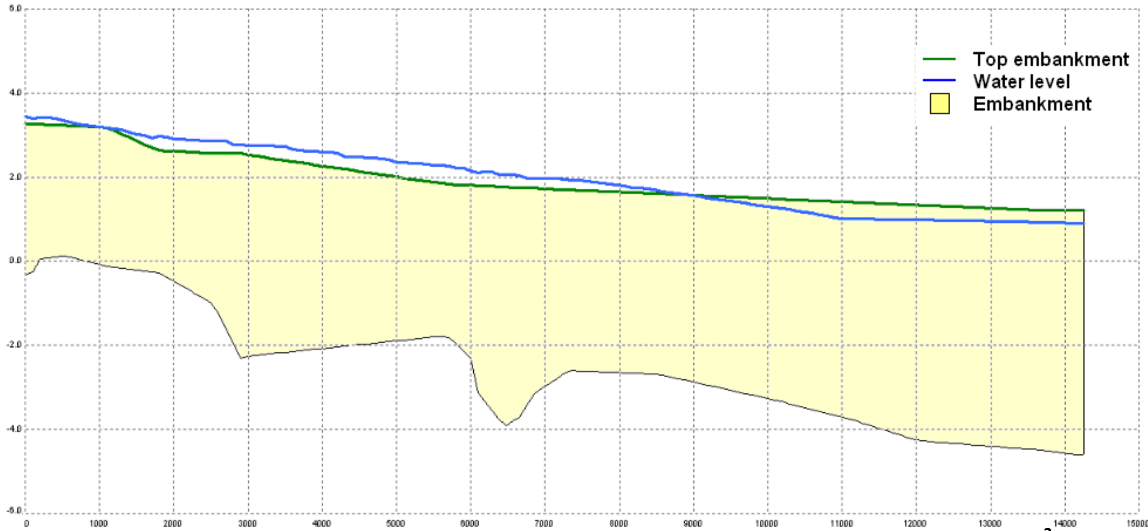

Figure 3.17: Overflow embankments Tortuguero Canal during peak water discharge of 2000 m^3/s

The overflowing of the embankment causes inundation of the low-lying flood-plains. Figure 3.18 shows a screenshot of an animation made in SOBEK. This is the situation a few hours after the peak discharge has passed. The blue compartments are the inundated areas.

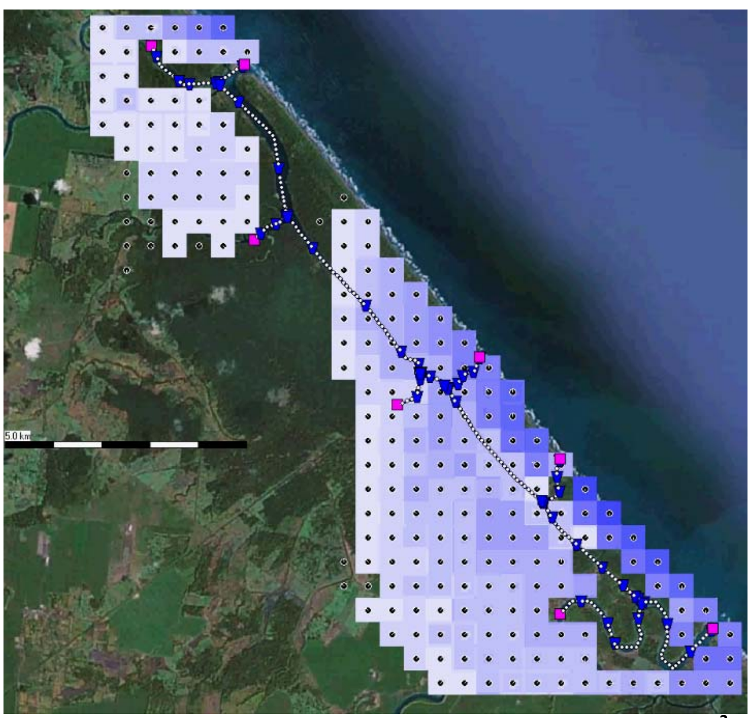

Figure 3.18: 2D screenshot inundation; peak discharge of 2000 m^3/s

In relation to the small-scale problem, the water level must exceed 1.25 metres above the reference level (i.e. mean sea level) (see Figure 3.13). This is the height of the barrier beach strip. When this level is exceeded by the lagoon water level, sediment is washed away and the barrier beach will decrease in height. Eventually, the lagoon will change from a storage basin in a rapid flowing river.

During normal conditions, i.e. a constant discharge of 100 m^3/s on the Río Matina and Río Pacuare, the water level in the Mondonguillo is around 0.40 metre above mean sea level (see Figure 3.19).

Note: 'above mean sea level' will be called 'AD' (above datum) in the rest of this report.

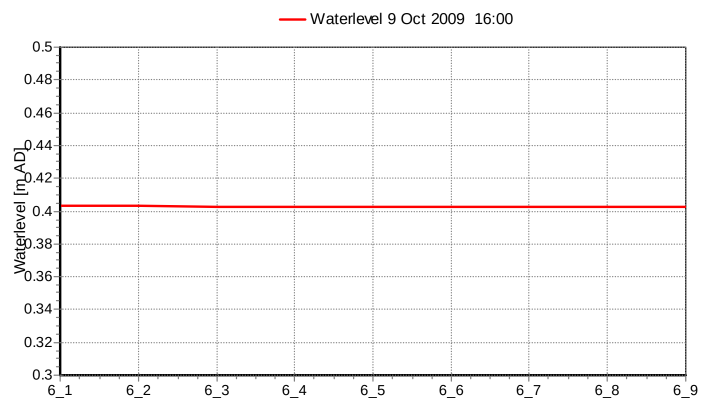

Figure 3.19: Water level, above MSL, Mondonguillo Lagoon under normal conditions

With the hydrograph from Figure 3.14 as boundary condition for the Río Matina and Río Pacuare, the maximum water level in the Mondonguillo Lagoon will be around 2.20 metres AD (see Figure 3.20).

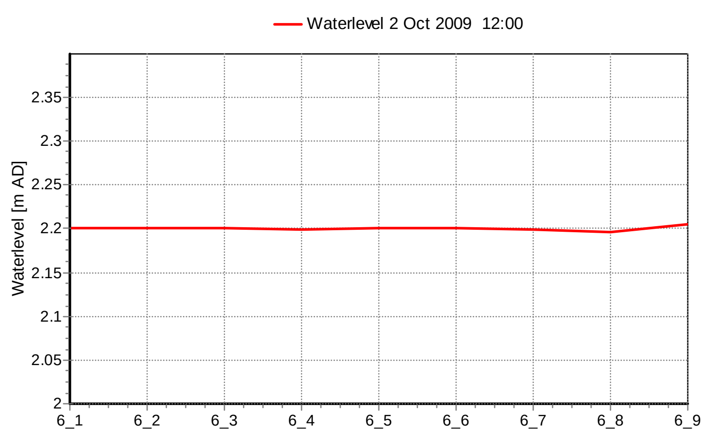

Figure 3.20: water level, above MSL, in Mondonguillo Lagoon under severe conditions.

Note: The downstream boundary condition in the SOBEK-Rural model is described by Q=0 m^3/s (discharge is zero). This means no water flows through this boundary. Figure 3.20 is therefore based on a situation where no water flows through this boundary. This is obviously not the case in the real situation, because when the water level exceeds the critical value of the barrier beach, the water will directly discharge on the open sea. These values are therefore indications on how much the water level rises or lowers in different circumstances.

The volumes of water which will be 'stored' in the area are shown in Figure 3.21. The figure shows that during the peak discharge distribution of 2000 m^3/s, which lasts six days, 28,000,000 m^3 of water is stored in the area. A significant part of this water will eventually flow back in the channels but nonetheless, about 8,000,000 m^3 will remain on the flood-plains. This water will evaporate or infiltrate.

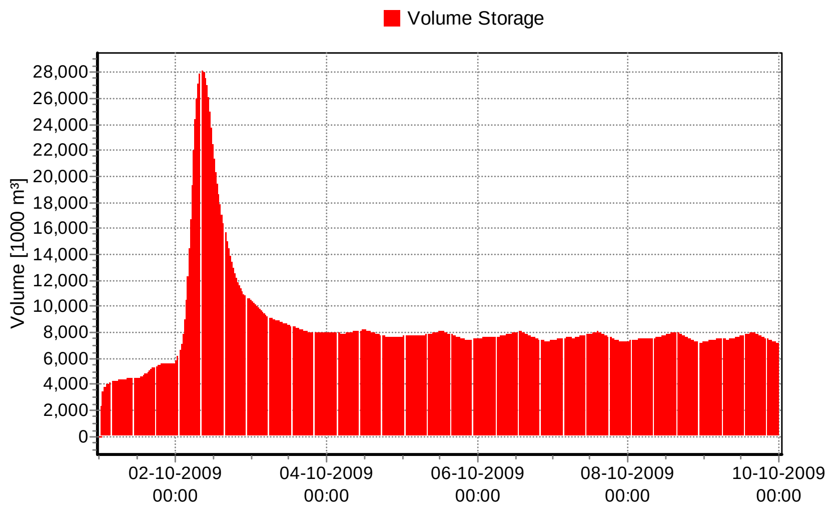

Figure 3.21: Storage in system during simulation period; peak discharge of 2000 m^3/s

Conclusion
The upstream channelisation of the Río Matina causes peak discharges which are not flattened as they would be when the flood-plains could inundate. This causes a rapid decrease in peak discharge due to inundation of the coastal plains. This confirms that the channelisation of the Río Matina is a cause of the breakthroughs and downstream inundations.

3.5.1.2 Earthquake 1991

Chapter 3.2.2 mentioned the tectonic uplift of parts of the Caribbean coast in the Limon province in 1991. Because there is no information available on the precise coastal (-plains) deformations, a validation in SOBEK is not possible and therefore kept qualitative.

Coastal uplift means, among others, a change in bed level slopes. The slope becomes gentler, which means that water does not discharge as fast on the open sea as before. This means accumulation of water and increased water levels. Inundation of the coastal plains is more likely.

Conclusion
The coastal deformations occurred on a large scale. As long as there is no information available about the precise situation before 1991, a validation within SOBEK is not possible. Furthermore, a Mother Nature induced cause is irreversible. The post earthquake coastal-plains are the initial conditions in our SOBEK models. Coastal deformations however certainly have effects on the hydraulics in the area.

3.5.1.3 Drainage canals

It has been mentioned that the cultivation of the valuable flood-plains for the sake of banana plantations might cause problems in safely discharging all the excess water towards the Caribbean Sea. Within SOBEK, this hypothesis is validated by setting peak discharge distributions to zero. This is the case when there are now drainage canals created and excess water normally overflows the flood-plains. Varying the discharge to a peak discharge of 400 m^3/s will show the impact of these drainage canals on the water levels in the Tortuguero Canal and the Mondonguillo Lagoon. In both cases, the discharge distribution in the Río Matina and Río Pacuare is set to a constant discharge of 1000 m^3/s. Figure 3.22 and Figure 3.23 show the differences in water level along the Tortuguero Canal (from south to north).

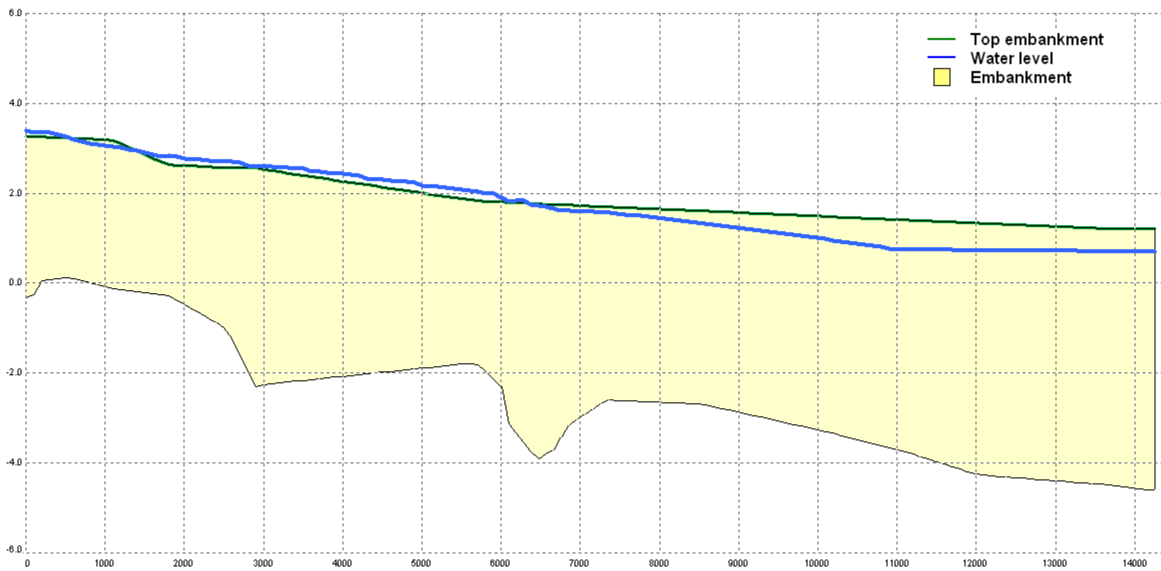

Figure 3.22: Maximum water level Tortuguero Canal with no drainage discharge (0 m^3/s)

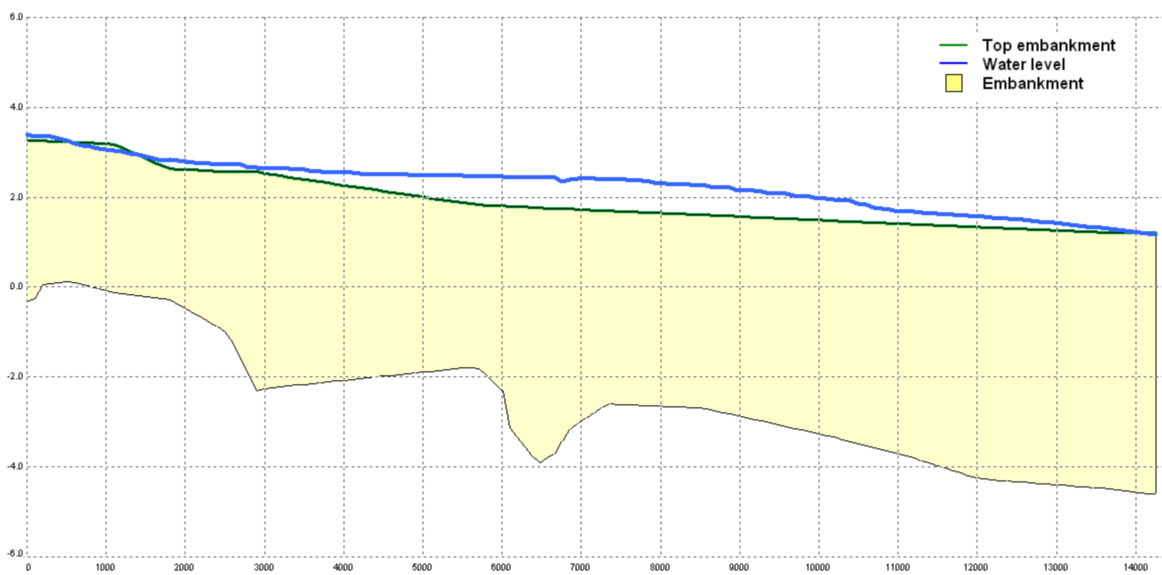

Figure 3.23: Maximum water level Tortuguero Canal with drainage discharge (≤ 400 m^3/s)

Figure 3.22 and Figure 3.23 show that water levels exceed the embankments more when the drainage canals discharge on the Tortuguero Canal. Of course, this would imply that the flood-plains will overflow. But the main problem is, is that the water level will rise in the Mondonguillo Lagoon. Figure 3.24 shows the maximum water level throughout the Mondonguillo Lagoon (from east to west) when no drainage discharge is applied. Figure 3.25 shows the maximum water level in the Mondonguillo Lagoon, when a peak discharge of 400 m^3/s is applied.

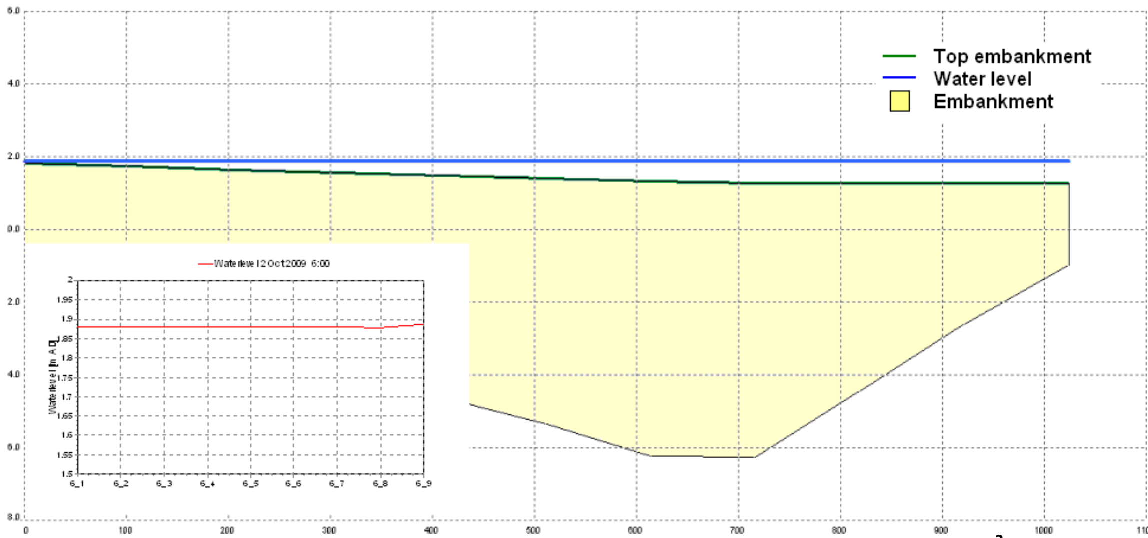

Figure 3.24: Maximum water level Mondonguillo Lagoon with no drainage discharge (0 m^3/s)

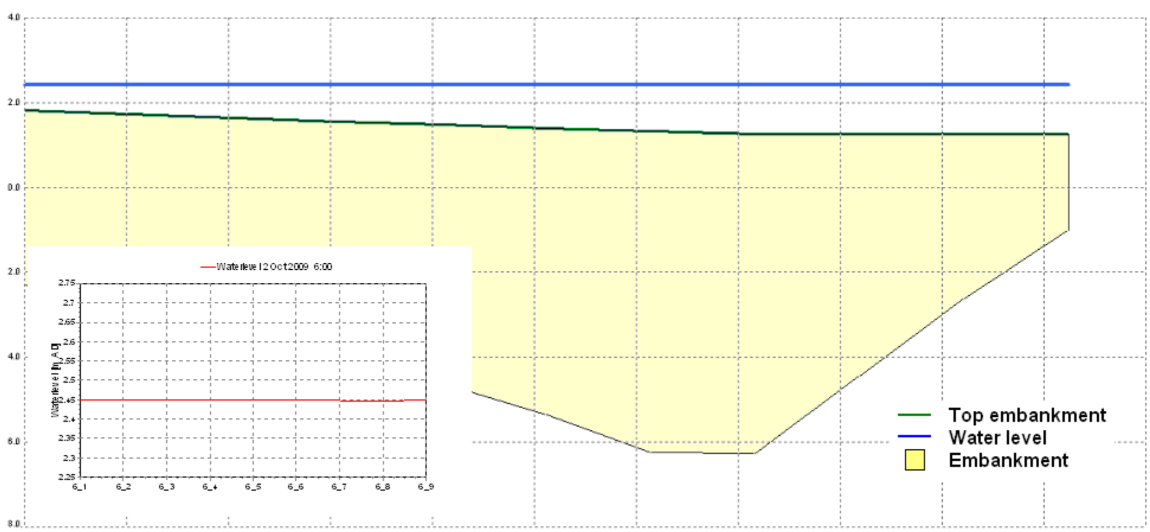

Figure 3.25: Maximum water level in Mondonguillo Lagoon with drainage discharge (≤400 m^3/s)

Conclusion

The difference between the two situations indicates an increased water level in the lagoon of 0.60 metre. Obviously, in both situations the maximum water level will exceed the 1.25 metres AD which starts the process of washing away the barrier beach strip. One should understand that the Río Pacuare and Río Matina are set to a high, and above all, discharge which makes these values rather hypothetical.

The SOBEK model does not simulate the time required for the barrier beach strip to erode completely. But this probably will take more time than the six to twelve hours mentioned here. Because the downstream boundary condition states a discharge of zero, no velocities or changes in velocities are present in the lagoon. This is because the lagoon is a storage basin under normal conditions. As soon as the barrier beach strip breaks through, the lagoon can be qualified as a rapid flowing river.

The modelling shows that the water level in the Mondonguillo Lagoon significantly rises due to discharges in the drainage canals. Therefore, the cultivation of flood-plains, and subsequently the drainage canals, cause erosion problems.

3.5.1.4 High rainfall

This hypothesis seems logical; more rain means more run off and subsequently big volumes of water in the river stretches. This hypothesis is being validated applying different peak discharge distributions on the upstream boundary nodes.

An important factor in qualifying the problems of high rainfall (or any cause for that matter) is checking the distribution of discharges over the confluences. In this case, checking the Río Matina – Tortuguero Canal confluence. Applying different peak discharge distributions show which part of the discharge will be flowing into the Tortuguero Canal. For instance, when applying a peak discharge distribution as the one in Figure 3.14, about 120 m^3/s of the 850 m^3/s coming from upstream regarding to the confluence, flows into the Tortuguero Canal, see Figure 3.28. The particular Río Matina stretch apparently cannot put 2000 m^3/s through, only 850 m^3/s reaches the confluence. The excess volume of water overflows the flood-plains. A similar distribution holds for the 1000 m^3/s discharge distribution (Figure 3.27), and for the constant discharge of 100 m^3/s (Figure 3.26). Table 3.2 summarizes the results.

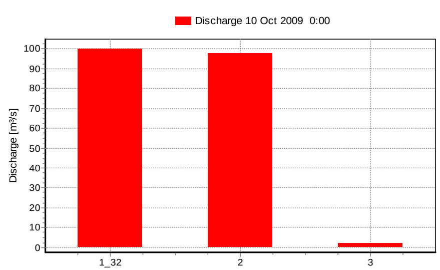

Figure 3.26: Discharge distribution confluence for constant discharge of 100 m^3/s

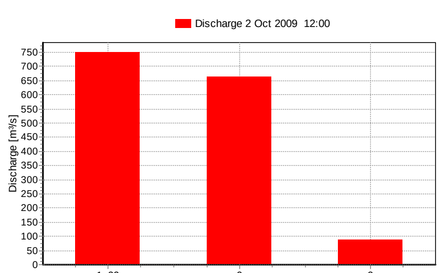

Figure 3.27: Discharge distribution confluence for peak discharge of 1000 m^3/s

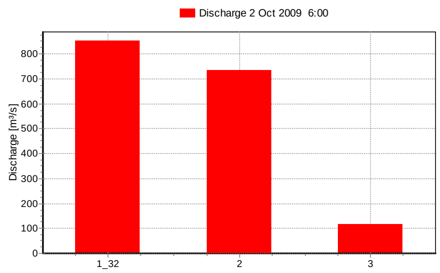

Figure 3.28: Discharge distribution confluence for peak discharge of 2000 m^3/s

	Río Matina (1_32) [m^3/s]	Río Matina →Caribbean Sea (2) [m^3/s]	Tortuguero Canal (3) [m^3/s]	Percentage flowing in Tortuguero Canal [%]
Q=constant = 100 m^3/s	100	97	3	3
Q=varying ≤1000 m^3/s	750	660	90	12
Q=varying ≤ 2000 ^{3}/s	850	730	120	14

Table 3.2: Summary discharge distribution confluence

The inability of the rivers to discharge these peak discharges indicates that the area will inundate. Figure 3.29 and Figure 3.30 show this in the form of a screenshot from the SOBEK animations. The figures show that the flood-plains almost completely overflow when there is a peak discharge of 2000 m^3/s set to the upstream boundaries. This is in line with the flattening of the flood wave which propagates through the rivers.

Figure 3.29: 2D screenshot inundation; peak discharge of 1000 m^3/s

Figure 3.30: 2D screenshot inundation; peak discharge of 2000 m^3/s

The distribution of discharges indicates a water level change in the Tortuguero Canal and subsequently in the Barrita and Mondonguillo Lagoon. Figure 3.31, Figure 3.32 and Figure 3.33 show the maximum water levels as they appear in the Tortuguero Canal during the three situations.

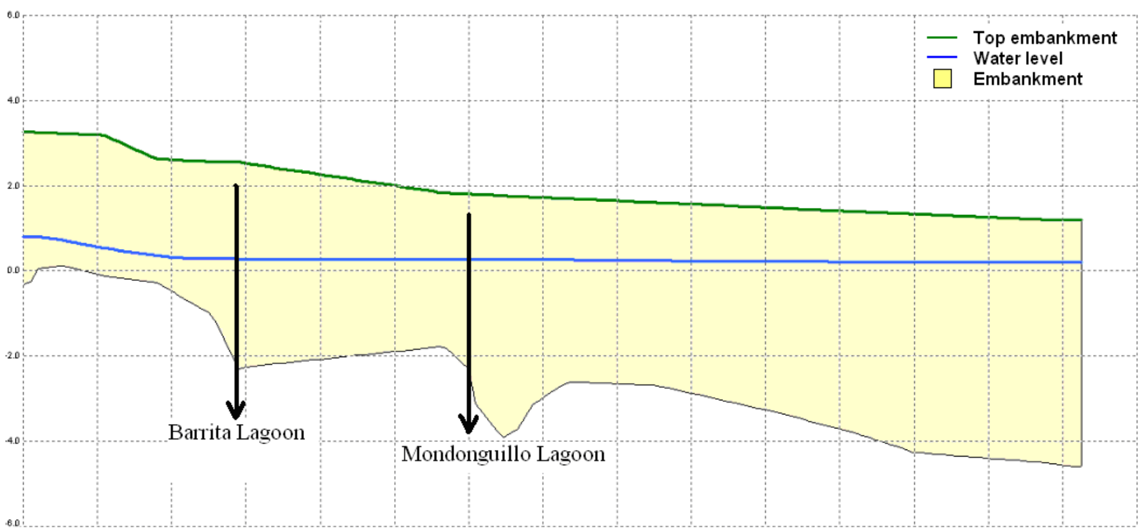

Figure 3.31: Maximum water level in Tortuguero Canal; constant discharge of 100 m^3/s

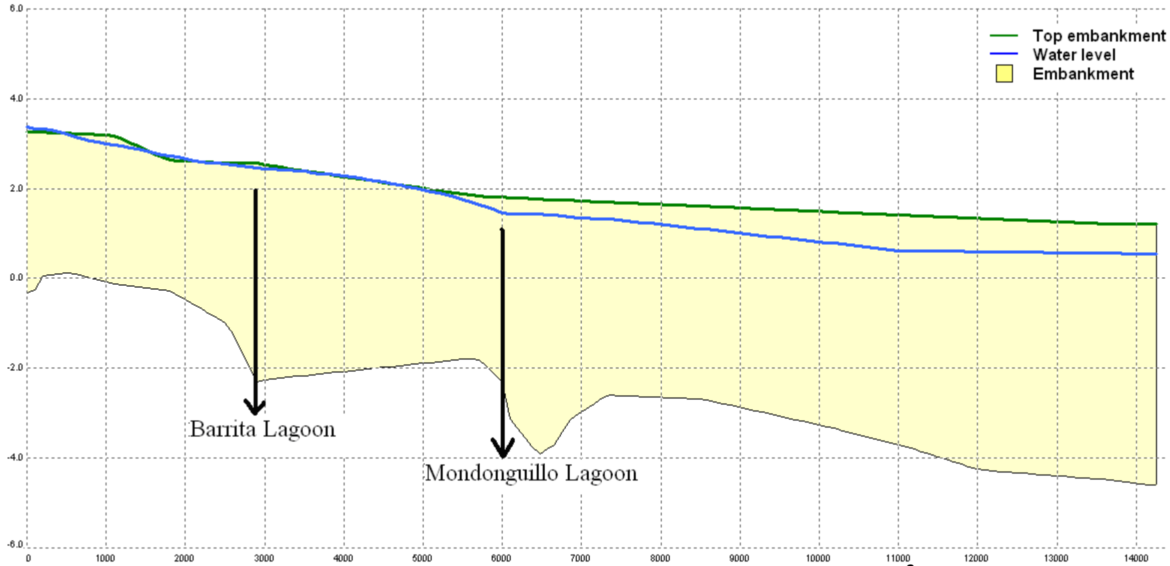

Figure 3.32: Maximum water level in Tortuguero Canal; peak discharge of 1000 m^3/s

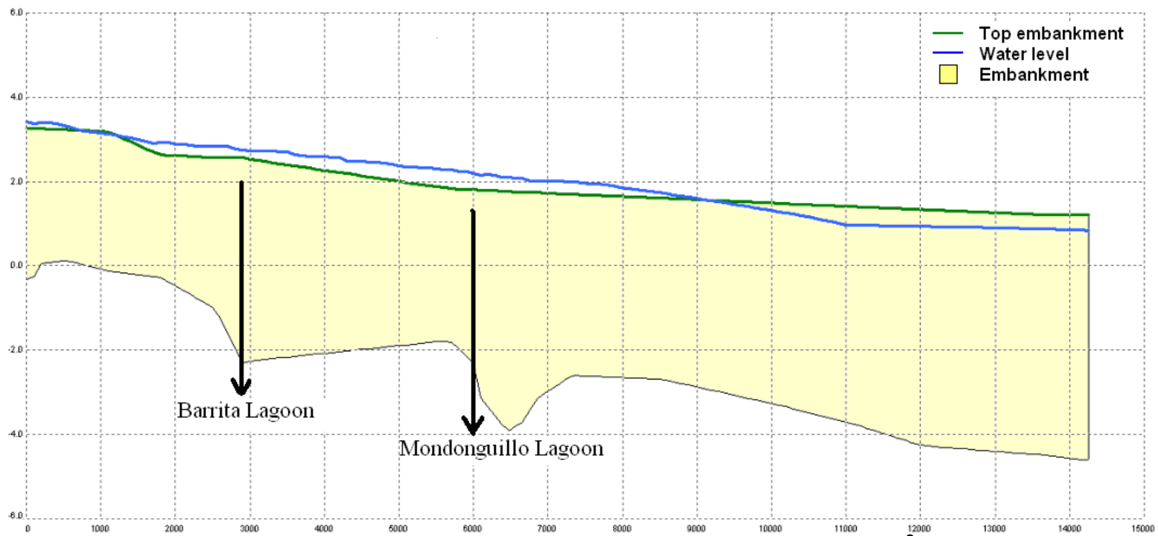

Figure 3.33: Maximum water level in Tortuguero Canal; peak discharge of 2000 m^3/s

The maximum water levels as they appear in the Mondonguillo Lagoon are shown in Figure 3.34, Figure 3.35 and Figure 3.36.

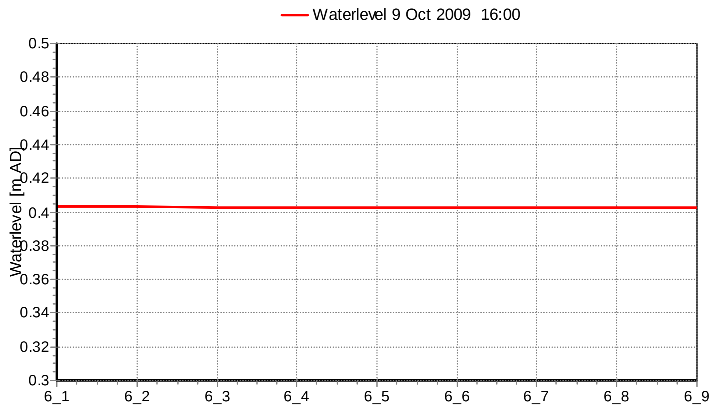

Figure 3.34: Maximum water level in Mondonguillo Lagoon; constant discharge of 100 m^3/s

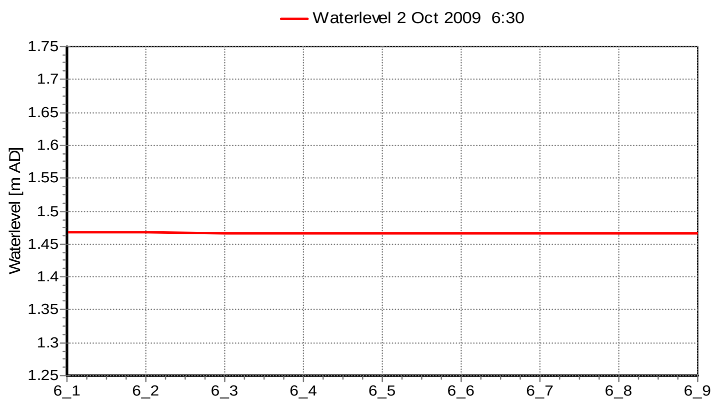

Figure 3.35: Maximum water level in Mondonguillo Lagoon; peak discharge of 1000 m^3/s

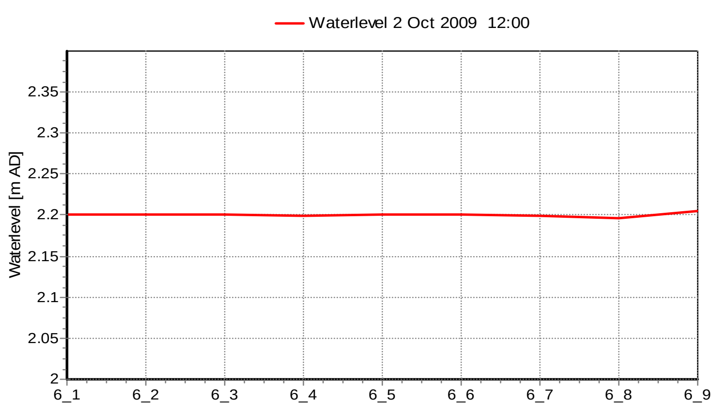

Figure 3.36: Maximum water level in Mondonguillo Lagoon; peak discharge of 2000 m^3/s

Conclusion

High amounts of rainfall will obviously increase discharges in the rivers and inundate the area more severely. Higher water levels in the Tortuguero Canal and Mondonguillo Lagoon increase significantly. A breakthrough might occur during periods of high rainfall. This confirms that high amounts of rainfall are a cause of the breakthroughs.

3.5.1.5 Artificial Tortuguero Canal

The excavation of the Tortuguero Canal connected several hydraulic components with each other. The water level in the Mondonguillo Lagoon is now subjected to the water levels in the Tortuguero Canal and indirectly to the one in the river stretches. Before the excavation of the artificial canal, the lagoon was an enclosed body of water. Breakthroughs could only occur when the surrounding coastal plains (rainforests) harboured large amounts of rainfall run off.

Conclusion

The fact that the water level in the Mondonguillo Lagoon follows the one in the artificial canal confirms that the excavation of the artificial Tortuguero Canal is a cause of the breakthroughs.

3.5.2 Validating possible solutions breakthrough

Chapter 3.3 described a number of possible solutions for discharging the water safely towards the Caribbean Sea. Within the SOBEK Rural model, these different solutions are being checked on their beneficial effects. Below, the different solutions are listed and results are sketched. These solutions can be seen as macro-scale solutions. Not only the Pacuare Nature Reserve suffered from erosion problems, along the Caribbean coast of Costa Rica and Panama this problem is widely encountered. The focus on the following solutions is on donating room for the rivers and canals in order to safely discharge the excess of water. These solutions are tested for the project area described in Chapter 2. Validation is mainly executed by checking differences in water level in the Mondonguillo Lagoon after implementation of the several solutions. These relatively small-scale problems serve as the main validation criterion.

Note: Solutions 3.5.2.1 – 3.5.2.3 are validated within the Río Matina model. Solutions 3.5.2.4 – 3.5.2.9 are validated within the Tortuguero model.

3.5.2.1 Fully channelise Río Matina and/or Río Pacuare

This solution seems very effective; no large amounts of discharges can enter the Tortuguero Canal. The channels and lagoons between the two rivers will be fed by the drainage canals only. One does not need a computer model to check its effect on water levels, for instance the one in the Mondonguillo Lagoon, which will be much lower. The disadvantages consist of the non-accessibility of the canals and lagoons which will have, next to inconvenience for the locals, a negative effect on the tourists and subsequently economics of the country. The building of structures like locks will be an option, this seems however a rather expensive option.

Flooding of the Río Matina used to occur on a regular basis. When the city Matina became bigger and more valuable, the government decided to embank the river so it could not flood the city of Matina that easily. Doing this, the flood problem was transferred downstream. This means that the banana plantations get the overload of water. As mentioned, bananas cannot grow in water. Further channelisation around the banana plantations was necessary to grow the bananas. Again the problem was transferred further downstream. Figure 3.37 shows the current Río Matina river stretch with the embanked part. In this case, the upstream boundary is the hydrograph of Figure 3.14 (peak discharge distribution with return period of five years). The figure shows the maximum water level throughout the river stretch. It is clear that the existing embankments will overflow around the confluence upstream and downstream around the Tortuguero Canal confluence. The problem of overflowing is transferred downstream.

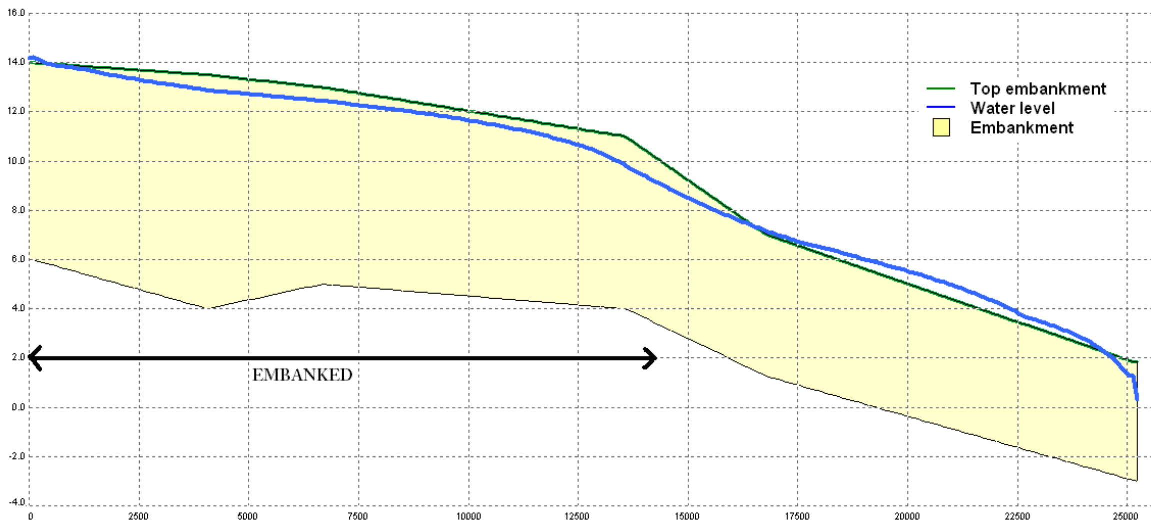

Figure 3.37: Maximum water level; partly embanked Río Matina

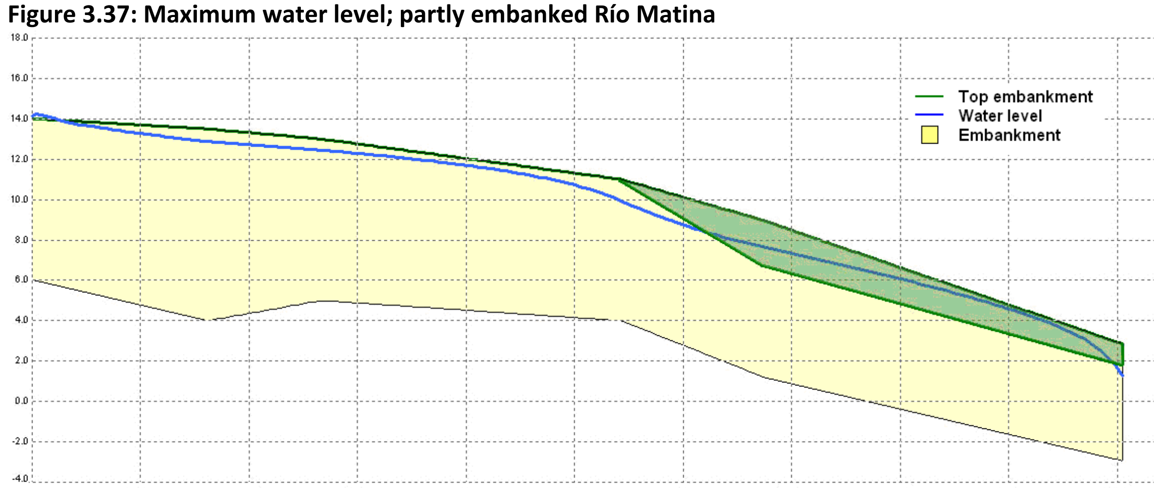

Figure 3.38: Embanked part downstream

If the Río Matina is embanked further downstream till the sea it is not possible to flood the coastal area (see Figure 3.38). In SOBEK, an additional embankment is set to the existing embankments (green part Figure 3.38). The original embankments are about two metres higher in the downstream region. When setting a hydrograph like the one in Figure 3.14 (peak discharge of 2000 m^3/s) a maximum water level is obtained and shown in Figure 3.39.

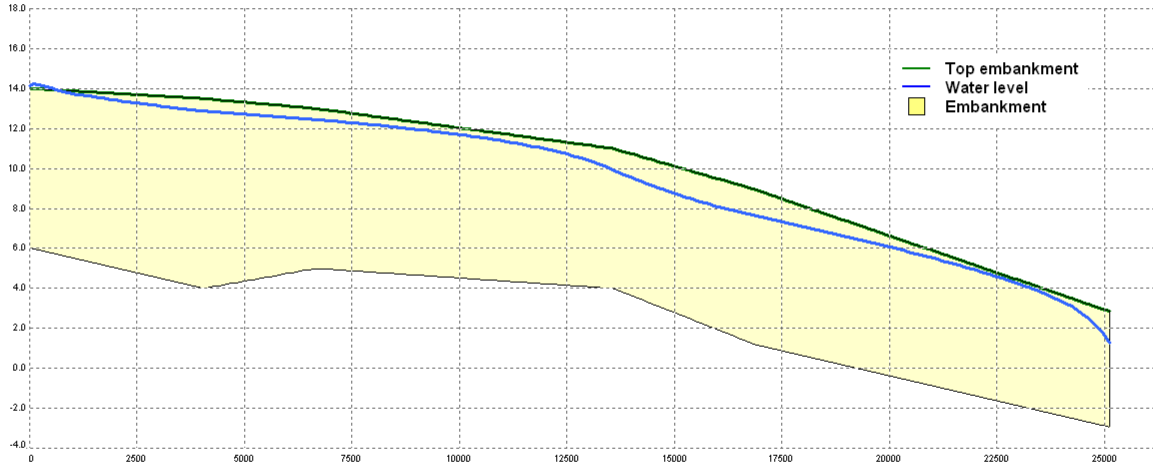

Figure 3.39: Maximum water level; fully embanked Río Matina

Figure 3.40 shows the propagation of the peak discharge 'wave' in the Río Matina. 'Discharge 1_1' is the water level at the upstream boundary and 'Discharge_250' is the water level at the downstream boundary. It seems that the peak discharge does not change in magnitude after the overflow around the upstream boundary.

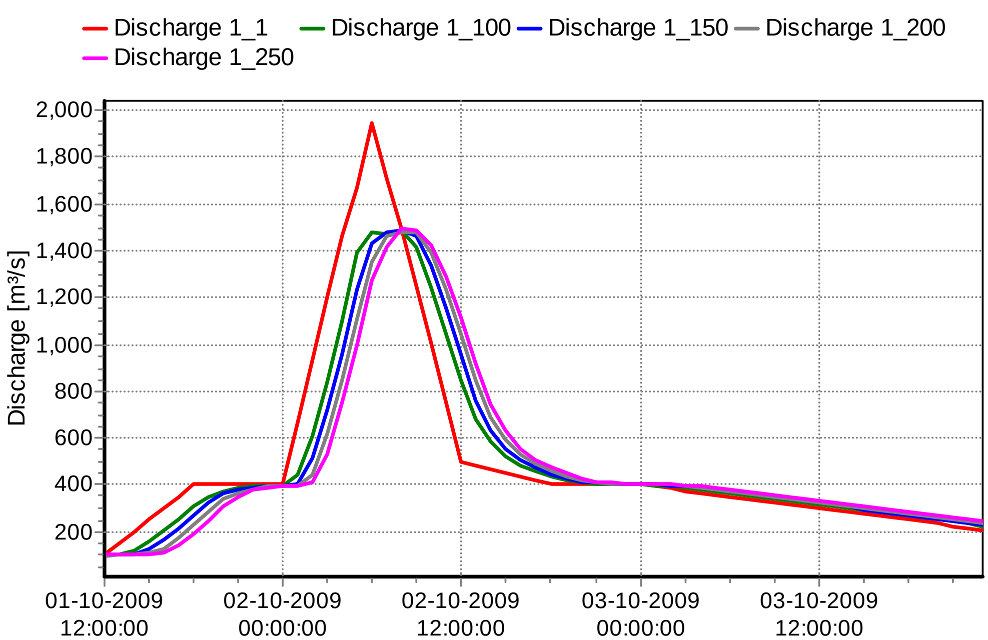

Figure 3.40: Discharge distribution over time

Conclusion
Embanking the whole Río Matina stretch is a good solution to prevent the area from flooding. Attention has to be given to the connection with the Tortuguero Canal and might be a deal breaker.

3.5.2.2 Broadening Boca Río Matina

Another solution is to broaden the Río Matina in order to flatten the peak wave. The only place where space is available to widen the river is at the mouth of the river. Other places are occupied for banana plantations. In SOBEK the Boca Río Matina is made twice as wide as before to look what happens with the peak wave. In Figure 3.41, the water level is shown. The peak wave is flattened enough. The advantage of this solution is the fact that the water level at Tortuguero Canal stays about the same as before, and the water level does not exceed the existing embankments.

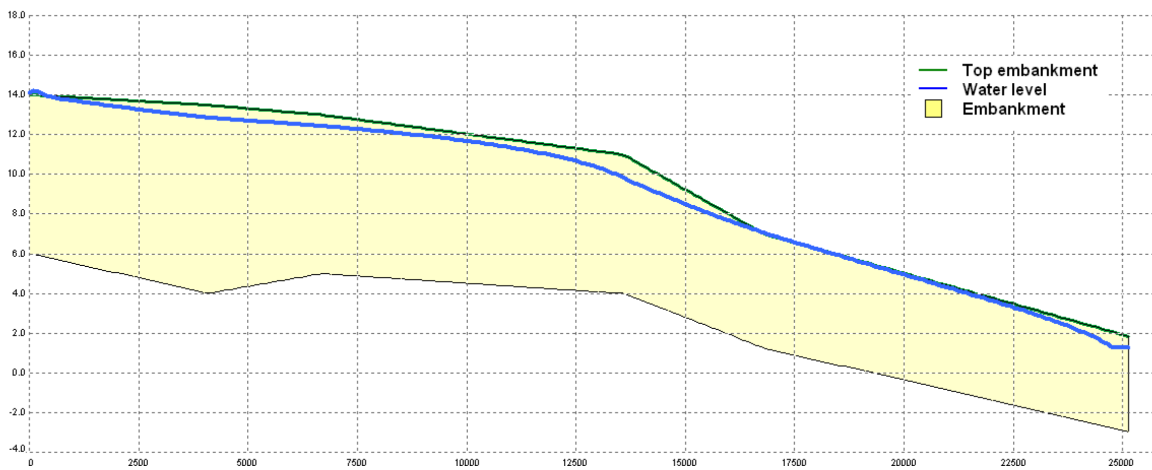

Figure 3.41: Water level at Río Matina with broadening the Boca del Río Matina

An important notion is the feasibility of this possible solution. Quite a lot of land has to be excavated which is rather expensive and big efforts have to be made. A more important aspect is the long-term dynamic equilibrium of the new river mouth. In Chapter 3.5.2.7, this possible solution is elaborated within the Tortuguero model.

Conclusion
This seems a good solution because the coastal area does not flood, and discharges large amounts of water on a safe basis. Further analysis on the excavation and dynamic equilibrium has to be done. Changes induced by this river mouth broadening on the hydrodynamics in the Tortuguero Canal and Mondonguillo Lagoon are elaborated in Chapter 3.5.2.7.

3.5.2.3 Dredging Río Matina

Dredging the Río Matina will obviously result in a lower water level. This will increase the safety against flooding of the coastal area. In SOBEK, the river bed is lowered about one metre at the river mouth till zero metres at seven kilometres upstream. Figure 3.42 shows the water level along the Río Matina river stretch. It is clear that the embankments do not overflow as much as in the case of no dredging.

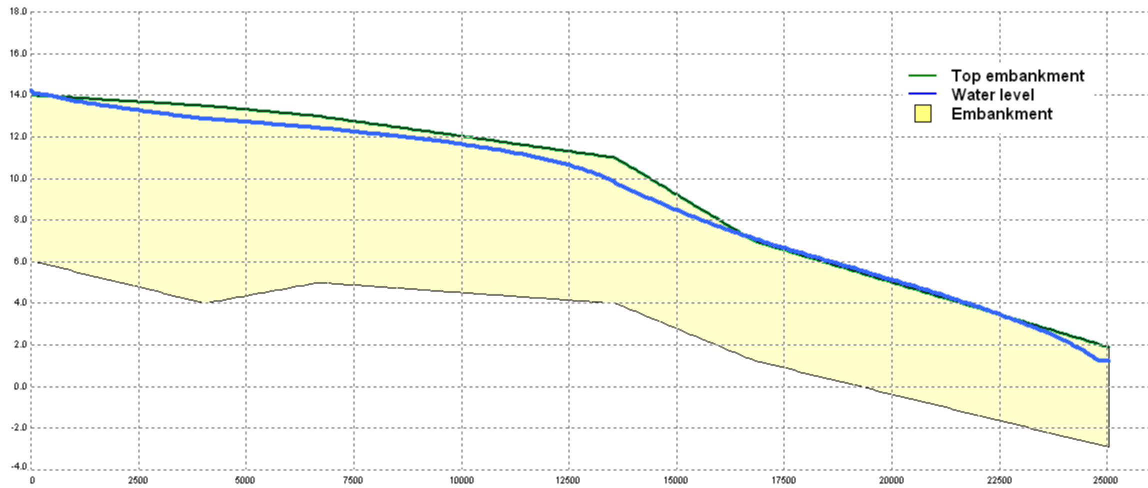

Figure 3.42: Water level at Río Matina with broadening the Boca del Río Matina

As in the widening of the river mouth, the dredging has influence on the dynamic equilibrium. Constant dredging is required to keep the river mouth deep enough. If this is feasible depends on the man-power, heavy equipment and knowledge available.

Conclusion

Dredging parts of the Río Matina is a possible solution to prevent the coastal area from flooding. It is however possible that the problem is being shifted. The Tortuguero Canal will be exposed to larger discharges which can worsen the problems near the coast, in this case the Pacuare Nature Reserve.

Note: The upcoming solutions are based on a new, more likely peak discharge distribution. This distribution is based on the propagation of such a peak through the Río Matina river stretch. The propagation of the discharge is modelled in the Río Matina model. Throughout the first section of this river stretch, the embankments will be overflown and the peak will decrease in magnitude. Appendix VIII elaborates on the determination of the used peak discharge distribution for the Tortuguero model. The upcoming solutions are modelled in the Tortuguero model.

3.5.2.4 Artificially breaching of Barrita barrier beach

This hypothesis is being validated in the SOBEK model. Changing the downstream boundary condition of the Barrita Lagoon to a tidal elevation can show a difference in water levels in the Mondonguillo Lagoon. Obviously, the opening of the Barrita Lagoon will not have any influence on flow velocities or discharges within the Mondonguillo Lagoon, this lagoon will remain a storage basin.

The difference in water levels in the Mondonguillo Lagoon says something about the use of the artificial opening of the barrier beach strip. Figure 3.43 clearly shows that the water level in the Mondonguillo Lagoon is lowered significantly when the Barrita barrier beach is (artificially) breached. In the situation when the Barrita Lagoon is enclosed from the sea, the maximum water level in the Mondonguillo Lagoon is 2.23 metres AD (blue line in Figure 3.43). When the Barrita Lagoon is in open relation with the sea, the water level in the Mondonguillo Lagoon will be lowered to 1.81 metres AD (red line in Figure 3.43).

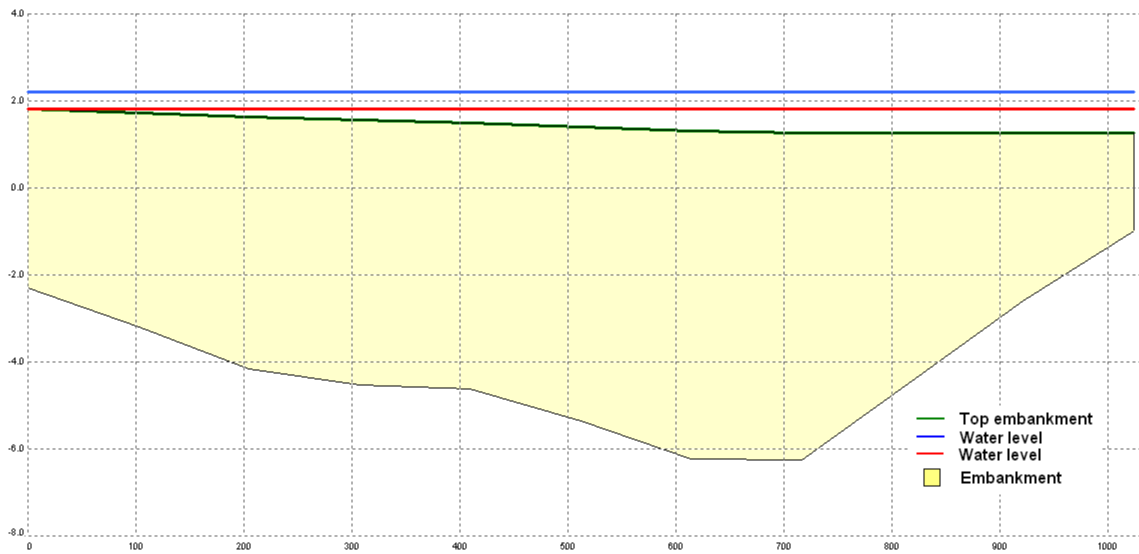

Figure 3.43: Maximum water levels in Mondonguillo Lagoon; breaching Barrita barrier beach

Figure 3.44 shows the maximum water levels in the Tortuguero Canal. The blue line represents the maximum water level when the Barrita Lagoon is still enclosed from the sea; the red line indicates the maximum water level when the Barrita Lagoon is in open relation to the sea. When the water level reaches its maximum, the water flowing in the Tortuguero Canal has one more option to discharge on sea. The opening of the Barrita Lagoon shows a flow towards this lagoon (red line). The surface level gradient is big between the Drainage Canal and the Barrita mouth. Subsequently, the water levels throughout the Tortuguero Canal will be lower during peak discharges.

Note: The downstream boundary condition in the SOBEK-Rural model is described by Q=0 m^3/s (discharge is zero). This means no water flows through this boundary. Figure 3.43 is therefore based on a situation where no water flows through this boundary. This is obviously not the case in the real situation, because when the water level exceeds the critical value of the barrier beach, the water will directly discharge on the open sea. These values are therefore indications on how much the water level rises or lowers in different circumstances.

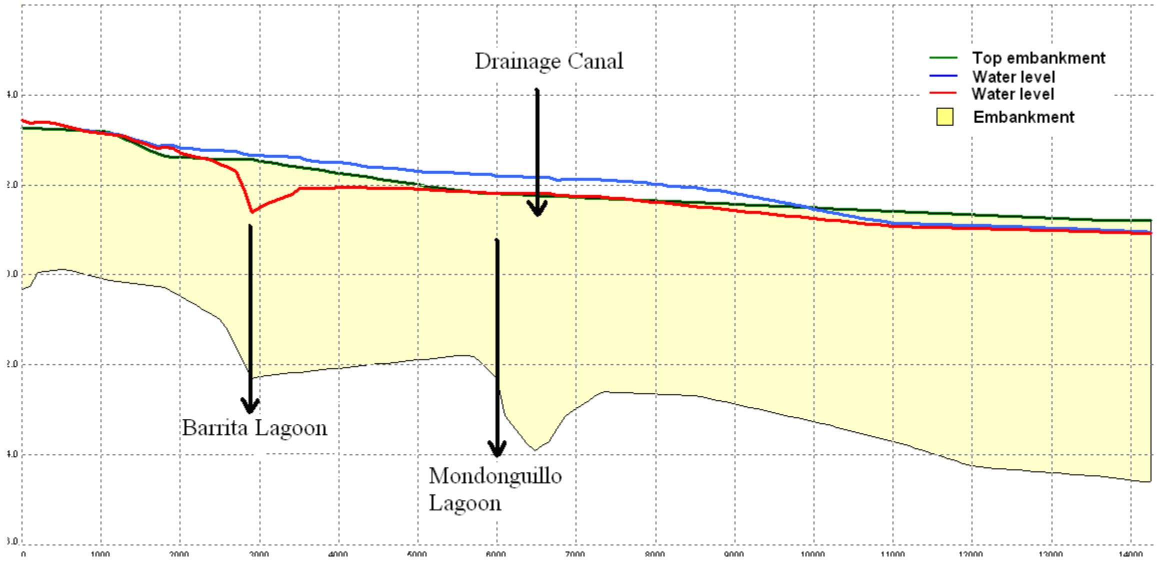

Figure 3.44: Maximum water levels in Tortuguero Canal; breaching Barrita barrier beach

Not only is the actual exceedence of the barrier beach important, the total time of exceedence is also of great importance. The longer the critical level is exceeded, the bigger the chance of breaching. Figure 3.45 shows that the water level is 14 hours above this datum, instead of 27 hours without implementing the solution.

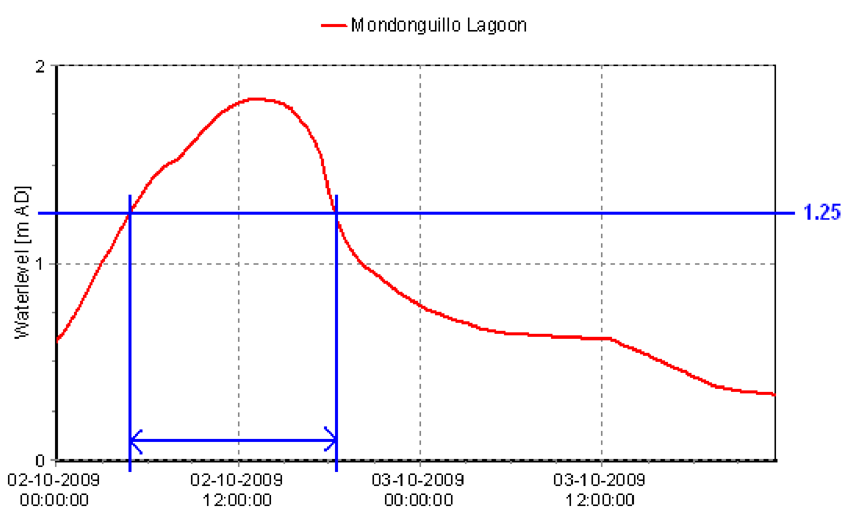

Figure 3.45: Total time of exceedence; breaching Barrita barrier beach

Conclusion

The computed 0.42 metre beneficial lowering of the water level in the Mondonguillo Lagoon indicates that artificially breaching the Barrita is a good option to prevent the erosion problems at the Reserve. Not only the magnitude of the maximum water level is an important indication of the use of the solution, also the time the water level is above the critical 1.25 metres AD is important. The time above the critical level is significantly lowered and therefore the chance of breaching is lower. The low costs and effort also speaks in favour of this option.

3.5.2.5 Artificial channel to Caribbean Sea

In this section, the excavation of an artificial channel to the Caribbean Sea is validated on its utility.

Applying such a waterway in the SOBEK model, one can check whether this solution has beneficial influence on the hydraulic conditions in and around the Mondonguillo Lagoon. Figure 3.46 shows a side view of the Mondonguillo Lagoon with two maximum water levels. The red line indicates the maximum water level without the implementation of the solution (2.23m AD). The blue line shows the maximum water level including the artificial channel to the Caribbean Sea (2.10m AD).

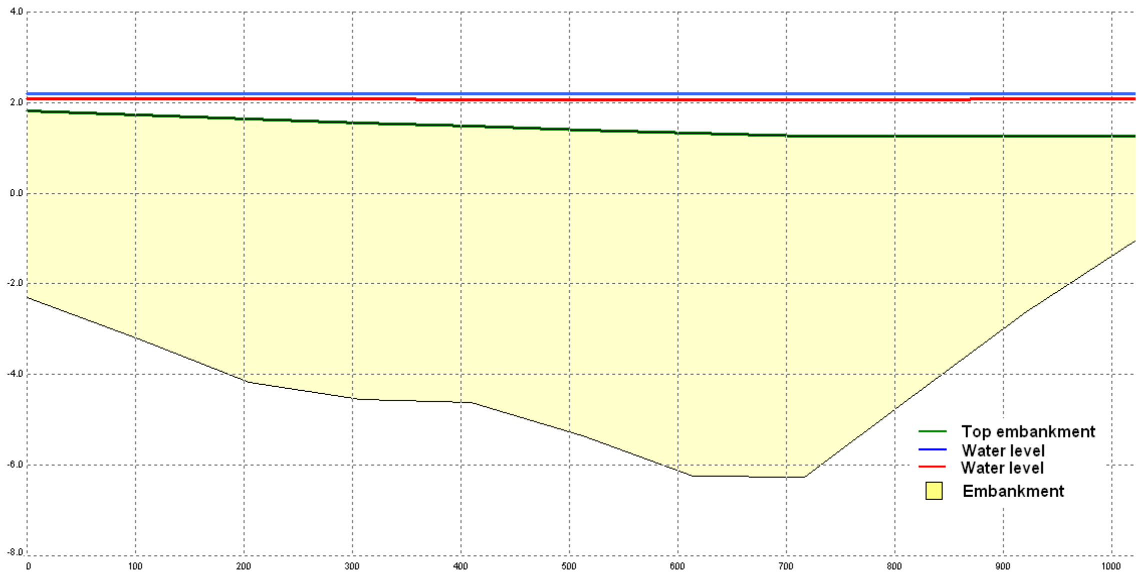

Figure 3.46: Maximum water levels in Mondonguillo Lagoon; artificial channel solution

Figure 3.47 shows the maximum water levels in the Tortuguero Canal. The blue line represents the maximum water level without the implementation of the solution, the red line indicates the maximum water level when the artificial channel is up and running.

The lowering of the water level in the Río Matina seems positive. The water level around the Mondonguillo Lagoon however, does not decrease much. Apparently, the water coming out of the drainage canals has a major impact on the water levels in the Tortuguero Canal. Creating more room for the river does not have the desired effect.

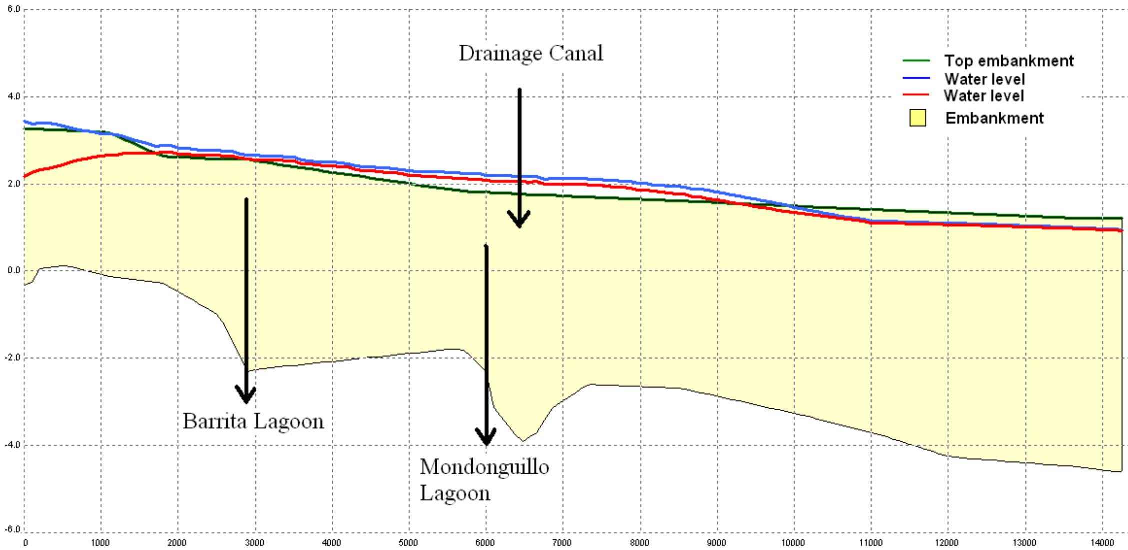

Figure 3.47: Maximum water levels in Tortuguero Canal; artificial channel solution

Not only is the actual exceedence of the barrier beach important, the total time of exceedence is also of great importance. The longer the critical level is exceeded, the bigger the chance of breaching. Figure 3.48 shows that the water level is 20 hours above this datum, instead of 27 hours without implementing the solution.

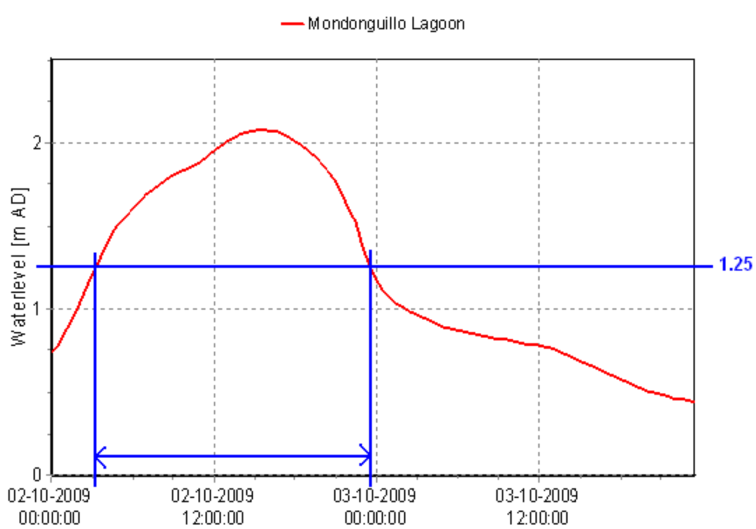

Figure 3.48: Total time of exceedence; artificial channel solution

Conclusion

If this option would result in significant lowering of water levels throughout the area, investments in such a channel would be a good option. The benefits clearly do not outweigh the economic and environmental sacrifices.

3.5.2.6 Extend drainage channel to Caribbean Sea

Chapter 3.5.1.3 indicated that the constant discharging of water on the Tortuguero Canal had massive impact on the duration and magnitude of the exceeding water level in the Mondonguillo Lagoon. The extension of the drainage canal through the rainforest towards the Caribbean Sea may be the solution for safely discharging all the excess water.

Figure 3.49 shows a side view of the Mondonguillo Lagoon with two maximum water levels. The red line indicates the maximum water level without the implementation of the solution (2.23m AD). The blue line shows the maximum water level including the extension of the Drainage Canal to the sea (1.67m AD).

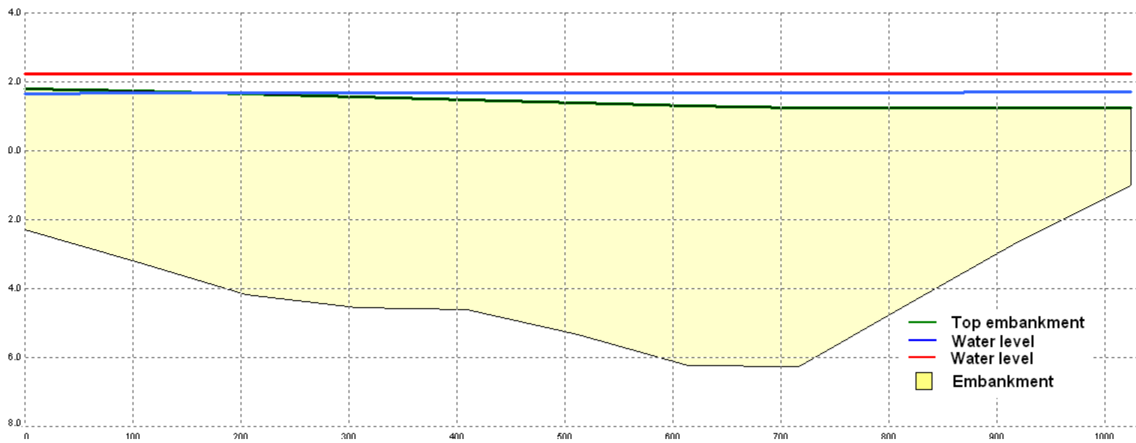

Figure 3.49: Maximum water levels in Mondonguillo Lagoon; extend drainage canal solution

Figure 3.50 shows the maximum water levels in the Tortuguero Canal. Again, the red line indicates the situation without the extended Drainage Canal and the blue line includes the solution. The extension shows that around the Mondonguillo Lagoon the water level is significantly lower. The new, nearby inlet discharges the water coming from the Drainage Canal at once towards the open sea. This causes a lower water level around the Mondonguillo Lagoon. Obviously, the embankments in the first kilometres of the Tortuguero Canal will overflow anyway.

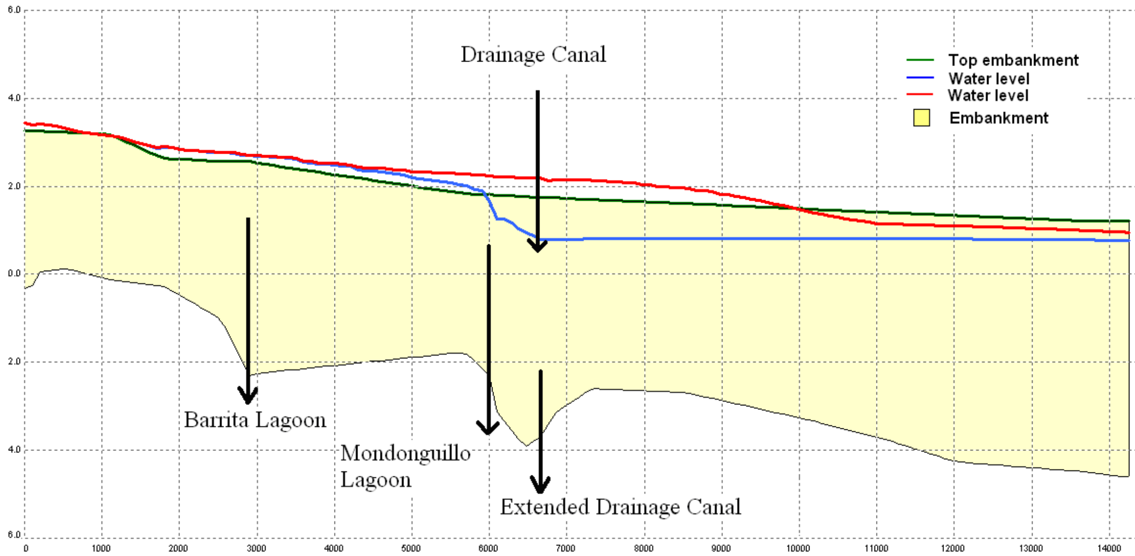

Figure 3.50: Maximum water levels in Tortuguero Canal; extend drainage canal solution

Figure 3.51 shows the maximum water level in the Drainage Canal and the extension of this canal. The embankments are the same height above MSL as the embankments (rainforest) in the nearby Mondonguillo Lagoon. The bottom level is about the same as in the Mondonguillo Lagoon. The width of the canal is set to 70 metres. The figure shows that these dimensions are sufficient to safely discharge all the excess water towards open sea.

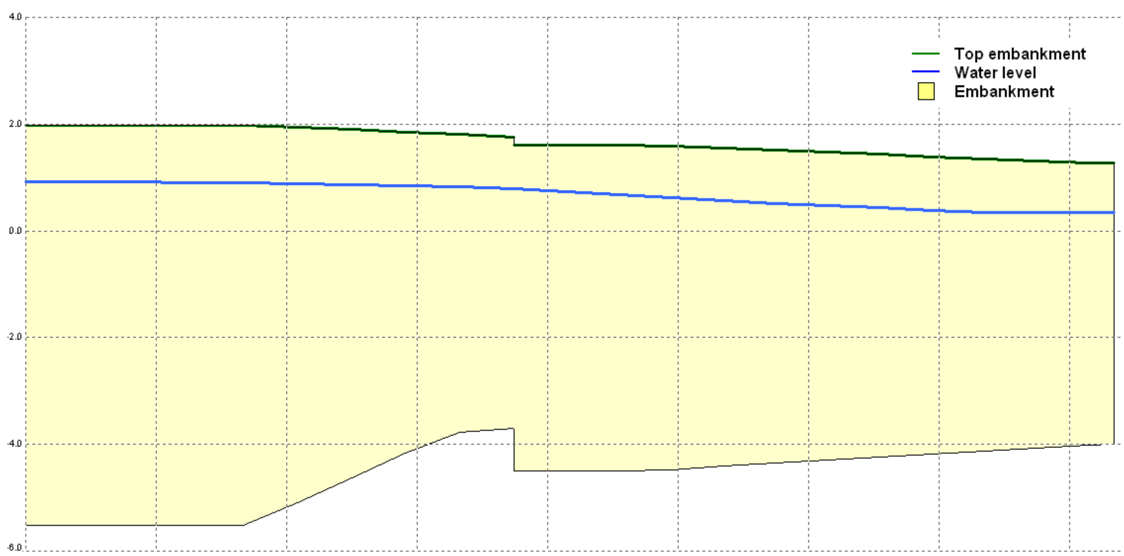

Figure 3.51: Maximum water level in (extended) Drainage Canal

Not only is the actual exceedence of the barrier beach important, the total time of exceedence is also of great importance. The longer the critical level is exceeded, the bigger the chance of breaching. Figure 3.52 shows that the water level is 8 hours above this datum, instead of 27 hours without implementing the solution.

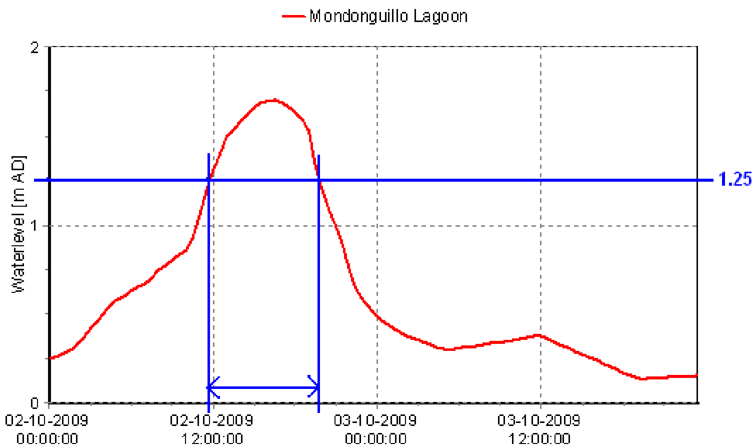

Figure 3.52: Total time of exceedence; extend drainage canal solution

Conclusion

The extension of the drainage canal has a positive effect on the water levels in the Mondonguillo Lagoon. Again, ecological criteria come into question. The newborn intersection of the Reserves' beach is also not desirable. Because of that, the extended drainage canal should be enclosed from the sea with a body of sand (the barrier beach). In periods of potential water hazard, this barrier beach should be artificially breached, just like the Barrita Lagoon.

3.5.2.7 Widen river mouth

This solution is in line with giving the rivers enough space for safely discharging water towards open sea.

Figure 3.53 shows a side view of the Mondonguillo Lagoon with two maximum water levels. The red line indicates the maximum water level without the implementation of the solution (2.23m AD). The blue line shows the maximum water level including the extension of the Drainage Canal to the sea (2.09m AD).

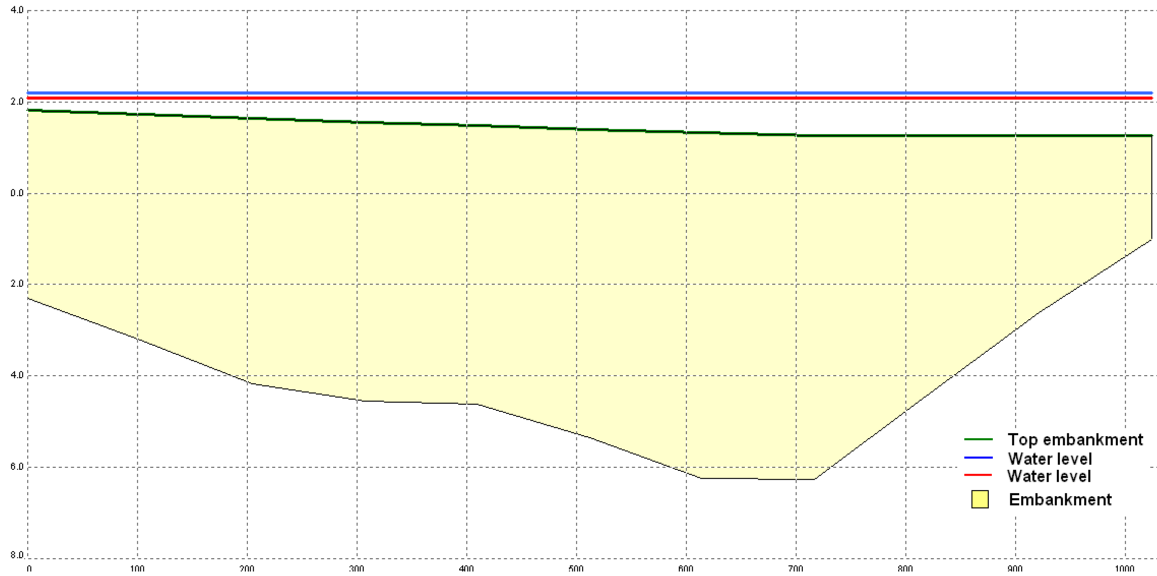

Figure 3.53: Maximum water levels in Mondonguillo Lagoon; widen river mouth solution

Figure 3.54 shows the maximum water levels in the Tortuguero Canal. Again, the red line indicates the situation without the widened river mouth and the blue line includes the solution. The widened river mouth causes a lower water level at the beginning of the Tortuguero Canal. This however has a counter effect. During the peak discharge, water is not flowing in the Canal but out. The flow direction changes. This is due to a change in water level slope. The water level in the middle of the Tortuguero Canal (around the drainage canal connection) will be higher than the one in the Río Matina.

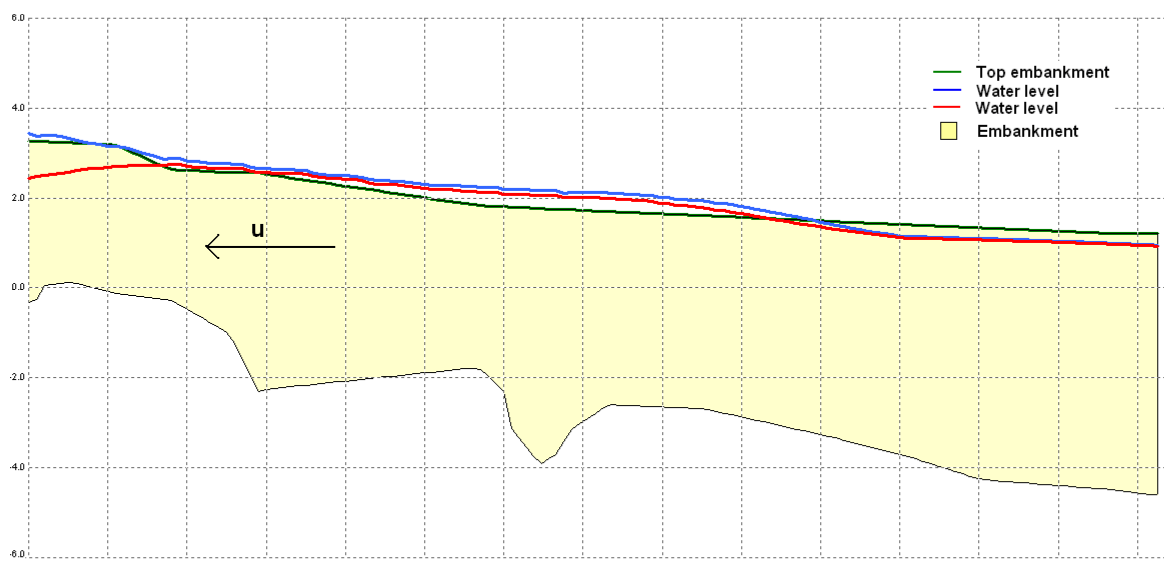

Figure 3.54: Maximum water levels in Tortuguero Canal; widen river mouth solution

Not only is the actual exceedence of the barrier beach important, the total time of exceedence is also of great importance. The longer the critical level is exceeded, the bigger the chance of breaching. Figure 3.55 shows that the water level is 24 hours above this datum, instead of 27 hours without implementing the solution.

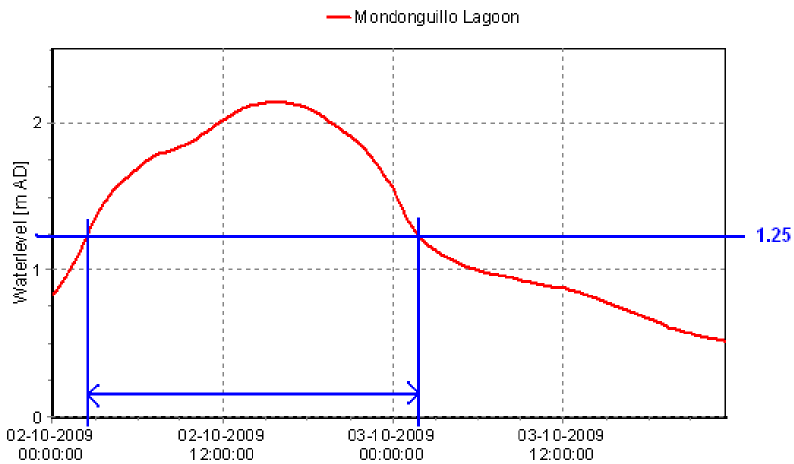

Figure 3.55: Total time of exceedence; widen river mouth solution

Conclusion

At first glance, this option does not seem very effective. The (maximum) water levels only lower 14 centimetres. The time of exceedence does not lower significantly. The inundation of the coastal plains will be less, which is positive about this solution. This option requires a lot of money and effort. Also ecological values come into question. This option reduces the amount of natural flood-plains and will result in a new hydrodynamic equilibrium which should be researched first. The utility that this option has hardly weighs against the cost and effort.

3.5.2.8 Stop cultivating land of banana plantations

Validating the probable cause 'drainage canals' in Chapter 3.5.1.3 showed significant lowering of water levels when assuming no drainage discharge which flows in the Tortuguero Canal. The climatic conditions are great for growing bananas, but will worsen the inability of discharging the excess water safely towards open sea. The surface cultivated for the sake of these banana plantations still grows rapidly, in a lot of cases this is even done illegally. A clear and fair legal provision, which also should be respected, will have to change this. A fair rule would be that for every cultivated square metre elsewhere one square metre of flood-plain must be formed by the banana plantations.

Conclusion

Knowing that the banana production is of paramount economic importance for a country like Costa Rica, 'out of the box'-solutions must be devised, like those mentioned in previous sections. Banana plantation exploiters should however know the consequences of their land-use.

Note: None of the solutions showed a sufficient lowering of water levels in the lagoon. Next, a combination of solutions is modelled.

3.5.2.9 Artificially breaching of Barrita barrier beach and extend drainage canals to Caribbean Sea

Combination of solutions is also possible. The solutions with the biggest beneficial water level lowering are combined within SOBEK. The general idea is to check whether the beneficial effects of the single solutions enforce each other. Figure 3.56 shows the maximum water level for the case of only the extended drainage canal (red line), and the maximum water level for the combination of the extended drainage canal and the artificial breaching of the Barrita barrier beach (blue line). The red line is 1.67m AD and the blue line is 0.70m AD. The lowering is significant and does not reach above the critical level of 1.25m AD.

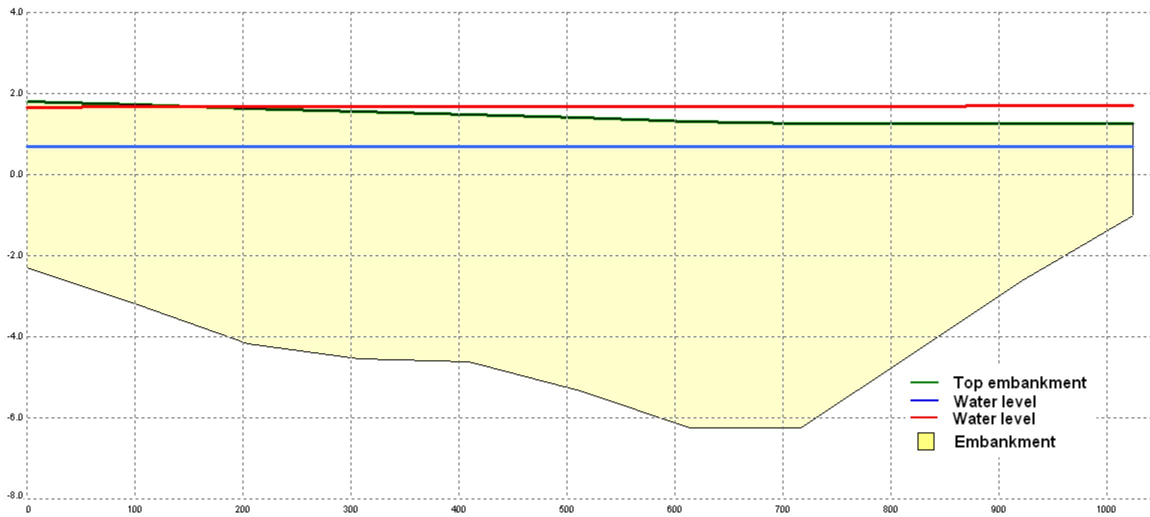

Figure 3.56: Maximum water levels in Mondonguillo Lagoon; combination of solutions

Figure 3.57 shows the maximum water levels for the same situations in the Tortuguero Canal. The figure clearly shows the withdrawing effect of these two new outlet systems. The two new gateways to the open sea exert a certain suction on the excess water in the system and subsequently lowers the water level in the Mondonguillo Lagoon.

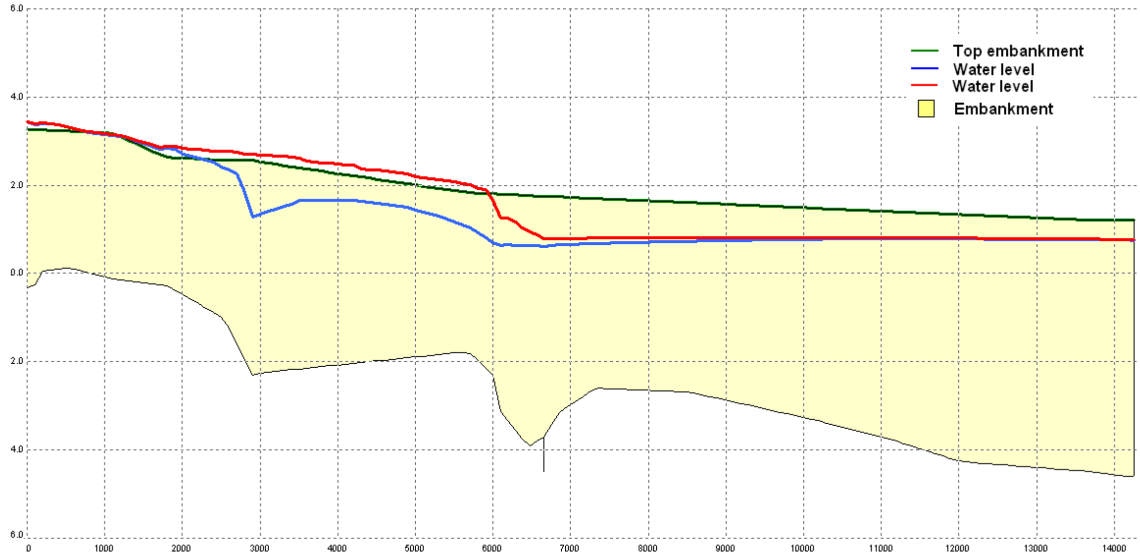

Figure 3.57: Maximum water levels in Tortuguero Canal; combination of solutions

Not only is the actual exceedence of the barrier beach important, the total time of exceedence is also of great importance. The longer the critical level is exceeded, the bigger the chance of breaching. Figure 3.58 shows that the water level never even reaches this datum.

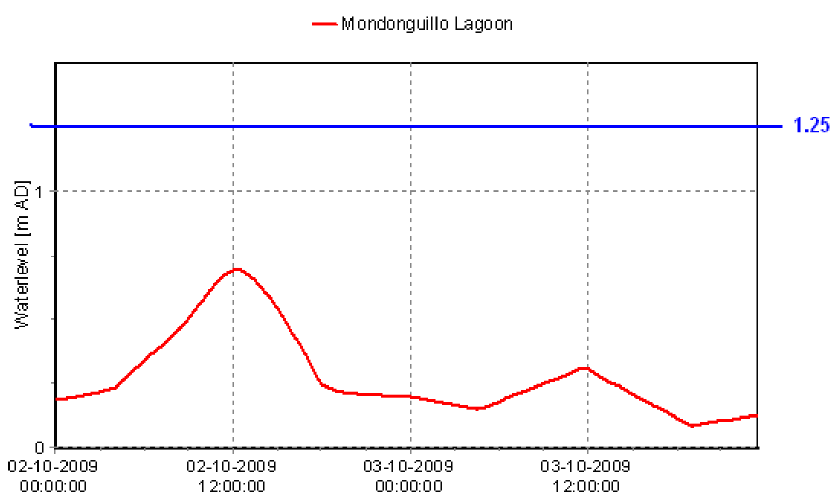

Figure 3.58: Total time of exceedence; combination of solutions

Conclusion

Combining the two solutions will result in a sufficient lowering of the water level in the Mondonguillo Lagoon. The newborn intersection of the Reserves' beach is not desirable. Because of that, the extended drainage canal should be enclosed from the sea with a body of sand (the barrier beach). In periods of potential water hazard, this barrier beach should be artificially breached, just like the Barrita Lagoon.

3.6 Multi Criteria Analysis

In this chapter the solutions will be compared to each other. Important aspects are the water levels in the Mondonguillo Lagoon (effect) and the possibility of implementing the various solutions (effort and ecological impact). A Multi Criteria Analysis[9] sums up all the solutions and to important criteria, points will be assigned. This way one can check which solution is the most sensible.

Chapter 3.5.2 sketched the results of the various solutions. These results consisted of exceedence of the barrier beach crest level, and the duration of the exceedence. Table 3.3 enumerates the solutions and states the positive lowering of the water level in the Mondonguillo Lagoon. Table 3.4 enumerates the solutions and states the time the water level is above the critical level of 1.25m AD. Obviously, the bigger the water level difference and how bigger the time difference, the better this solution qualifies.

The possible solutions are verified with two different models. The first three solutions in Table 3.3 and Table 3.4 were verified in the Río Matina model. The main objective in this model was to see how the peak discharge propagates in the river and to see where the embankments will overflow. This model does not give data with respect to the water levels in the Mondonguillo Lagoon. The last solution was difficult to qualify and model in SOBEK. The magnitude and duration of exceedence for these solutions are not included.

[9] Ridder de, H.A.J. (2004): Integraal ontwerpen in de Civiele Techniek – Ontwerpproject I. TU Delft, The Netherlands.

	Maximum water level before applying solution [m AD]	Maximum water level after applying the solution [m AD]	Water level difference [Δm]
1. Fully channelise Río Matina and/or Río Pacuare	2.23	-	-
2. Broadening Boca Río Matina	2.23	-	-
3. Dredging Río Matina	2.23	-	-
4. Artificially breaching of Barrita barrier beach	2.23	1.81	0.44
5. Artificial channel to Caribbean Sea	2.23	2.10	0.13
6. Extend drainage canals to Caribbean Sea	2.23	1.67	0.56
7. Widen river mouth	2.23	2.09	0.14
8. Stop cultivating land for banana plantations	2.23	-	-
9. Combination of 4. and 6.	2.23	0.70	**1.53**

Table 3.3: Beneficial lowering water level Mondonguillo Lagoon

	Time above critical water level before applying solution [h]	Time above critical water level after applying solution [h]	Time difference [Δh]
1.Fully channelise Río Matina and/or Río Pacuare	27	-	-
2.Broadening Boca Río Matina	27	-	-
3.Dredging Río Matina	27	-	-
4.Artificially breaching of Barrita barrier beach	27	14	13
5.Artificial channel to Caribbean Sea	27	20	7
6.Extend drainage canal to Caribbean Sea	27	8	19
7.Widen river mouth	27	24	3
8.Stop cultivating land for banana plantations	27	-	-
9.Combination of 4. and 6.	27	0	**27**

Table 3.4: Beneficial decrease of time above exceedence level Mondonguillo Lagoon

The solution 'Extend drainage canal to Caribbean Sea' seems to have the best impact on the water level in the Mondonguillo Lagoon. Nonetheless, the water level will exceed the critical level anyway. A combination of solutions is off course also possible. The option 'Extend drainage canal to Caribbean Sea' and 'artificially breaching of Barrita barrier beach' will result in a maximum water level of 0.70m AD. This is far below the critical value.

The above checked every solution on its effect. Next, every solution is appointed with points on several criteria. These criteria are described below:

Effect = the effect the solution will have on the water level in the Mondonguillo Lagoon.
Effort = the effort the solution will take to accomplish the solution.
Knowledge available = the availability of man-power, knowledge and heavy equipment in the area + the degree of further studies necessary.
Ecological impact = the total of negative effects on the flora and fauna.

To determine the mutual importance of each criterion, they are put in Table 3.5. If the criteria in the row is more important than in the column it is given a one, if it is not than it is given a zero.

	Effect	Effort	Knowledge available	Ecological impact	Total score
Effect		1	1	1	3
Effort	0		0	0	0
Knowledge available	0	1		0	1
Ecological impact	0	1	1		2

Table 3.5: Determining mutual importance

Note: The combination of solutions cannot be part of this Multi Criteria Analysis, appointing scores to this solution will not be in coherence with the single solutions.

The criteria 'effort' does not score in the table. Though it has influence in the MCA. To give it any influence it is given the weight 'one'. Al the criteria are multiplied with a factor two. In Table 3.6 the weight factor is calculated.

		Weight factor
Effect	6	6/13=0.46
Effort	1	1/13=0.08
Knowledge available	2	2/13=0.15
Ecological impact	4	4/13=0.31
	$\sum = 13$	$\sum = 13$

Table 3.6: Determining weight factor

The solutions are criticized on every criterion with a grade 1-10 (in which 1 is negative and 10 is positive). Knowing the score and the weight factor, the total score of the solutions can be calculated. The score of each solution is multiplied with the weight factor of each corresponding criteria. The maximum score is 1000. In Table 3.7 this is all ordered.

	Effect	Effort	Knowledge available	Ecological impact	Total score
WF	[46]	[8]	[15]	[31]	
1. Fully channelise Río Matina and/or Río Pacuare	8	2	4	2	506
WF*score	368	16	60	62	
2. Broadening Boca Río Matina	4	3	4	4	392
WF*score	184	24	60	124	
3. Dredging Río Matina	5	5	6	4	484
WF*score	230	40	90	124	
4. Artificially breaching of Barrita barrier beach	7	9	10	8	792
WF*score	322	72	150	248	
5. Artificial channel to Caribbean Sea	3	5	6	2	330
WF*score	138	40	90	62	
6. Extend drainage canal to Caribbean Sea	9	5	6	2	606
WF*score	414	40	90	62	
7. Widen river mouth	4	3	4	4	392
WF*score	184	24	60	124	
8. Stop cultivating land for banana plantations	9	3	10	9	867
WF*score	414	24	150	279	

Table 3.7: Determining total score of each solution

To complete the MCA the costs of each solution have to be divided by the corresponding total score. Because there are no real costs of the possible solutions there are used fictive costs. The fictive costs are values which are determined with respect to the other solutions.
For example; ‘broadening Boca Río Matina’ is in the same order of costs as ‘widen river mouths’ so both are rated with the value 1000. Compared with ‘artificially breaching

Barrita barrier beach' this is much less, cost value about 100. 'Stop cultivating land for banana plantations' will cost the banana companies, and ultimately the country, a lot of money. The cost value is set to 5000. This is all ordered in Table 3.8.

	Cost values	Total score	Costs value/total score
1. Fully channelise Río Matina and/or Río Pacuare	1500	506	3.0
2. Broadening Boca Río Matina	1000	392	2.6
3. Dredging Río Matina	1500	484	3.1
4. Artificially breaching of Barrita barrier beach	100	792	0.1
5. Artificial channel to Caribbean Sea	1000	330	3.0
6. Extend drainage canal to Caribbean Sea	1000	606	1.7
7. Widen river mouth	1000	392	2.6
8. Stop cultivating land for banana plantations	5000	867	5.8

Table 3.8: Multi Criteria Analysis

The solution 'Artificially breaching of Barrita barrier beach' scores by far the best on these criteria. It has a positive effect on the water level and does not require much cost and effort. Moreover, the locals are familiar with this interference.

The next best solution is 'extension of the drainage canal to the Caribbean'. As mentioned, this solution decreases the water level in the Mondonguillo Lagoon significantly. The combination of artificially breaching of Barrita barrier beach and extend drainage canal to Caribbean Sea is a good solution.

4. Analysis of beach system

4.1 Approach

In order to sufficiently reach the objectives, a clear approach was defined. The project is divided in phases; analysis, gathering data, fieldwork and modelling. Each phase is elaborated on further.

4.1.1 Analysis

The first important step is to analyze the beach system. In order to create better understanding of the problems a clear project objective is necessary. The results of this analysis are described in Chapter 1.2.

4.1.2 Gathering data

In order to reach the objectives sketched in Chapter 1.3, several data is required. Table 4.1 states the data necessary and if this information is available. Appendix IV and X contain the available data.

Data	**Availability**
Wave statistics offshore	
- *wave angle*	Available
- *wave heights*	Available
- *wave periods*	Available
Wave statistics near shore	
- *wave angle*	Unavailable
- *wave heights*	Unavailable
- *wave periods*	Unavailable
Tidal information	
- *tidal elevations*	Available
- *tidal velocities*	Available
Sediment properties	
- *D50*	Unavailable
- *D90*	Unavailable
Bathymetry	
- *Beach profile*	Unavailable
- *near shore profile*	Unavailable
- *offshore profile*	Available
wind statistics	
- *velocities*	Available
- *wind directions*	Available
General beach system	Unavailable

Table 4.1: Necessary data and availability

Because not all the necessary data is available or even exists, fieldwork is necessary. The obtained data is required input for our computational models.

4.1.3 Fieldwork

In order to draw conclusions with the help of computer models, the unavailable data has to be gathered on site. The fieldwork concerning the beach system consists of several measurements and observation. Measurements of beach sections were executed and some samples of sediments were taken. By observations and interviewing locals general information was gathered of the beach system. Appendix VI sketches the measurement techniques and the results.

4.1.4 Modelling

The next step is to use all the gathered data and put this in a computer model. Causes and solutions can be validated within this model.
In this report there is a distinction between long shore computations and cross shore computations. For both computations also wave computations were made. First the cross shore computations are discussed, followed by the long shore computations and finally the wave computations.

4.1.4.1 Cross shore computations

For the cross shore transport computations the Unibest TC model is used. Unibest TC derives its name from UNIform BEach Sediment Transport Time dependent Cross shore. The model incorporates models for hydrodynamic processes, sediment transport and bed level models. Despite the fact that cross shore transport processes are not fully understood at the moment, the model is able to give coastal profile changes in time. Since the first release of Unibest TC, the model has been applied successfully on many cases in the Netherlands and abroad[10]. Considering the physical model formulations incorporated, Unibest TC is the most sophisticated morphological model of Deltares[11] and the software is free to use at the Delft University of Technology.

The Unibest TC model can be applied on several coastal problems, e.g.:

- Dynamics of cross shore profiles.
- Cross shore development due to seasonal variations of the incident wave field.
- To check the stability of beach nourishments and foreshore nourishments.
- To estimate the impact of sand extraction on the cross shore bottom profile development.

The first three points are important for this study.

[10] Walstra, D.J.R. (2000): Unibest-TC Userguide. Deltares, The Netherlands.

[11] Deltares (1999): Unibest-TC; A generic tool to investigate the morphodynamic behaviour of cross shore profiles, User manual V2.02. Delft, The Netherlands

4.1.4.2 Long shore computations

For the long shore transport computations[12] the Unibest CL+6.1 model is used. Unibest CL+ also derives its name from UNIform BEach Sediment Transport but consists of two integrated sub-modules: Unibest LT (Long shore Transport) and Unibest CL (CoastLine dynamics). The LT module calculates the long shore sediment transports. These transports are then used by the CL module to simulate coastline changes. In this module structures such as groynes, breakwaters and revetments can be implemented.

Unibest CL+ has been used on coasts world-wide and is a flexible and easy-to-access tool capable of simulating a large variety of coastal problems. If required the effect of cross shore phenomena can be included by importing the results of the modules Unibest TC.

Unibest CL+ can be applied on:

- Analysis of the large scale morphology of coastal systems to predict causes of erosion or to predict the impact of planned structures on the coast.
- Analysis on a smaller scale, like the evaluation of the shoreline around coastal protection works.
- The functional design of coastal defence schemes and the prediction of their impact on the coast in the feasibility stage and in many cases also in the detailed design stage of projects.

Unibest CL+ cannot be applied on:

- Analysis of short-term fluctuations, like summer-winter profiles and rhythmic beach patterns, in which no trend in the position of the coastline can be detected.
- Analysis of coastal changes dominated by tidal currents and local scour around structures.

Since this is a preliminary study towards beach processes Unibest CL+ can be applied.
There has been chosen to use Unibest CL+ instead of other coastal dynamics models, such as GENESIS, LITPACK, SAND94, because this package is available at the Delft University of Technology and a lot of knowledge is available. From a study Comparative Analysis of coastline models[13] it can be concluded that Unibest is a good choice because it offers a better compromise between accuracy of physical description and the user's intuition compared to the other programs. Delft3D is also a program that can be used to model coastal dynamics and is available at the Delft University of Technology. This program is not used because of the lack of available

[12] http://www.wldelft.nl/soft/chess/unibest-cl/index.html
[13] http://www.ibwpan.gda.pl/projects.php

information. The program makes a 2D/3D model while a 1D model is sufficient for the available data.

4.1.4.3 Wave computations

For the wave computations, SwanOne is used. SwanOne is a software program used to model waves propagating under influence of wind and bathymetry. In this study SwanOne is directly ran from Matlab version 7.7. The most important aspect of the wave model is to compute waves propagating from deep water to the coastal zone and the thereby induced effect on the wave parameters. Wave height, wave period and the wave angle near shore belong to the most important outputs of SwanOne in this study. The output of SwanOne is required as input for the Unibest models.

SwanOne is used because it is a computer program that has been written by the Delft University of Technology, in particularly the section Hydraulic Engineering. SwanOne is in 1D mode, which makes it easy to use and requires only a beach profile, deep water wave height and period as input. Furthermore the orientation of the coast, the direction of the waves, wind-conditions and currents may be implemented. This data is available or measured.

4.2 Probable causes beach/land erosion

The erosion problems at the Pacuare Nature Reserve can have several causes. In this paragraph the probable causes of the erosion problems are being elaborated. These causes are still hypothetical, purely based on common sense and the fieldwork done, and will be validated in the used computer models. Some of the possible causes are related to temporary occurred conditions and some possible causes are related to structural problems occurring gradually over the years.

4.2.1 Long-term erosion

The sediment transport parallel to the coastline and the depth contour lines may lead to negative (erosion) or positive (accretion) sediment balances. This can only occur if there is a gradient in the long shore sediment transport ($dS/dx \neq 0$). Sediment transport in itself does not cause any changes in the topography of the coastline.

Gradients in the long shore transport are caused by incident waves under a different angle, wave height differences along the coast, bottom material changes and wind, wave and tide driven currents[14], see also Appendix X.

When the coast in front of the Reserve erodes the buildings can be in danger. Accretion of the coast will take away the risk of short-term erosion in the long run. The beach in front of the Reserve is not likely to accrete. Most coasts throughout the world suffer from erosion caused by sea level rise, see Chapter 4.2.4. This does not mean that the coast cannot be in equilibrium. Observations however indicate that there might be

[14] d'Angremond, K. and Pluim-vander Velden, E.T.J.M. (2001): Introduction Coastal Engineering. TU Delft, The Netherlands.

erosion of the beaches in front of the Reserve. There is also an indication that long shore sediment transport at the North Station is larger then in the South Station, because the beach around the South Station is wider than the beach at the North Station.
Beach changes caused by the long shore transport do not happen overnight, like the short-term erosion where in hours/days the beach profile is changed.

4.2.2 Short-term erosion

A beach is nature's best form of defence. The beach strip in front of the Reserve is very dynamic. Periods without any beach at all change relatively rapidly in periods with a beach strip in the order of magnitude of 40 metres. This is a natural process. The profile reshapes with changing hydraulic conditions. This process is called cross shore transport and means transport in onshore and offshore direction. The coast profile changes, without actually changing the total sediment content of the profile. Sand is being moved up or down the profile, without leaving the profile.

A severe storm-surge with high waves and a higher water level can sweep parts of the beach away. A new coastal profile is formed. The shape of a cross shore profile encountered after the storm surge is often called "erosion profile". In a stable case there will be no loss of sediments out of the so called control volume, see Figure 4.1. A stable case means that there is no structural erosion due to gradients in the long shore transport. During tranquil conditions the coastal profile will gradually restore itself into the initial profile.

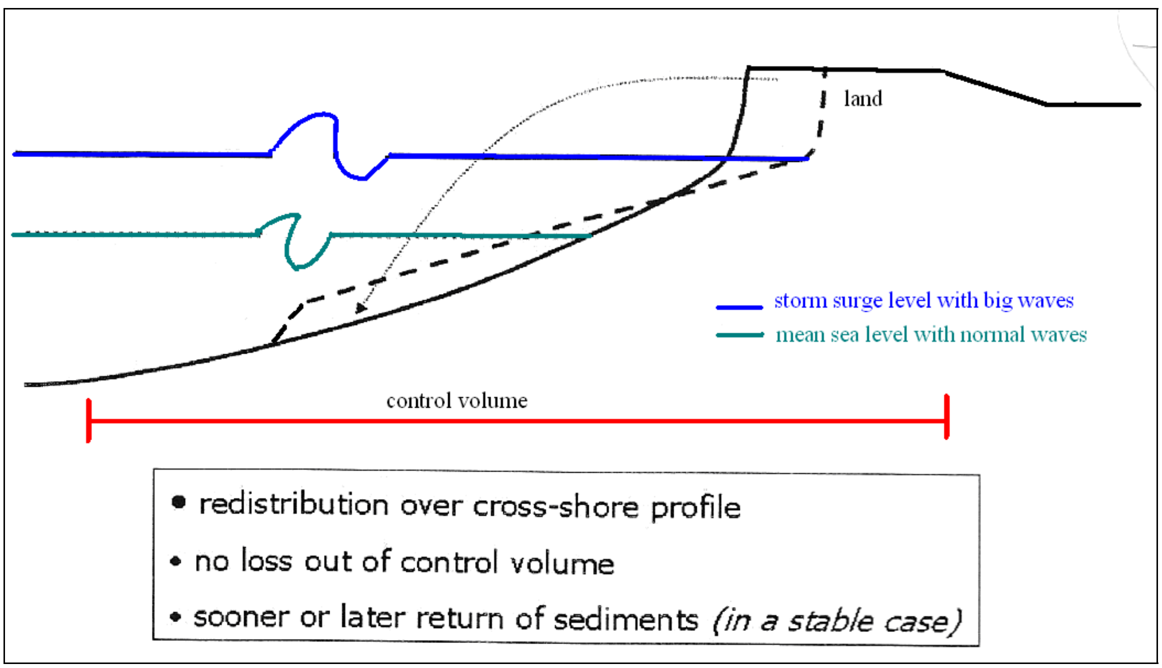

Figure 4.1: Coastal profile dynamics

If the situation is unstable, storm conditions can cause indirectly permanent damage. The beach is swept away by the storm and is transported by the long shore current.

Then it is not possible to restore the beach naturally in tranquil conditions, because the sand is not in the profile anymore.

Furthermore when structures are built within the erosion profile extremely dangerous situations and damage can occur. Storms can also sweep away vegetation which form a protection against erosion because the roots keep hold of the sediments. When there is no vegetation this part can also be eroded easily.

4.2.3 Lagoon breakthrough

The erosion problems occurred after a lagoon breakthrough was the starting point for this report. Since 1989 the lagoon breached three times and each time there were erosion problems.
The problems occur when high discharges of the rivers results in high water levels in the lagoon. The barrier beach will be exceeded by the water level and washed away. The lagoon transforms in a rapid flowing river, while the complete barrier beach erodes.
In 2009 large areas of land were eroded on the north side of the lagoon. The main problems arose, however, when the flow to sea stopped. The beach in front of the Reserve was completely eroded due to the breakthrough. Normally the waves will break offshore induced by limited depths, but now the complete beach was gone and the waves were able to hit the land interface. The Reserve lost about one metre land a day. The Reserve was rescued by coincidence; a large fallen tree served as a breakwater.

4.2.4 Sea level rise

The climate in the world is changing. The global surface temperature on the earth is increasing. The Intergovernmental Panel on Climate Change (IPCC) concludes that most of the observed temperatures increased since the middle of the 20th century. The increasing temperatures are mainly caused by increasing concentrations of greenhouse gases resulting from human activity such as fossil fuel burning and deforestation. Higher temperatures cause ice sheets to melt and an expansion of the water, which both cause sea level rise. These changes will have major effect on local conditions. The estimates for the future sea level rise vary widely. In this report a sea level rise of 3 millimetres a year is assumed[15]. Other consequences of a climate change may be a change in frequency; duration and impact of a tropical storm or hurricane, but this not clear yet. Therefore this is not taken in account in this report.

Due to a higher mean sea level the shape of the cross shore does not fit anymore with the tide and wave conditions. The actual cross shore profile seems to be too steep. Morphological processes will start to achieve again an equilibrium situation. In an entirely natural development that means that coastal retreat will occur.

4.2.5. Reduction of sediment supply

The beach consists of sediment which finds its origin in the river. The sediment is eroded and transported by the river and finally the sediment reaches the sea, where it is

[15] http://weather.an/reports/index.asp

transported by the long shore sediment transport. The sediments in the rivers are the main source of the beaches in the project area. Man-induced changes in the characteristics of the Río Matina and the Río Pacuare might result in a reduction in fluvial sediment supply to the coast. When this occurs, it is also to be considered as a structural erosion problem for some stretches of the coast; the control volume in a cross shore profile is reducing with time. Sooner or later the interest at the mainland will be endangered as well.

4.3 Possible solutions

This section describes possible solutions to prevent beach- and land erosion. Some solutions will not stop the erosion, but an option is presented to safely undergo the effects of erosion.

After the precarious situation in early 2009 the Reserve decided to build new installations further inland. The new station is located about 50 metre further inland than the old South Station. The current buildings will remain intact and are preferably preserved as long as possible. To avoid the loss of these buildings, solutions are presented in this study. Also solutions are listed in this chapter to avoid the loss of these buildings. This is done to widen the choice of the Reserve and these solutions could also serve as guidance for similar problems along the entire coast of Costa Rica and Panama.

4.3.1 Allow natural processes

The Reserve has already chosen to relocate, but wants to keep the old buildings intact as long as possible. An option is to allow the natural processes and see what eventually will happen. If the buildings are out of the erosion profile, they will not be at risk. If the buildings are in the erosion-zone they will eventually be destroyed. The time-scale of this differs significantly and depends on the occurrence of a severe storm.
There can also be structural erosion due to the long shore transport. This process has a larger time scale (years) then cross shore transport (storm days).

4.3.2 Relocate buildings

As described in the introduction, the Reserve is building completely new installations further landward. This relocation can be a safe choice to guarantee the safety of the workers and the volunteers of the Reserve. The expansion is also capacity-related. Of course it was also an expensive solution to build a whole new installation. This solution will not prevent the erosion. In case of storm conditions, the total beach can disappear. In this study there will be examined if this new location is far enough inland to be out of the erosion-zone.

4.3.3 Sandbags/revetment

Sandbags and revetments, when properly build, can prevent erosion of the Reserve during storms. During these heavy conditions, scour holes in front of the sandbags or revetment are expected. These scour holes can be so deep that the entire construction might be undermined and the structure completely loses its function. If this occurs, the situation will even worsen because there is more depth in front of the mainland and higher waves will erode the land more quickly.

The main differences between a sandbag-construction and a revetment are that a revetment has a distinct slope, the surface of a revetment might be either smooth or rough and that the height of a revetment does not necessarily fill the total height difference between beach and mainland.

In the actual situation the transition of beach – mainland at the South Station is protected with a sandbag construction of approximately 0.7 - 1 metre high, see Figure 4.3. A problem, which is the case at the moment, is that many sandbags are torn apart by the heat of the sun, ongoing maintenance will be sensible. In the models a proper sandbag-construction is tested.

Also one timber revetment structure has been built in front of the lodge, see Figure 4.3.

The sandbags or revetment are **no solutions if there is structural erosion caused by a gradient in the long shore sediment transport**. Neither revetments nor sandbags interferes the morphological processes under ordinary conditions. The transport along the coast will continue, see Figure 4.4.

Figure 4.2: Sandbags around the Reserve's land

Figure 4.3: Timber revetment in front of the lodge

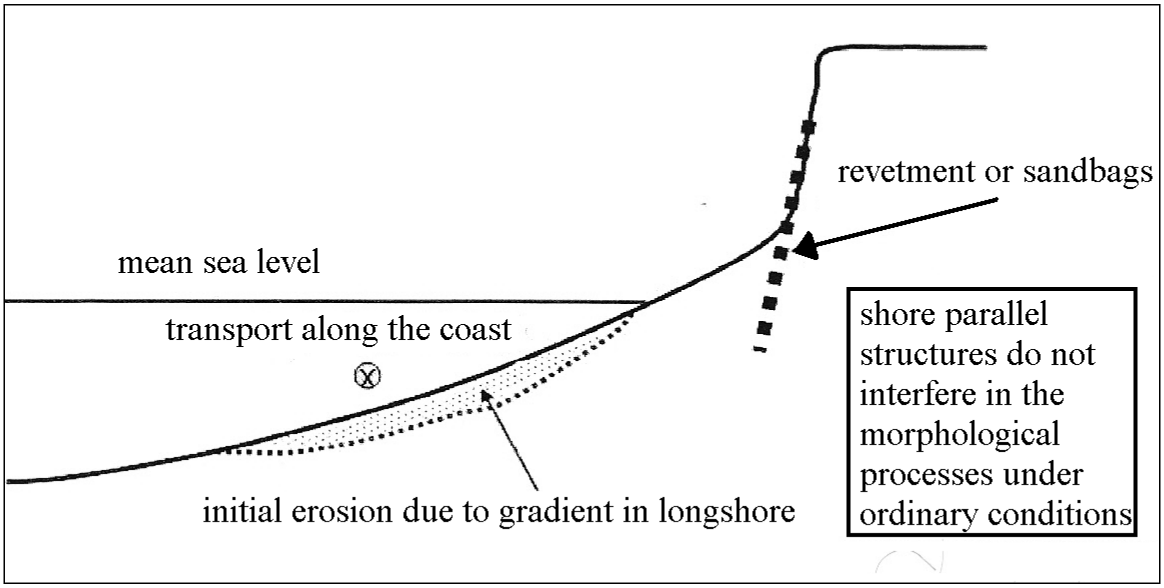

Figure 4.4: Shore parallel structures on a structural eroding coast

4.3.4 Artificial reef

A possibility for protecting the beach and the buildings of the Reserve is to place an artificial reef in front of the coast. An artificial reef is capable of initiating wave breaking and thus dissipates the energy of waves. Lower waves will reach the coast and the erosion will be reduced. If the artificial reef is build properly, the system will also ensure that the impact of a breakthrough of the lagoon will decrease significantly, because the higher wave waves already lost their energy.

Note: *The artificial reef will not only interfere in the cross shore transport processes but also changes in long shore transport are expected.*

4.3.5 Beach nourishment

Another possible solution would be to apply sand repeatedly in front of the Reserve and the lagoon. This will protect the Reserve in two ways. First, it will be less likely that the lagoon breaks through because the beach will be wider and thus it will form a bigger barrier for the lagoon. Second, the wave energy will be much lower at the land crest, because the waves have been broken and lost their energy in an earlier stage of the coastal profile. The sand of the nourishment will distribute over the entire coastline over time due to long shore transport. In fact the width of the beach in front of the Reserve and the lagoon will become smaller in time, see Figure 4.5.

The nourishment operation has to be repeated after a certain time. This eternal repetition might be considered as a serious disadvantage of this method, but in many cases beach nourishment turns out to be the most cost effective method. Other positive aspects of the application of artificial nourishment are that no lee-side erosion occurs and a wider beach might be beneficial for the turtles.

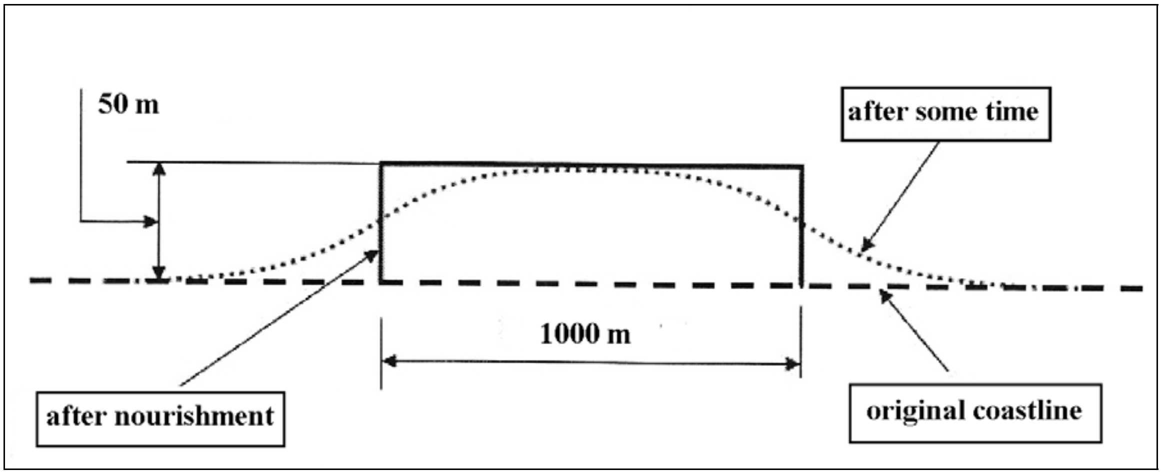

Figure 4.5: Processes of a nourishment

4.3.6 Under-pinning installations

The most valuable asset of the Pacuare Nature Reserve is the lodge which is situated next to the lagoon. When the barrier breaks trough, the waves easily erode the shore in front and next to the lodge, see Figure 4.6.

Figure 4.6: The lodge next to the Mondonguillo lagoon

The lodge is build upon piles. The main floor is about four metres above ground level. Unfortunately, the foundation of these piles is about half a metre under the ground. When a breakthrough actually occurs, the land can be eroded till a depth of approximately two metres. This is also much deeper than the foundation depth. Instead of protecting the shore it is also possible to protect the structures of the buildings. A good method is to extend the existing piles. **This is a structural modification and will not be a solution to prevent any form of erosion but it will extend the lifetime of a building.** The method will be expensive, therefore this solutions is only examined for the most expensive building in the Reserve; the lodge. The use of this method is not tested in computer models, but is examined with the use of rules of thumb.

4.3.7 Embankment in barrier beach strip

An embankment on the barrier beach strip in front of the lagoon will not counteract the erosion due to the sea, but it surely prevents breakthroughs of the lagoon due to high river discharges**. When the barrier beach does not vanish, no erosion problems will occur.** Although in this chapter erosion due to a breakthrough of the lagoon is less enlightened, it is of major impact on the shoreline around the Reserve. In fact, the most erosion takes place after a lowering of the river discharges. Large generated waves are then able to erode the coast quickly. A small and possible easy-to-build embankment could be capable to retain the water in the lagoon and thus prevent the massive erosion due to breakthroughs.

4.4 Computational modelling

Note: High river discharges and storm conditions often occur simultaneously which results in an extremely dangerous condition. This condition could not be modelled in the Unibest TC model nor in the Unibest Cl+ model. The model output has to be interpreted to minimize the consequences of this condition and to avoid such situations in the future.

4.4.1 Unibest TC

This chapter provides a short description of the model based on Wiersma (2002), for further details of the model one is referred to Bosboom et al. (1997) and Walstra (2000)[16].

4.4.1.1 Model description Unibest TC

In general, the model is based on the assumption that the bottom profile is uniform along the coast. Based on the wave energy balance of Battjes and Janssen (1978)[17] the cross shore distribution of wave height, dissipation and set-up can be provided. Together with tidal and wind influences, the wave parameters can be used to model long shore and cross shore velocity profiles. In combination with a model for the near-bed velocity a prediction can be made of the long shore and cross shore sediment transport rates.

The model requires an initial profile, grain sizes and offshore boundary conditions for waves, water level, tidal velocity and wind velocity.

[16] Bosboom, J., Aarninkhof, S.G.J., Reniers, A.J.H.M., Roelvink, J.A. and Walstra, D.J.R. (1997): UNIBEST-TC 2.0. Overview of model formulations. Delft, The Netherlands.

[17] Battjes, J.A., and J.P.F.M. Janssen (1978). Energy loss and set-up due to breaking in random waves. Delft, The Netherlands.

The UNIBEST TC model consists of six sub-models, see Figure 4.7:

- *Wave propagation model*
- *Mean current profile model*
- *Wave orbital velocity model*
- *Bed load transport model*
- *Suspended load transport model*
- *Bed level model*

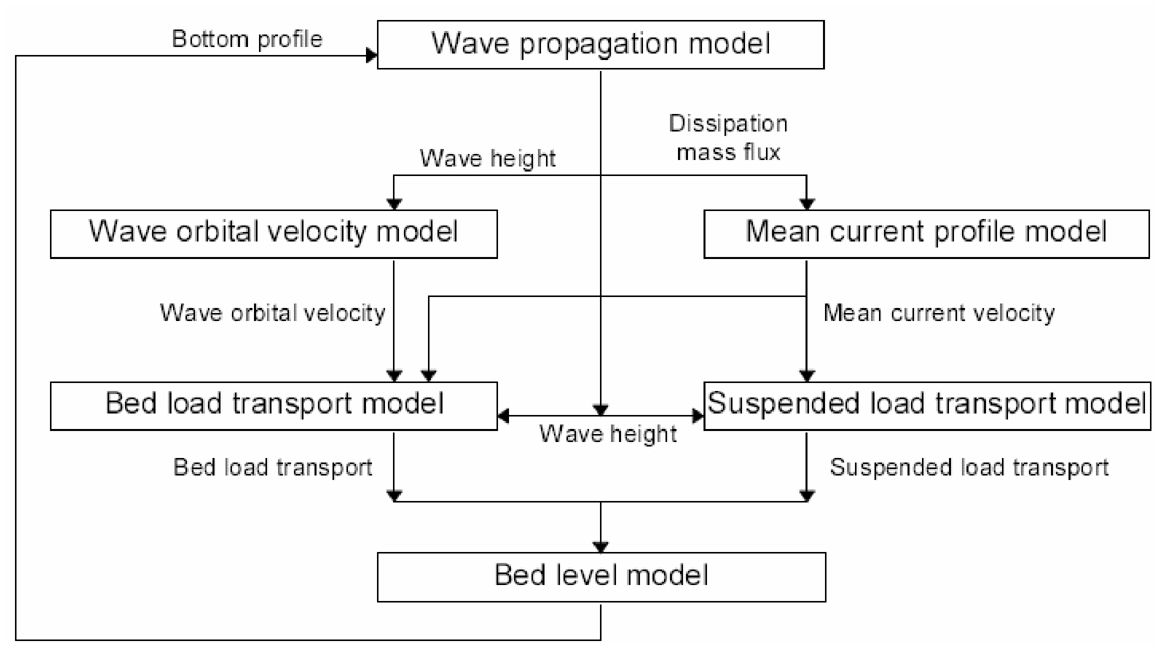

Figure 4.7: Schematic representation of the UNIBEST TC model[18]

- Wave propagation model

The wave propagation model computes the wave energy along a cross shore ray. The model consists of three first order differential equations: the wave energy balance, the wave set-up equation and a balance equation for the energy contained by surface rollers in breaking waves. The three coupled equations generate input on vertical velocity profiles, vertical concentration and bed load transport for the other sub models.

- Mean current profile model

The mean current profile model computes the vertical distribution of the wave averaged mean current. The wind shear stress, wave breaking, bottom dissipation in the wave boundary layer and the slope of the free surface are taking into account.

[18] Wiersma, N.R., Stive, M.J.F., Rijn van, L.C.,Stelling, G.S, Graaff van de, J., Walstra, D.J.R. (2002): Evaluation of the Egmond shoreface nourishment. Part II: Validation of the morphological UNIBEST-TC model. Delft, The Netherlands.

• Wave orbital velocity model

The wave orbital velocity model calculates time series of the near-bed wave orbital velocity. These time series contain contributions due to wave asymmetry, wave groups and long waves are taking into account the irregularity of waves.

• Bed load and suspended load transport model

The sediment model uses bed load and suspended load. Bed load is the part of the load that is in contact with the bed, contrary to suspended load which take place in whole the water layer. It is assumed that the suspended load transport is dominated by the transport of the mean current. The bed load transport is computed as a function of the instantaneous bed shear stress. The bed shear stress is determined by the near-bed velocity. The near-bed velocity consists of a near-bed wave orbital velocity and an averaged current velocity near the bed.

• Bed level model

After the computation of the transport rates along the profile, the bed level changes are calculated from the depth-integrated mass balance:

$$\frac{\partial z}{\partial t} + \frac{\partial S_{bed+suspended}}{\partial x} = 0 \qquad (1.4)$$

With:

z = vertical water column	[m]
t = time step	[s]
S = bottom and suspended sediment transport rate	[m^3/s/m]
x = distance along profile	[m]

For each grid point the transport rate is calculated. The difference in transport rates between two grid points results in a bed level change between these two grid points.

4.4.1.2 Model domain

An Unibest TC run is only capable to study one profile, in fact a straight line from a landward boundary to a seaward boundary. The profile which is examined is located just in front of the main building. This building has been build very close to the beach and during storms this building is in direct danger by beach erosion. The bathymetry of this profile is exactly measured by the levelling rod and sonar device at the sea, see Appendix VI. At this moment the land is protected by some sandbags, which are placed after the most recent severe conditions. Whether the sandbags will work well is not known yet, this will be examined by the Unibest TC model. Also runs are made without sandbags. In that case the situation for profiles of the natural stretch of the beach is also examined, because these profiles are quite comparable with the profile in front of the main building without the sandbags. Pictures of the used coast profile are given in Figure 4.8 and Figure 4.9.

Figure 4.8: Coast profile examined in Unibest TC during normal conditions

Figure 4.9: Coast profile (red line) examined in Unibest TC during a storm, protected with gibbons.

4.4.1.3 Boundary conditions

A time based model like Unibest TC requires boundary conditions. The boundary conditions for the Unibest TC model can be split up in two parts: profile characteristics and hydrodynamic conditions.

- Profile characteristics

The profile characteristics consist of a fixed layer and a bottom profile. The fixed layer is the layer which cannot be moved by transport. With the fixed layer it is possible to model sandbags and other hard structures in the profile. The sandy bottom is exposed to currents and will be moved by transport. This bottom is modelled as the initial bottom profile.

• Hydrodynamic boundary conditions

The following boundary conditions are required:

- tidal elevation [m]
- tidal velocity [m/s]
- wave angle [deg]
- wave height [m]
- peak wave period [s]
- wind velocity [m/s]
- wind direction [deg]

In Unibest TC, it is possible to vary the hydrodynamic boundary conditions for every time step. Obviously the tide, wind and wave conditions vary constantly and it will be very unrealistic to keep these boundary conditions constant over time. In order to obtain reasonably reliable output from the Unibest TC model, a fictional year is simulated.

The wave and wind conditions are based on the observations from the wave buoy of NOAA, see Appendix X. To achieve realistic values for the wave statistics the model Swan is used to calculate near shore conditions, see Appendix XI.

Tidal information is collected at the Instituto Meteorológico Nacional website[19], see Appendix IV.

The fictional year which is used consist of normal conditions and some heavy storm conditions. For the complete explanation of the used boundary conditions and the parameter settings a reference is made to Appendix XII.

4.4.2 Unibest CL+

4.4.2.1 Model description Unibest CL+

The Unibest CL+ model consists of two sub models, namely Unibest LT and Unibest CL.

In Unibest LT, the surf zone dynamics are computed by a random wave propagation and decay model (Battjes and Stive, 1984)[20]. In the model, the long shore current distribution across the beach profile is obtained from the momentum equation alongshore. The sediment transport formulae are all based on the physical concepts that there is a threshold of motion and a maximum sediment capacity that the flow can carry.

The Unibest CL model is based on the single line theory, by Pelnard Considère (1956).

The basic assumption in this theory is that the shape of the cross shore profiles does not change while the position of the coastline is changing in time[21]. The entire profile moves seaward/landward with a horizontal distance *a* depending on the sediment

[19] www.imn.ac.cr

[20] Deltares (2005): User & Theoretical Manual Unibest CL+ 6.0. Delft, The Netherlands.

[21] Graaff van de, J. (2009): Coastal Morphology & Coastal Protection. TU Delft, The Netherlands.

balance, see Figure 4.10. This assumption also requires a horizontal part in the underwater profile. This is required because otherwise unrealistic large quantities of sand might be required for a small seaward movement of the shoreline.

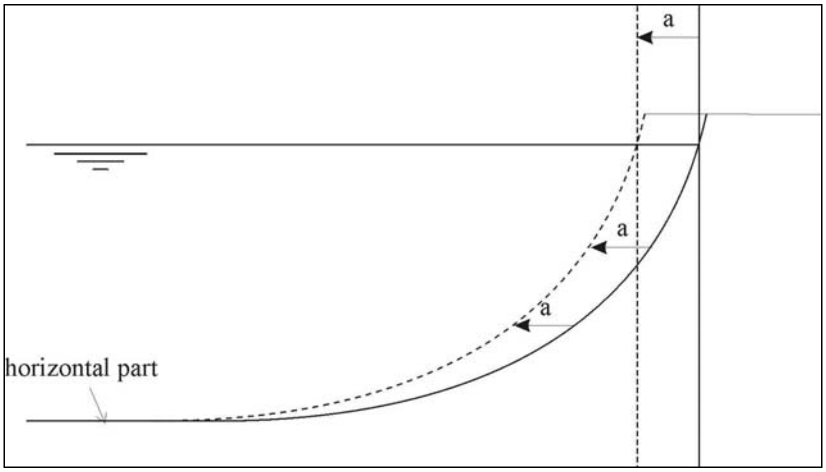

Figure 4.10: Single line theory

4.4.2.2 Model domain

The Unibest model domain contains all profiles and should be as large as the area of interest. This means that the coast in front of the Reserve should be in the domain. Furthermore the sediment input of the rivers is important for the sediment balance. Finally, the boundary conditions should be far away to have no influence on the area of interest. Therefore a beach of 25 kilometres is schematised, see also Appendix XIII for more information on the model domain and grid-points. Different time-steps can be chosen.

4.4.2.3 Boundary conditions

In the Unibest CL model the seaward boundary of the coastal profile is determined by the closure depth. The closure depth means that after this depth the bottom profile will not change. This coincides with the assumption of a horizontal part in the underwater profile. The landward boundary of the coastal profile is upper limit of the active profile.

At both beach ends the coastal angle is kept constant. For more information about the input and settings of the Unibest CL+ model check Appendix XIII.

4.5 Results

Chapter 4.2 listed a number of probable causes of the erosion problems at the Reserve and beach erosion. Within the Unibest TC and the Unibest CL+ models, these different hypotheses are being validated. The different causes are listed and results are sketched in this chapter.

4.5.1 Validating probable causes erosion

This section describes possible causes of the beach- and land erosion. Within the Unibest TC - and the Unibest CL+ model, these different causes are being checked on their effects on the beach. Below, the different causes are listed and the obtained results are presented. Validation is mainly executed by checking differences in erosion rates after implementation of the initial and storm conditions. A validation in the Unibest models was not possible for some causes and therefore the validation is kept qualitative for these causes.

4.5.1.1 Long-term erosion

To validate the cause of erosion due to the long shore sediment transport, Unibest CL+ is used. For this run all profiles are used and the rivers are schematised as sources. Because the long shore transport depends a lot on the wave direction, different wave directions are used. Storm conditions are not taken into account because there is no interest in the short-term effects. See also Appendix XIII for the input and settings of the Unibest CL+ model.

The Unibest LT output shows the transport per ray (profile). The results are shown in Appendix XIII. These results indicate that at all the profiles the long shore transport is directed to the north. Furthermore it is shown that the transport at the North Station is much higher (± twice that high) than the sediment transport at the South Station. This indicates a gradient in de long shore sediment transport and thereby erosion/accretion.

Figure 4.11 shows the theoretical coastline development near the river outflow. In the Unibest CL model there is no river schematised; there is no interruption in the coastline but the overall shape is the same. The long shore transport distributes the sediment outflow along the coast.

Unibest CL models the beach with the sources and boundary conditions. In Figure 4.12 the model is shown with a run-time of 50 years (500steps). The straight black line indicates the initial situation. In the figure it is shown that in the fifty years erosion of the coast takes place. The accretion at the river mouths is also shown.

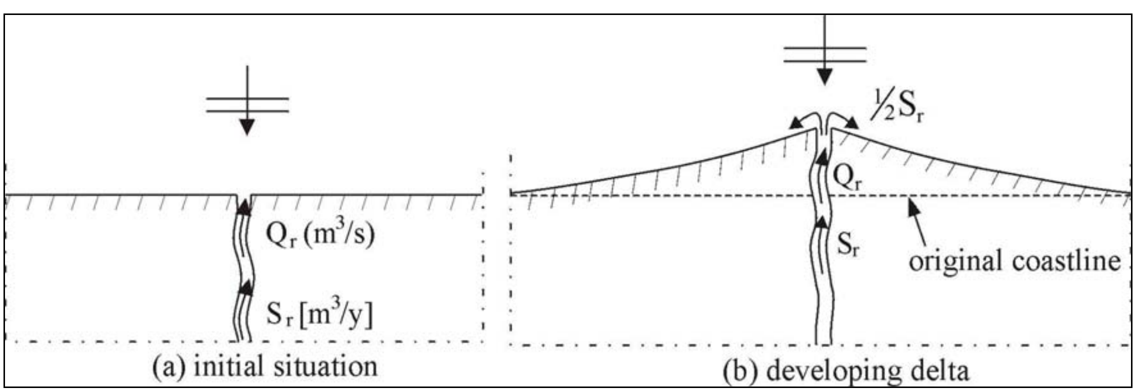

Figure 4.11: Development of coastline near river outflow.

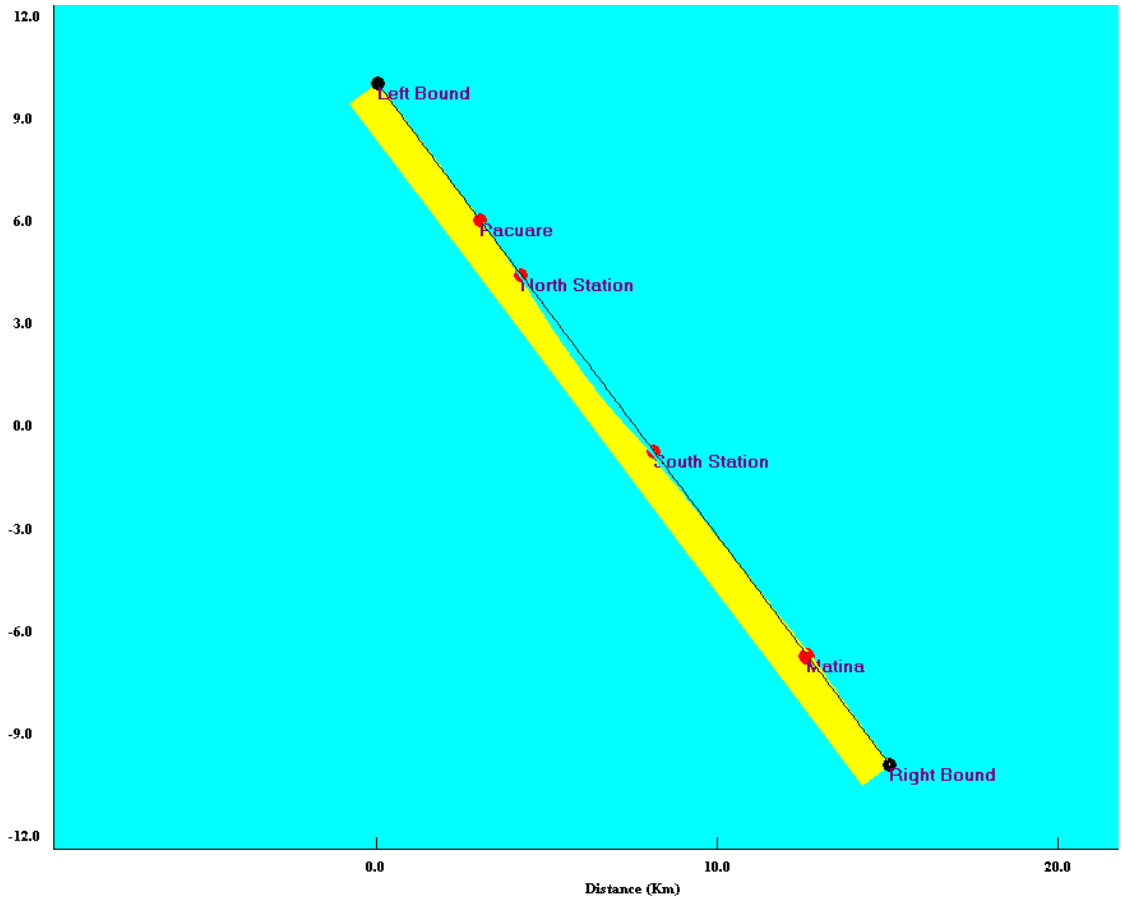

Figure 4.12: Coastline after 50 years

The erosion takes place between the North and South Station. Figure 4.13 and Figure 4.14 show a close-up of the erosion near the North and South Station.

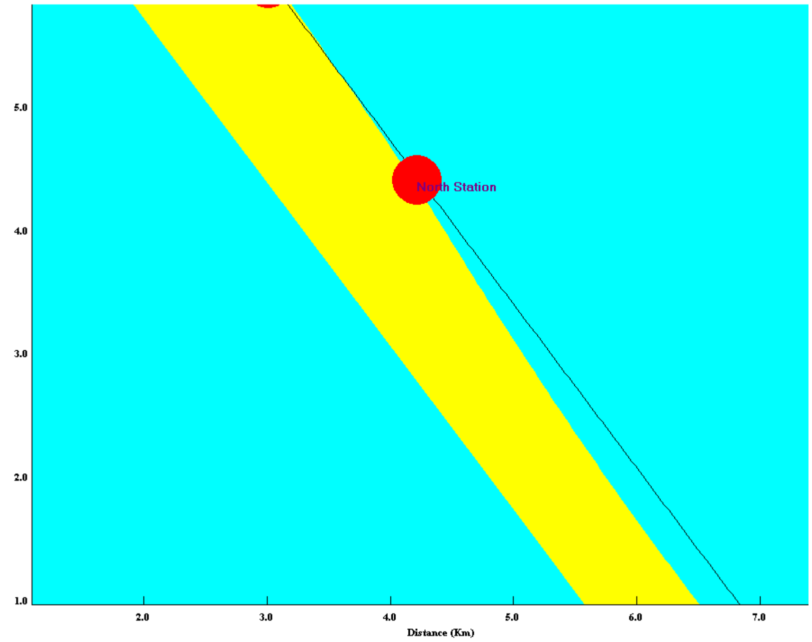

Figure 4.13: Coastline North Station after 50 years

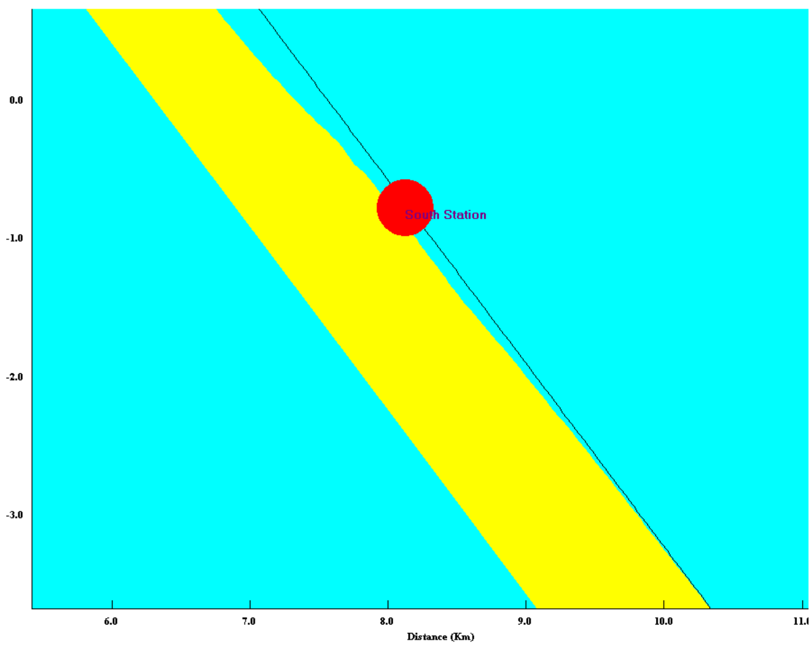

Figure 4.14: Coastline South Station after 50 years

That the erosion is mainly between the North and South Station is because the Unibest model linearises between the last ray at the North Station and the last ray at the South Station. Between the last rays at both stations and the boundaries, the sediment transport is assumed to be constant and therefore there is no gradient and no erosion/accretion (not taken into account the sediment input from the rivers, which are also in between the boundaries and the last rays of both stations).

The tables obtained in the Unibest CL model show that the accretion at the Río Pacuare is 16 metres after five years, the accretion at the Río Matina is 26.4 metres and the highest erosion rate is 37.4 metres. After fifty years these values become 27.5 metres for the Río Pacuare, 83.5 metres for the Río Matina and a maximum of 264.7 metres erosion in between.

Roughly said, the accretion rate at the Río Pacuare is 0.55 metres per year, for the Río Matina 1.67 metres per year and the erosion rate in between is 5.29 metres per year. Especially the erosion rate of 5.29 metres is very high. The calculation of these rates is very controversial, because they do not show the process in between. These rates are mean values of the processes during the 50 years of modelling.

Figure 4.15 shows the Unibest CL model on a Google Earth screenshot. The initial line of the coast in Unibest CL is roughly the same as the coastline in Google Earth, except for some accretion at the river mouths. The erosion of the coast is not shown in the Google Earth snapshot.

Note: The dimensions are not exactly the same, especially in the landward direction. The picture gives a more clear view on where the coast is and where the erosion/accretion will take place.

Figure 4.15: Google Earth with overlay of Unibest CL model.

Note: There are a couple of restrictions that have to be taken into account to judge the output values. Firstly, the input data of the wave and tidal information is not complete. The wave data is obtained far out of the coast and had to be transformed to near shore conditions with the program SwanOne. The tidal velocity was unknown and therefore a velocity of 0.1 m/s was assumed. This value is very low and generated a higher total sediment transport at the rays, then when for instance a velocity of 0.25 m/s is used. This does not mean that a lower velocity generates a higher transport, but that the direction of the sediment transport generated by the lower velocity is the same as the sediment transport generated by other mechanisms. Furthermore, the sediment input of the rivers had to be calculated and different assumptions were made.
The beach was schematised as a straight line. Topographical maps and Google Earth shows that the coast is more curved, with accretion at the river mouths. This means that the simulation in Unibest CL+ calculates with an initial angle while in reality the coast has already formed itself due to wave angles etc. This means that the values could be higher in the Unibest CL+ then in reality. Finally, the beach does not have a width of hundreds of metres. The erosion is likely to be stopped or be reduced (significantly) because of the vegetation and other sediment properties of soil.

Conclusion
Erosion of the coast due to long shore transport is to be expected but has to be treated with great care and a sane judgement. The values predicted are likely to be inaccurate. To say more about the erosion/accretion of the coast a monitoring programme is a sensible idea. This way models can be validated with real data obtained over years. Furthermore, sediment transport in the rivers should be examined. Especially the flow velocity is important to know, because this term is very sensitive in the sediment formulae.

4.5.1.2 Short-term erosion

To validate the cause of erosion due to occurrence of storms, two runs in Unibest TC were performed. Run one consist of only the derived daily conditions, so a root-mean-square wave height of 1.1 metre at the seaward boundary and a water level which only depends on the tidal elevation. Storm surges were not included.
Another run uses more realistic boundary conditions and also some storms are included. The exact boundary conditions are given in Appendix XII. As expected, storms can and will cause erosion. However, with more tranquil conditions restoration takes place. The differences are clearly shown in Figure 4.16 and Figure 4.17. Figure 4.16 shows a situation where the coast has been subject to daily conditions only. The figure shows that the beach in these conditions even slightly grows.
Figure 4.17 has outlined a situation where the coast has been subject to a once-a-year-storm. It is assumed that beach/land interface is well protected by the actual sandbag construction. In this situation the sand of the beach is moved to a near shore bar.

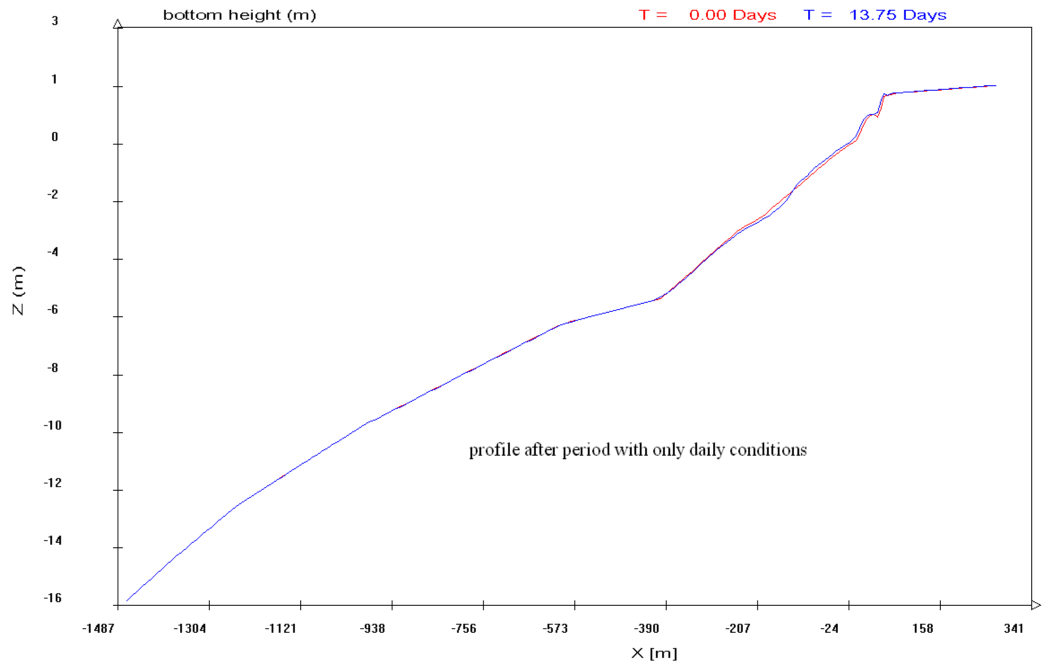

Figure 4.16: Coastal profile after a period with only daily conditions

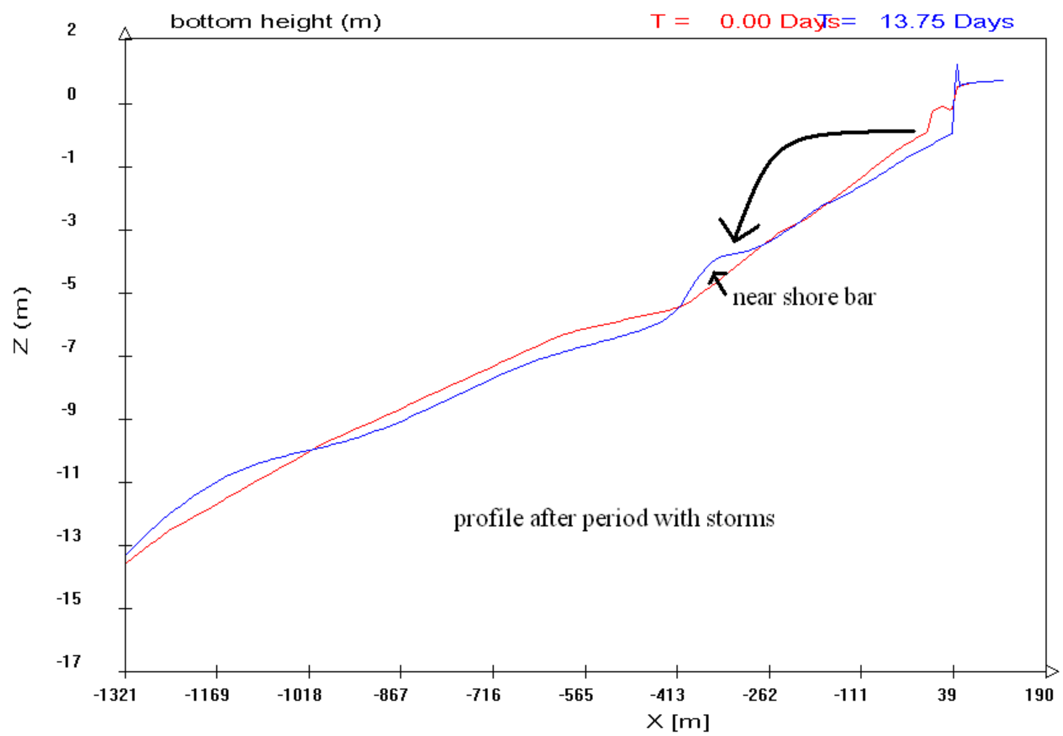

Figure 4.17 Coastal profile after a period with storms.

On the long-term, the beach will grow during daily weather conditions. Long-term calculations of Unibest TC should be regarded as very inaccurate, but can help to understand the evolution of the coastline in different conditions.

In Figure 4.18 a coastal profile is plotted for a situation without the occurrence of one single storm in 200 days. This situation is not very realistic but will show that a period without storms will lead to accretion of the beach and the land.

Figure 4.19 shows that the beach in the long-term with the occurrence of storms also will restore to the old situation, but less quickly. The figure also shows the formation of two bars, if this formation will actually happen is doubtful.

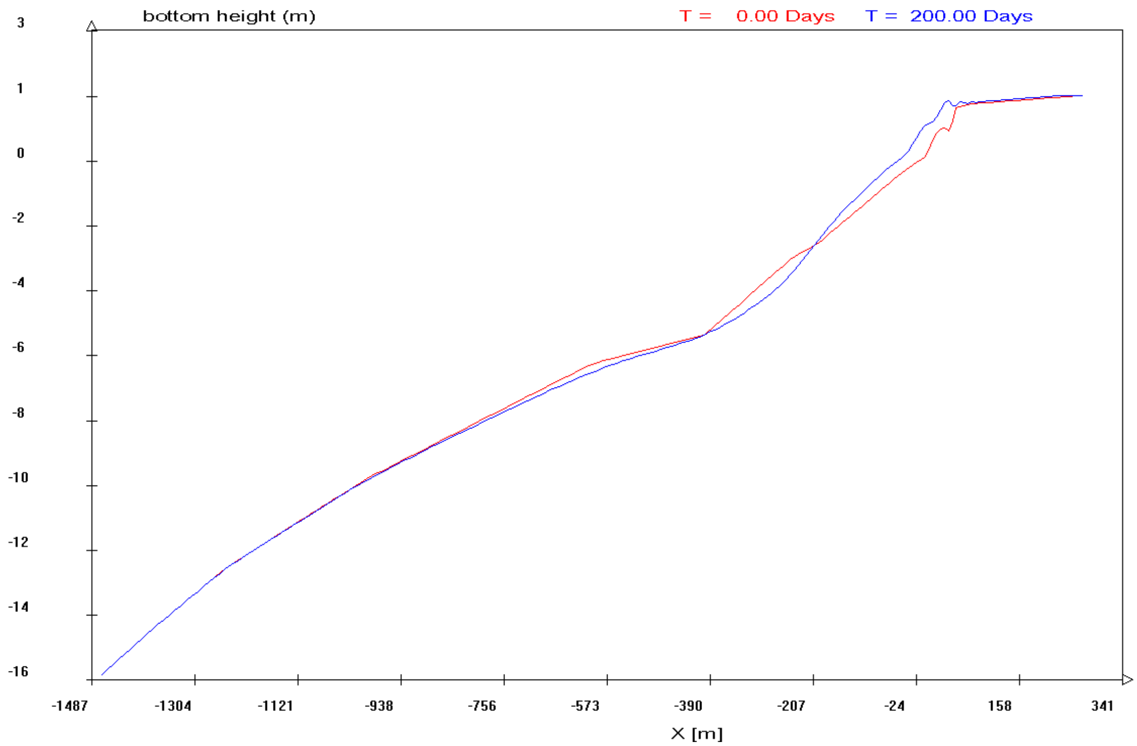

Figure 4.18: Coastal profile after a long period without any storms

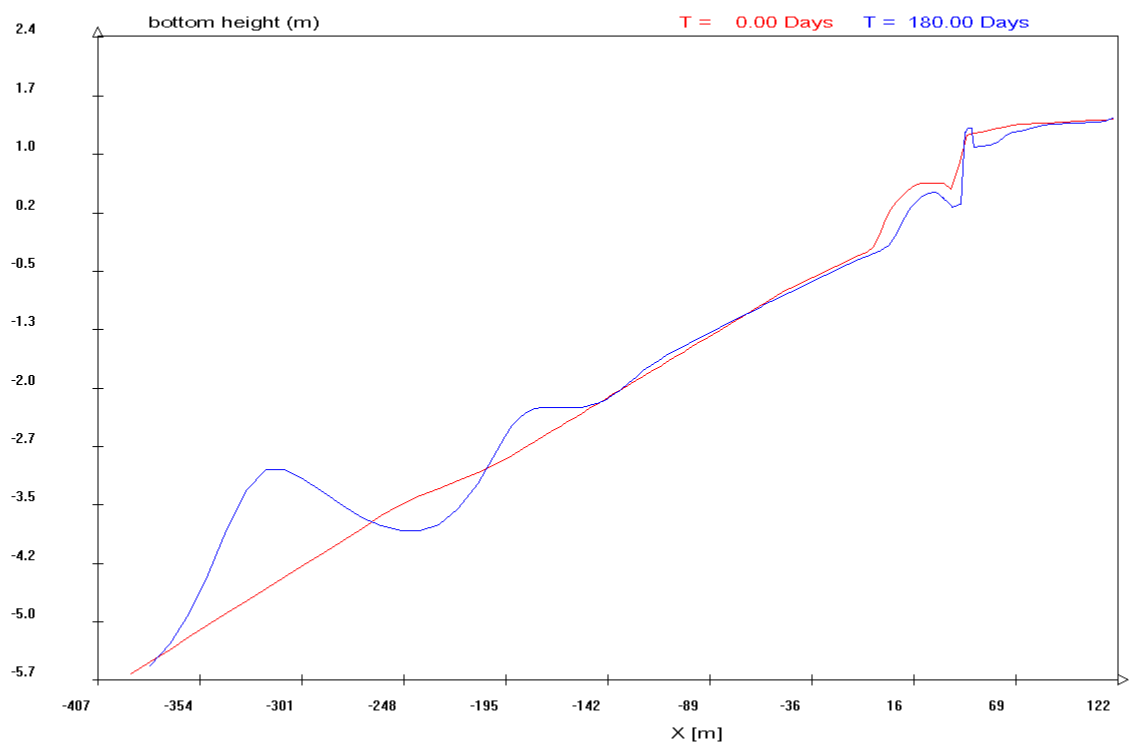

Figure 4.19: Coastal profile after 180 days with periods of storms and periods with normal conditions

Conclusion
Obviously, storms can cause erosion. Without a properly functioning land protection-work, land erosion will occur for sure. In a stable situation (no structural erosion due to gradients in long shore transport) the coastal profile restores to the initial profile. This is a dynamic process and will only cause dangerous situations for short periods of time. Protection is required to maintain the buildings of the Reserve.

4.5.1.3 Lagoon breakthrough

With the available models it is not possible to validate a lagoon breakthrough as a probable cause of the erosion problems at the Reserve. The interaction between the sea and the inlet currents requires a 2D/3D modelling system. Such programs will be capable to investigate the hydrodynamics, sediment transport and the morphology during breakthroughs and the period of closing.
Despite the validation in the form of model output is missing, it is obvious that the actual breach is a cause of erosion. In fact, it was the reason of writing this report. In Appendix II, the breaching developments and the morphology is fully explained.

4.5.1.4 Sea level rise

With the assumption of a sea level of 3 millimetres[22] a year a sea level rise of 15 centimetres is obtained after 50 years. The critical importance of sea level is its relation to shoreline change. Due to a higher mean sea level the shape of the cross shore does not fit anymore with the actual tide and wave conditions. The actual cross shore profile seems to be too steep. Morphological processes will start to achieve again an equilibrium situation, which means that coastal retreat will occur.
Bruun (1962)[23] developed a method of equating rates of shoreline recession with the annual rise in sea. The Bruun Rule states that beaches and near shore profiles, when subjected to a sea level rise, will translate upward and landward, maintaining their shore-normal geometry. If the amount of sea-level rise and the shape of the original offshore profile are known, the rule can be used to quantify the resulting shoreline retreat. The Bruun rule is given as:

$$a = (SLR * L)/(d + h) \tag{1.5}$$

Where:

a	=	horizontal shift
SLR	=	sea level rise
L	=	fill distance
d	=	closure depth
h	=	height of the berm

For clarity, Figure 4.20 shows the profile adaptation due to sea level rise.

[22] http://weather.an/reports/index.asp
[23] Bruun, P. (1962) Sea-level rise as a cause of shore erosion

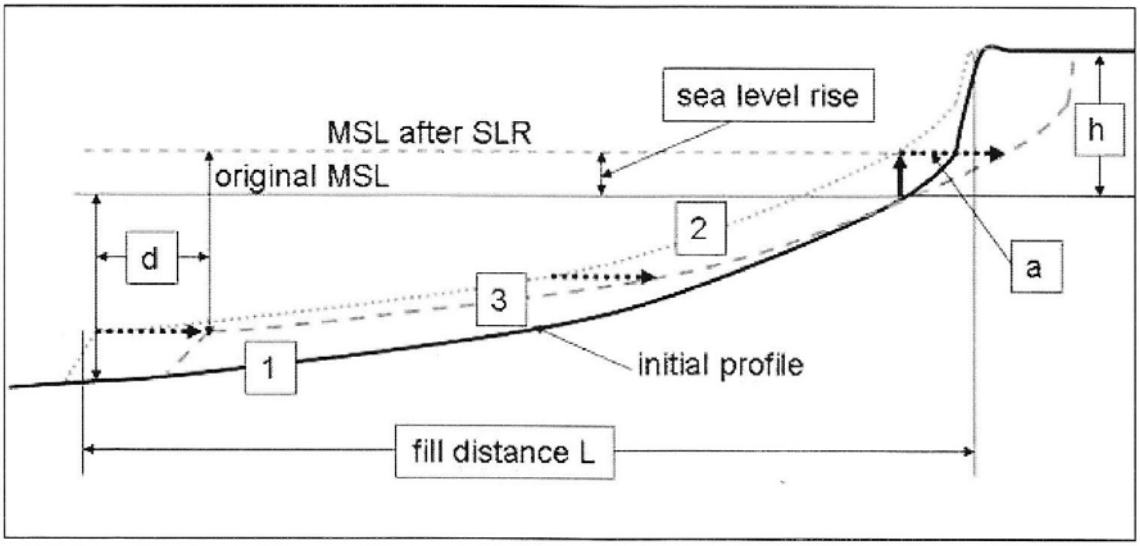

Figure 4.20: Profile adaptation due to sea level rise (SLR)[24]

The measured profile [1] is assumed to be in equilibrium with the wave and tide conditions. After sea level rise the position of the coastal profile [1] in horizontal sense would still be the same if a layer with thickness SLR (vertically) is added over a sufficient distance (fill distance L in Figure 4.20) in seaward direction; profile [2]. The beach will at the same position before SLR, but at a higher level compared to the original mean sea level (MSL). If nature is fully allowed to do the adaption job without human interference, a new equilibrium profile is achieved by a horizontal shift [a] of profile [2] towards profile [3].

With the values SLR = 0.15m, L = 500m, d = 6m and h = 2m, a becomes 9.4m after 50 years. This has to be considered as a gradual beach retreat. A monitoring programme will be necessary to achieve more accurate values, which is explained in Appendix XIV.

There are a number of specific problems with the Bruun Rule[25]. The fundamental problem is that the rule is never been modified to post-1960 shore face theory. The Bruun Rule is a "one model fits all" approach, which is, in fact, unsuitable for a highly complex sedimentary environment such as the near shore zone with large spatial and temporal variations in sediment supply, wave conditions and coastal retreat rates. In addition, there has not been a single field verification that the Bruun Rule actually operates as Bruun 1962 envisioned it. The three main groups of reasons that the Bruun Rule is not reliable are as follows:

1. The assumptions behind it are so restrictive that they probably do not exist in nature.
2. It omits many important variables.
3. It relies on outdated and erroneous relationships.

[24] Graaff van de, J. (2009): Coastal Morphology & Coastal Protection. TU Delft, The Netherlands.
[25] Cooper A.G. and Pilkey, O.H.(20040: Sea-level rise and shoreline retreat: time to abandon the Bruun Rule.

Conclusion

In conclusion, the obtained coastal retreat with the Bruun rule has to be regarded as a rough estimate. Still it is certain; without human interferences the sea level rise will lead to coastal retreat. A monitoring programme may provide critical information for future decisions and will serve for data for further studies.

4.5.1.5 Reduction of sediment supply

Serious sand mining processes or possible damming for hydro-power purposes in the rivers will result in a reduction of the sediment supply at the beach. At the moment plans are made to dam the Río Pacuare for hydro-power purposes.

There is insufficient information to determine the impact of the damming process in detail. Further research is required to find out the consequences for the beaches of the east coast of Costa Rica.

In this chapter changes in the sediment supply are examined by the Unibest CL+ model.

In the Unibest CL model the input of the rivers is downgraded by 50%. Figure 4.21 shows the output of the Unibest CL model. The figure shows that once again erosion can be expected.

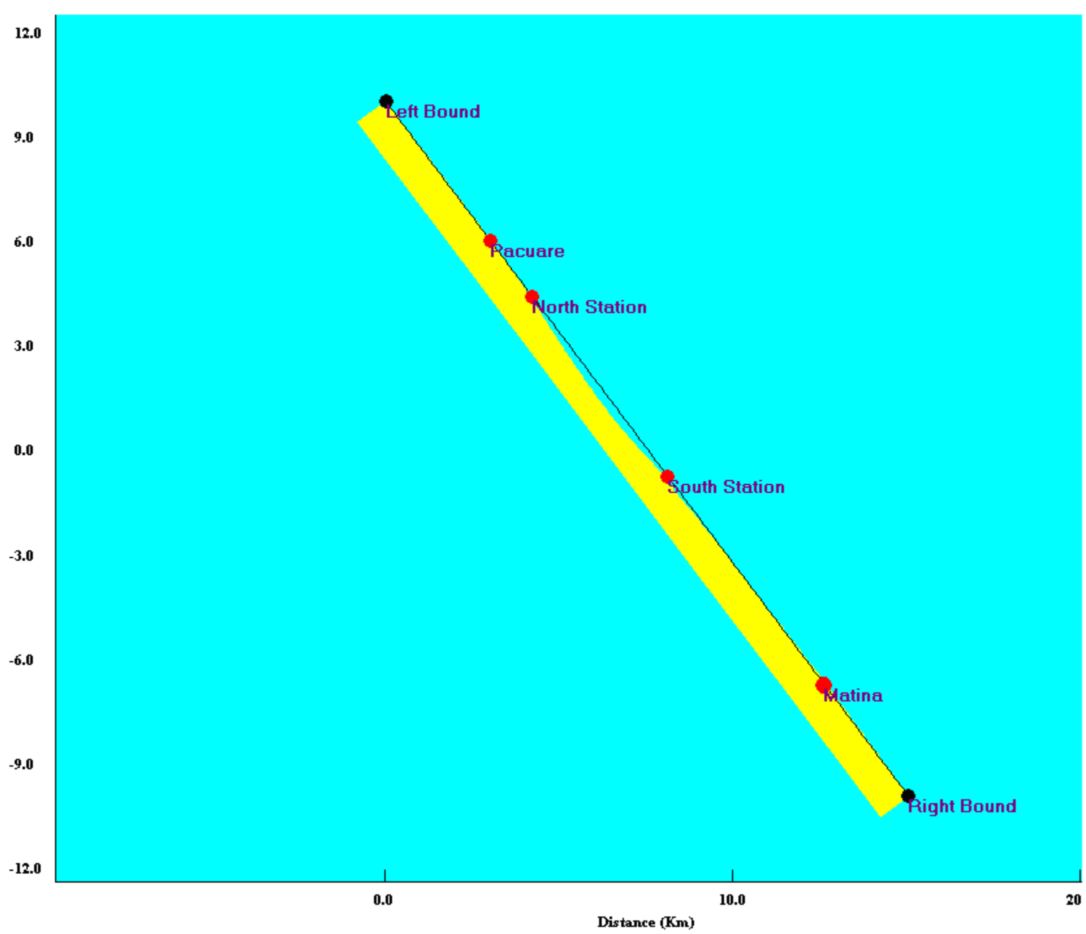

Figure 4.21: Coastline after 50 years less sediment

The tables obtained from the Unibest CL model show that the accretion at the Boca del Río Pacuare is only 7.9 metres after fifty years (this value is more northward, at the Boca itself the value is 4.1 metres), the Boca Río Matina only 41.6 metres and the erosion in between has a maximum of 266.3 metres. That the erosion is higher (the accretion less) is reasonable, because there is less sediment in the domain, there will also be less sediment that can be used to accrete the coast. The maximum erosion in between however does not change much. This means that the erosion there is influenced more by other processes then only the sediment input of the rivers or the time-step is too small to have any influence of the sediment input at the river mouths yet.

Note: The sediment supply of the rivers was calculated with the formula of Engelund&Hansen. This formula depends very much on the flow velocity, which was assumed to be one metre per second. A small difference in the flow velocity will change the sediment transport significantly. That is why there is also a calculation done with a three times higher sediment transport. After 50 years the accretion at Boca del Río Pacuare is 121.8 metres, the accretion at Boca Río Matina 255 metres and the erosion in between is 258.2 metres. This shows again that at the river mouths the accretion changes much, but the erosion in between changes not that much. The same reasons as above count.

Conclusion
When there is less sediment input the accretion becomes less. At the Reserve a negligible change in the erosion rate is observed. In the used time step there is thus no influence of the river sediment input. Over the long run, less sediment in the domain will mean more erosion over the whole stretch.

4.5.2 Validating possible solutions

This section describes possible solutions to prevent beach- and land erosion. Within the Unibest TC - and the Unibest CL+ model, these different solutions are being checked on their beneficial effects. Below, the different solutions are listed and the obtained results are presented. These solutions can be seen as small scale solutions; the solutions will prevent the negative effects of erosion but do not change the water system as a whole. The Pacuare Nature Reserve is not unique in erosion problems, along the Caribbean coast of Costa Rica and Panama this problem is widely encountered.
The main focus on the following solutions is to avoid the erosion problems in the near future. Some solutions do not prevent the actual erosion but a method is presented to guarantee the safety of the volunteers and the employees on the long-term. Validation is mainly executed by checking differences in erosion rates after implementation of the several solutions. A validation in the Unibest models was not possible for some solutions and therefore the validation is kept qualitative for these solutions.

4.5.2.1 Allow natural processes

For safety reasons, sandbags are placed to protect the buildings of the South Station. To examine if this is a good solution to prevent erosion, a situation without any form of protection works is studied. In practice, the sandbag construction could be undermined and a condition like no form of protection could be formed.

Furthermore, only the beach may be sufficient to prevent future erosion problems. The whole coastal system is very dynamic, the system redresses after the severe conditions. In a stable situation there will be no permanent loss of land. Once again, the effect of structural erosion/accretion due to long shore sediment transport is not included in the computations.

The erosion due to storms should be interpreted as a temporary loss of land, but also the temporary erosion can cause fatal damage to buildings and could be dangerous for humans in the immediate vicinity.

To model the natural process, the fixed layer, which simulates the sandbags, is totally removed in the model. The land is covered with grass and other vegetation and will erode not that easily compared to the normal beach. It is not possible to include a vegetation layer in the Unibest TC model. To schematise this layer as good as possible, the size of the grains of the sediment at land has been increased by a factor of 5.

The Unibest-TC output shows that especially after a once-a-year storm, the situation will be very threatening without use of any form of protection. After a heavy storm a land loss in the order of 10 metre will occur, see Figure 4.22. This should be regarded as a first rough estimate, but it shows that both the lodge as the kitchen building would find themselves in real danger.

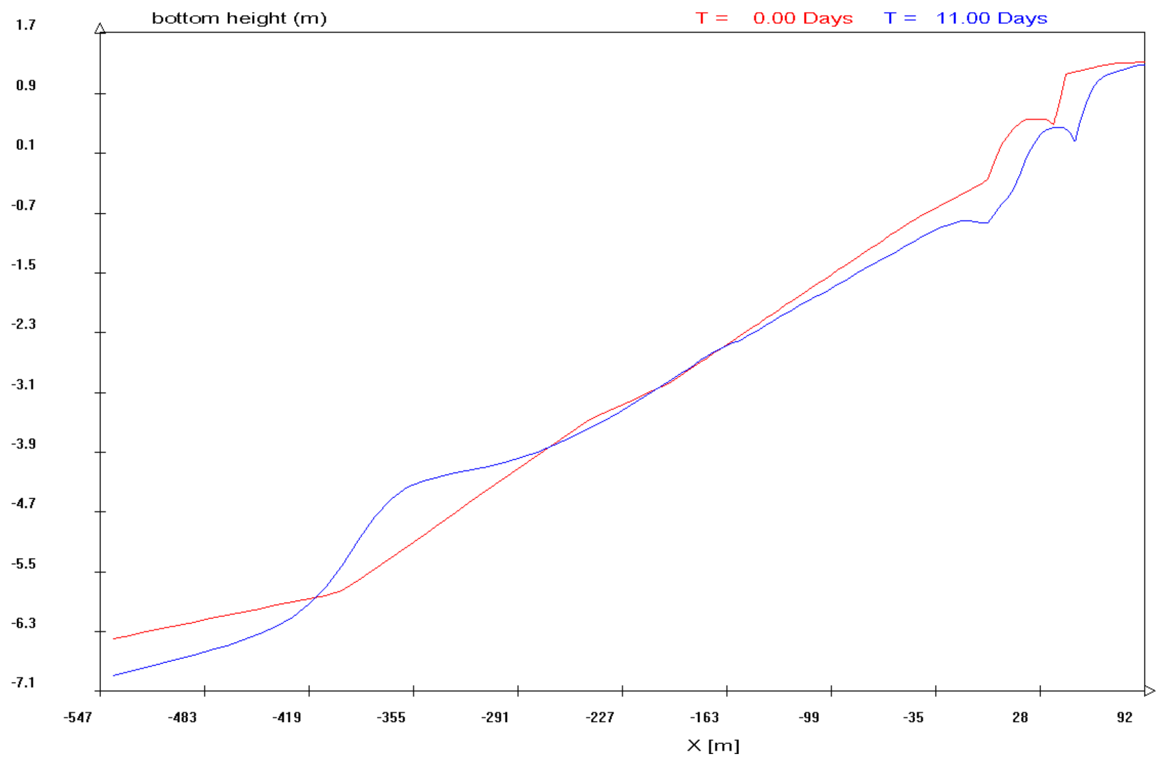

Figure 4.22: Natural erosion profile

Figure 4.23 shows a profile after 180 days. It shows that the loss of land will not restore quickly into the former situation. The beach actually has been restored in terms of width after 180 days, however Unibest TC indicates that the land does not naturally grows towards the sea. In practice, the grass and other types of vegetation that grows on the landside slowly but surely holds the sand and the land will gain position over the sea. It is not possible to model this process with the Unibest TC model.

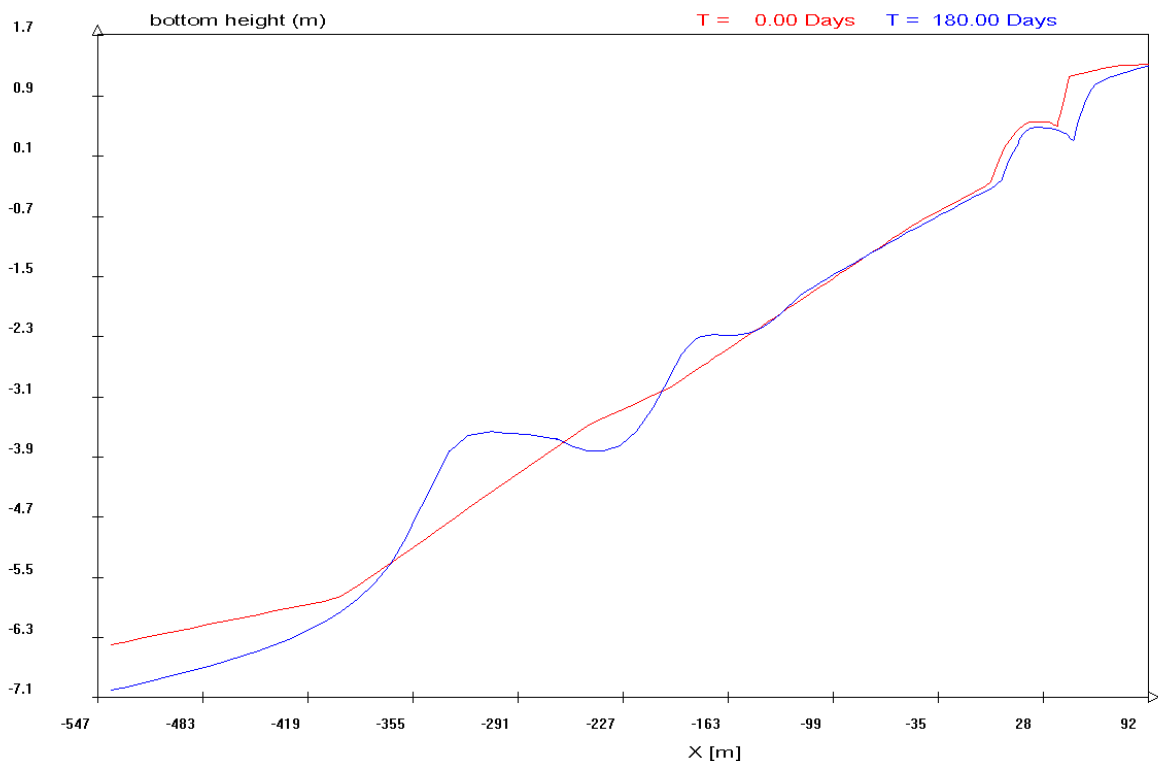

Figure 4.23: Coastal profile after 180 days

Erosion is expected due to the long shore transport, see Chapter 0. This erosion will be no threat for the Reserve on the short-term, but may be on the long run.

Conclusion

No form of protection works in front of the beach/land interface will lead to highly unsafe conditions and loss of land during severe storms. Especially the current kitchen building and the lodge are located within the erosion zone. In time, the land will regain position relative to the sea. With the used models it is not possible to predict the time of this process accurately. To maintain the current buildings it is wise to apply any protection works.

4.5.2.2 Relocation of the South Station

This solution is not tested in a computer model. The new station is built in the style of the North Station. The buildings are placed approximately 50 metres more inland compared to the old situation. In the past there was never a threatening situation at the North Station. Even without the use of sandbags/revetment this will be a safe solution. This is illustrated by the previously examined situation without sandbags. A once-a-year-storm causes a loss of land of about 10 metres, see Figure 4.24. The buildings are therefore built at a safe distance from the sea.

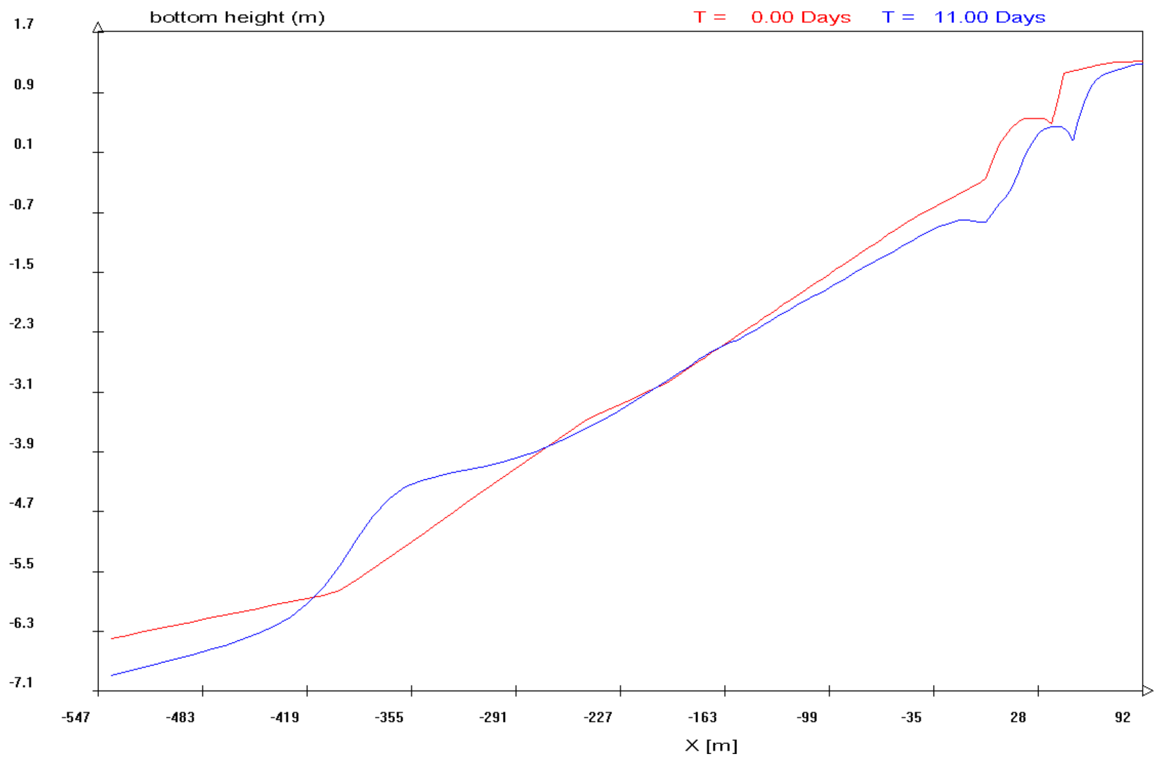

Figure 4.24: Erosion profile of an unprotected coast

Also lagoon breakthroughs do not form a threat because the buildings are built quite far from the lagoon, see Figure 4.25.

Figure 4.25: Relocation/expansion of Reserve's buildings

Conclusion

The relocation of the installations is a safe solution to guarantee the safety of the volunteers and employees on the long-term. It is assumed that some buildings of the old station will be lost in the future. Also any possible structural beach erosion is not counteracted by this solution.

4.5.2.3 Sandbags/revetment

As previously indicated, the Reserve has placed sandbags and a timber revetment. In the current state, immediate maintenance will be required to the sandbags to function properly. The results discussed in this chapter are based on an efficient working protection. A few recommendations to improve the beach-land interface are also included in this chapter.

During heavy storms, deep scour holes can be created in front of the bags. According to Figure 4.26 such holes can reach depths of two metres. Such deep holes could lead to a failure of the structure. However, the figure also shows that a good sandbag/revetment work will prevent loss of land; the loss of land is limited. The sea has no chance to erode the land of the Reserve.

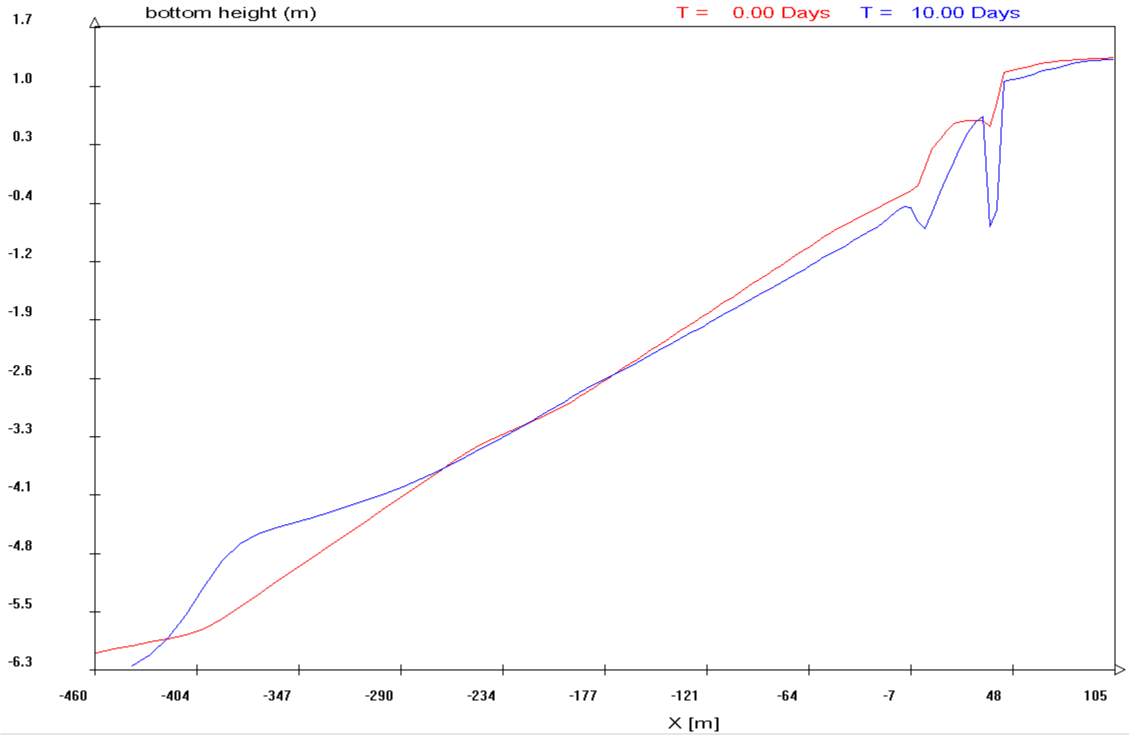

Figure 4.26: Erosion profile with a good working sandbag/revetment work.

A computation for the long run shows that restoration takes place. The coastal profile after 180 days still shows a beach lowering of 20 centimetres, see Figure 4.27. A difference of 20 centimetres compared with the initial profile is for a long-term run of Unibest TC model negligible. Also in this case the formation of the two bars in the profile is doubtful.

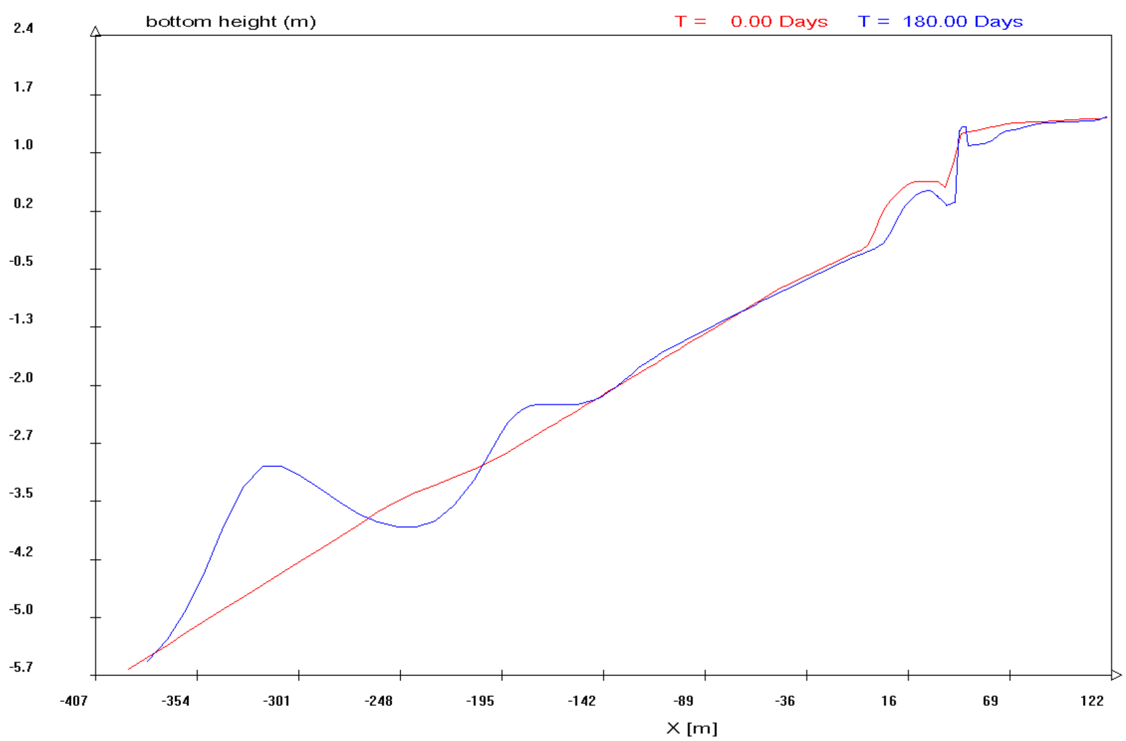

Figure 4.27: Coastal profile after 180 days with a good working sandbag/revetment work

Structural erosion caused by a gradient in the long shore sediment transport is not prevented by the sandbags. This is because shore parallel structures do not interfere in the morphological processes under normal conditions. By protecting the mainland with sandbags, one indeed prevents that sediment is transported in seaward direction, but the gap in front of the bags becomes deeper and deeper and eventually the beach will disappear. When there is no beach in front of the sea, wave attacks become more frequently and damages will occur.

Conclusion
Sandbags could be a good solution to prevent land erosion, but the bags should be placed to a certain depth to avoid undermining or sliding. Another problem which is the case at the moment is that many sandbags are torn apart by the heat of the sun. In fact, a protection layer or densely applied vegetation is necessary and ongoing maintenance will be sensible. The current sandbags are not built deep enough to counteract the possible undermining process. This problem can be avoided by placing bamboo poles in front of the sandbags. In this way the bags are held in position, as shown in Figure 4.28 and Figure 4.29. Figure 4.30 shows the cross section of this construction. The embedment of the bamboo piles should be twice the retaining height, so three metres embedment will be sufficient.

Figure 4.28: Sandbags with bamboo poles

Figure 4.29: Sandbags with bamboo poles

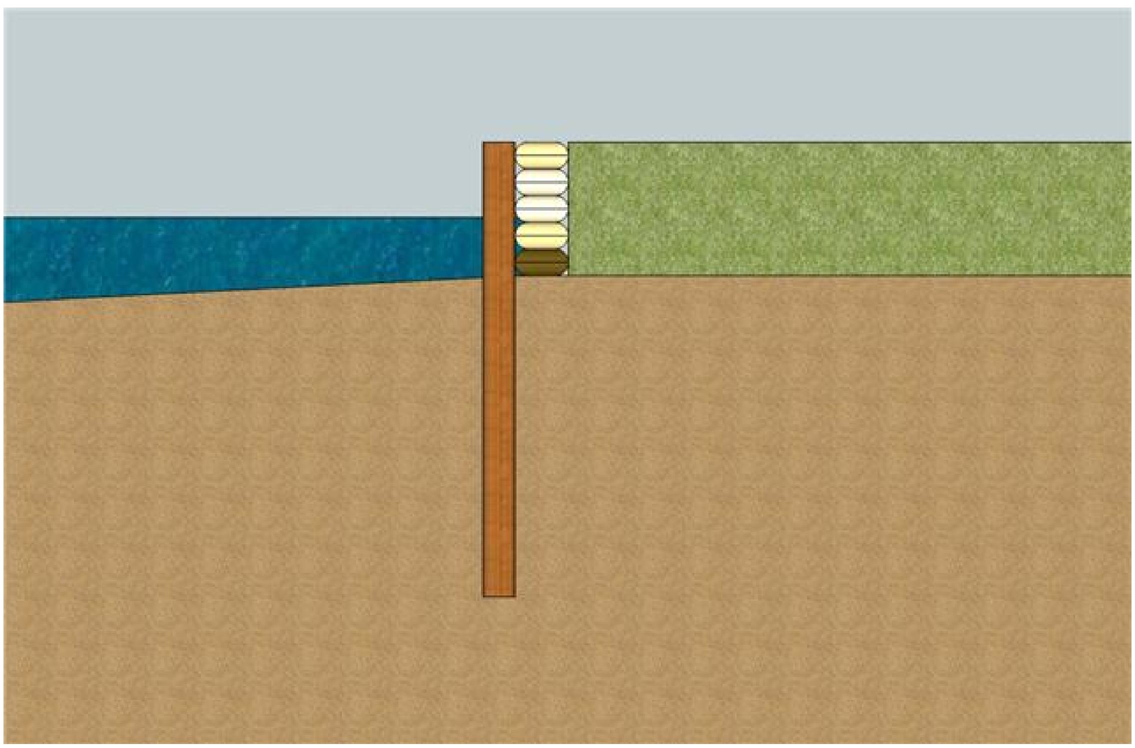

Figure 4.30: Cross section sandbags/bamboo poles construction

Note: In the following presented solutions it is assumed that a well-built sandbag structure is present at beach-land interface. This is chosen because it is shown that such protection work is very effective to minimize erosion of the land. Furthermore, in the current situation sandbags are already present.

4.5.2.4 Artificial reef

To examine this alternative with the Unibest TC program a solid layer, with a width of twenty metres and a height of five metres, is added approximately 550 metres in front of the coastline.

This gives a good simulation of a possible artificial reef. Most waves will break at the reef and will lose energy. In addition, the sand in the upper parts of the profile is being held in the upper parts of the profile by the artificial reef. Figure 4.31 shows that the waves at the reef very shortly gain altitude and ultimately break. The red line indicates normal conditions and the blue line shows the once a year storm conditions.

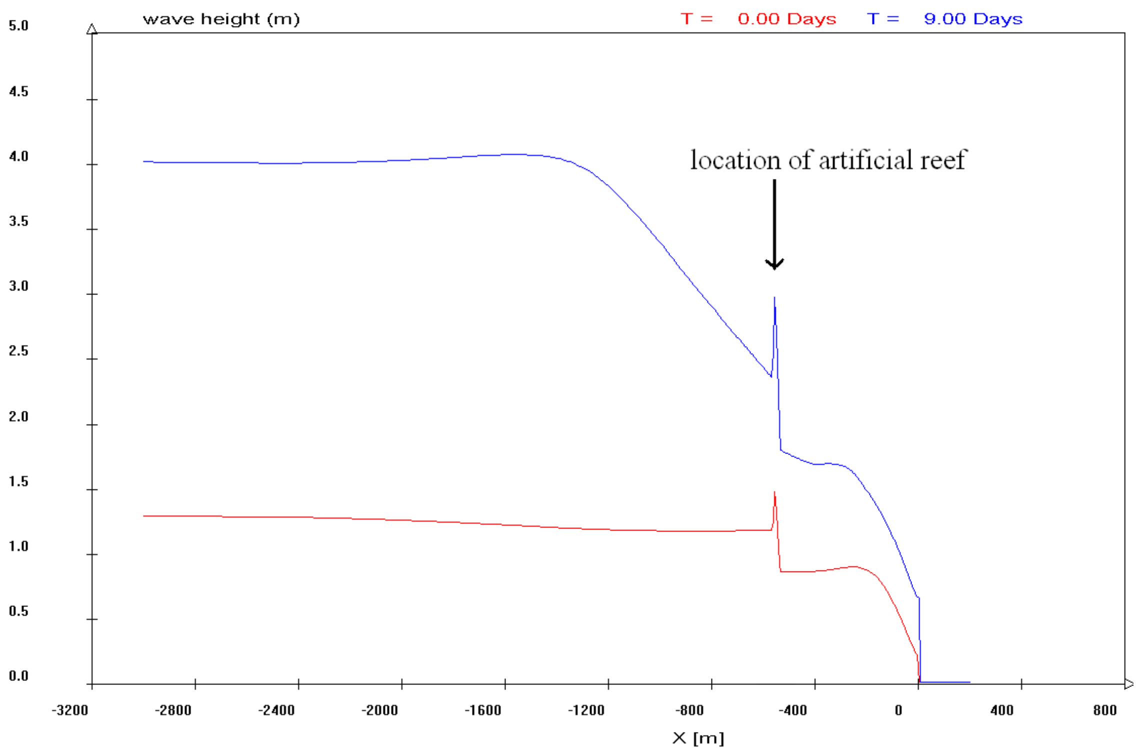

Figure 4.31: wave height with an artificial reef

The effects of the storm are barely noticeable on the beach and at the land crest. According to Unibest TC, sand will be even deposited on the beach during the once-a-year-storm, see Figure 4.32. Even the long-term coastal profile near the beach will grow, which is clearly shown in Figure 4.33.

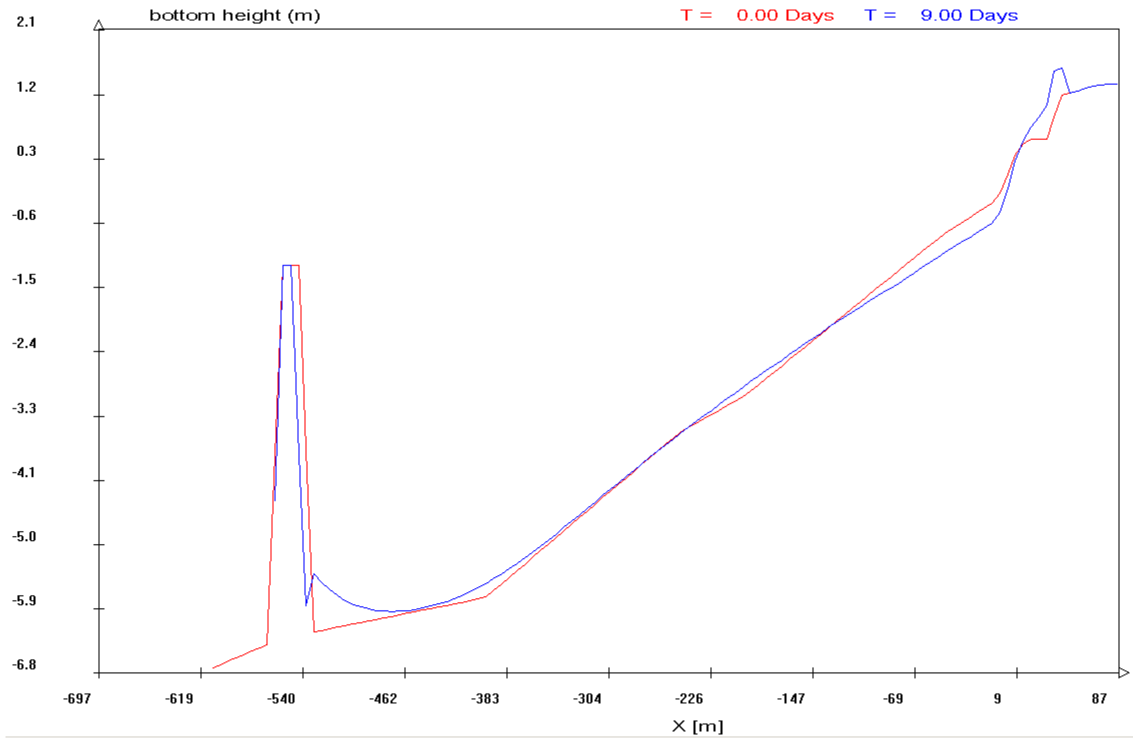

Figure 4.32: Coastal profile with artificial reef during storm conditions.

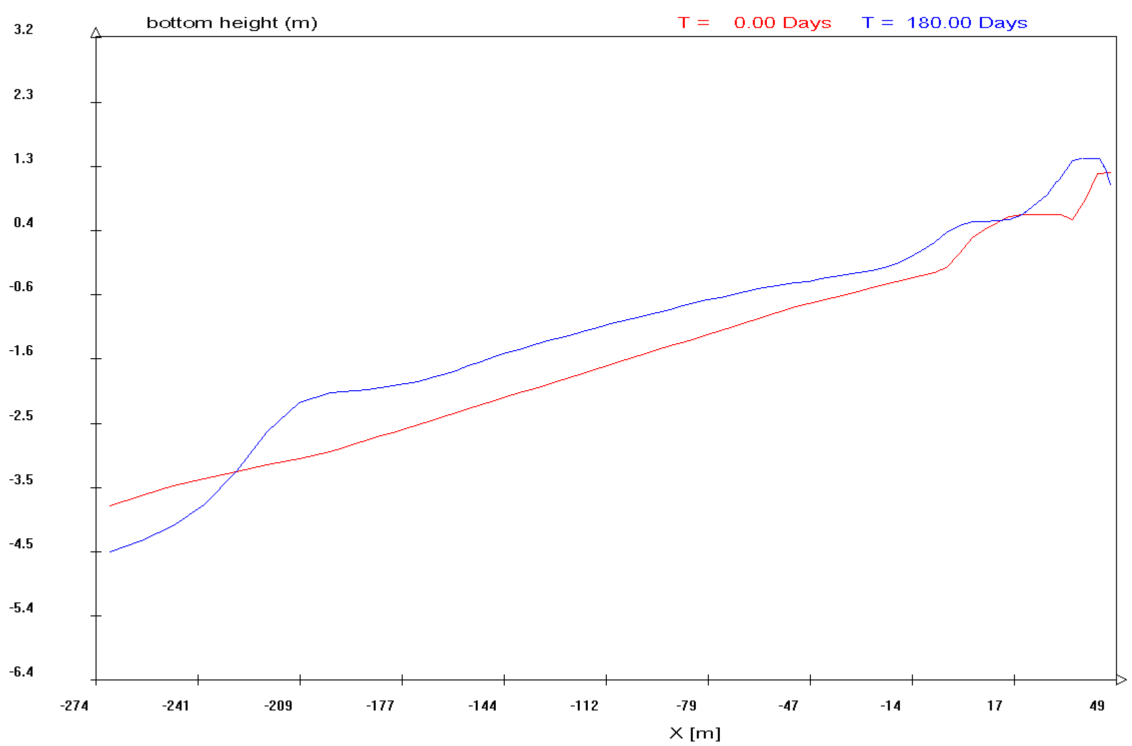

Figure 4.33: Coastal profile after 180 days after completion of artificial reef

Conclusion

An artificial reef will be good solution to protect the Reserve against coastal erosion. In the case of a breakthrough of the lagoon, the waves will have little energy to further erode the land and it is expected that the lagoon will close quickly if the water level in the lagoon will decrease. This is however an expensive solution, and is probably only feasible if the beach will be more extensively used in the future (for instance for recreational purposes).

4.5.2.5 Beach nourishment

In the Unibest TC model it is assumed that the coastal profile is stable. After a nourishment an unstable situation will occur, because a gradient in the long shore transport is created. The program does not include accretion and erosion caused by possible gradients in the long shore transport.
The calculation that is performed by Unibest TC is wrong in principle, but should be considered as clarification of the effect of a sand supplementation. How the shore transport process works and how fast this process takes place is calculated with Unibest CL.

In the model, the actual beach is extended by 50 metres. It is assumed that the applied sand has the same grain size of the current sand. A popular slogan in the world of coastal engineering is: ‘a beach is nature's best form of defence’. That this slogan is true is proven by the output of the Unibest TC model. After the once-a-year-storm the beach has only been eroded by a few centimetres and the scour hole in front of the sandbags is much less deep than in a situation without nourishment, this is shown in Figure 4.34.

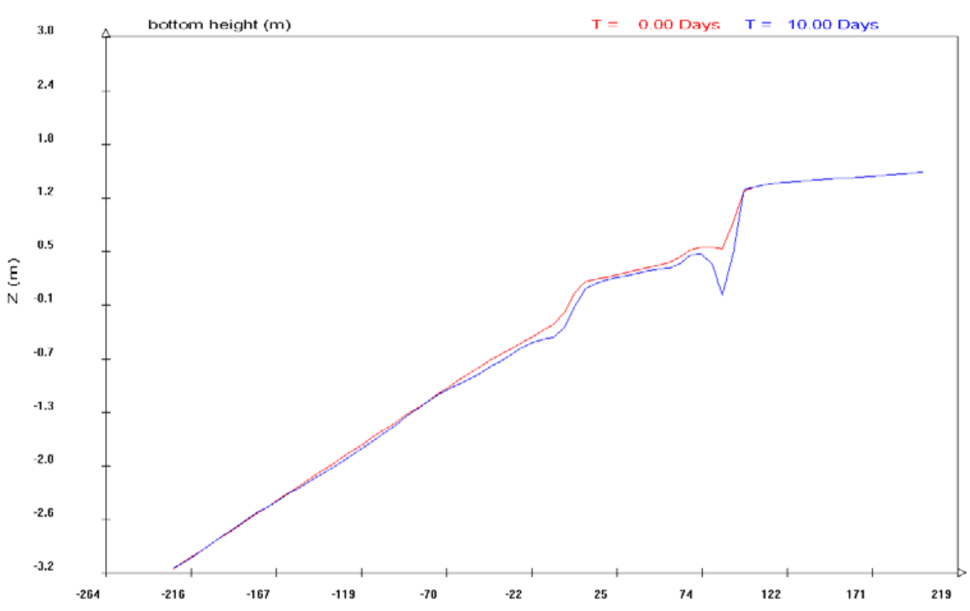

Figure 4.34: Erosion profile of the extended beach

The modelled long-term effects are inaccurate because the long shore transport is not included. The image sketched by the Unibest TC output is likely to be too positive.

Because of only cross shore transport the beach loses about 10 metres in length after 200 days. This is shown in Figure 4.35.

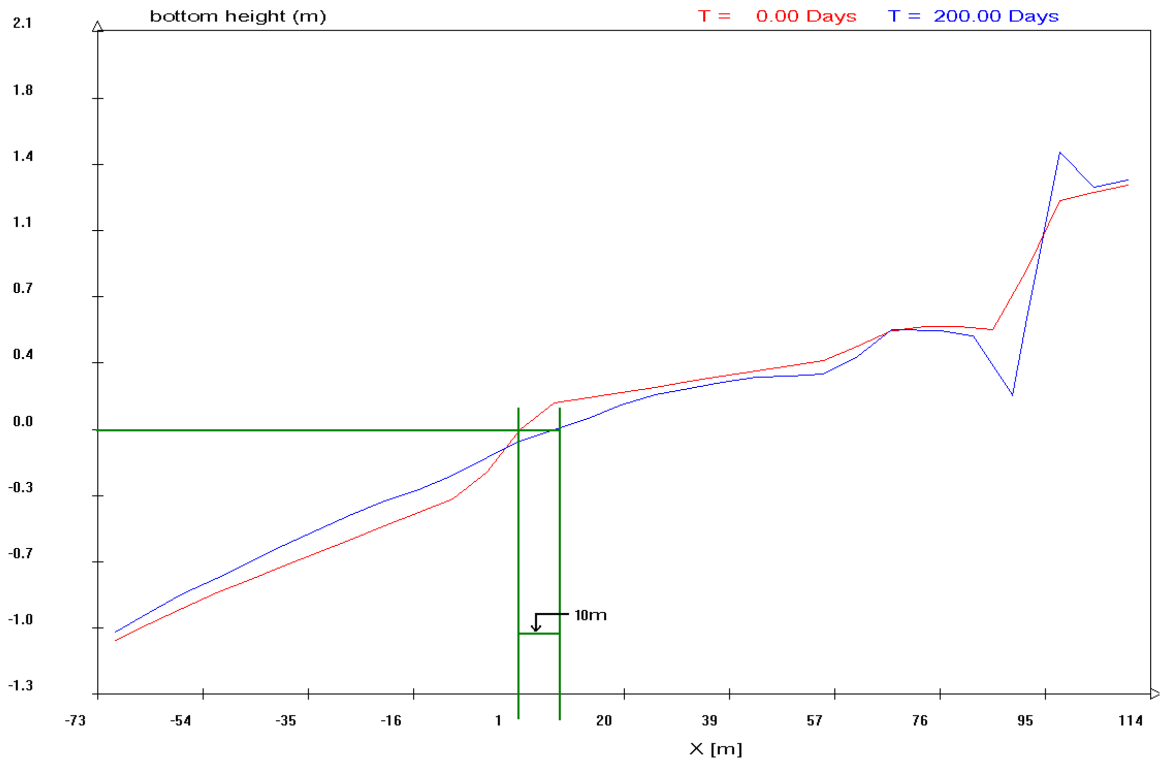

Figure 4.35: Coastal profile with an extended beach after 200 days

In Unibest CL+ the beach nourishment is also simulated, with a length of 1 kilometres and a width of 50 metres; with the South Station halfway. Figure 4.36 shows the coastline after ten years. The figure shows the nourishment has disappeared after ten years and in front of the Reserve the initial coastline is reached.

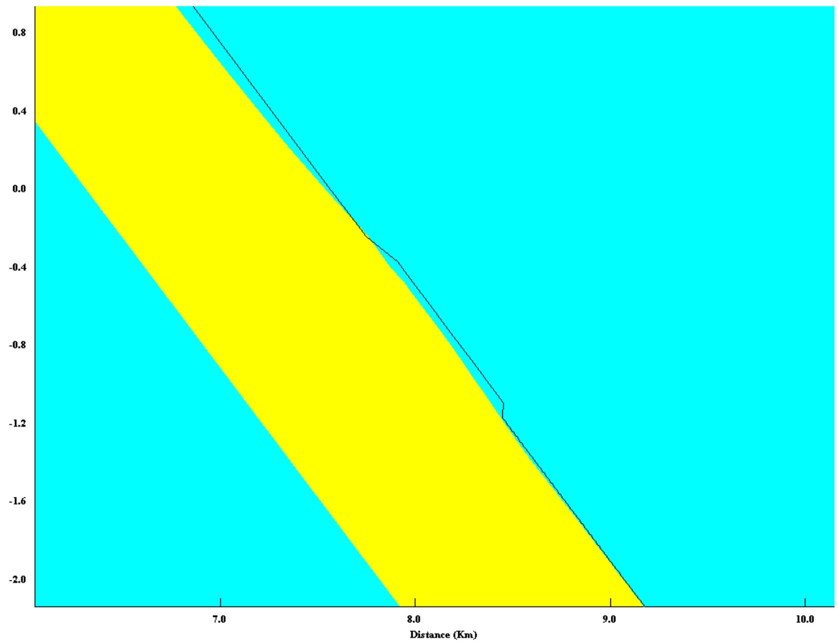

Figure 4.36: Beach nourishment after ten years

Conclusion

A beach nourishment will be a good solution to prevent erosion of land. This measurement must be repeated continuously, because it does not counteract the actual erosion. These cyclic costs can be very expensive for the Reserve. Important to mention: an extended beach will also be a good solution to prevent a breakthrough of the Mondonguillo lagoon; it will form a bigger barrier to erode during high river discharges. It is expected that a wider beach might be beneficial for the hatching areas of the sea turtles as well. This is however an expensive solution, and is probably only feasible if the beach will be more extensively used in the future (for instance for recreational purposes).

4.5.2.6 Under-pinning installations

The lodge is constructed of very expensive hardwood and is therefore extremely valuable. The lodge is located directly next to the lagoon and close to the sea. Therefore this building is at risk during severe storms and lagoon breakthroughs. Under-pinning can be applied to extend the lifetime of the building. This method is studied in this section. **Under-pinning is a structural modification and will not be a solution to prevent any form of erosion.**

A common method is to put helical piles or jet grout piles next to the existing building and anchor them to the existing foundation, see Figure 4.37. Heavy equipment is required and that is not possible at the Pacuare Nature Reserve. Hand-made solutions have to be considered. Other methods than extending the piles are not really suitable. So the only solution is to excavate the ground by hand under the foundation and obtain cylindrical 'holes'. Next, pouring concrete in these excavated cylindrical holes is required. Figure 4.34 shows that the foundation is situated about half a metre under ground level.

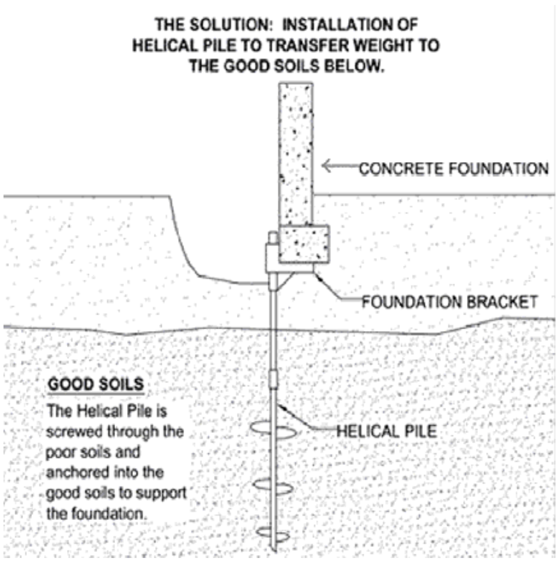

Figure 4.37: Extending piles with common method[26]

Figure 4.38: Foundation of the lodge

To determine the depth of the piles, erosion due to wave impact and currents are important aspects. Erosion depths which are deeper than this apparent foundation depth can cause failure of stability of the lodge.

Wave impact

Figure 4.22 shows that the erosion of the land due to wave impact during a storm can be up to one metre. In an unprotected scenario the water level in the lagoon during a severe storm is about the same as the ground level around the lodge.

Currents

During a breakthrough, the lagoon is directly connected with the sea. Water from the sea flows in the lagoon and vice versa, which generates currents. Currents around the foundation piles might cause scour holes. For an estimation of the depth of the scour hole a rule of thumb (equation (1.6)) is used[27]. With this formula the scour is dependent of the water depth and the diameter of the piles. The diameter of the piles is half a metre and the water depth is one metre.

$$\frac{h_s}{D} \approx 2\tanh\left(\frac{h_o}{D}\right) \qquad (1.6)$$

In this formula D is the diameter of the pile and has a value of 0.5m. h_0 is the water depth and has a value of 1.0 metres. h_s is the depth of the scour hole, which now can be calculated with equation (1.6). h_s becomes $\pm$ 1 metre.

[26] http://www.northeasthelical.com/index_files/images/Underpinninggif.gif
[27] Schiereck, G.J. (2004): Introduction to Bed, bank and shore protection. The Netherlands.

The depth of the foundation piles below ground level consists of 1 metre for the water depth, 1 metre for the scour hole and 1 metre for extra safety (h+). This means that the total depth of the foundation piles below ground level becomes 3 metres. The existing foundation is 0.5 meter below ground level. Hence, the extension of the piles is 2.5 metres, see Figure 4.39 and Figure 4.40.

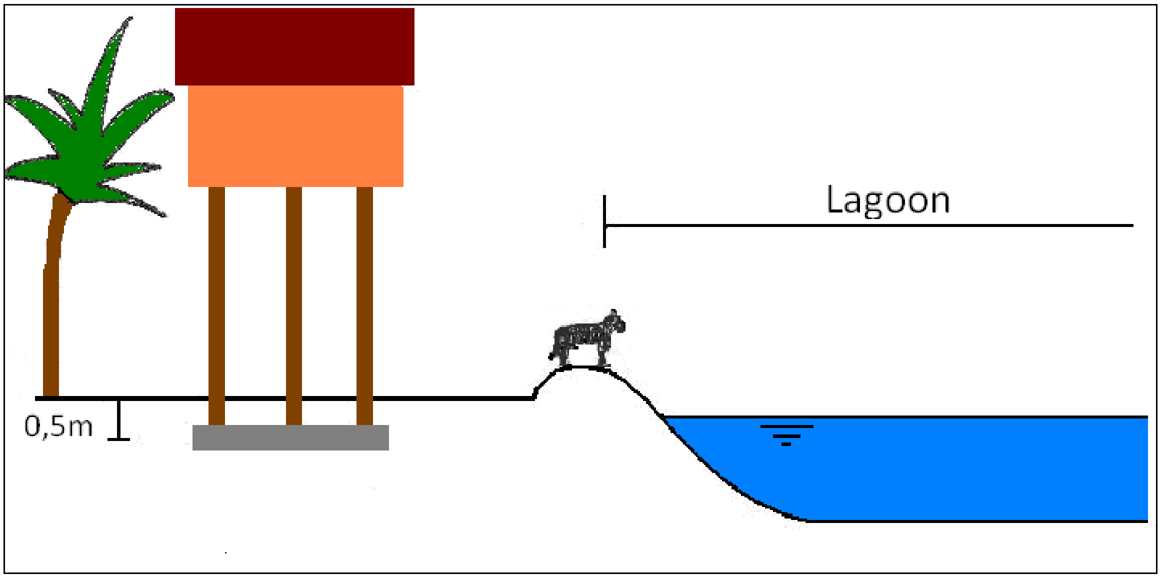

Figure 4.39: Foundation lodge in initial situation

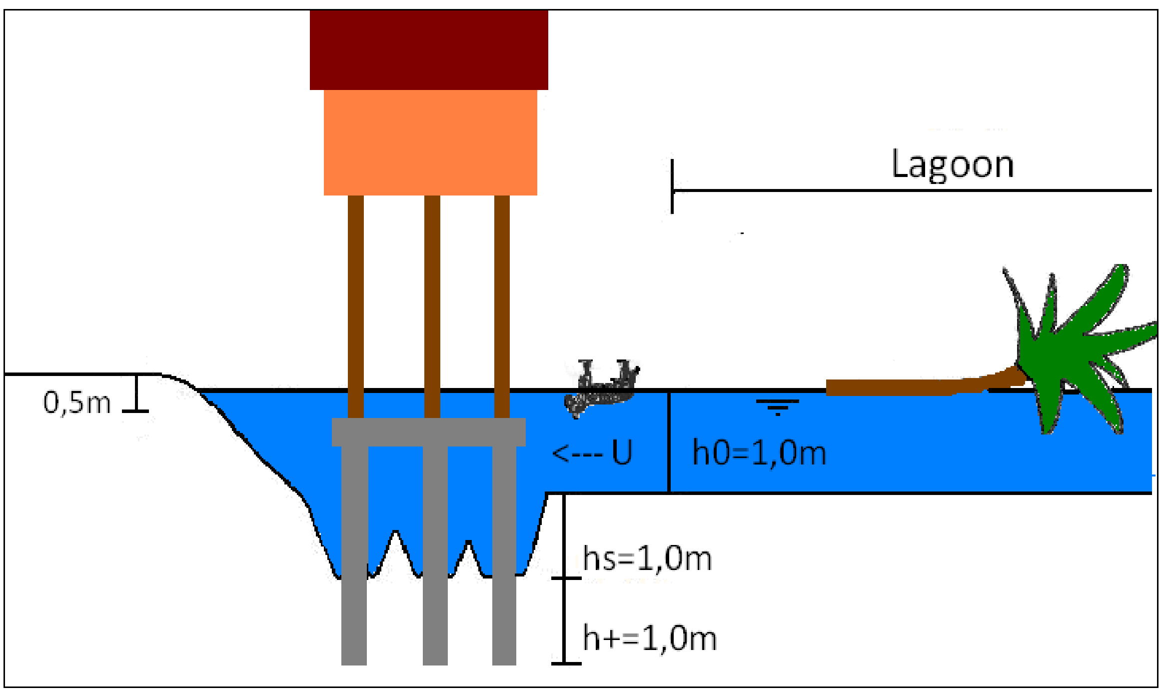

Figure 4.40: Extension of foundation lodge during precarious situation

Figure 4.41 shows this extension in relation to the lodge its surroundings.

Figure 4.41: Extension foundation piles

Conclusion

Under-pinning will be a very good method to protect the lodge. It is an expensive option, yet acceptable, especially if the extended life time and the increased safety of the lodge are considered. The feasibility is also an important aspect for the Reserve. This structural modification can be performed without the use of heavy equipment, so there will be no logistical problems to under-pin the lodge.

Further research is necessary to qualify the possible circumstances more specified. A comprehensive study can result to predict the rates of erosion in detail. Also the impact of waves which produce a horizontal force should be included in further calculations.

Note: The following presented solution will prevent a breakthrough of the lagoon only.

4.5.2.7 Embankment in the barrier beach of the lagoon

The effect of an embankment is not modelled in the Unibest TC model, because it has to prevent a breakthrough of the lagoon initiated by high river discharges. In the Unibest TC model it is not possible to model river discharges. Output of SOBEK is used to determine the minimal height of the construction to retain the water in the lagoon. Output of SOBEK is used to determine the minimal height of the construction to retain the water in the lagoon. The maximum water level of the lagoon is 2.2m AD, see Figure 3.20. For safety reasons it will be recommendable to use a minimum height of 2.5m AD. The highest level of the barrier beach strip is at 1.25m AD, see Figure 3.13. The actual retaining height of the dike construction will be 1.25 metres.

Figure 4.42 shows a visual representation of this embankment during severe conditions; high water levels at the lagoon and the sea.

Figure 4.42: Visual representation of an embankment at the barrier beach strip

Under normal conditions, the lagoon can be described as a storage basin, no significant flow velocities occur. If the water level in the lagoon exceeds the highest level of the barrier beach the water will form a way to the sea. The water level in the lagoon will be much higher than the water level at sea. This high water level difference between the lagoon and the sea results in high velocities and massive erosion. An embankment will be capable to retain the water in the lagoon and the lagoon remains a storage basin in this case. It is expected that the low-lying areas in the direct surroundings of the lagoon will be flooded due to this retaining structure. No problems will occur until the water constitutes a channel next to the embankment to the sea. It is not likely this will happen because the area is densely vegetated, the surface levels in the surroundings are higher than the lagoon and the water levels will drop rapidly due to instantaneous rainfalls.

This solution will not prevent erosion due to storms on the ocean, but will be very effective to avoid a breakthrough of the lagoon.

Conclusion

A dike could be an excellent solution to prevent breaching of the Mondonguillo lagoon due to high river discharges. A simple embankment of sandbags would be able to retain the water in the lagoon. The Reserve will be capable to build an embankment of sandbags by their own. In combination with a good sandbag structure the Reserve is also protected against storm erosion, as described in Chapter 4.5.2.3. Figure 4.43 shows a possible stable cross section of the embankment in a situation after a breakthrough of the Barrita Lagoon (maximum water level of 1.81m AD in Mondonguillo Lagoon, see Figure 3.43).

A possible embankment of rock material will be more expensive and harder to build, but also more sustainable.

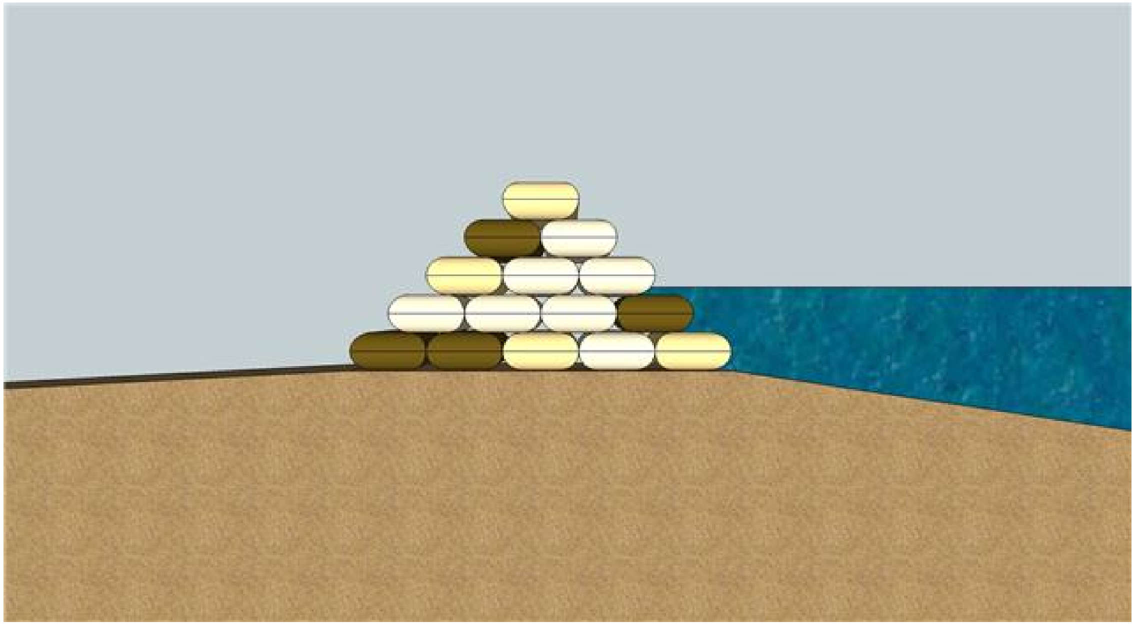

Figure 4.43: cross section of the possible embankment of sandbags

4.6 Multi Criteria Analysis

In this chapter the possible solutions will be compared to each other. Important aspects are the safety which is created and the possibility of implementing the various solutions. In a Multi Criteria Analysis the possible solutions are summed up and points will be assigned for important criteria. The criteria being important in these analyses are described below:

Safety = the safety for the buildings and the people of the Reserve which is created by the solution. The solutions which are able to prevent lagoon breakthroughs will score more points for this criterion.
Effect on beach = the total of positive effects on the beach.
Effort = the effort the solution will take to accomplish the solution.
Knowledge available = the availability of man-power, knowledge and heavy equipment in the area + the degree of further studies necessary.
Ecological impact = the total of negative effects on the flora and fauna.
Esthetics = the total of negative effects on the surroundings.

Some of these criteria are much more important than other ones. To determine the mutual importance of each criterion a special table has to be used. If in Table 4.2 a criterion in the row is more important than in the column it is given a one, if it is less essential than it is given a zero.

	Safety	Effect on beach	Effort	Knowledge available	Ecological impact	Esthetics	Total score
Safety		1	1	1	1	1	5
Effect on beach	0		1	1	0	1	3
Effort	0	0		0	0	0	0
Knowledge available	0	0	1		0	0	1
Ecological impact	0	1	1	1		1	4
Esthetics	0	0	1	1	0		2

Table 4.2: Determining mutual importance

The criteria ‘effort’ seems to have no importance at all, because a total score of zero is given in the table. Nevertheless it has influence in the decision making which solution has to be applied and therefore it is valuable criterion in the MCA. To give it some influence it is given the weight ‘one’ and all the other criteria are being multiplied with a factor two. The weight factor is being calculated in Table 4.3.

		Weight factor
Safety	10	10/31=0.32
Effect on beach	6	6/31=0.19
Effort	1	1/31=0.03
Knowledge available	2	2/31=0.07
Ecological impact	8	8/31=0.26
Esthetics	4	4/31=0.13
	$\sum = 31$	$\sum = 31$

Table 4.3: Determining weight factor

The solutions are rated on every criterion with a grade 1-10 (in which 1 is negative and 10 is positive). A combination of an embankment at the barrier beach and a sandbag structure is also examined. The total score of the solutions can be calculated. All the scores for each criterion are being multiplied with the weight factor of the matching criterion, which results in the total score. The maximum score is 1000. The results are given in Table 4.4.

	Safety	Effect on beach	Effort	Knowledge available	Ecological impact	Esthetics	Total score
WF	[32]	[19]	[3]	[7]	[26]	[13]	
1. Do nothing	1	6	9	6	6	9	488
WF*score	32	114	27	42	156	117	
2. Relocate buildings	10	6	2	8	6	8	756
WF*score	320	114	6	56	156	104	
3. Sandbags/ revetment	6	5	8	6	7	5	600
WF*score	192	95	24	42	182	65	
4. Artificial reef	8	7	2	3	6	8	676
WF*score	256	133	6	21	156	104	
5. Beach nourishment	9	9	4	3	8	9	817
WF*score	288	171	12	21	208	117	
6. Under-pinning installations	8	6	6	5	6	7	670
WF*score	256	114	18	35	156	91	
7. Embankment barrier beach strip	6	6	8	6	7	4	606
WF*score	192	114	24	42	182	52	
8. Embankment + sandbags/ revetment	9	6	7	6	8	4	725
WF*score	288	114	21	42	208	52	

Table 4.4: Determining total score of each solution

Now the value of every solution is known. A beach nourishment program seems to be the best solution, but to complete the MCA the costs of each solution have to be divided by the corresponding total score. The real costs of the possible solutions are not being calculated exactly in this report; instead fictive costs are being used. With respect to the other solutions, fictive costs are being determined. In this way the costs are being applied in MCA without knowing the exact costs.
The solution 'do nothing' is rated with a cost value of 700, because it assumed the lodge and the kitchen building will be lost in the near future. The costs of a beach nourishment will be rather high, because this solution has to repeated every few years. The solutions with sandbags will be quite cheap compared to the other solutions. The cost value divided by the total score is given in Table 4.5.

	Cost values	**Total score**	**Costs value/total score**
1. Do nothing	700	488	1.4
2. Relocate buildings	1000	756	1.3
3. Sandbags/revetment	200	600	0.3
4. Artificial reef	2000	676	3
5. Beach nourishment	1500	817	1.8
6. Under-pinning installations	400	670	0.6
7. Embankment barrier beach strip	200	606	0.3
8. embankment + sandbags/revetments	350	725	0.5

Table 4.5: Multi Criteria Analysis

In Table 4.5, it is shown there are four solutions which score quite close to each other at the end. These four solutions which finally score the best are:

- Sandbags/revetment
- Under-pinning installations
- Embankment barrier beach strip
- Combination of embankment + sandbags/revetment

All these four solutions are compared to other solutions and if they are cheap and easy to apply. The combination of an embankment in the lagoon and a proper sandbag protection line in front of the coast will probably be the best solution. The Reserve is, after applying of this combination, safeguarded against erosion of the sea and also against erosion due to lagoon breakthroughs. An under-pinning method will be suitable to extend the lifetime of the expensive lodge.

The decision of the organisation to relocate the buildings of the Reserve has to be considered as a expensive solution, yet the safest solution. In order to obtain the highest safety level of the volunteers and the employees of the Reserve, it is still the most sensible solution.

5. Conclusions & Recommendations

5.1 Conclusions

The results sketched in Chapters 3.5 and 4.5 are summarized in this chapter. These results are linked back to the objectives in Chapter 1.3. The main objective was described as 'presenting recommendations for an unconditional safe discharge of water within the project area, after studying probable causes'. This objective indicates finding solutions for the macro-scale problem. These solutions are tested in the Chapter 3 (analyzing river system). The sub objective 'presenting solutions for safeguarding the Pacuare Nature Reserves' installations' indicates finding solutions for the small-scale problem. These solutions are elaborated in Chapter 4 (analyzing beach system). Finally, the sub objective 'presenting approaches to realize long-term data' is elaborated in Appendix XIV.

Macro-scale

It is clear that the current situation is precarious. Inundations are common and endanger lives of local population and cattle. In line with these inundations, problems on the smaller scale occur. Problems like the loss of land due to the mentioned breakthroughs or storm conditions on sea.

The conclusions regarding causes of the macro-scale problem:

- Channelisation increases problems in low-lying areas.
- Earthquakes have impact on hydrodynamics in the system.
- Drainage canals (cultivation of rainforest) increases incapability of safely discharging water.
- Tropical climate has major impact on peak discharges and subsequently on the safely discharging of this water.
- Excavation of the Tortuguero Canal leads to directly connected bodies of water in the coastal plains. A breakthrough is more likely in this man-induced situation.

The conclusions on the different possible solutions for the macro-scale problem:

- Creating room for the river in Río Matina does not have major impact on water levels in Tortuguero Canal, but does have positive impact on inundations.
- Discharge in drainage canal has major impact on water levels in Tortuguero Canal. Creating ways to directly discharge this excess of water is beneficial for the water level in the Mondonguillo Lagoon.
- The cultivation of land worsens the problem. The excess of water cannot spread over large quantities of flood-plains and will accumulate in smaller plains, resulting in higher water levels.
- The (artificial) breaching of the Barrita barrier beach strip results in a beneficial lowering of water levels in the Mondonguillo Lagoon.

Chapter 3.5.2 summed up all the possible solutions. The final review of the solutions in Chapter 3.6 pointed out that the combination of artificially breaching of Barrita barrier beach and extend drainage canal to Caribbean Sea was the best option. Mitigation factors like ecological and economical values were dodged and they optimised hydrodynamic conditions.

Small-scale

The dynamics of the beach is also a mitigating factor for every day life in the region. The current use of the beaches is basically limited to hatching areas for turtles. If the use of the beaches will be extended in the future (for instance for the purpose of tourism) knowledge of the beach dynamics will have to be available.

The conclusions regarding the causes of the small-scale problem:

- Tropical storms will undoubtedly result in erosion. In more tranquil conditions the coastal profile restores to the initial profile. These changes in the coastal profile are considered as a natural dynamic process and will only cause dangerous situations for short periods of time. Protection is required to save the buildings of the Reserve.
- The gradient in the long shore sediment transport will result in structural erosion problems. This is also the case around the South- and North Station.
- The erosion due to a lagoon breakthrough is not structural, but could lead to precarious situations and could be fatal for the buildings of the Reserve.
- Without human interferences sea level rise will lead to permanent coastal retreat. A monitoring programme may provide critical information for future decisions and will serve as data for further studies.
- Possible sand mining and damming will result in a reduction of sediment supply to the beach. On the long-term, less sediment in the domain will mean increased erosion over the whole stretch.

The conclusions on the different possible solutions for the small-scale problem:

- No form of protection works in front of the beach/land interface will lead to highly unsafe conditions and loss of land during severe storms. Especially the current kitchen building and the lodge are located within the erosion zone.
- A well-build sandbag structure prevents land erosion, but ongoing maintenance will be sensible. A sandbag structure does not protected against structural erosion due to the long shore transport.
- Beach nourishments will be costly, but highly beneficial for the Reserve.
- An under-pinning method will extend the lifetime of the lodge significantly. The method can not be used to prevent any form of erosion.
- The relocation of the installations is a safe solution to guarantee the safety of the volunteers and employees on the long-term.
- An embankment at the barrier beach strip will be an excellent solution to prevent breaching of the Mondonguillo lagoon. A simple embankment of sandbags would be able to retain the water in the lagoon.

Chapter 4.5.2 summed up all the possible solutions. The final review of the solutions in Chapter 4.6 pointed out that applying a higher barrier beach was the best option. A dike could be an excellent solution to prevent breaching of the Mondonguillo Lagoon due to high river discharges. A simple embankment of sandbags would be able to retain the water in the lagoon. In combination with a good sandbag structure the Reserve is also protected against storm erosion.

5.2 Recommendations

The presented solutions will be elaborated in this section. Necessary further studies before implementing solutions will be mentioned. There is made a clear distinction between cases where no further research is necessary and cases where further studies are obligatory.

Recommendations with immediate use regarding global problem:

- Proactively engage local government, University of San Jose and corresponding companies. The distribution of this report might contribute of creating awareness of this problem.
- Find alternate locations banana plantations or create natural flood-plains.

Recommendations with immediate use regarding Pacuare Nature Reserve:

- Applying sandbags with bamboo pile support to prevent Pacuare Nature Reserve from eroding.
- Under-pinning of valuable installations.
- Phased relocation/ expansion of installations.
- Applying embankment across barrier beach strip Mondonguillo Lagoon to prevent barrier beach from breaching.
- Artificially breaching of Barrita barrier beach during wet periods; this is already being executed.
- Immediate commencement of Monitoring Programme (see Appendix XIV)
    - Beach regression/progression.
    - Water levels and discharges in rivers, channels and lagoons.

Recommendations further studies:

River related:

- Study possibility of extending drainage canal. Effectiveness has been proven; mitigating factors have to be studied further.
- Execute similar studies in areas with similar problems and compare results.
- Study peak discharge distributions and annual averages of Río Matina and Río Pacuare

- In accordance to the previous recommendation; study/measure sediment transports (peak/yearly) throughout the river stretches.
- Further investigation of influence embankments on inundation of coastal areas in relation to growing cultivation of flood-plains.
- Applying more accurate 2D-grid in river hydrodynamic models.
- Sensitivity analysis on parameters like bed roughness, tidal variation, storm surge boundaries, 2D grid changes et cetera.
- Undertake separate ‘Environmental Impact Assessment’ to study impact solutions on the environment.
- Undertake separate ‘Feasibility Analysis’ to study economic impact of the solutions.

Beach related:

- Accurate bathymetry survey.
- Locating possible ‘non-eroding’ reefs.
- Implementing wave measurement tools (wave buoys) in the vicinity of the Caribbean coast (NOAA does not execute measurements in the vicinity of this coast).
- Study reduced sediment supplies after damming Río Pacuare.

Integration river- and beach processes:

- Model area in a 3D model (for instance Delft3D) to integrate hydrodynamics with morphology.


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List of figures

List of tables