Coastal evolution Guyana

Modelling and a historical investigation

MSc. Thesis
S.J. Welage
Final version
April 2005
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‘Een parelukerv reest de modder niet’
-Multatuli-

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PREFACE

The report you are reading is the final result of my master thesis. With this project I will finish the educational programme of Hydraulic Engineering at the faculty of Civil Engineering and Geosciences of Delft University of Technology.

The study is carried out in cooperation with Royal Haskoning B.V., division Coastal and Rivers International, and is titled:

'Coastal evolution Guyana; modelling and a historical investigation'

This thesis proceeds from the project ‘Institutional Capacity Building Activities on Guyana Sea Defences’ with the overall objective of building and improving the capacities of the Sea and River Defence Division and other agencies in Guyana that are involved in integrated coastal zone management. The combination of a mathematical model and a historical investigation of the coastline evolution in this study perhaps contribute to a better insight in the coastal dynamics of Guyana. Idealised, this insight can be used to optimise the planning of construction and maintenance works on the Guyana sea defences.

Finally I would like to thank the following people and instances for making this project possible: Royal Haskoning, especially Frank Wiersma and Henry Opdam, for the opportunity that was given to me, the other committee members Han Winterwerp, Marcel Stive, and Herk-Jan Verhagen, furthermore WL|Delft Hydraulics, Arjen Luijendijk, Reimer de Graaff, Sander Vlotman, Ries Kluskens, Jurriaan de Jong, Marco Westra, Stephen Pearson, Cathelijne van Haselen, George Howard, Omadat Persaud and my friends and family.

April 2005,

Stijn Welage.
ABSTRACT

The mudbanks along the Guyana coast are dynamic features that have a significant influence on the coastal environment. The highest parts of the mudbanks occur at an average interval of about 40 km. The mudbanks move along the coast at a rate of about 1.5 km/year. The passage of mudbank 'crest' coincides with accretion, while the passage of mudbank 'trough' tends to result in erosion. The period of this cyclic pattern of erosion and accretion varies between 20 and 40 years. The formation of the Guyana coast is the result of a net accretive trend over the last millennia. However, the last decades this trend tends to be more erosive than accretive and the coast is undergoing a general recession.

One of the reasons of general recession can be the decline of mangrove areas (which serve as natural sea defence) especially in the last decades as result of intensive use of the coastal area together with the cyclic pattern of erosion and accretion. Upon the loss of mangroves, the coast is no longer protected and starts to erode.

It is hypothesised that the reduction of onshore sediment transport by tidal filling is the cause of rapid retreat. Because of the construction of dykes close to the coastline a substantial part of the intertidal area is lost. Hence, the cross-shore sediment transport component is reduced. As a result, much less sediment is transported towards the mangrove system, while sediment loss due to erosive processes cannot be supplemented.

The overall objectives of this study were to establish a better understanding of processes that govern erosion and accretion with the help of mathematical modelling, and analyse the coastal evolution of Guyana since 1950. A 2D cross section is modelled to investigate the sensitivity of the results to variation in a number of important parameters. Furthermore, the influence of land use in the intertidal area on erosion/sedimentation patterns was studied. The coastal evolution since 1950 is investigated for the area between Demerara and Berbice River with the help of aerial photographs and satellite images. Relations between coastline evolution, position of mudbanks, evolution of mangroves and breaches are examined.

The main conclusion from the modelling study is that the total sediment supply in the intertidal area decreases for a situation with a dam/dyke in the intertidal area. This result supports the hypothesis that the loss of onshore sediment transport by tidal filling can be the cause of coastline retreat.

The analysis of the aerial/satellite images revealed that the coastline in general has been eroding over the last 50 years. Furthermore, a relation between the erosion/accretion of the coastline and the position of the mudbanks could be deduced. Erosion tends to occur when a mudbank ‘trough’ is in front of the coast. A stable coastline or accretion occurs with a mudbank ‘crest’ in front of the coast. This relation is further substantiated by the specific time & location of the breaches.

As early as 1950 the coast between the Demerara and the Mahaica River is protected by hard sea defences. Almost all the mangrove areas between the Demerara and the Mahaica River degenerated before 1980. The conditions for regeneration of mangroves in this area do not seem to be favourable. This observation supports the hypothesis that a ‘buffer’ length is needed to maintain or restore an intertidal area with mangroves.

Combining both studies (modelling & coastal evolution) indications can be found that the use of land in the intertidal area plays a role in a decrease of the sediment budget for the intertidal area. Sediment loss due to erosive processes cannot be supplemented. Fringes of mangroves with hard sea defences shortly behind tend to erode and conditions for regeneration of mangroves do not seem to be favourable.

It is recommended to setup a system in Guyana to monitor the evolution of the coastline and the positions of the mudbanks in the future. This can be done by a combination of a number of methods: analysing satellite pictures, visual/field observations, pictures from flights along the Guyana coast and bathymetric surveys. Insight in the behaviour of the coastal system can be gained which can be used for planning of maintenance and construction works on the sea defences.
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1 INTRODUCTION

1.1 GENERAL

The low-lying coastal zone of Guyana occupies less than 5% of the country’s total area but is of vital importance because the major administrative and economic activities are concentrated along the coast. Cultivation takes place almost entirely along a narrow coastal strip which has rich alluvial soils. The capital Georgetown and other important towns like New Amsterdam, Rose Hall, Corriverton and Anna Regina are all located along the coastline. As a result around 90% of the population (approximately 773,000 in 1999) lives on the coast. The Guyana coast extends some 425 km from the Waini River to the Corentyne River, and is interrupted by the Pomeroon, Essequibo, Demerara, Mahaica, Mahaicony, Abary and Berbice River, see Figure 1-1.

Figure 1-1: Map of Guyana

The coastal plain is partly protected from flooding by man-made sea defences, some constructed many decades ago. The first earthen dams were built behind the mangrove coastline to protect the hinterland from flooding and to make agricultural activities possible. At several eroding places earthen dams were replaced by concrete structures. Guyana, since its independence in 1966, has implemented several programmes concerning the rehabilitation of the sea defences. However, in recent decades, due to the lack of adequate maintenance of the sea defences and to the gradual
destruction of mangrove forests, the protection of the coastal zone has been reduced along approximately 50% of the coastline.

By 1996, some 40 km of existing embankment along a coastline of 425 km were in critical condition and in recent years a number of breaches have occurred. Another 130 km of embankment protection is rapidly eroding, but the remaining 255 km of the coast are still protected by mangrove forests and mudbanks.

In Guyana as well as in Surinam and French Guiana the young coastal plain consists of vast swamps which alternate with sandy ridges, cheniers¹, orientated parallel to the shore. Along the shoreline, shoreface attached mud banks interchange with developing cheniers and/or beaches. Mangrove forests occur and are locally abundant.

The main factors involved in the formation of the coastal area of the three countries are currents, waves and tides, the longshore sediment supply and the discharge of water and small amounts of sediment by local rivers. Along its entire length the coast between the Amazon and Orinoco Rivers is characterized by a westward directed littoral transport of large quantities of fine grained sediments. These sediments are supplied by the Amazon River. Sediment quantities delivered by other rivers are generally insignificant, except for the larger rivers (i.e. the Corentyne and the Essequibo Rivers) which supply some sand, see Figure 1-2.

Figure 1-2: The Guiana coast (Augustinus, 2004)

The transport of fine grained sediments partly takes place in suspension and partly by means of steadily migrating mudbanks. Mudbanks migrate alongshore driven by oblique wave attack. Erosion of the trailing edge feeds growth of the leading edge in the manner of a migrating bed form. These banks occur in a zone landward of the 20 meters isobath extending approximately 20 km from shore. The banks are not attached to the shoreline having an angle of about 20 to 30 degrees.

¹ Cheniers are water-deposited sand ridges resting on clay or mud along a seaward-facing tidal shore. Cheniers differ from beach ridges in that they commonly rest on marsh clay and mangrove mudflats with their bases near high water mark, whereas normal beach ridges and coastal barriers have sandy bases extending below high water mark. (Coastal sand dunes – their vegetation and management; The formation and function of coastal dunes, Leaflet No. II-03, Beach protection Authority Queensland)
1.2 **PROBLEM ANALYSIS**

1.2.1 **PROBLEM DESCRIPTION**

The mudbanks along the Guyana coast are dynamic features that have a significant influence on the coastal environment. The highest parts of the mudbanks occur at an average interval of about 40 km. The mudbanks move along the coast at a rate of about 1.5 km/year. Wave refraction diagrams for idealized mudbanks indicate that maximum convergence of wave energy occurs in mudbanks 'troughs' and wave divergence occurs on mudbanks 'crests', see Figure 2-2. Therefore the passage of mudbank 'crest' coincides with accretion and the passage of mudbank 'trough' erosion. The period of this cyclic pattern of erosion and accretion varies between 20 and 40 years. The formation of the Guyana coast is the result of a net accretive trend in the last millennia. However, the last decades this trend tends to be more erosive than accretive and the coast is undergoing a general recession (Nedeco, 1972).

One of the reasons of general recession can be the decline of mangrove areas (which serve as natural sea defence) especially in the last decades as result of intensive use of the coastal area together with the cyclic pattern of erosion and accretion. Upon the loss of mangroves, the coast is no longer protected and starts to erode.

According to this theory, about three times per 100 years accretion (or erosion) occurs at any point along the coast. Moreover at any time there should be about 8 stretches of erosion in the part from the Pomeroon to the Corentyne River. The reality however, displays more variations.

At this moment no good monitoring system is in use to identify stretches of eroding coast and therefore adequate measures cannot be taken to prevent damage to sea defence structures. The physical boundary conditions favourable for mangrove rehabilitation are also not known.

Furthermore, costly rehabilitation projects of sea defences in the previous decades have not always been effective. In some cases large accumulation of mud took place in front of a newly constructed sea defence and therefore these structures became useless for a longer period.

1.2.2 **PROBLEM DEFINITION**

There is a need for a better understanding of the coastal morphology. More insight is needed in the processes that govern the observed pattern of erosion and accretion in combination with the movement of mudbanks.

1.2.3 **OBJECTIVE**

**Overall objectives**

The overall objectives of this study are:

- establish a better understanding of processes that govern erosion and accretion with the help of mathematical modelling, and
- analyse the coastal evolution of Guyana since 1950.

**Specific objectives**

Determine the sensitivity of:

- hydraulic parameters (tide, waves, current, bottom roughness),
- sediment parameters (critical shear stress for erosion, erosion parameter, settling velocity),
- bed profiles, and
- land use of the intertidal area,

on erosion/sedimentation patterns in the intertidal area.

Establish quantified relations between:

- the coastal erosion / accretion,
- the position and migration speed of mudbanks,
- the development of mangrove areas,
- the damage to or breaches of the sea defences, and
- the findings of the sensitivity analysis on initial erosion/sedimentation patterns.
1.2.4 PROBLEM APPROACH

Modelling
A 2DV cross section is modelled in a 3D environment with ten layers in the vertical and six cells wide. Sensitivity calculations in Delft3D with different parameters are done to establish the mentioned relation. A basic model is used as reference case. The model is not calibrated since no data is available. Sensitivity calculations are done by varying different input parameters as:
- tide
- waves
- longshore current
- silt
  - erosion parameter
  - critical shear stress for erosion
  - settling velocity
- bathymetry
  - slope
  - land use

The sensitivity calculations are based in differences of the hydraulic conditions in Guyana over the month/year (waves, wind, current, tide), see section 3.3. The cyclic presence of mud shoals at locations along the coast is taken in account by varying the bathymetry.

Coastal evolution
Aerial photographs from 1950, 1970, 1972 and 1979/80 are available as well as high-resolution satellite pictures of the area for the years 1987, 1992 and 2001/03. Recent field measurements of the bottom topography give information of the current position of the coastline and mudbanks. If this is combined with visual field observations and aerial/satellite pictures a good perception can be acquired of the present situation.

With this information the distribution in time and space of accretion and erosion along the Guyana coast can be generated and as well as the position, the length and the migration velocity of the mudbanks. Interesting aspects/relationships which are investigated:
- occurrence of accretion and erosion and the position of the mudbanks
- occurrence of breaches and the positions of the mudbanks.
- length and migration speed of mudbanks
- the development of the mangrove areas and the position of the mudbanks
- the development of the mangroves areas and the use of the intertidal area
1.3 Outline of the Report

This report describes the results of the research on the coastal evolution of Guyana. After the introduction in this chapter, Chapter 2 discusses relevant literature. In Chapter 3 the modelling of Guyana cross-section in Delft3D is explained. The setup of the model, the reference case, the sensitivity analysis and the conclusions are described. In Chapter 4 the coastline evolution between the Demerara and the Berbice River since 1950 is investigated. Relations between erosion, accretion, positions of mudbanks, mangrove areas and breaches are discussed. Finally in Chapter 5 the discussion, conclusions and recommendations are presented.

A separate document contains the appendices. In Appendix A figures of the modelling study are given. In Appendix B, C and D the specific input parameters of the model are described. Appendix E gives more information about the sensitivity analysis. In Appendix F figures of the coastline evolution study are given.
2 LITERATURE STUDY

2.1 INTRODUCTION

For the description of the coastal phenomena, the Guyana coast cannot be considered separately from the whole Guyana coast (French Guiana, Surinam & Guyana) see Figure 2-1. The geological origin of the area and the present phenomena show a great degree of similarity along the 1,600 kilometres long coast between the deltas of the Amazon and Orinoco Rivers. The geological origin is described in section 2.2.

Figure 2-1 : Map of the Guianas

The common conception about the origin of the Guiana Mud is that the water-sediment discharge of the Amazon River is transported in suspension by ocean currents along the Guiana coast. Trade winds drive the Guiana current north-westward. These phenomena will be called ‘macro-system’ and are explained in section 2.3.

From various sources (nautical charts, aerial photographs) it appears that the transported sediment occurs in mudbanks in a wave like pattern in the nearshore area (20-50 kilometres from the shore line). This results in a succession of shoals and troughs. Due to the combined action of waves and currents the shoals and troughs have an average movement in the north-west direction. The phenomenon of shoals and troughs will be called ‘meso-system’ and is described in section 2.4.

Due to large supply of fine-grained sediment a fluid-mud formation appears mainly in the intertidal zones and can attenuate the incoming waves from the Atlantic Ocean effectively. The incoming waves from the Atlantic Ocean or locally wind driven waves suspend the mud from the seabed. The phenomena in the intertidal zone will be named the ‘micro-system’ and are explained in section 2.5.

The influence of mangroves and the use of land in the intertidal area are described in section 2.6.

2.2 GEOLOGICAL ORIGIN

The biggest part of the area between the Amazon and Orinoco Rivers consist of the pre-Cambrian rocks of the Guiana Shield. Only the higher western part is partly covered with younger formations. A belt of sediments has been deposited around the Guiana Shield now forming the coastal plain, the Continental Shelf and the valleys of the Amazon and Orinoco Rivers. The coastline separates the low Holocene coastal plain from the continental shelf and is intersected by the mouths of the large rivers. In Guyana by the Corentyne, Berbice, Demerara and Essequibo which flow perpendicularly to coast and by a number of smaller ones which show a tendency to bend to the west shortly before reaching the coast or the mouth of a larger river.
2.3 **MACRO SYSTEM**

The global system for transport of sediment along the coast of the Guianas is driven by three main phenomena:
1. input of sediments from the discharge of the Amazon River,
2. the wind-driven ocean currents, and
3. waves (see section 2.4).

### 2.3.1 **AMAZON RIVER**

#### Discharge

The discharge cycle of the Amazon River can be divided into:
1. wet or rainy season from January to June and
2. dry or less rainy season the rest of the year.

During the dry season the discharge of the Amazon River is around $60,000 \, \text{m}^3/\text{s}$, in the wet season discharge can reach $300,000 \, \text{m}^3/\text{s}$ (Nedeco, 1968). The Amazon’s average annual discharge is $175,000 \, \text{m}^3/\text{s}$.

#### Sediment transport

In the wet season the suspended load in the Amazon River can increase to as much as 6 times the dry season concentrations. The wet season discharge may be five fold of the dry season, resulting in a suspended sediment discharge variation of 30 times between the seasons. This gives a mean discharge of suspend sediment around $1.4 \times 10^6 \, \text{tons/day}$, varying between $0.1 \times 10^6 \, \text{tons/day}$ in dry periods to $3 \times 10^6 \, \text{tons/day}$ in the wet season. The yearly total amount of suspended sediment is round $500 \times 10^6 \, \text{tons}$ (Nedeco, 1968). The Amazon River is the source of the sediment in the Guyana coastal system.

### 2.3.2 **WIND-DRIVEN OCEAN CURRENTS**

The Trade Wind system in the Atlantic induces the South and Northern Equatorial Current. The South Equatorial current carries South Atlantic Central water along the Brazilian and Guiana coasts and then mixed with water coming from the North Equatorial Current into the Caribbean Sea. The wind-driven Guiana Current represents an extension of the South Equatorial Current and flows in a northwest direction parallel and close to the coast in the relatively shallow fore-shore. Surface velocities around April vary from 1 m/s in French Guiana to 0.60 m/s in Guyana. They are less, 0.70 m/s to 0.30 m/s respectively, during the second half of the year (Nedeco, 1972). The prevailing trade winds blowing from North East directions produce waves that result in a steady longshore current flowing northwardly in the shallow water along the shore.

### 2.3.3 **SEDIMENT TRANSPORT**

Approximately 25 % to 50 % of the total amount of suspended sediment discharged by the Amazon River is transported north-west direction. Transport rates, calculated from waterflow and suspension concentrations vary from $2 \times 10^6 \, \text{tons/month}$ during August through September to $25 \times 10^6 \, \text{tons/month}$ during April and May (Nedeco, 1968). The period of high sediment transport precedes the period of high sediment output (thus precluding that the Amazon directly influences turbidity variations along the coast.).
2.4 Meso System

On a smaller scale a pattern of shoals and troughs, migrating from the east to the west, can be recognised along the Guiana coast. The Guiana Current, the tidal current, ocean swell and wind waves are driving forces.

2.4.1 Hydraulic Conditions

Equatorial Current
As described in section 2.3.2 surface velocities of the Guiana Current differ between 0.6 m/s (April) and 0.30 m/s.

Tidal Current
The tidal wave results in an almost synchronous rise and fall of the water along the whole length of the Guiana coast. The tidal range varies between 1.5 and 2 metres, the velocity of the tidal component of the current over the continental shelf varies between 0.15 and 0.25 m/s (Nedeco, 1972). The propagation speed of the tidal wave is relatively large in the deep Atlantic Ocean. As a result, tidal filling and emptying of the Guiana coastal system occurs more or less perpendicular to the coast and the tide does hardly generate longshore currents.

Wind
The predominant wind is the Trade Wind, which blows mainly from the North-east. During the wet season (June – August), temperatures are lower and temperature gradients are smaller, thus wind strength decreases. Hence, strongest winds are found in the period December – March/April (Royal Haskoning, WL | Delft Hydraulics, 2005)

Wave Climate
The pattern of wave directions and heights greatly resembles the pattern of the trade wind, with waves of about 2 metres from December to June and 1 to 1.5 metres from July to November. The observed waves mainly originate from the north-east and east. The period of waves varies between 5 and 13 seconds; in deep water the lengths range between 40 and 250 metres (Nedeco, 1972).

River Flow
In the mouth of a river the hydraulic conditions are completely different for areas with continues shoreline. The tidal component of the current is dominating. This also influences the seabed topography; especially concerning the passing of migrating mudbanks.

2.4.2 Migrating Mudbanks

Nedeco's comparison of successive sounding maps shows that the pattern of shoals and troughs (mudbanks) slowly moves from East to West. This phenomenon and the more or less periodic occurrence of accretion and erosion has been noticed by several authors (Zonneveld, 1954; Coubert and Boye, 1959). No similar features are known from other parts of the world and it is not really known why the shoals occur.

The average angle between the crest of the mud bank and the coast line varies between 20 and 30 degrees with a length of around 30 km and a height of 5 - 10 m. According to Nedeco (1972) the propagation of the shoals must involve erosion along the eastern flank and sedimentation on the other side. The results of a mathematical mudbank model in Delft3D (Royal Haskoning, WL | Delft Hydraulics, 2005) point in the same direction. Nedeco's pattern of erosion and sedimentation is obtained by shifting the pattern of an average shoal by 1.5 km and deriving the difference with the original pattern. The computed wave patterns show that coastal erosion occurs in areas of convergence. Accretion seems to be facilitated by divergence of waves.

Refraction
Waves are an import factor in the process of sediment transport. In a highly generalized representation (Nedeco, 1968 & 1972), see Figure 2-2 (D), one can see that due to refraction, there are areas of convergence and divergence. Over the south-eastern slope of the banks waves converge, especially near the coast. The increase of wave height will partly be counteracted by the effects of friction on these gently slopes, see Figure 2-3. These higher waves can be seen on aerial
photographs and the areas of convergence appear to correspond with the places where erosion prevails (Nedeco, 1968).

**Figure 2-2: Generalized pattern; (Nedeco, 1968)**

**Attenuation**

When waves are travelling from deep to shallower water, the wave velocity is decreasing. With a persisting wave period (far from breaking) the wavelength is decreasing. Consequently the wave height is increasing if conservation of energy per wave (eg$H^2/8$) is assumed, which is allowed for the relatively steep slope. This does not hold for gentle slopes and for long wave period according to Eagleson (1962), see Figure 2-3.

**Figure 2-3: Attenuation wave height over a sloping bottom with friction (Nedeco, 1968)**
Position of mudbanks
The location of the mudbanks between 1960 and 1970 is given in Figure 2-4. It is clearly visible that the mudbanks are moving in western direction and that the large mudbanks occur at regular intervals along the entire Guyana coast.

Figure 2-4: Location of mudbanks in 1960; arrows indicate their location in 1972 (Nedeco, 1972)

In Figure 2-5 a compilation of the locations of the mudbanks along the Guyana and Surinam coast is shown. The points and the lines in this graph indicate the positions in time and space of the places where the clearly visible front of a mudbank meets the shore (Nedeco, 1972), showing a periodicity of about 30 years. Some irregular shifting of the speed of the mudbanks occurs. Furthermore a new mudbank appeared between the Mahaica and Mahaicony River.

Figure 2-5: Migration of mudbanks in x-t diagram
When a mudbank is in front of the coast the drying line may lie some kilometres seaward from the high water line. The bank protects the coast against the attack of waves and currents. Some time later mangroves start growing on the soft mud when its surface rises above mean sea level. The occurrence of juvenile mangroves is a clear indication of accretion. The fringe of mangrove trees gradually moves seaward over the mud flat over the course of time, see Figure 2-6.

Figure 2-6: Accretion and erosion by a not defended (I) and defended (II) coast (Nedeco, 1972)

Meanwhile, the mudbank erodes and gradually it becomes narrower. The vegetation stops advancing. Later, when the erosion reaches the mangrove fringe the vegetation is affected and trees are seen dying; even farther landward. The offshore becomes steep in the area where a trough between two mudbanks meets the shore. Often this part of the eroding shore shows a succession of typical small bays, see Figure 2-7.

Figure 2-7: Small bays (amateur aerial photographs)

Erosion has formed a specific pattern of small gullies in front of the steep edge of the eroding consolidated mud. These phenomena characterize the eroding coast (Nedeco, 1972).

In Figure 2-6 the accretion and erosion cycle is visualised for a defended and a not defended recessive coast.
2.5 MICRO SYSTEM

2.5.1 MUD

Mud is basically composed of a mixture of water, fine sediments and usually a significant amount of organic matter. The particle sizes are generally smaller than approximately 60 μm (silt) and a significant fraction is smaller than 2 μm (clay). The clay particles play a dominant role in the cohesive properties of mud (de Wit, 1995). They have a very large specific surface, carry an electric charge and interact with ions in (saline) water. The particles are light compared with the inter-particle (electric) forces, so flocculation easily can occur and cohesion is a characteristic property.

In general mixtures of fine sediments and water (mud) exist in three states:
1. mobile suspension
2. static suspension
3. settled mud

![Diagram of mud states](image)

**Figure 2-8: Cycle for various states of mud (after Parker and Kirby, 1977)**

At concentrations up to 100 g/m$^3$ no flocculation occurs and there is no significant influence on the viscosity and density of the water. At higher concentrations, 100 g/m$^3$ to 10 kg/m$^3$ flocculation becomes important and settling becomes evident. At even larger concentrations, 50 – 500 kg/m$^3$, a big difference in viscosity and density occurs. For a bulk density of about 1100 - 1200 kg/m$^3$, the fluid is thickly viscous. The suspension behaves as fluid mud and can move under its own gravity. When the bulk density exceeds about 1350 kg/m$^3$ the mud becomes cohesive and firm material.

2.5.2 EROSION & TRANSPORT

Erosion of mud occurs when the shear stress exceeds a critical value. This value depends on the bed material characteristics and bed structure. The erosion rate for a bed of constant density is, generally, expressed as (Partheniades, 1963):

\[
E = \begin{cases} 
0 & \text{if } \tau_b < \tau_c \\
M \left( \frac{\tau_b}{\tau_c} - 1 \right) & \text{if } \tau_b \geq \tau_c 
\end{cases}
\]

where:

- $M$ erosion parameter (kg/m$^2$/s)
- $\tau_b$ bed shear stress (N/m$^2$)
- $\tau_c$ critical shear stress for erosion (N/m$^2$)

Once the sediment particles are eroded and entrained into the water, they move under actions of gravity and turbulence. The gravity is causing sedimentation, the turbulence a (vertical) transport.
2.5.3 SETTLING, DEPOSITION & CONSOLIDATION

In saline water and at higher sediment concentrations particles stick together and form flocks. In the flocculated state the settling velocity is much higher than for the elementary particle. At a certain concentration, the settling velocity decreases with increasing concentrations due to the hindered settling effect. At very large concentrations the vertical fluid flow can be so strong that the upward fluid drag forces on the flocs become equal to the downward gravity forces resulting in a temporary state of dynamic equilibrium with no net vertical movement of the flocs. This state which occurs close to bed, is generally called fluid mud (van Rijn, 1993).

The rate of deposition can be described as:

\[ D = w_f c_s \]

where:

- \( w_f \) fall velocity (hindered) (m/s)
- \( c_s \) sediment concentration (kg/m\(^3\)).

When the sediment particles have been deposited and stay at rest consolidation of the mud layer occurs due to its own weight. The time for consolidation is generally proportional to the square of the thickness of the layer, but according to laboratory tests for the Surinam fluid mud it appears to be linear with time (Nedeco, 1968).

2.5.4 TIDAL EFFECT

In an oscillating tidal flow system the flow velocity varies periodically. Consequently the process of erosion, vertical transport, floculation, deposition and consolidation sustain in a fluctuating sediment transport rate. Besides the tidal current there is the effect of currents induced by the orbital motion of wind waves.

2.5.5 WAVE INDUCED EFFECTS

In the case of an oscillating current in the orbital motion of a wave system, material is also brought in suspension if the critical value for shear stress is exceeded during the passing of the wave crest. Because the settling process takes more time than the erosion process, the amount of sediment deposited during the passing of the wave trough does not equal the amount of sediment that was stirred up. In the case of a non-linear wave form advection of water in the direction of wave propagation occurs and consequently transport of suspended sediment. Wells, Coleman and Wiseman (1978) calculated that a large amount of sediment could be transported taken into account the non-linear effect of the wave form only.

In general the location of the mudbanks can be 'interpreted' from the appearance of the specific wave pattern. In the troughs between the mudbanks attenuation is substantially less than on the mudbanks. Also effects of refraction are perceptible. It was observed that on the mudbank a wave seldom breaks, while in the interbank areas they do.
2.6 Mangroves

A clear indication of accretion, as mentioned in section 2.4.2, is the occurrence of juvenile mangrove trees. An eroding shore shows a succession of typical small bays where the vegetation is affected and trees are seen dying, even farther landward. An analysis of aerial photographs (1950 – 1999) of the Bang Khun Thien area, Upper Gulf of Thailand (Winterwerp, Bost, de Vries, 2004), revealed that at eroding sites the remaining narrow belt of mangroves consists of mature trees only. Coastline erosion is characterised by destruction of these grown-up trees as a result of wind and/or wave impact. Upon the loss of trees, the muddy coast is no longer protected anymore and is eroding rapidly. In the same study it is hypothesised that the (entire) loss of onshore sediment transport by tidal filling is the cause of rapid retreat. Because of the construction of dykes close to the coastline the intertidal area is lost. Hence, the cross-shore sediment transport component ($v$) is lost, see Figure 2-9.

![Figure 2-9: Role of hinterland](image)

As a result, much less sediment is transported towards the mangrove system, and sediment loss due to erosive processes cannot be supplemented. Restoration of the intertidal area to a sufficient width (called the ‘buffer length’) is the only way to restore the sedimentation rates. Small mangrove fringes are doomed to die. Winterwerp et al. (2004) estimate that this buffer area should have a width of a few 100 m up to maybe 1 km.

The position of the coastline is depicted by the following conceptual formula:

$$\frac{dcl}{dt} = \text{sedimentation rate} - \text{erosion rate}$$

where:

$$\frac{dcl}{dt} \quad \text{coastline development}$$

If the sedimentation rate exceeds the erosion rate, accretion is the result; vice versa, if the erosion rate is the larger the coastline will retreat. Eleven processes governing the coastline development in Guyana are recognised (Royal Haskoning, WL | Delft Hydraulics, 2005); seven processes governing the rate of erosion and four processes the sedimentation.
The rate of erosion is determined by:
- erodibility of non-vegetated mud deposits (stabilisation by mangroves),
- exposed location of mud deposits, i.e. not protected by a mudbank from the waves,
- normal waves (even capillary waves) can have a significant erosive effect on the mud at the water line of the mangrove coast,
- extreme waves: during storm events the highest waves can certainly erode the soft mud coast
- storm events and/or high waves can cause falling of mangrove trees as their root system do not provide sufficient anchoring,
- transport by longshore currents, these currents carry away sediments, which is mobilised by eroding waves, and
- subsidence.

The sedimentation rate is determined by:
- sediment supply by Guyana current (Amazon mud),
- protection by mud banks and fluid mud,
- trapping efficiency of mangroves, almost 100% of the suspended fine sediments entering the mangrove system during flooding are trapped, and
- sediment mobilisation and supply by larger waves.

Larger waves have favourable as well as adverse effects on the coastal evolution: the larger waves mobilise sediments on the seabed offshore the can be transported towards the coast by tidal filling, but erode the coast itself as well.
3 MODELLING

3.1 INTRODUCTION

In this part of this study the mathematical modelling of a cross-section of the Guyana coast is described. In section 3.2 the used mathematical model is explained. The input of the model is described in section 3.3. In section 3.4 the used reference case is given. The analysis of the sensitivity of the results to variation of important parameters is described in section 3.5. In section 3.6 the sensitivity of land use of the intertidal area on erosion/sedimentation patterns is investigated. In section 3.7 the conclusions are given.

A 2DV cross section is modelled in a 3D environment with ten layers in the vertical and six cells wide. Sensitivity calculations are done to determine the influence of a number of important parameters on erosion/sedimentation patterns. Simulations with a dam represent the loss of the intertidal area by building dykes.

3.2 DESCRIPTION OF THE MODELLING SYSTEM

3.2.1 INTRODUCTION

The morphological development of the coast is subject to complex interactions between currents, waves, sediment transport and bed level variations. Besides this, almost every coastal area is subject to human interference in the form of structures, dredging or nourishment. During the past decade, so-called process based morphodynamic models have been developed to simulate these processes and their interactions and to predict the morphological development. Figure 3-1 shows the concept of most morphological models. The essence of these models is the simulation of physical processes, based on physical principles, such as conservation of mass, momentum and energy.

![Diagram of morphological process based models]

**Figure 3-1: Concept of morphological process based models**

In this study the morphodynamic model Delft3D will be used. Delft3D is a software package developed by WL | Delft Hydraulics to simulate two-dimensional or three-dimensional processes. Several phenomena and their interactions can be simulated in space and time. These phenomena are integrated in eight different modules:

- A hydrodynamics module (Delft3D-FLOW)
- A wave module (Delft3D-WAVE)
- A water quality module (Delft3D-WAQ)
A particle tracking module (Delft3D-PART)
An ecological module (Delft3D-ECO)
A sediment transport module (Delft3D-SED)
A chemical components module (Delft3D-CHEM)
A morphodynamic simulation module (Delft3D-MOR)

In this study only the FLOW, WAVE and MOR modules are used and they are described in the next sections.

3.2.2 Delft3D-FLOW

The Delft3D-FLOW module is a multidimensional hydrodynamic simulation program, which calculates non-steady flow and transport phenomena, resulting from tidal and meteorological forcing on a rectangular or a curvilinear, boundary fitted grid. The model can be used for both two-dimensional (depth-averaged) or three-dimensional calculations on coastal, river or estuarine areas where the horizontal length and time scales are significantly larger than the vertical scales. Typical applications of Delft3D-FLOW are simulations of tide and wind driven flows, stratified and density driven flows, river flow, transport of dissolved material and pollutants.

The following physical phenomena are taken into account:
- Tidal forcing;
- The effect of the earth's rotation (Coriolis force);
- Density driven flows;
- Space and time varying wind and atmospheric pressure;
- Shear-stresses at the bottom;
- Wave induced stresses (radiation stress) and mass fluxes;
- Drying and flooding;
- Turbulence induced mass and momentum fluxes.

Delft3D-FLOW solves the Navier-Stokes equations for an incompressible fluid, under the shallow water and Boussinesq assumption. In the vertical momentum equation the vertical accelerations are neglected, which leads to the hydrostatic pressure equation. The system of partial differential equations for conservation of mass and momentum is solved with a finite difference method on a rectangular, orthogonal curvilinear or spherical grid. The principle variables, such as water level, bottom level and velocities, are arranged in a special way that is known as a staggered grid, see Figure 3-2.

Figure 3-2: The Delft3D staggered grid

The past 2 years have seen the development of a hydrodynamic module that is capable of simultaneous sediment transport modelling and morphological updating while performing the hydrodynamic simulation. This "online sediment version" works by treating sediment as another constituent (in addition to salinity and temperature) allowing it to be calculated in three dimensions, and subsequently feeding the density effects of the sediment back into the flow simulation. This version includes linked hydrodynamics, wave processes, sediment transport and morphological changes.
One of the complications inherent in carrying out morphological projections on the basis of hydrodynamic flows is that morphological developments take place on a time scale several times longer than typical flow changes. One technique for approaching this problem is to use a "morphological time scale factor" whereby the speed of the changes in the morphology is scaled up to a rate that it begins to have a significant impact on the hydrodynamic flows. This can be achieved by specifying a non-unity value for the variable MORFAC in the morphology input file.

The implementation of the morphological time scale factor is achieved by simply multiplying the erosion and deposition fluxes from the bed to the flow and vice-versa by the MORFAC-factor, at each computational time-step. This allows accelerated bed-level changes to be incorporated dynamically into the hydrodynamic flow calculations.

Up to 5 separate sediment fractions may be specified in a simulation and any combination of sand and mud fractions is allowed. Interaction with the bed for sand fractions is computed, based upon the sediment pick-up functions of Leo van Rijn; bed load transport is included. For mud fractions the widely recognised sediment flux expressions of Partheniades and Krone are used.

The ability to model fixed, non-erodible areas is also included. To bridge the gap between morphological and hydrodynamic time-scales a morphological acceleration factor can be used. Significant is the inclusion of improved formulations that describe the effects of waves on the three-dimensional flow pattern.

For an elaborate description of the FLOW module, one is referred to the Delft3D-FLOW user manual (WL | Delft Hydraulics, 2003).

### 3.2.3 Delft3D-WAVE

The WAVE module is based on either HISWA or SWAN. In this study, SWAN is used for wave simulations. SWAN, an acronym for Simulating WAves Nearshore, is a third generation, spectral wave model that computes the non-steady propagation of short crested waves over an uneven bottom, considering wind action, dissipation due to bottom friction, wave breaking, refraction, shoaling and directional spreading. The SWAN model takes into account the following physics:

- Wave propagation in time and space, shoaling, refraction due to current and depth, frequency shifting due to currents and non-stationary depth;
- Wave generation by wind;
- Dissipation by white-capping, depth-induced breaking and bottom friction;
- Non-linear wave-wave interactions;
- Wave induced set-up;
- Wave blocking by flow;
- Transmission through and reflection from obstacles.

SWAN does not account for:

- Diffraction;
- Scattering reflections.

SWAN computations can be made on a regular and a curvilinear grid in a Cartesian or spherical coordinate system.

The wave conditions (i.e. wave forces based on the energy dissipation rate or the radiation stresses, orbital velocity) calculated in the Delft3D-WAVE module are used as input for the Delft3D-FLOW module, to compute wave driven currents, enhanced turbulence, bed shear stress and stirring up by wave breaking.

For an elaborate description of the Delft3D-WAVE module, one is referred to the Delft3D-WAVE user manual (WL | Delft Hydraulics, 2003).

### 3.2.4 Delft3D-MOR

Delft3D-MOR is a steering module that controls and integrates the effects of different processes, such as waves, currents and sediment transport on morphological developments. Each of these processes is dealt with in separate modules. The steering module allows the user to link model inputs and outputs for the model components. The morphological process is modelled as a
hierarchical tree structure of processes, as shown in Figure 3-3. Time intervals for the elementary processes are defined and the processes are executed for a fixed number of time steps.

![Diagram of hierarchical tree structure of processes with steering module (MOR) and sub-processes: currents (Delft3D-FLOW) and waves (Delft3D-WAVE).]

**Figure 3-3: Overview of the used Delft3D components**

In this study, FLOW and WAVE are operated sequentially, but they are using each other's results. The morphological changes are computed with 'Sediment Online'. There is a feedback of the bottom changes to the hydrodynamic computation and the influence of waves is also taken into account. The steering module MOR calls the computational modules in a prescribed order, arranges the time process of each module and allows iterations between the modules.

For an elaborate description of the MOR module, one is referred to Delft3D-MOR user manual (WL | Delft Hydraulics, 2003).

### 3.2.5 COHESIVE SEDIMENT

In this section the way mud transport is calculated by Delft3D will be discussed. For all other processes one is referred to the various Delft3D manuals. The mud transport is highlighted in this report because the sensitivity calculations are done with these formulations.

For cohesive sediment fractions the fluxes between the water phase and the bed are calculated with the well-known Partheniades-Krone formulations. The following advection-diffusion equation is used:

$$\frac{\partial h c_i}{\partial t} + \frac{\partial}{\partial x} \left( h u c_i - \epsilon h c_i \frac{\partial c_i}{\partial x} \right) + \frac{\partial}{\partial y} \left( h u c_i - \epsilon h c_i \frac{\partial c_i}{\partial y} \right) = E - D \ [kg/m^3/s]$$

where the erosion flux is given by

$$E = \begin{cases} 0 & \text{if } \tau_{cw} < \tau_e \\ M \left( \frac{\tau_{cw}}{\tau_e} - 1 \right) & \text{if } \tau_{cw} \geq \tau_e \end{cases}$$

and the depositing flux

$$D = \begin{cases} w_s c_s \left( 1 - \frac{\tau_{cw}}{\tau_d} \right) & \text{if } \tau_{cw} < \tau_d \\ 0 & \text{if } \tau_{cw} \geq \tau_d \end{cases}$$

where:

- $M$ erosion parameter [kg/m$^3$/s]
- $\tau_{cw}$ max bed shear stress due to current and waves

---

2 The Delft3D flow manual, March 2003, version 3.10, describes $\tau_{cw}$ as the ‘mean bed shear stress due to current and waves’. A check in the Delft3D-code revealed that the ‘max bed shear stress’ is used instead of the ‘mean bed shear stress’.
\( \tau_e \) critical shear stress for erosion \((\text{N/m}^2)\)

\( w_f \) fall velocity (hindered) \([\text{m/s}]\)

\( c_s \) average sediment concentration in the near bottom computational layer \([\text{kg/m}^3]\)

\( \tau_d \) critical shear stress for sedimentation \((\text{N/m}^2)\)

Effects of consolidation time on the strength of cohesive sediment on the bed are not taken into account. The parameters of the silt formula strongly depend on the specific case considered. It is therefore difficult to suggest general applicable ranges for the input parameters.
3.3 MODELLING OF A GUYANA CROSS-SECTION IN DELFT3D

3.3.1 GRID

Flow grid
For the FLOW module, a grid is chosen with relatively coarse grid cells at the offshore boundary and finer cells near the shore, in total 477 cells. The grid is based on bottom slope of 1:1500 (typical average slope for Guyana) with a maximum water depth of 20 meters with respect to MSL and a highest land point of 1.5 meters above MSL. The flow computational grid and the bathymetry in cross shore direction are shown in Figure 3-4.

Wave grid
Because of boundary disturbances, the computational SWAN grid needs to be larger than the area of interest that equals the FLOW bottom and computational grid. Within the SWAN bottom grid, the bathymetry is used from the FLOW calculations. This is illustrated in Figure 3-5 from plan view perspective.
3.3.2 HYDRAULIC INPUT PARAMETERS

Viscosity and diffusivity parameters
The viscosity and diffusivity can influence the velocities, concentrations and transports. The values used in combination with the algebraic turbulence model are shown in Table 3-1. The vertical eddy viscosity and diffusivity are calculated by Delft3D.

| Table 3-1 : Viscosity & diffusivity values algebraic turbulence model |
|-------------------------|--------|
| Horizontal eddy viscosity | 1 [m²/s] |
| Horizontal eddy diffusivity | 1 [m²/s] |

Bottom roughness
In this study it was chosen to use the bed roughness description of Chezy. The values used varied between 70 m¹/²/s and 90 m¹/²/s (see section 3.5.3).

Vertical tide
The tide is uniform along the Guyana coast, non-astronomical disturbances of the sea levels are weak and the rise and fall of water is almost synchronous along the whole length of the coast. The tidal range varies between 1.2 and 2.5 meter (neap and spring) with an average of 1.8 meter.

The tide is semi-diurnal with inequalities in the daily high and low waters, due to diurnal components which can add up to an amplitude of about 0.20 meters. Tidal constants for 2 locations are given in Table 3-2.

<table>
<thead>
<tr>
<th>Location</th>
<th>S</th>
<th>Tidal Constants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ki</td>
</tr>
<tr>
<td></td>
<td>h</td>
<td>a</td>
</tr>
<tr>
<td>Demerara B</td>
<td>3.45</td>
<td>11</td>
</tr>
<tr>
<td>Corentyne B</td>
<td>3.30</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 3-2 : Tidal constants (Nedeco 1972)

Horizontal tide
The perpendicular incidence of the tidal wave causes the tidal currents at sea to flow perpendicular to the coast. The tidal component of the current over the continental shelf varies between 0.15 and 0.25 m/s.
Waves
The pattern of directions and heights of waves greatly resembles the pattern of the trade wind with waves of 2 meters from December to June and 1.25 meters from July to November. The waves mainly originate from north-easterly to easterly direction. Wave periods vary between 5 and 13 seconds; in deep water the lengths range between 40 and 250 meters, with an average of 60 meters. Waves with periods of more than about 10 seconds are attributed to swell originating from far away (relatively weak local winds).

The results of 4 series of observations are summarized in Table 3-3. The average values are based on a 50% probability of exceedance.

<table>
<thead>
<tr>
<th>Location</th>
<th>Significant wave height (m)</th>
<th>Period (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean (5°10' N, 50°60' W)</td>
<td>Average</td>
<td>Max.</td>
</tr>
<tr>
<td>Buxton (6°54' N, 57°57' W; 11 meters water)</td>
<td>0.75</td>
<td>2.4</td>
</tr>
<tr>
<td>Demerara Becon (6.5 meters water)</td>
<td>0.65</td>
<td>1.7</td>
</tr>
<tr>
<td>Kitty Groove</td>
<td>0.3</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 3-3: Wave observations (Nedeco 1972)
The values in Table 3-3 illustrate the attenuation of waves on their way to the coast. There is a decrease of wave height by friction and breaking and an increase of the wave period because the short waves are damped faster than the longer waves. Based on the NOAA data model for the location 7.00° N 57.5° W (period 1-1-1997 to 31-5-2004; season all year, approximately at a depth of 25 m), the significant wave height for 50% probability of exceedance is around 1.6 meters, main direction north-east. The accompanying period is around 7 seconds.

Current
According to Nedeco, 1972, the strongest current offshore is the Guiana current. It is a continuation of the South Equatorial Current and it flows along the coast from East to West. Velocities at the surface show a maximum of about 0.60 m/s around April. They are less, approximately 0.30 m/s during the second half of the year.

Wind
The winds in the area blow mainly from directions between north-east to east. The average wind speed at sea is about 6 m/s and it rarely exceeds 12 m/s. Tropical storms or cyclones do not occur in the area. Relatively strong and persistent winds blow from the north-east (east-north-east) from December until May (Nedeco, 1972). This is in good accordance with the NOAA data model for the location 7.00° N 57.5° W (period 1-1-1997 to 31-5-2004; season all year).

Bathymetry
The average slope of the foreshore area is approximately 1:1500. However, this slope varies between the shoals and troughs of the mudbanks see Figure 3-6.
3.3.3 Silt Input Parameters

Erosion parameter
Estimated values of erosion parameter (M) are between $10^{-5} - 10^{-3}$ kg/m$^2$/s, based on expert opinion (Winterwerp).

Critical shear stress for erosion
An important property of sediment is its erodibility by flowing water. The properties of soil mainly depend upon the degree of consolidation. Only old sediments can be expected to have a high erosion resistance. Figure 3-7 shows the critical flow velocity observed in experiments with sediments from the Guyana coast. In the flocculent and sling mud ranges the process of erosion is more or less a mixing between fluids of different densities.

Estimated values for the critical shear stress are between 0.5 and 3 N/m$^2$. This agrees well with Figure 3-7.

\[ \text{Sediment content (kg/m}^3) \]

\[ \text{Critical shear stress (N/m}^2) \]

![Figure 3-7: Relation sediment content and critical shear stress](image)

Critical shear stress for sedimentation
The sedimentation rate depends on the settling velocity and the concentration and not on the shear stress. To express this in the Delft3D calculations, a high value of the critical shear stress for sedimentation has to be taken.

Settling velocity
Flocculation is an important phenomenon influencing the properties of suspensions of fine sediments. Up to the content of 5,000 g/m$^3$ the settling velocity increases with the sediment content but in more concentrated suspensions the settling velocity is influenced by counterforces. Figure 3-8 shows the results of tests with sediments from Guyana and Suriname in sea water with increasing concentration.

Estimated values for the settling speed are between 0.1 and 1 mm/s. This agrees well with Figure 3-8.
3.3.4 Overview input parameters

<table>
<thead>
<tr>
<th>Hydraulic parameters</th>
<th>Range</th>
<th>Silt parameters</th>
<th>Type</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal range</td>
<td>1.2 - 2.5 m</td>
<td>Erosion parameter</td>
<td>10^{-5} - 10^{-3} kg/m²/s</td>
<td></td>
</tr>
<tr>
<td>Waves (Hₜ deep water)</td>
<td>1 - 2 m</td>
<td>Critical shear stress erosion</td>
<td>0.5 - 5 N/m²</td>
<td></td>
</tr>
<tr>
<td>Period (Tₚ deep water)</td>
<td>5 - 13 s</td>
<td>Settling velocity</td>
<td>0.1 - 1.0 mm/s</td>
<td></td>
</tr>
<tr>
<td>Wind</td>
<td>0 - 12 m/s</td>
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<td>0.30 - 0.60 m/s</td>
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<td></td>
</tr>
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<td>Bathymetry</td>
<td>different slopes</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3-4: Overview input parameters
3.4 **REFERENCE CASE**

3.4.1 **GENERAL**

A reference case has been setup as a basis for sensitivity analysis with the various hydraulic and silt parameters. Some input parameters for the reference case are listed in Table 3-5. All the input parameters for the FLOW and WAVE module and the morphology input files are given in respectively Appendix B, C and D.

<table>
<thead>
<tr>
<th>Type</th>
<th>Value</th>
<th>Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tide (M2)</td>
<td>1 m</td>
<td>Erosion parameter</td>
<td>10^{-4}  kg/m²/s</td>
</tr>
<tr>
<td>Waves (Hs;Tp)</td>
<td>1.3 m; 6 s</td>
<td>Critical shear stress erosion</td>
<td>1 N/m²</td>
</tr>
<tr>
<td>Wind</td>
<td>6 m/s</td>
<td>Settling velocity</td>
<td>0.25 mm/s</td>
</tr>
<tr>
<td>Current (alongshore)</td>
<td>0 m/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bathymetry</td>
<td>1:1500</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 3-5 : Input parameters Reference case**

All computations (reference case and sensitivity) are done for a timeframe of 2.5 days, both with and without morphological bottom updating. In the first 0.5 day (one tide cycle) no morphological bottom updating is activated to allow the model to adapt to the boundary conditions.

The erosion flux is determined by the bed shear stress, the erosion parameter (constant during run) and the critical shear stress for erosion (constant during run). The depositing flux is determined by the mud concentration in the bottom layer and the settling velocity (constant during run). The bottom shear stress and the mud concentrations in the bottom layer are the most direct parameters to use for analysing and comparing results. The flow velocities, the bed shear stresses, the mud concentrations (all in points) and the sediment transport (through section) are used to analyse and compare the results together with the (initial) cumulative erosion / sedimentation pattern.

In Figure 3-9 the initial bed level, mean sea level and high and low water of the reference case are plotted.

![Figure 3-9 : Initial bed level & MSL](image)

A close up of the intertidal area, with the low water, high water and mean sea level line is given in Figure 3-10. The cross sections that are used are also plotted in the figure.
3.4.2 MODEL TUNING

The model cannot be calibrated based on the limited data that is available. The computational data of the reference case is analysed thoroughly and part of the analysis is described in the next section. Because the aim of this study is not reproduce (calibrate, validate) a specific case of the reality, this way of modelling is acceptable and also suitable, with sensitivity analysis as the main objective.

After the analysis, questions arose about two important aspects; the sediment balance and the equilibrium situation.

**Sediment balance**

Analysis of cumulative erosion and sedimentation plots revealed that the sediment balance was not closed, even though no sediment was lost through model boundaries. Short term computations yielded a loss of sediment, longer term computations in generation of sediment. A Matlab routine was written to compare the changes of the total amount of sediment in suspension and the total amount of sediment at the bed. A Delft3D output file gives two possibilities for the sediment on the bed: available mass of sediment (kg/m$^2$) and changes in bed level (m). Both parameters are used for the comparison, see Figure 3-11.

To solve this problem several aspects were investigated; time step, grid size, uniformity of the grid, sediment losses at the offshore boundaries, etc.; without conclusive results. In Figure 3-11 (a) it can be seen that the changes in the amount of sediment on the bed and in suspension do not have the same values (for bed level changes): $+7.3\%$ difference at $t = 120$ (sediment on the bed $(2x)$ is plotted negative). The small difference when compared with the available mass of sediment is remarkable: $+0.15\%$ difference at $t = 120$ h.

The adjustment of the morphological time scale factor (see section 3.2.3) gave more insight in the problem, see Figure 3-11 (b). When the ‘morfac’ was changed from 15 to 90 the sediment balance was almost correct; available mass of sediment $+0.66\%$ difference; changes in bed level $-0.28\%$ difference.

An explanation for the increase in accuracy has to be found in the precision of the stored values for bottom changes and available mass of sediment (and maybe for the values of suspended sediment). When calculating with mud, bed level changes per time step are very small. In this case, increasing the ‘morfac’ with a factor 6, which also means increasing the bed level changes with a factor 6, seems to be enough to get accurate results. But on a longer time scale inaccuracies increase; available mass of sediment $+2.5\%$ difference; changes in bed level $+11.9\%$ difference, see also Figure A2 in the appendix.
Figure 3-11: Sediment balance; (a) morfac 15 (b) morfac 90

At this moment Delft3D is using single precision to store these values. Switching to double precision would be the solution to achieve better results.

Equilibrium situation
Computations without morphological updating of the bed converge to a stable equilibrium situation after a row of tide cycles. Stable equilibrium situations are very suitable to compare results when carrying out a sensitivity analysis.

No equilibrium situation could be found with morphological updating of the bed. A reason can be the problem with the sediment balance described before. Cumulative erosion and sedimentation patterns also become ‘unstable’ for longer term computations, see figure A1 (the time scales of years is obtained by multiplying the modelling time with the ‘morfac’ of 90). Very gentle slopes (<< 1:1500) in combination with small water depths leads to inaccuracies in flow velocities and morphological changes. No solution was found to solve this problem.

3.4.3 RESULTS

The results for the reference case with and without morphological updating are plotted together for the points or cross sections at -5, -1 and 0 m mean sea level (figures with an ‘A’ refer to appendix A):
- depth average velocity: Figure A3
- mean bed shear stress: Figure A4
- sediment concentration: Figure A5
- instantaneous total transport: Figure A6
As described in section 3.2.4, the erosion rate is calculated with the maximum bed shear. However, Delft3D does not save this parameter to the output files; therefore the mean bed shear stress is plotted. It can be seen that the mean bed shear stress by far does not reach the critical shear stress for erosion (1 N/m²) even though erosion of the bed occurs. The mean bed shear stress must be seen as indication of the maximum bed shear stress.

In the Figures A1 up to A4 small differences can be recognised between the reference case and the reference case with morphological updating due to changes of the bed. In Figure 3-12 an example for the sediment concentrations is given.

**Figure 3-12: Sediment concentration (kg/m³) at -1 m msl**

In Figure 3-13 (as well as in Figure A7) an indication of the significant wave height, the wave period and the wave length are given.

**Figure 3-13: Wave height, wave period & wave length**
The cumulative erosion / sedimentation pattern for the computation with morphological bottom updating is given in Figure 3-14 and more detailed in Figure A8. One can clearly see the increased erosion in the shallower part due to the larger effect of the waves on the bottom. The sediment that was stirred up is deposited mainly in the (intertidal) area between -2 m and 1 m in respect to MSL.

Figure 3-14: Cumulative erosion / sedimentation (reference case; morpud)

In Figure 3-15 (as well in Figure A9) the average sediment concentration distribution is given for the typical situations; max. ebb velocity (a); low water (b); max. high tide velocity (c) and high water (d).

Figure 3-15: Sediment concentrations (kg/m$^3$)
3.5 **SENSITIVITY ANALYSIS**

3.5.1 **INTRODUCTION**

In this section the sensitivity of the results to variation in a number of important numerical, hydraulic and silt parameters is described. Data from computations without morphological bottom updating is used to analyse the sensitivity of the parameters. Data from computations with morphological bottom updating is used to show the initial erosion and sedimentation patterns. These initial erosion and sedimentation patterns should be considered as an indication only.

3.5.2 **NUMERICAL PARAMETERS**

The variation of the numerical parameters is described in Appendix E.

3.5.3 **HYDRAULIC PARAMETERS**

**Waves**

The sensitivity for higher waves is investigated. The results are given in Figure A10 – A13. The depth average velocities are nearly identical because they are mainly induced by tide. The mean bed shear stresses are higher (maximum bed shear stress even more), especially in the offshore area. More sediment is stirred up and kept in suspension and the total onshore transport is as well bigger. This results in more sedimentation in the intertidal area as can be seen in Figure 3-16 and more detailed in Figure A14.

![Figure 3-16: Cumulative erosion/sedimentation waves](image)

*Figure 3-16: Cumulative erosion/sedimentation waves*

It is noted that sediment is lost through the offshore boundary. The large amount of erosion at deep water is not realistic and probably due to boundary effects.

**Tide**

The sensitivity of the tidal amplitude is investigated for bigger amplitude, see Figure A15 – A19. It is obvious that bigger tidal amplitude generates higher velocities and higher bed shear stresses. The sediment concentrations increase and therefore the onshore sediment transport increases. The net result is more erosion at deeper water and more sedimentation in the intertidal area, as can be seen in Figure 3-17 and more detailed in Figure A19.
Figure 3-17: Cumulative erosion/sedimentation tide

**Bottom roughness**

The sensitivity for variations in the bottom roughness is investigated for smoother bed (higher value of Chezy), see Figure A20 – A24. The depth average velocities do not differ much with the reference case (bottom roughness does not have much effect on the tidal cycle). The mean (and maximum) bed shear stresses are even so low that almost no erosion of the bed occurs, see Figure 3-18. The selected value of the roughness of the bottom has a significant influence on the sediment transport.

Figure 3-18: Cumulative erosion/sedimentation bottom roughness

**Current**

See Appendix E.

3.5.4 **SILT PARAMETERS**

In this model setup, silt parameters do not influence the velocities or shear stresses. This can be seen in Figure A25 and A26 for example.

**Critical shear stress for erosion**

The sensitivity of the critical shear stress for erosion is investigated for a smaller value, see Figure A25 – A29. A decrease of the critical shear stress for erosion increases the erosion flux (see section 3.2.5) and therefore the sediment concentrations and the transport of sediment. Increase of sedimentation occurs in the intertidal area where the shear stresses are low, see Figure 3-19. It is noted that sediment is lost through the offshore boundary. The large amount of erosion at deep water (0-4km) is not realistic and probably due to boundary effects.
The sensitivity of the settling velocity is investigated for a higher value, see Figure A30 – A34. The settling velocity is affecting the deposition flux (erosion parameter and critical shear stress for erosion are affecting the erosion flux). A higher settling velocity will increase the depositing flux with equal sediment concentrations. The net effect on bed level changes is smaller, see Figure 3-20.

Decreasing the erosion parameter with a factor ten, will also decrease the erosion flux with a factor ten (see section 3.2.5). As less sediment is stirred up, less sedimentation takes place, see Figure A35 – A39.
3.5.5 Bathymetry

For three different bottom profiles sensitivity calculations are executed. The first two bottom profiles are based on the bathymetric survey 2003-2004 carried out by Royal Haskoning:

- with mudbank (block 5, line 02, see bathymetric survey report)
- without mudbank (block 5, line 14, see bathymetric survey report)

Both profiles are plotted together with the 1:1500 bed in Figure 3-22 and more in detail in Figure A40. The third profile is based on the 1:1500 bed with a schematised intertidal area at -0.5 msl, see Figure 3-27.

![Figure 3-22: Bed levels (survey 2003-2004)](image)

With mudbank

A close-up of the profile is given in Figure 3-23 together with the defined sections. The results are given in Figure A41 - A46.

![Figure 3-23: Bottom profile with mudbank](image)

Because of the difference in water depth, especially at section -1 m msl, it is more difficult to compare the results. At first the cumulative erosion/sedimentation pattern in Figure 3-24, and more in detail in Figure A45, seems to be quite irregular. Looking at Figure A46 one can see the bottom profile is being smoothened. The total amount of sedimentation in the intertidal area is smaller because the foreshore is steeper, the tidal prism is smaller and therefore the total transports are smaller too. Sediment concentrations are comparable with the reference case.
Figure 3-24: Cumulative erosion/sedimentation with mudbank

Without mudbank
A close-up of the profile is given in Figure 3-25 together with the defined sections. The results are given in Figure A47 - A52.

Figure 3-25: Bottom profile without mudbank

The depth average velocities and mean bed shear stresses are significantly lower because the flow surface profile is roughly twice as big. At section -5 m msl the shear stresses are too low to erode any sediment at all, see Figure 3-26. Even though no high values for the mean bed shear stress are recognised, high sediment concentrations occur in Figure A49(b). Waves are damped less and wave induced shear stresses become higher closer the shoreline.

Figure 3-26: Cumulative erosion/sedimentation absent mudbank
**Intertidal area**

A close-up of the profile is given in Figure 3-27 together with the defined sections. The results are presented in Figure A53 - A58.

**Figure 3-27 : Bottom profile 1:1500 with schematised intertidal area at -0.5 msl**

The depth averaged velocities and mean bed shear stresses are significantly higher because of the greater tidal volume. This also influences the sediment concentrations and the total transports. Smoothening of the bed can be seen as well as sedimentation in the intertidal area, see Figure A58. The initial erosion/sedimentation pattern is given in Figure 3-28. In the entire and bigger intertidal area sedimentation occurs. The total amount of sedimentation is bigger.

**Figure 3-28 : Cumulative erosion/sedimentation intertidal area**
3.5.6 Overview results sensitivity analysis

In Table 3-6 an overview is given of the sensitivity of the results to variation in the parameters on three characteristics:

1. Erosion offshore; determines the available amount of sediment in the system,
2. Sedimentation in the intertidal area; gives insight in magnitude of sedimentation in the area of interest,
3. Distribution sediment intertidal area; gives insight in the dimension of the affected area, in relation to the reference case.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Erosion offshore</th>
<th>Sedimentation in the intertidal area</th>
<th>Distribution sediment intertidal area</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0. Reference case</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>1. Higher waves</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>loss offshore boundary</td>
</tr>
<tr>
<td>2. Bigger tidal amplitude</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>same shape cum. e's</td>
</tr>
<tr>
<td>3. Smoother bed</td>
<td>--</td>
<td>--</td>
<td>0</td>
<td>very significant!</td>
</tr>
<tr>
<td>4. Smaller critical shear</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>loss offshore boundary</td>
</tr>
<tr>
<td>stress erosion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Higher settling velocity</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>same shape cum. e's</td>
</tr>
<tr>
<td>6. Smaller erosion parameter</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>same shape cum. e's</td>
</tr>
<tr>
<td>Bathymetry</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. With mudbank</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>smoothing bed</td>
</tr>
<tr>
<td>8. Without mudbank</td>
<td>-</td>
<td>-</td>
<td>--</td>
<td>high sediment concentrations intertidal area</td>
</tr>
<tr>
<td>9. Intertidal area</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>wide distribution</td>
</tr>
</tbody>
</table>

Table 3-6: Overview results sensitivity analysis
3.6 **LAND USE OF THE INTERTIDAL AREA**

With the help of the mathematical model the stated hypothesis in section 2.6 is investigated. The simulations with a dam represent the loss of the intertidal area by building dykes. Simulations have been carried out for two situations.

**Dam -0.5 m msl reference case**
A close-up of the profile is given in Figure 3-29 together with location of the dam and the defined sections. The results are given in Figure A59 - A63.

![Figure 3-29: Location of dam reference case](image)

Due to the smaller tidal volume depth average velocities and mean bed shear stresses are smaller, resulting in smaller the sediment concentrations and total transports. This results in a smaller total amount of sedimentation and erosion (13%) and also in less sedimentation in the intertidal area, see Figure 3-30.

![Figure 3-30: Cum. erosion/sedimentation reference case dam -0.5 msl](image)

This observation supports the hypothesis, stated in section 2.6, that the cross-shore sediment supply in the intertidal area will decrease significantly when dams or dykes are build in the intertidal area. Because less sediment is available, mangroves will not be able to trap as much sediment as they could do without a dam. This change in supply of sediment will influence the system drastically.

**Larger scale**
When looking at a larger scale it can be observed that the erosion/sedimentation pattern is moving offshore. This implies that the whole system is moving in offshore direction, including the intertidal area. In spite of this, the sediment supply and therefore the total amount of sedimentation is smaller than without a dam in the intertidal area.

In this case the effect of a longshore current, see section 2.6, is not taken into account (a more extensive modelling approach is needed to do this, see Appendix E). If a longshore current is
capable of keeping sediment outside the intertidal area in suspension and carrying it away, the system would not move in offshore direction, and less sediment will be available in the intertidal area.

Permeable groins are believed to generate favourable conditions for fine sediment deposition. The decrease in flow velocity decreases the longshore sediment transport, increasing suspended sediment concentrations locally (Royal Haskoning WL | Delft Hydraulics, 2005).

**Dam at -0.5 m msl intertidal area**
A close-up of the profile is given in Figure 3-31 together with the defined sections. The results are given in Figure A64 - A69.

![Cross section -1 m msl](image)

**Figure 3-31 : Location of dam intertidal area**
Due to the smaller tidal volume depth average velocities and mean bed shear stresses are smaller, just as the sediment concentrations and total transports. This results in a smaller total amount of sedimentation (14.5%) and also in less sedimentation in the intertidal area, see Figure 3-32.

![Cum. erosion/sedimentation intertidal area dam -0.5 msl](image)

**Figure 3-32 : Cum. erosion/sedimentation intertidal area dam -0.5 msl**
For this case the same conclusions can be drawn as for the reference case with a dam at -0.5 msl.
3.7 **CONCLUSIONS MODELLING**

The main conclusions for this part of the thesis can be summarised as follows:

**Regarding the model setup:**

- The boundary conditions for the 2DV model are based on the conditions for the coast of Guyana. Because of the uniformity of the boundary conditions the results do not represent reality. Therefore the results should only be seen as an indication.

- The 2DV model has inherent limitations in the current setup. An important limitation is the fact that it is not possible to simulate a longshore current.

**Regarding Delft3D:**

- In Delft3D the effect of consolidation on the strength of cohesive sediment on the bed is not taken into account (critical shear stress for erosion is constant). This shortcoming should be kept in mind when interpreting computed sediment concentrations and morphological changes.

**Regarding inaccuracies:**

- Due to round off errors the sediment balance in Delft3D is prone to inaccuracies in case of very small bed level changes. This becomes significant when simulations are carried out with a low morphological scale factor or for a longer time scale.

- Very gentle slopes (<< 1:1500) results in small water depths and lead to inaccuracies in flow velocities and morphological changes. Therefore, it was not possible to find an equilibrium situation.

**Regarding results:**

- Because of (numerical) inaccuracies in morphological calculations one should be careful drawing hard conclusion on morphological results.

- Higher waves and bigger tidal amplitudes result in an increase of sediment concentrations, sediment transport, erosion at deeper water and sedimentation in the intertidal area.

- The amount of erosion, sedimentation and sediment transport is very sensitive to variations in the values of the bottom roughness.

- In this model the silt parameters do not influence the velocities and the bed shear stresses. The amount of erosion, sedimentation and sediment transport is sensitive to the selected values of the silt parameters.

- The bathymetry influences flow velocities, shear stresses, sediment concentrations & transport and erosion/sedimentation patterns.

- The total sediment supply in the intertidal area decreases for the situation with a dam/dyke in the intertidal area. This result supports the hypothesis that the loss of onshore sediment transport by tidal filling can be the cause of coastline retreat.

- When looking on a larger scale, the total amount supplied sediment in the whole system is also smaller with a dam/dyke in the intertidal area, but a movement of the whole system in offshore direction is recognisable. If it is possible to trap and stabilise the sediment more offshore, accretion may be the result.
4 COASTLINE EVOLUTION

4.1 INTRODUCTION

In this chapter the coastline evolution since 1950 is investigated for the area between the Demerara and the Berbice River with the help of aerial photographs and satellite images. In section 4.2 the results of the study by Augustinus (1984) are given. In section 4.3 the available data and the method used are discussed. The coastline evolution and the position of the mudbanks are described in section 4.4. In section 4.5 the evolution of the mangroves is explained. In section 4.6 the relation between breaches and the position of the mudbanks is investigated. In section 4.7 the conclusions are given.

4.2 PREVIOUS STUDY


4.2.1 EVOLUTION OF THE COASTLINE

The coastline was divided in sections of 1.0 kilometre. Net accretion/erosion within each section for the studied period was measured, giving the average displacement of the high water-line for each section. In Figure 4-1 the balance of accretion and erosion is given for the period between 1942 and 1984. In Appendix F, Figure F-1 balances for smaller data sets in time are given.

Figure 4-1: The balance of accretion and erosion of the Guyanese coast (1942-1984)

The main conclusions from Augustinus (1984) were:

- No clear relationship appears to exist between the occurrence of accretion and erosion of the coast and the position of the mudbanks and corresponding troughs. And exception must be made for the area just west of the mudbank front where usually erosion occurs. This is expected partly due to the fact that the positions of the shoals are derived from instantaneous photographs, while the occurrence of accretion and erosion is determined for a certain period.
- Some sections of the studied part of the Guyanese coast show a great amount of fluctuation in the rate of accretion and erosion; these alternate with other sections that have only little variation, if any at all. Moreover, it is observed, that some sections along the coast during the studied period (1942-1984) show only erosion. An explanation for this phenomenon was not given.
- From the balances of accretion and erosion it is conspicuous that the coastline of Guyana in general is retreating. It was hypothesised the explanation might be the lack of abundant mangrove vegetation.
4.2.2 **POSITION OF MUD SHOALS**

In the period of 1942 – 1984, 5 shore face attached mudbanks were recognised in the study area, which are moving from South-East to the North-West along the coast, see Figure 4-2.

![Figure 4-2: Mudbanks (Augustinus, 2004)](image)

The main conclusions with respect to the mudbank behaviour are:
- during the entire period of observations (1942-1984) five individual shoals were distinguished.
- the length of the observed emerging parts varies between 4.5 and 41 kilometres, with an average of 21 kilometres
- the migration speed of the front of the shoal varies between 2.28 and -0.08 kilometres (which means: in opposite direction) per year. The average speed of migration is 1.1 kilometres per year
- the behaviour of the emerging parts of the shoals appears to be rather erratic. No trends were observed with respect to an overall increasing length or migration speed for certain periods, certain sectors or types of coast.
4.3 AVAILABLE DATA AND METHOD

4.3.1 AREA DEFINITION

The reconstruction of the position of the coastline and the mudbanks is carried out for the area between the Berbice and the Demarara River. Because these two rivers are relatively small in comparison with the Corentyne and Essequibo River, the effect on the coastal system will be smaller. The area is also the most densely populated one as well as the area where the most information is available from previous studies.

4.3.2 AVAILABLE IMAGES

Aerial photographs
Guyana Lands and Surveys Commission is the custodian of existing aerial photographs in Guyana. Suitable images were selected from the different year series having at least 20% overlap. The images were scanned with a 600 dpi resolution, see Table 4-1.

<table>
<thead>
<tr>
<th>Year</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950</td>
<td>93</td>
</tr>
<tr>
<td>1970</td>
<td>175</td>
</tr>
<tr>
<td>1972/75</td>
<td>Referenced by GLSC</td>
</tr>
<tr>
<td>1979/80</td>
<td>51</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>319</strong></td>
</tr>
</tbody>
</table>

Table 4-1: Available aerial photographs

As the Guyana Lands and Surveys Commission had already referenced an ortho-photo series from 1972/75 this used as a reference in combination with the 1:50,000 paper maps to rectify these new photos.

Aerial photographs from 1942, 1962/64 and 1984 are used in the study from Augustinus (1984). At this moment it is not known if these photographs still exist. It would be useful to rediscover these missing photographs.

Satellite images
To enable reconstruction of the position of the coastline and the mudbanks after 1980 satellite images covering the area between the Demerara and Berbice River are used, see Table 4-2.

<table>
<thead>
<tr>
<th>Year</th>
<th>Type</th>
<th>Resolution</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987</td>
<td>Landsat 4-5 TM</td>
<td>30 m</td>
<td>1</td>
</tr>
<tr>
<td>1992</td>
<td>Landsat 4-5 TM</td>
<td>30 m</td>
<td>1</td>
</tr>
<tr>
<td>2001-2003</td>
<td>Aster</td>
<td>20 m</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>5</strong></td>
</tr>
</tbody>
</table>

Table 4-2: Available satellite images

4.3.3 ACCURACY

Although it is a given fact that each aerial image has a displacement at the corner because of the camera lens deflection, it was chosen to use 1st order referencing. 2nd order referencing would give a lower error but also unpredictable distortion of the image at any place. In case the 1st order rectification resulted in an error > 15 meters points were concentrated along the coastline as the main focus is the coastline evolution. This implicates that these images should only be used for studying coastline evolution as the distortion of land inward features will be higher.

The rectification work resulted in 4 complete sets of rectified photos with an estimated error of the order of 9 meters or less along the coast, see Figure 4-3 and Figure 4-4.
Figure 4-3: Overview of geo-referenced aerial photographs series of 1950 & 1970

Figure 4-4: Overview of geo-referenced aerial photographs series of 1972 & 1979/80

Figure 4-5: Overview of geo-referenced satellite images series of 1987-1992 and 2001/03
In Figure 4-5 an overview is given of the satellite image used. These images are rectified with an error smaller than 15 m, although the resolution is 20 or 30 m. This was possible by choosing clear intersecting boundary lines as reference points.

### 4.3.4 MAPPING OF THE COASTLINE

The definition of the coastline is very important when a comparison of different years has to be made. Commonly the coastline is defined as the high water-line. Especially for mangrove areas, which lie in the intertidal area, it is not possible to work with this definition. The following definition for the coastline is used:

“The coastline is defined as a line extending along the seaward edge of the concrete sea defence structures; where vegetation is present it is taken as a line running along the edge of the vegetation; where (earthen) embankments are present the line is taken along the seaward edge of the embankment.”

In Figure 4-6 an example is given of digitised coastlines deduced from different photo series in the Abary River area.

![Figure 4-6: Example digitised coastline from various years (photo 1979/80 displayed)](image)

When digitising, zooming in and out on the image impacts the quality. Zooming in can increase the quality while zooming out leads to faster digitisation. However, when too few vertices are added along jagged coastlines, it is not possible to resolve the coastline adequately. Along straight man-made sea defence structures a vertex at every 200 m is placed; where the coastline is not straight, a vertex is placed at least at every 50 m approximately.

A scale of 1:7500 or smaller is used to digitise the coastline from the aerial photographs and satellite images, which results in an error <15 m. Something that can lead to greater errors or differences is the interpretation of aerial photographs / satellite images (probably up to 20-60 m). Sometimes it hard to distinguish tidal mudflats from real land, and if you can make the distinction the precise border line is often arbitrary. However, the magnitude of coastline erosion/accretion is significant larger, as can be seen in section 4.4.

### 4.3.5 MAPPING OF THE MUDBANKS

A mudbank can often be recognised by:

- a bounded area on its western edge, in which wave activity is absent (the calmness of the sea is a result of the presence of fluid mud),
vegetation on the mudflat some kilometres to the East, and
straight erosion channels, beaches and recent wash-over deltas more to the East; this indicates
erosion at the tail of the shoal and the new exposed coastline.
The eastern end of the shoal is often difficult to establish.

Sometimes it is easier to recognise the mudbanks ‘troughs’. The ‘trough’ just West of the western
edge a mudbank is often characterised by braking waves near the shore for a length up to 6-10 km.
See Figure 4-7.

![Image of Recognizing mudbanks](image)

**Figure 4-7 : Recognizing mudbanks**

Because only features that are situated above the water surface are clearly visible, aerial / satellite
pictures have some limitations. Apart from the areas emerging during low water, the mudbanks
remain largely invisible.

### 4.3.6 Method

Along the coastline between the Demerara en the Berbice River a baseline is defined, orientated
parallel to the main direction of the coastline, see Figure 4-8.

![Image of baseline](image)

**Figure 4-8 : Baseline**
This baseline is divided in sections of 100 m by lines perpendicular to the baseline, which are defined in the form $y = ax + b$. See Figure 4-9.

**Figure 4-9: Method of comparing coastlines**

For the digitised coastlines and mudbanks, $x$- and $y$-coordinates are generated every 100 m. Each section of 100 m is also defined in the form $y = ax + b$. By calculating the intersection points, the distance from the baseline to a digitised line is known. Now it is possible to compare digitised lines from different years.
4.4 COASTLINE AND MUDBANKS FROM 1950 TO 2003

4.4.1 EVOLUTION OF THE COASTLINE

In Figure 4-10 the evolution of the coastline since 1950 is plotted (1950 = zero line). In Figure 4-11 the average erosion and accretion per period per year is given. The actual erosion/accretion per period is given in Appendix F, Figure F2.
Figure 4-11: Average erosion/accretion per year (21th moving average)
In Table 4-3 the erosion / accretion (km$^2$) and the average coastline displacement (m) over the section is given. The totals are the sum of the bold numbers in a column only, because of overlap in time.

<table>
<thead>
<tr>
<th>Year</th>
<th>Demerara - Mahalca (±10 km)</th>
<th>Mahalca - Mahalony (±18 km)</th>
<th>Mahalony - Abary (±8 km)</th>
<th>Abary - Berbice (±38 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>erosion / accretion (km$^2$)</td>
<td>coastline displacement (m)</td>
<td>erosion / accretion (km$^2$)</td>
<td>coastline displacement (m)</td>
</tr>
<tr>
<td>1950 - 1970</td>
<td>-2.6</td>
<td>-85.2</td>
<td>1.0</td>
<td>52.0</td>
</tr>
<tr>
<td>1970 - 1972</td>
<td>-0.6</td>
<td>-19.5</td>
<td>-0.1</td>
<td>-7.2</td>
</tr>
<tr>
<td>1970 - 1972</td>
<td>-0.6</td>
<td>-19.5</td>
<td>-0.1</td>
<td>-7.2</td>
</tr>
<tr>
<td>1972 - 1979/80</td>
<td>-1.2</td>
<td>-37.2</td>
<td>-2.2</td>
<td>-124.4</td>
</tr>
<tr>
<td>1979/80 - 1987</td>
<td>-0.1</td>
<td>-8.2</td>
<td>-0.1</td>
<td>3.0</td>
</tr>
<tr>
<td>1987 - 1992</td>
<td>-1.0</td>
<td>-32.3</td>
<td>-0.1</td>
<td>-8.2</td>
</tr>
<tr>
<td>1987 - 2001/03</td>
<td>-0.1</td>
<td>-104.3</td>
<td>-0.8</td>
<td>-44.8</td>
</tr>
<tr>
<td>1992 - 2001/03</td>
<td>0.8</td>
<td>25.9</td>
<td>0.3</td>
<td>14.8</td>
</tr>
<tr>
<td>Total</td>
<td>-4.6</td>
<td>-147.3</td>
<td>-1.3</td>
<td>-73.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4-3: Average erosion / accretion and coast displacement per section

Due to inaccuracies by referencing (<10 m aerial photographs, <30-60 m satellite images), mapping (<15 m) and interpretation, calculated displacements of the coastline can have errors up to 100 m. This becomes clear when you look at Figure 4-10 to the coastline evolution between 1979/80 and 2001/03 in the area between the Demerara and the Mahaica River. The hard sea defences structures that cover almost the entire length of the coast, are made from concrete and build before 1980. This implies that the bigger part of the coastline is fixed (also no significant growth or decline of mangrove areas) and therefore coastline displacements are due to inaccuracies, see also section 4.5.

The main conclusions to be obtained are:

- there is a significant variation in the amount of erosion and accretion,
- the coastline in general is eroding the last 50 years,
- the Abary – Berbice area shows the biggest variation, this is also the area without sea defences structures.

Comparison Augustinus (1984)

On comparison the differences turn out to be small when results from Augustinus (1984) and results from this study are put together, see Figure 4-12. The values for erosion/accretion in the period between 1972/75 and 1979/80 are plotted for both studies.
4.4.2 POSITION OF THE MIGRATING MUD SHOALS

The positions of the mudbanks since 1942 along the coast between the Demerara and the Berbice River are presented in Figure 4-13. Trend lines, which indicate the migration speed of the fronts of the mudbanks are also plotted. The average length varies between 13.5 and 27 km, the average migration speed is between 0.70 and 0.90 km/yr.

As discussed in section 4.3.5, mapping of mudbanks by using aerial photographs has limitations. Because of these limitations it was decided to schematise the mudbanks based on the average length and migration speed. The result is given in Figure 4-14.

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Figure 4-13: Positions of mudbanks since 1942 (Demerara (0) - Berbice (100))

Figure 4-14: Schematised mudbanks
4.4.3 RELATION EROSION / ACCRETION & POSITION MUDBANKS

The relation between the erosion/accretion of the coastline and the (schematised) position of the mudbanks is investigated. To get a better view, the average erosion/accretion (m/year) is plotted in a x,t diagram. The positions of the mudbanks are also given, see Figure 4-15. The western (left) side of a mudbank is visualised by a line. The eastern (right) side is not visualised by a line to make clear that the final end of a bank can often not be established exactly.

Figure 4-15: Average erosion/accretion & mudbanks

Explanation of the numbers in Figure 4-15:
1. Significant erosion occurs in the period without mudbank (or with a trough).
2. Smaller changes when mudbank is present, accretion and some erosion occurs.
3. Mainly erosion occurs in periods without mudbank, variation in amount of erosion.
4. Smaller changes when mudbank is present, accretion and some erosion occurs.
5. Average erosion is calculated over the period 1950 to 1972. It is plausible that the erosion occurred between 1950 and 1960/65 when a trough was present and not between 1960/65 and 1972. This assumption is strengthened by information from the NDS where is written: ‘...by 1958, heavy erosion started between Seafield and Kingelly on the West Coast Berbice’. (Seafield, km 69; Kingelly km 73).
6. Erosion occurs in period without mudbank.
7. Erosion occurs when a mudbank is in front of the coast. However the presence of this schematic mudbank is based on an assumption and not on observations. This assumption might be wrong because it is not completely clear how the mudbanks ‘pass’ the estuary. It is believed that a mudbank tends to fade out in the estuarine area and then returns westward of the estuary, see Figure 4-16.

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8. A lot of accretion in the period 1972 to 1980 when a mudbank is absent. This cannot be explained on the basis of the position of the mudbanks and troughs. The influence of the Berbice River, see Figure 4-16, may play a role in this area.

Despite the imperfections it can be said that a relation between erosion/accretion of the coastline and the position of the mudbanks exists. Many of the apparent irregularities may be due to lack of detailed information.

![Figure 4-16: Berbice estuary](image)

In Figure 4-17 (a) the average erosion/accretion in meter per year is plotted versus the fraction of time that a mudbank is in front of the coast (for all data points). To get a better insight in the relation a linear regression line is plotted. A trend of more erosion without a mudbank and less erosion with a mudbank is recognizable, although the correlation is negligibly small ($R^2 = 0.031$). This changes when the data of the area between the Abary and the Berbice River is left out, see Figure 4-17 (b). The trend becomes more clear and the correlation increases ($R^2 = 0.2409$).

![Figure 4-17: Relation erosion/accretion & position mudbanks](image)

The relation between the position of the mudbanks and erosion/accretion is also investigated for smaller data sets in time and space; for some examples see Appendix F, Figure F-3 to F-5. No data sets could be found with a stronger correlation.
As mentioned in section 4.3.5, mudbanks can be recognised by the mudbank 'troughs' because of the wave action. This wave action is resulting in an attack on the coast. The relation between the erosion/accretion and the fraction of time that a trough (width 10 km, west of front mudbank) is in front of the coast is plotted in Figure 4-18 (a) & (b).

**Figure 4-18 : Relation erosion/accretion & position troughs**

This time the trend is the other way around, more erosion with a trough and less erosion without a trough. The correlation with troughs is stronger \( R^2 = 0.2921 \) than with mudbanks \( R^2 = 0.2409 \). The correlation for a trough with a width of 6, 8, 12 and 14 km is lower than for a trough with a width of 10 km.
4.5 Evolution of Mangrove Areas

To get a better understanding of what type of erosion / accretion has taken place, the visible vegetation on the aerial / satellite pictures in combination with the deduced coastline evolution was investigated. Because of the low quality and / or resolution of the pictures it is difficult to be very specific. Therefore it was chosen (after the first analysis) to divide the erosion / accretion in only three types:

1. Erosion & accretion of mangrove / intertidal area
2. Erosion & accretion of swamp / land / intertidal area
3. No significant erosion & accretion

Type one is characterising areas where mangrove trees are clearly visible. Type two is less distinct and characterising swampy areas or areas which can get (partly) flooded under (more) extreme conditions (no seawall or earthen embankment close to shoreline). Some mangrove trees or other types of vegetation can be present. Type three can be interpreted as areas where no significant erosion / accretion occur.

In Figure 4-19 the evolution of type 1: mangrove / intertidal area is given. The white / unfilled areas in the x,t diagram are marked with numbers which indicate other types of erosion / accretion. Almost all the mangrove areas between the Demerara and the Mahaica River deteriorated before 1980. As mentioned in section 4.4, the reason that no significant erosion / accretion occurs in large parts of this area (especially after 1980) is the presence of the hard sea defences. The conditions for regeneration of mangroves do not seem to be favourable.

The area between the Mahaica River and around 5 km east of the Abary River can be characterised as a dynamic mangrove area. Erosion as well accretion occurs through the years. The sea defence structures, mostly earthen embankments, lie further inland.

![Figure 4-19: Evolution mangrove / intertidal area](image)
In Figure 4-20 the evolution of type 2: Swamp / land / intertidal area is given. As mentioned above the definition of type 2 is vaguer. The absence of abundant mangroves and hard sea defences is believed to be the reason of the large amount of erosion in the past 50 years.

Figure 4-20: Evolution swamp / land / intertidal area
4.6 BREACHES, CONSTRUCTION AND MAINTENANCE WORKS AT SEA DEFENCES

4.6.1 GENERAL

There are several types of sea defences in Guyana. These include concrete walls (approx. 100 km); mangrove forests with earth embankments (approx. 145 km); natural sand reefs (approx. 80 km) and riprap (approx. 15 km). Land levels on the coastal plain are about one metre below the high tide level. Over the last 12 years, there has been funding for sea defences from the Government of Guyana; USAID (PL480); European Union; Inter-American Development Bank; the International Development Association; the World Bank and the United Nations Development Programme. From 1992 to 2004, Government has spent more than $5.7B, while international funding has amounted to over $5.6B. An overview for the East Coast Demerara and West Coast Berbice is given below.

<table>
<thead>
<tr>
<th>Sea defences</th>
<th>Metres constructed (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mon Repos/Lusignan, ECD</td>
<td>2600</td>
</tr>
<tr>
<td>Bel Air/Mon Chosi, WCB</td>
<td>2200</td>
</tr>
<tr>
<td>Trafalgar/Union, WCB</td>
<td>200</td>
</tr>
<tr>
<td>No. 77, Corentyne, WCB</td>
<td>400</td>
</tr>
<tr>
<td>No. 79, Corentyne, WCB</td>
<td>600</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sea defences</th>
<th>Metres to be constructed (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belladrum, WCB</td>
<td>280</td>
</tr>
<tr>
<td>Profit/Foulis, WCB</td>
<td>1800</td>
</tr>
</tbody>
</table>

The hard sea defence structures generally consist of an earthen embankment protected on the seaward side by either a concrete (coping) wave wall or by rock armouring (rip-rap). The majority of the concrete structures are between the 30 and 70 years old. They have functioned quite well over the past years. Many of these structures have now passed their functional design life and are in need of rehabilitation or upgrading. At the East Coast Demerara a major rehabilitation of sea defences took place between 1965 and 1975. During this period approximately 15 km of sea defence structures were constructed. Following this period a low priority was placed on sea defence construction and maintenance. In consequence the sea defences suffered deterioration leading to an increase of number of sea defences breaches.

4.6.2 YEAR AND LOCATION OF BREACHES

Data of breaches since 1950 is collected. An overview for the East Coast Demerara and West Coast Berbice is given in Table 4-4.

<table>
<thead>
<tr>
<th>YEAR</th>
<th>LOCATION OF BREACH</th>
<th>YEAR</th>
<th>LOCATION OF BREACH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1957</td>
<td>Enmore East Coast Demerara</td>
<td>1992</td>
<td>Craig East Coast Demerara</td>
</tr>
<tr>
<td>1961</td>
<td>Buxton East Coast Demerara</td>
<td>1993</td>
<td>Mon Repos East Coast Demerara</td>
</tr>
<tr>
<td></td>
<td>Bladen Hall East Coast Demerara</td>
<td></td>
<td>Lusignan East Coast Demerara</td>
</tr>
<tr>
<td>1964</td>
<td>Ogle East Coast Demerara</td>
<td>1995</td>
<td>Buxton East Coast Demerara</td>
</tr>
<tr>
<td></td>
<td>Turkeyen East Coast Demerara</td>
<td></td>
<td>Strathspey East Coast Demerara</td>
</tr>
<tr>
<td>1968</td>
<td>Mon Repos East Coast Demerara</td>
<td>1996</td>
<td>Melanie East Coast Demerara</td>
</tr>
<tr>
<td>1969</td>
<td>Triumph East Coast Demerara</td>
<td></td>
<td>Mon Repos East Coast Demerara</td>
</tr>
<tr>
<td>1971</td>
<td>Paradise East Coast Demerara</td>
<td></td>
<td>Enmore East Coast Demerara</td>
</tr>
<tr>
<td>1972/73</td>
<td>Chateau Margot East Coast Demerara</td>
<td>2000</td>
<td>Foulis East Coast Demerara</td>
</tr>
<tr>
<td>1974</td>
<td>Georgetown East Coast Demerara</td>
<td></td>
<td>Vigilance East Coast Demerara</td>
</tr>
<tr>
<td>1978/79</td>
<td>Turkeyen East Coast Demerara</td>
<td></td>
<td>Buxton East Coast Demerara</td>
</tr>
<tr>
<td>1989</td>
<td>Clonbrook East Coast Demerara</td>
<td>2002</td>
<td>Profit West Coast Berbice</td>
</tr>
<tr>
<td></td>
<td>Enmore East Coast Demerara</td>
<td></td>
<td>Foulis West Coast Berbice</td>
</tr>
<tr>
<td>1990</td>
<td>Mon Repos East Coast Demerara</td>
<td></td>
<td>Belladrum West Coast Berbice</td>
</tr>
<tr>
<td></td>
<td>Phoenix West Coast Berbice</td>
<td></td>
<td>Litchfield West Coast Berbice</td>
</tr>
<tr>
<td></td>
<td>Moor Park West Coast Berbice</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4-4: Breaches
The data is obtained from various sources: internet archive ‘Stabroek News’ and ‘Guyana Chronicle’; document with records of breaches drafted by ‘Guyana Sea Defences’ and interviews with Mr. Omadat Persaud, ‘Work Services Group, Minister of Public Works and Communication’ and George Howard, head of ‘Sea and Rivers Defence Division’.

In Figure 4-21, the breaches are plotted in the x,t diagram of Figure 4-15.

Figure 4-21: Average erosion/accretion, mudbanks & breaches in sea defences

Three areas with breaches can be recognised:
1. 1955 - 1980 in the area between the Demerara and Mahaica River,
2. 1990 - 2000 in the area between the Demerara and Mahaica River, and
3. 1990 - 2002 in the area between the Abary and Berbice River.

The areas of breaches and their period correspond with the presence of a trough in front of the coast. As mentioned in section 4.5 no significant erosion occurs in the period 1990-2000 between the Demerara and Mahaica River (area 2.). The deeper foreshore and the strong wave attack during the period of a trough are due to the breaches.
4.7 **CONCLUSIONS COASTAL EVOLUTION**

The main conclusions for this part of the thesis can be summarised as follows:

- Since 1950 there is a significant variation in the amount of erosion and accretion between the Demerara and Berbice River.

- The coastline in general is eroding the last 50 years, this is in line with the findings of Nedeco (1972).

- The Abary – Berbice area shows the biggest variation, this is also the area without hard sea defences.

- From the interpretation of the x,t diagram with the average erosion/accretion in meters per year and the positions of the mudbanks, a relation between the erosion/accretion of the coastline and the position of the mudbanks becomes clear despite the apparent irregularities in the diagram. Erosion occurs with a mudbank ‘trough’ in front of the coast. A stable coastline or accretion occurs with a mudbank ‘crest’ in front of the coast.

- The relation between accretion of the coastline and the position of the mudbank ‘crests’ and between erosion and the position of the mudbanks ‘troughs’ does not seem to be very strong according to the defined correlation factors. This can be due to the lack of detailed information.

- The relation between erosion of the coastline and the position of mudbank troughs is stronger than the relation between accretion of the coastline and the position of mudbank crests.

- As early as 1950 the coast between the Demerara and the Mahaica River is protected by hard sea defences. Almost all the mangrove areas between the Demerara and the Mahaica River degenerated before 1980. The conditions for regeneration of mangroves in this area do not seem to be favourable. This observation supports the hypothesis that a ‘buffer length is needed to maintain or restore an intertidal area with mangroves.

- The area between the Mahaica River and around 5 km east of the Abay River can be characterised as a dynamic mangrove area. Degeneration as well as regeneration of mangroves occurs. This observation supports the stated hypothesis, because no hard sea defences are situated in the intertidal area.

- The absence of abundant mangroves and hard sea defences in the area between the Abay and the Berbice River is believed to be the reason of the large amount of erosion in the past 50 years.

- The relation between accretion and the position of a mudbank ‘crest’ and erosion and a mudbank ‘trough’ is enforced to a bigger extent by the specific time & location of the breaches. The breaches in the area between the Demerara and Mahaica River between 1990 and 2000 are not due to significant coastal erosion but due to the deeper foreshore and stronger wave attack during the period with a trough in front of the coast.
5 DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

5.1 DISCUSSION

The two objectives for study were: establish a better understanding of processes that govern erosion and accretion with the help of mathematical modelling, and analyse the coastal evolution of Guyana since 1950. The modelling part is described in Chapter 3, the coastal evolution in Chapter 4. The conclusions for both parts are given in section 3.7 and 4.7 respectively. The main conclusions are repeated in the next section.

Interpretation of the results of the modelling and coastal evolution study is interesting. Combining both studies, indications can be found that the use of land in the intertidal area plays a role in a decrease of the sediment budget for the intertidal area (modelling). Sediment loss due to erosive processes cannot be supplemented. Fringes of mangroves with hard sea defences shortly behind degenerate and conditions for regeneration of mangroves do not seem to be favourable (coastal evolution). This is an important observation which can ground the stated hypotheses in section 2.6.

However, one should be careful with this observation. For instance, the analysis is based on a very simple model with inherent inaccuracies and uncertainties in morphological changes that are computed. Also no thorough research was done to exclude other causes of degeneration of mangrove areas such as pollution or cutting down of mangrove trees.

5.2 CONCLUSIONS

The main conclusions can be summarised as follows:

Regarding modelling study:

- Due to round off errors the sediment balance in Delft3D is prone to inaccuracies in case of very small bed level changes. This becomes significant when simulations are carried out with a low morphological scale factor or for a longer time scale.

- The total sediment supply in the intertidal area decreases for the situation with a dam/dyke in the intertidal area. This result supports the hypothesis that the loss of onshore sediment transport by tidal filling can be the cause of coastline retreat.

- When looking on a larger scale, the total amount sediment supplied in the whole system is also smaller with a dam/dyke in the intertidal area, but a movement of the whole system in offshore direction is recognisable. If it is possible to trap and stabilise the sediment at some distance offshore, accretion may be the result.

Regarding coastal evolution:

- The coastline in general is eroding the last 50 years, this is in line with the findings of Nedeco (1972).

- From the interpretation of the x,t diagram with the average erosion/accretion in meters per year and the positions of the mudbanks, a relation between the erosion/accretion of the coastline and the position of the mudbanks becomes clear despite the apparent irregularities in the diagram. Erosion occurs with a mudbank ‘trough’ in front of the coast. A stable coastline or accretion occurs with a mudbank ‘crest’ in front of the coast.

- As early as 1950 the coast between the Demerara and the Mahaica River is protected by hard sea defences. Almost all the mangrove areas between the Demerara and the Mahaica River degenerated before 1980. The conditions for regeneration of mangroves in this area do not seem to be favourable. This observation supports the hypothesis that a ‘buffer length is needed to maintain or restore an intertidal area with mangroves.'
The relation between accretion and the position of a mudbank 'crest' and erosion and a mudbank 'trough' is enforced to a bigger extend by the specific time & location of the breaches. The breaches in the area between the Demerara and Mahaica River between 1990 and 2000 are not due to significant coastal erosion but due to the deeper foreshore and stronger wave attack during the period with a trough in front of the coast.

5.3 **RECOMMENDATIONS**

The recommendations can be summarised as follows:

- At this moment Delft3D is using single precision to store calculated values. Switching to double precision should avoid inaccuracies in morphological modelling with cohesive sediment in case of very bed level changes. It also would be useful if not only the values for the mean bed shear stresses, but also the values for the maximum bed shear stress are stored in the Delft3D output files.

- Further research is needed to verify the stated hypothesis. This can be done with a more extensive model setup. This extensive model should be a full 3D-model. Effect of wave damping, longshore currents, consolidation time, etc. should be taken into account.

- The coastal evolution study is carried out for the small area between the Demerara and the Berbice River. It is recommended to investigate the coastal evolution of the whole Guyana coast or even on a larger scale in cooperation with Surinam and French Guiana. A better insight in the behaviour of the coastal system can be acquired.

- A system has to be setup in Guyana to monitor the evolution of the coastline and the positions of the mudbanks in the future. This can be done by analysing satellite pictures ('Aster' images can be downloaded for free), visual/field observations, pictures from flights along the Guyana coast and bathymetric surveys. Insight in the behaviour of the coastal system can be gained which can be used for planning of maintenance and construction works on the sea defences.
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27. Wang, Y. & Healy, T., Research issues of muddy coasts, in Muddy coasts of the world: Processes, Deposits and Function, 2002

Essential research issues of muddy coasts are described and knowledge gaps are identified for muddy coasts.

28. Wang, Y. & Healy, T., Definition, properties, and classification of muddy coasts, in Muddy coasts of the world: Processes, Deposits and Function, 2002

In this paper a general definition of muddy coasts is given. Examples are given and factors facilitating formation of muddy coasts are mentioned.

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The volume transport of 3 to 70 x 10^6 m^3 can be explained by waves alone, using the solitary wave theory.


Coastal evolution Guyana

Modelling and a historical investigation

Appendices

APPENDIX A : FIGURES MODELLING
APPENDIX B : INITIAL FLOW INPUT PARAMETERS
APPENDIX C : INITIAL WAVE INPUT PARAMETERS
APPENDIX D : MORPHOLOGY INPUT PARAMETERS
APPENDIX E : SENSITIVITY ANALYSIS
APPENDIX F : FIGURES COASTLINE EVOLUTION
APPENDIX A: FIGURES MODELLING

- Sediment balance
- Morphological time scale factor = 90

Delft3D

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Fig A1
Reference morph computation
(a) bed level; (b) cum. erosion/sedimentation;
(c) bed level (zoom); (d) cum. erosion/sedimentation (zoom);
Reference computation
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;
Reference computation
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

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Fig A4
Reference computation
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;
Reference computation:
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

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Fig A6
Reference model computation
(a) water levels; (b) cum. erosion/sedimentation; (c) bed levels
(d) cum. erosion/sedimentation; (e) bed levels;

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Fig A8
Sediment concentrations (Reference)
(a) max. ebb velocity; (b) low water;
(c) max. high tide velocity; (d) high water;

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Fig A9
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

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(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

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Fig A13
(a) water levels; (b) cum. erosion/sedimentation; (c) cum. erosion/sedimentation (zoom);
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

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Fig A15
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

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Fig A16
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

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Fig A18
(a) water levels; (b) cum. erosion/sedimentation; (c) cum. erosion/sedimentation (zoom);
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

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Fig A21
(a) - 5 m msl; (b) - 1 m msl; (c) 0 m msl;
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

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Fig A23
(a) water levels; (b) cum. erosion/sedimentation; (c) cum. erosion/sedimentation (zoom);
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

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Fig A25
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

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Fig A26
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;  

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Fig A28
(a) water levels; (b) cum. erosion/sedimentation; (c) cum. erosion/sedimentation (zoom);
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

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Fig A33
(a) water levels; (b) cum. erosion/sedimentation; (c) cum. erosion/sedimentation (zoom);
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

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Fig A35
Figure A36 shows the mean bed shear stress (N/m²) over time (h) at three different water levels:

- (a) - 5 m msl
- (b) -1 m msl
- (c) 0 m msl

The graphs demonstrate the fluctuations in shear stress with time, indicating variations in the hydraulic conditions at each water level.

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WL | DELFT HYDRAULICS
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

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Fig A38
(a) water levels; (b) cum. erosion/sedimentation; (c) cum. erosion/sedimentation (zoom);
Depth msl based on reference cases:
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

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depth msl based on reference case:
(a) -5 m msl; (b) -1 m msl; (c) 0 m msl;
depth msl based on reference case:
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;
depth msl based on reference case:
(a) -5 m msl; (b) -1 m msl; (c) 0 m msl;

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Fig A44
(a) water levels; (b) cum. erosion/sedimentation; (c) cum. erosion/sedimentation (zoom);
With mud shoal
(a) bed level;
(b) cum. erosion/sedimentation;

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Fig A46
Depth msl based on reference case:
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

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Fig A47
depth msl based on reference case:
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

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Fig A48
(a) 

(b) 

(c) 

depth msl based on reference case:
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

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Fig A49
Depth msl based on reference case:
(a) -5 m msl; (b) -1 m msl; (c) 0 m msl;

Delft3D

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Fig A50
(a) water levels; (b) cum. erosion/sedimentation; (c) cum. erosion/sedimentation (zoom);
Absent mudshoal
(a) bed level;
(b) cum. erosion/sedimentation;

Dell3D

WL | DELFT HYDRAULICS

Fig A52
depth msl based on reference case!
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

Delft3D

WL | DELFT HYDRAULICS

Fig A53
(a) depth msl based on reference case:
- (a) -5 m msl;
- (b) -1 m msl;
- (c) 0 m msl;

Delft3D

WL | DELFT HYDRAULICS

Fig A54
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Delt3D

WL | DELFT HYDRAULICS

Fig A55
depth msl based on reference case:
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Delft3D

WL | DELFT HYDRAULICS

Fig A56
(a) water levels; (b) cum. erosion/sedimentation; (c) cum. erosion/sedimentation (zoom);

Dell3D

WL | DELFT HYDRAULICS

Fig A57
Intertidal area
(a) bed level;
(b) cum. erosion/sedimentation;
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

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Fig A61
(a) - 5 m msl; (b) -1 m msl; (c) 0 m msl;

Delft3D

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Fig A62
(a) - 5 m mst; (b) -1 m mst; (c) -0.5 m mst (30000 m);

Delft3D

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Fig A64
(a) - 5 m msl; (b) -1 m msl; (c) -0.5 m msl (30000 m);

Delft3D

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Fig A65
(a) - 5 m msl; (b) -1 m msl; (c) -0.5 m msl (30000 m);

Delft3D

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Fig A65
(a) - 5 m msl; (b) - 1 m msl; (c) - 0.5 m msl (30000 m);

Delft3D

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Fig A67
(a) water levels; (b) cum. erosion/sedimentation;
(c) cum. erosion/sedimentation (zoom);

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Fig A68
(a) intertidal area dam
   (a) bed level;
   (b) cum. erosion/sedimentation;

Delft3D

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Fig A69
## APPENDIX B: INITIAL FLOW INPUT PARAMETERS

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## APPENDIX C: INITIAL WAVE INPUT PARAMETERS

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</table>
Appendix D: Morphology Input Parameters

This appendix describes the morphological input file parameters. First, the 'mor'-file is given and secondly, some parameters are explained and/or the choice of the assigned initial value will be explicated.

'mor'-file
9.0000000e+001 [-] :MORFAC, morphological scale factor
7.2000000e+002 [min] :MORSTT, spin-up interval before morphological changes
5.0000000e-002 [m] :THRESH, threshold sediment thickness
.true. :MORUPD, update bathymetry during FLOW simulation
.false. :EQMBC, equilibrium sediment concentration profile at open boundary
.false. :DENSIN, include effect of sediment on water density
1.0000000e+000 [-] :AKSFAC, van Rijn's reference height factor
2.0000000e+000 [-] :RWAVE, estimated ripple height factor
.false. :ROUSE, set equilibrium sediment conc. to Rouse profiles
1.0000000e+000 [-] :ALFABS, long. bed gradient factor for bed load transport
1.5000000e+000 [-] :ALFABN, tran. bed gradient factor for bed load transport
1.0000000e+000 [-] :SUS, current-related reference concentration factor
1.0000000e+000 [-] :BED, current-related transport vector magnitude factor
1.0000000e+000 [-] :SUSW, wave-related suspended transport factor
1.0000000e+000 [-] :BEDW, wave-related bed-load transport factor
1.0000000e-001 [m] :SEDTHR, minimum depth for sediment calculation
0.0000000e+000 [-] :THETSD, global / maximum dry cell erosion factor
1.5000000e+000 [m] :HMAXTH, maximum depth for variable THETSD
0.0000000e+000 [-] :FWFAC, tuning parameter for wave streaming

Parameters
MORFAC Morphological scale factor, the change in quantity of bottom sediment is multiplied by this factor. In this study MORFAC=15 is used. Together with 2 days simulation time, 'one month' of morphological changes can be simulated.
MORSTT During the stabilising period from the initial conditions to the boundary conditions, the patterns of erosion and accretion do not reflect the true morphological development and should therefore be ignored. This factor makes it possible to delay the morphological bottom updating. The time of one tide-cycle is used.
THRESH Below this threshold depth, the bed load transports are gradually reduced to zero when the sand layer thickness approaches zero. In this study 0.05 is used.
MORUPD The user can specify whether or not to update the bathymetry. The bathymetric updating is used in this study.
EQMBC When activating this parameter will use equilibrium concentration at inflow boundaries. All the sand load entering though the boundaries will thereby near-perfectly adapted to the local flow conditions. In this study, this option is not used.
DENSIN This parameter includes the effect of sediment on density gradient. With large concentration it is expected that the effect of sediment on the density will be enough significant to use this option. In this study, this option is not used.
AKSFAC Van Rijn's (1993) reference height. In this study default value 1 is used.
RWAVE Wave roughness adjustment factor; Van Rijn Recommends range 1-3, in this study the default value 2 is used.
ROUSE Set equilibrium sediment concentration values to standard Rouse profiles. In this study, this option is set on false.
ALFABS Longitudinal bed gradient factor for bed load transport, default value 1 is used.
ALFABN Transverse bed gradient factor for bed load transport, default value 1.5 is used.
SUS Multiplication factor for suspended sediment transport. The default value 1 is used.
BED Multiplication factor for bed load transport. The default value 1 is used.
SUSW Wave-related suspended sediment transport factor, 1 is used.
BEDW Wave-related bed-load sediment transport factor, 1 is used.
SEDTHR Minimum threshold depth for sediment computations (m), in this study 0.1 is used.
THETSD Fraction of erosion to assign to adjacent dry cells; this factor lies between 0 and 1 and represents the portion of erosion of the last wet computational cell that is assigned to the adjacent dry cell instead of the wet cell itself. In this study, the value 0 is used.
HMAXTH Max depth for variable THETSD; In this study the value 1.5 is used. (no influence)
FWFAC Tuning parameter for wave streaming; In this study value 0 has been used.
APPENDIX E : SENSITIVITY ANALYSIS

Numerical parameters

Time step
The time step is reduced from 0.5 minute to 0.1 minute to get accurate results.

Grid size
Doubled grid size gave same results. The course grid is maintained to avoid possible inaccuracies in the future.

WAVE updating interval
As mentioned in section 3.2 the WAVE and FLOW modules use each other’s output. SWAN uses the bathymetry and water level calculated in FLOW and FLOW uses the SWAN output. With a fixed bed and water level, equilibrium will be established after a few WAVE-FLOW successions, as no circumstance changes. Changes in the bathymetry and / or water level will have an effect on the wave conditions. In this case there is special interest for the intertidal area. With a very gentle slope of 1:1500 and a tidal range of 2 meters the intertidal becomes 3 km wide. This area will be flooded or dried in 6 hours. The interval time for a new wave field calculation should therefore not be too big.

The reference case has an interval time of 30 minutes. The longer time scale computations are done with a time interval of 60 minutes to save computational time. The results are as good as the reference case.

Morphological time factor
See section 3.2.2.

Current

The intention was to execute sensitivity calculations with a longshore current to imitate the Guiana current. Despite a lot of effort no stable model setup could be found. The addition of a longshore current in the model has been tried on three different ways, by means of:
- velocity boundaries on two sides,
- Neumann boundaries on two sides (enforcement of a water level gradient),
- discharge boundaries on two sides.

A FLOW stand-alone simulation, without the water level boundary at deep water (tide), was all ready resulting in an unstable model for the one with the velocity boundaries (emptying of the model). A FLOW stand-alone simulation, with the water level boundary at deep water (tide), was all resulting in an unstable model for the one with the Neumann boundaries (again emptying of the model). The model with the discharge boundaries was still stable. When adding the effect of waves, this model became also unstable, again emptying of the model. No solution (a.o. smaller time step) could be found for these problems.

It is common knowledge that adding two of the same boundaries in the same direction can cause problems, especially with velocity boundaries. In longshore direction the model is only 150 meter wide (6 cells). Every disturbance will travel easily from boundary to boundary; the model does not have change to filter disturbances out. The solution can be enlarging the size of the model in longshore direction.
APPENDIX F: FIGURES COASTLINE EVOLUTION

Figure F-1: The balances of accretion and erosion of the Guayanese coast
Figure F-2: Actual erosion/accretion per period
Figure F-3: Relation erosion/accretion & position mudbanks (1950-2003; Demerara-83km)

Figure F-4: Relation erosion/accretion & position mudbanks (1972-2003; Demerara-Abary)

Figure F-5: Relation erosion/accretion & position mudbanks (1972-2003; Demerara-83km)