Master of Science Thesis

Analysis of the morphological behaviour along the Luanda coast

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Deltares
Enabling Delta Life

TU Delft
Delft University of Technology

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Master of Science Thesis

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Abstract

Deltares is currently involved with multiple Angolan companies to advice on several coastal projects along the Angolan coast, especially in the Luanda area. Luanda is expanding rapidly trying to keep up with its economic growth as such coastal projects like land reclamation occur often these days. Still there is little understanding of the coastal systems along the coast of Luanda, whereas the demand for information and knowledge is rising. To increase efficiency of coastal projects, information about the Luanda coastal area is highly preferable. Main features of the Luanda coastal area are the Kwanza River, the Bay of Mussulo, the Island of Mussulo, the submerged shoal, the Luanda bay and the Island of Luanda. The objective of this research is to increase the insight of the Luanda coastal area by analysing the longshore sediment transport. In particular the sediment transport between the Island of Mussulo and the Island of Luanda. Relevant information will be bundled and used to set-up relevant models which are used to describe the sediment transports.

With the help of old charts an analysis is made of the long scale changes along the Luanda coast. It is shown that the coast undergoes some major changes between 1870 till 1950. The Island of Mussulo is reformed as the inlet existing nowadays was shifted south (or this inlet was filled and the nowadays opening in the Bay of Mussulo happened due to a breach). During the last 60 years no major changes were observed. With the help of the software packages UNIBEST-CL+ and Delft3D multiple model simulations were made to get an insight in the sediment transport rates at the Luanda coastal area. The simulations were validated with the help of observation. To qualitatively increase the insight in the Luanda area conceptual models were made which indicates the range within the real LST has to be in. This was first done for each area separate. By combining these models the sediment transport between the Island of Mussulo and the Island of Luanda via the shoal could be investigated.

The following conclusions were drawn from the research. The sediment transport along the coast is mainly driven to the north by waves approaching from the south-west. The Kwanza River is not seen as a main sediment supplier for the present Luanda area. Sediment supply at the south is mainly expected to be from the coastal area south of the Kwanza River. Part of the sediment transported along the tip of the Island of Mussulo will be transported to the shoal and partly to the tip of the Island of Mussulo where it will settle. The tide has a relatively small influence on the interaction between the shoal and the Bay of Mussulo. The dredged channel in the shoal will act as a sand trap and reduce sediment to be transported to the north. This will not have a large effect and a short time scale but can have a major impact on the long term. The LST by the sandbars via the shoal supplies the Island of Luanda with sediment as well as sediment transport from the coast south of the Island of Luanda. The Island of Luanda suffers from structural erosion as the supplied sediment is not enough in order to keep up with the LST. The erosion is nowadays compensated with beach nourishment and coastal structures such as groynes.

Preface

Hereby I would like to thank everyone who has supported me throughout this thesis and my study.

As my daily supervisors, I would like to thank Arjen Luijendijk and Jaap van Thiel de Vries for their patience and guidance throughout my thesis. Furthermore I would like to thank Professor Stive and Joep Storms for sharing their opinions during our meetings.

I would like to thank my family for their unconditional support during all these years of study. Special thanks to my girlfriend for supporting me even during the months I was abroad. For all their support I would like to thank the Ting family.

Thanks to all my friends. Especially the guys from Pax 69 with whom I always lived with a lot of pleasure. The students of Deltares, thanks for the small talk and all the cookies.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

This chapter contains the scope and objective of this research. It starts with a brief introduction of the coast of Angola after which the area of interest is presented. After presenting the problem description an objective is formed with help of one main question and several sub questions. The chapter will end with a description of the approach method with an overview of the subjects per chapter.

1.1 Background

As part of the master Hydraulic Engineering at Delft University of Technology (DUT) a master thesis is obliged to graduate, as such, this report is the product of nine months of work. The research is done in cooperation with the company Deltares. “Deltares is an independent institute for applied research in the field of water and infrastructure.” Deltares operates throughout the world with a main focus on deltas, coastal regions and river basins to work on smart solutions, innovations and applications for people, environment and society.

Deltares is currently involved with multiple Angolan companies to advice on several coastal projects along the Angolan coast, especially in the Luanda area. Due to the rising economy, the city of Luanda is one of the most expensive cities in the world. Luanda is expanding rapidly trying to keep up with its economical growth. Not only inland as well as seawards. As such coastal projects like land reclamation occur more and more these days. Still there is little understanding of the coastal systems along the coast of Luanda, whereas the demand for information and knowledge is rising. To increase efficiency of future coastal projects, information about the Luanda coastal area is highly preferable.

Important features in the Luanda area, shown in Figure 1.1, are:

- Kwanza River; river 60 km south of the city of Luanda which is considered to be the main sediment source.
- Bay of Mussulo; bay lying south-west of the city of Luanda.
- Island of Mussulo, spit which partly encloses Mussulo bay.
- Submerged shoal; underwater shoal which is connected to the north with the Island of Luanda and in the south with the Island of Mussulo. A channel has been dredged in through the shoal.
- Luanda bay; bay lying at the west of the city of Luanda.
- Island of Luanda; spit which partly encloses the bay of Luanda.

Along the Luanda coast several coastal projects are being planned or already conducted of which a few investigated by Deltares. The large scale transport of sediment gives an indication of the type of coast and the effect of an intervention on the Luanda coast. Still this has not been investigated properly and assumptions are made and used as input for different projects based on experience instead of research. Adding information about the coastal area will help future projects already in the design phase. The goal of this report is therefore to increasing the insight of the coastal area by looking at the longshore sediment transport along the Luanda coast both qualitative and quantitative. Especially at the interaction between the Island of Mussulo and the Island of Luanda with the submerged shoal in the middle as a channel has recently been dredged.

Area of interest

The area of interest is needed to control the goal and limit the scope of the research. The area of interest is called the ”Luanda area” and is bounded in the north at the end of the Island of Luanda and in the south by the mouth of the Kwanza River.

1.2 Problem description

Due to the expanding city of Luanda multiple coastal projects are planned nowadays. These projects will change the hydrodynamics and therefore possible morphodynamics which can, besides

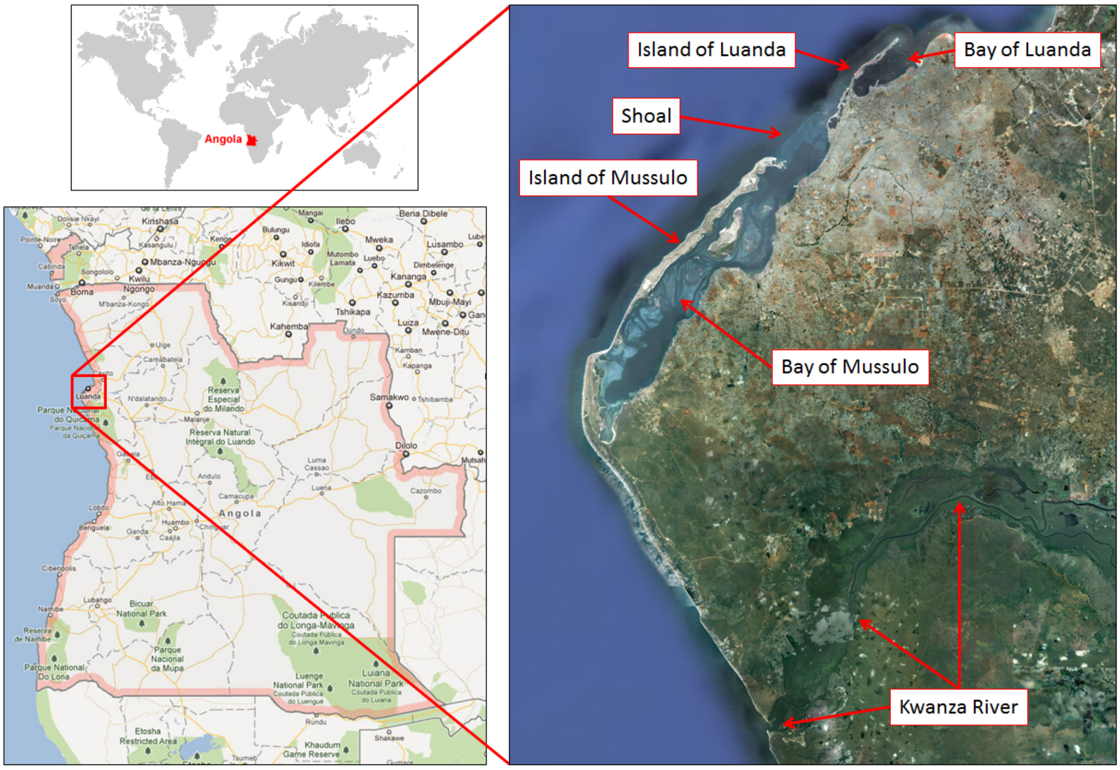

Figure 1.1: Overview important features Luanda area. Top left: Location Angola on the world map. Bottom left: Map of Angola in which the location of the Luanda area is marked. Right: Main features in the Luanda area.

a local effect, affect the large scale coastal system. By analysing the longshore sediment transport of the Luanda area effects of human interventions can be estimated. This has not been done at this moment. It is therefore not known if the coast is in an equilibrium or a dynamic state which makes it difficult to predict the effect of ongoing and future projects.

1.3 Objective

It has been noticed that data availability is limited and basic knowledge about the coastal area is lacking. The objective of this research is to increase the insight of the Luanda coastal area by analysing the longshore sediment transport. In particular the sediment transport between the Island of Mussulo and the Island of Luanda. Relevant information will be bundled and used to set-up relevant models which are used to describe the sediment transports. Research questions will act as a guideline for the report, as such a main question is formed:

Main question

What are the main characteristics which influence the coastal systems of the Island of Mussulo and the Island of Luanda and how differs the longshore sediment transport along the Luanda coast in particular at the area between the Island of Mussulo and the Island of Luanda?

The following questions are formed which will help to answer the main question.

Sub questions

- What are the main features of the coastal system in the area of interest?
- What drives the longshore sediment transport and how does the longshore sediment transport changes along the coastal stretch?
- What is causing coastline changes and what is the large scale evolution of the coastline?
- What is the long term development of the shoal and what is the effect of the dredged channel?
- How does the interaction, with respect to the sediment transport, works between the Mussulo Bay, Atlantic Ocean, Island of Mussulo and Island of Luanda works?

1.4 Approach

The report will start with an area description in Chapter 2 in which the main features and characteristics such as physical features, geological features and hydrodynamics are discussed. Furthermore the long term development is investigated with help of maps and aerial images and there is a section which will elaborate on relevant theories. Model simulations in order to define the LST along the Luanda coast are done in Chapter 3. Validation of these model simulations done with observations are discussed in Chapter 4. With all the insights gained with the help of the simulations and validation a concepetual model of the Luanda coastal area is made in Chapter 5. With the help of the conceptual models the research questions as well as recommendations for a possible future investigation are answered in Chapter 6.

Chapter 2

Important features of the Luanda coast

This chapter will elaborate on the most important aspects and processes influencing the Luanda coastal area. At first, Angola as a whole is investigated by looking at geological features and wave climates, tide and wind. After the large scale features are investigated the focus is set to the area of Luanda. The Luanda area is divided into several areas each with its specific characteristics. Hereafter, the historical coastal changes are determined with the help of old charts. This chapter will end with a description of the most important processes which are applicable for the coast of Luanda.

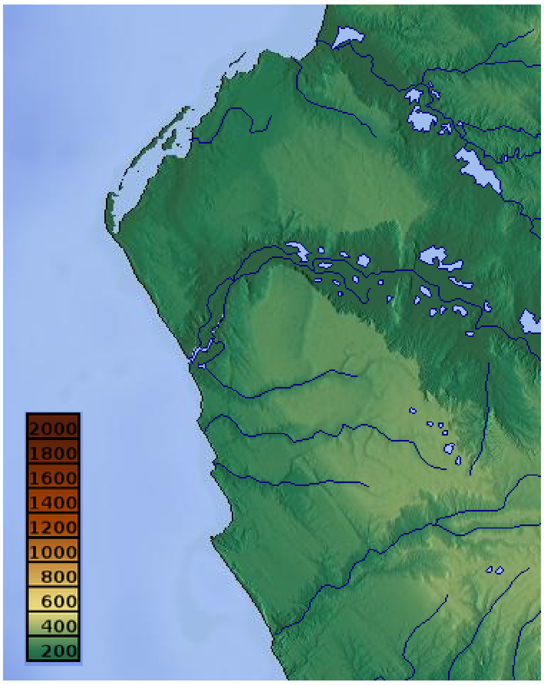

Figure 2.1: Golbal relief Luanda area.

2.1 Large scale characteristics

The Angola coast, which is adjacent to the South Atlantic Ocean, has a total length of 1650 km which lies between 5°00' and 5°47'S (Provence of Cabinda which is enclosed by the Democratic Republic of the Congo) and 6°05' and 15°17'S (mainland Angola). The mainland of Angola shares its border in the north with the Democratic Republic of the Congo, in the East with Zambia and in the south with Namibia. This section will handle the large scale characteristics of the Angolan/Luanda coast. at first topics such as the type of shell, the basic relief and the evolution of the Kwanza basin are covered after which tide and currents are discussed.

2.1.1 Geological

The Angolan coast can be classified with the help of an analysis made by Inman and Nordstrom [1971] which state that a broad coastal characteristic such as shelf width and coastal topography are related to the position on the moving tectonic plates. In this context the coast of Angola is seen as an Afro-trailing edge coast i.e. a coast of which the coast on the opposite of the continent is also trailing. Typical features are pronounced continental shelves and coastal plains, furthermore these edges lack more mature coasts and sedimentary features as described in Bosboom and Stive [2012]. The western margins consist, from north to south, of the Congo, the Kwanza and the Namib marine coastal basin. These basins are covered by Cretaceous to Pleistocene marine sediments.

Relief and depth contours

Depth contours of the Luanda area are shown in Figure 2.2. An interesting feature is the steep bottom profiles in north-west direction in front of the Island of Luanda and the Island of Mussulo. The bottom profiles have a slope varying between 1/12 to 1/20. The steep profiles does not stop at the coast but continue landwards as the land reaches not far from the Atlantic sea a height of 200-300 m above sea level, as shown in Figure 2.1.

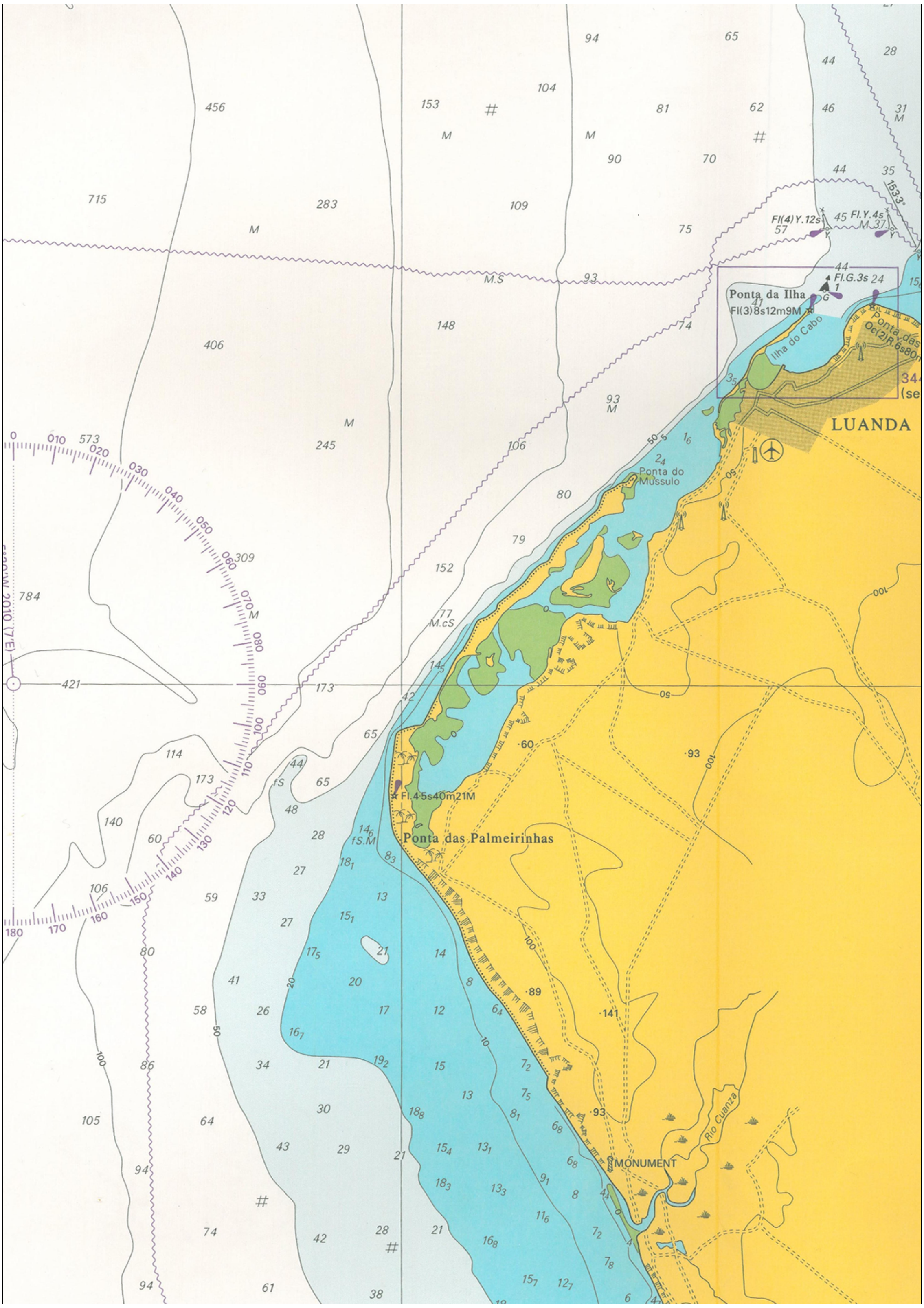

Figure 2.2: Admiralty Charts of the bathymetry of the Luanda coastal area.

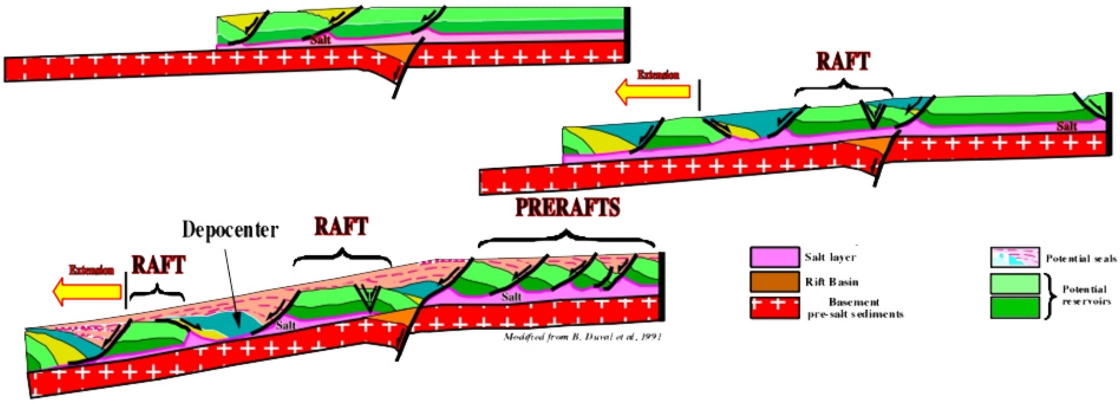

Figure 2.3: Schematic explanation of raft tectonics.

Evolution of the Kwanza basin

Luanda lies in the Kwanza (Cuanza) basin which is a Cenozioc and mid-Mesozoic Era (which was between 144 and 65 million years ago, also known as Cretaceous and Tertiary era) sedimentary basin which extends about 315 km along the north-western coast of Angola and is about 170 km broad [Brognon and Verrier, 1966]. The Kwanza basin is famous for its raft tectonics. Raft tectonics occurs due to cracks in a geological layer where salt escapes through. The décollement of salt formed beneath this layer will decrease as an effect of the outflow of salt and the geological layer will fill up the empty space. Rafts will isolate due to this concept and the area in between will fill up with sediment, so called depocenters. These rafts determine the geology of these areas. This concept is also shown in Figure 2.3.

The Kwanza basin is divided into an Inner and Outer Kwanza salt basin. In between these areas lies a syn-rift basement highs on which Aptian salt is thin or absent, [Jackson and Hudec, 2005]. The Inner Kwanza Basin will further be discussed as the Luanda area is located in this basin.

Inner Kwanza Basin

The Inner Kwanza is divided into five provinces: Quenguela, Muxima, Kissam, Morro Liso and Porto Amboim Province. Between the provinces the basement geometry, structural elevation and salt related structural style changes at the boundaries. The boundaries consist of transfer zones and are directed NW to SE which is in agreement with the direction of rifting of the South Atlantic margin. Due to shortening the transfer zones were reactivated. According to Jackson and Hudec [2005], basement shortening[1] is assigned to the fact that the lithosphere is weakened and probably facilitated basement inversions. Jackson and Hudec [2005] suggest that several techniques are responsible for shortening during different ages: ridge push forces (Albian), plate reorganization (Senonian) and mantle-driven uplift of the African superswell (Oligocene, Holocene).

The geology of the Luanda area varies between sediment from the Pleistocene landwards and sediment of the Miocene along the coast as shown in Figure 2.4 in which the red lines show the fault zones determined by Jackson and Hudec [2005], also the various provinces as mentioned earlier are shown in this figure.

2.1.2 Currents, waves, tide and wind

Waves and tide will influence the behaviour of the coastal area. In order to get an insight in these processes the following information was gathered.

[1] decrease of basement length

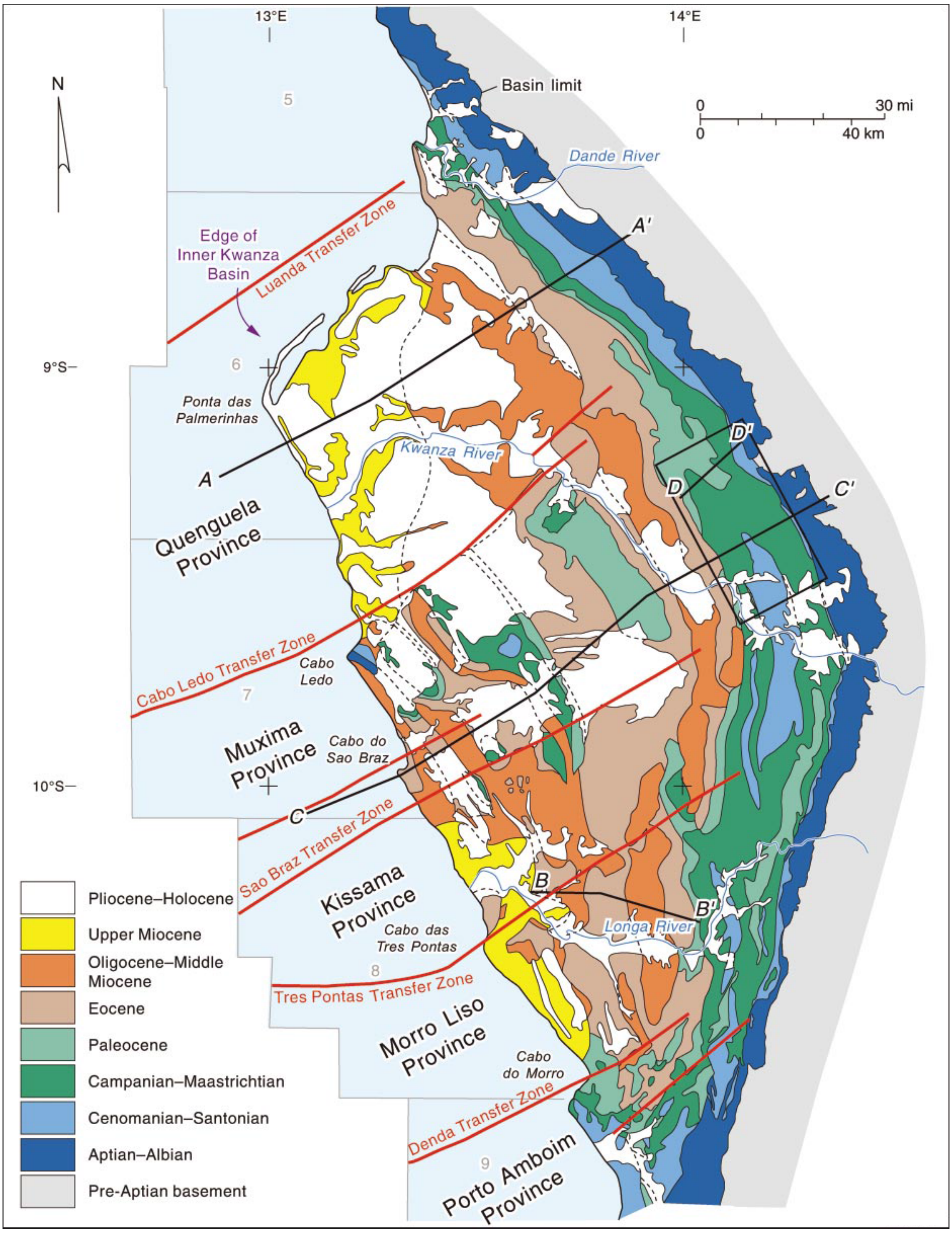

Figure 2.4: Geologic map of the Inner Kwanza Basin, Angola, showing approximate location of rift-related transfer zones (red). Surface geology from Jackson and Hudec [2005].

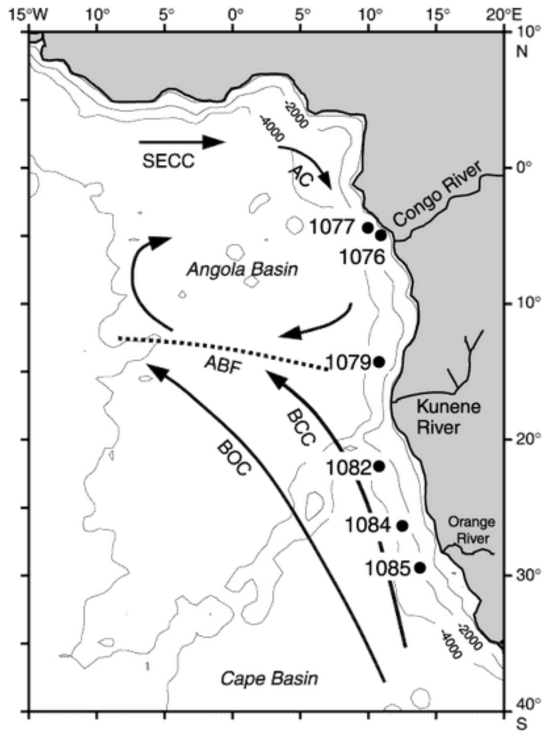

Figure 2.5: Major water currents along the Angola coast.

Currents

Two main ocean currents are dominant in the area of Angola; the Benguele current and the Angola current. The Benguele current (BC) is the eastern boundary current of the South Atlantic subtropical gyre. Typical speed of the BC are between 0.2 m/s up to 0.5 m/s.[2] The BC starts at the Cape of Good Hope and flows to the North where most of it separates from the coast and bends towards the Northwest, the Benguele Ocean Current (BOC). Still two branches continue along the coast and join the Angola current. The Angola current (AC) is likely to be formed by the South Equatorial Counter Current (SECC) which flows along westerly Ghana. The Angola current acts like a cyclonic gyre which lies mostly in the Gulf of Guinea. Around 12° until 15° the AC and BCC meet each other where they merge and flow in to the west to form the Angola Benguele Front (ABF). All above is shown in Figure 2.5.

Waves

Near the Congo River at the deep water area a 100-yr design maximum wave height of 6-7 m[3] is observed, mostly swell generated by strong winds at hundreds of kilometres to the South. Local winds are dominated by the SE Trades. This has also been confirmed in the analysis of Deltares [2013] and Scott and Wilson [2005] which makes uses of different datasets. Due to the direction of the waves the sediment transport by Schwartz [2006] is described as a predominant north-flowing littoral drift. Which basically means transport of non-cohesive sediment, along the foreshore and the shoreface due to the action of the breaking of waves and the longshore current in northern direction.

Tides

[2] http://www.saeonmarine.co.za/SADCOFunStuff/MajorOceanCurrents.htm
[3] http://www.onepetro.org/mslib/servlet/onepetropreview?id=OTC-10749-MS

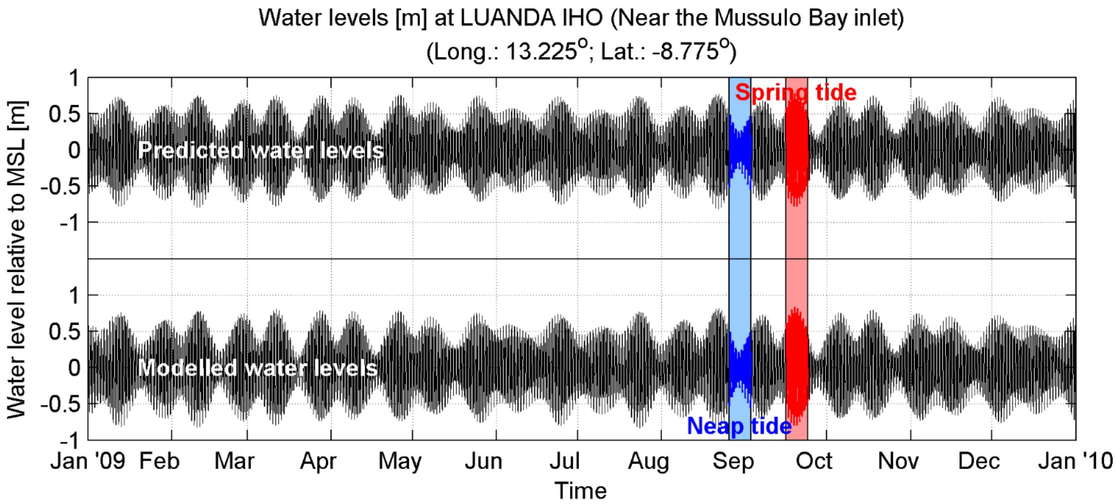

Figure 2.6: Water levels for a specific location within the Bay of Mussulo for a year. Taken from Deltares [2013]

According to Deltares which did a study for the Futungo beach, a beach located within the Bay of Mussulo [Deltares, 2013], astronomical tides vary with a maximum of $+0.7\ m$ till $-0.7\ m$ with a mean elevation of $1.2\ m$. Deltares simulated the tide with the help of Delft3D. The water level effect by the tide was validated with actual data as is shown in Figure 2.6.

Wind

Deltares also investigated wind statistics with the following results. The wind climate is characterized as calm with a typical daily returning land-sea breeze as is shown in Figure 2.7. The mean direction of the wind is located similar as the direction of the swell namely SSW to SW.

The differences in seasons could have an effect on the morphological activity. In the dry (May to October) season there are less wave activity compared to the wet/rainy season (October to May) this could result in less sediment transport. Deltares also acquired offshore wind and wave data, so called WANE2 from Oceanweather Inc. and ERA-interim data from the European centre for medium range weather forecast which will be used in this report for setting up wave climates.

2.2 Luanda area

The Luanda coastal area is highly influenced by local features such as rivers, spits and bays. These features are discussed in this chapter and will help defining different areas.

Rivers[4]

Rivers are important as they are potential sediment suppliers. Reduction of sediment transport delivered by rivers can therefore induce erosion. Five rivers flow in the Atlantic Sea in the surrounding area of Luanda, namely:

- The Longo Rivers (10°15'S; 13°30'E); shown in Figure 2.8, also known as Rio Longo is located 150 km to the south of Luanda. The Longo watershed is divided into several areas in which more than five rivers flow in the Atlantic Ocean. The most southern river outflow in the

[4]Most data found in Source book for the inland fishery resources of Africa, Vol. 1

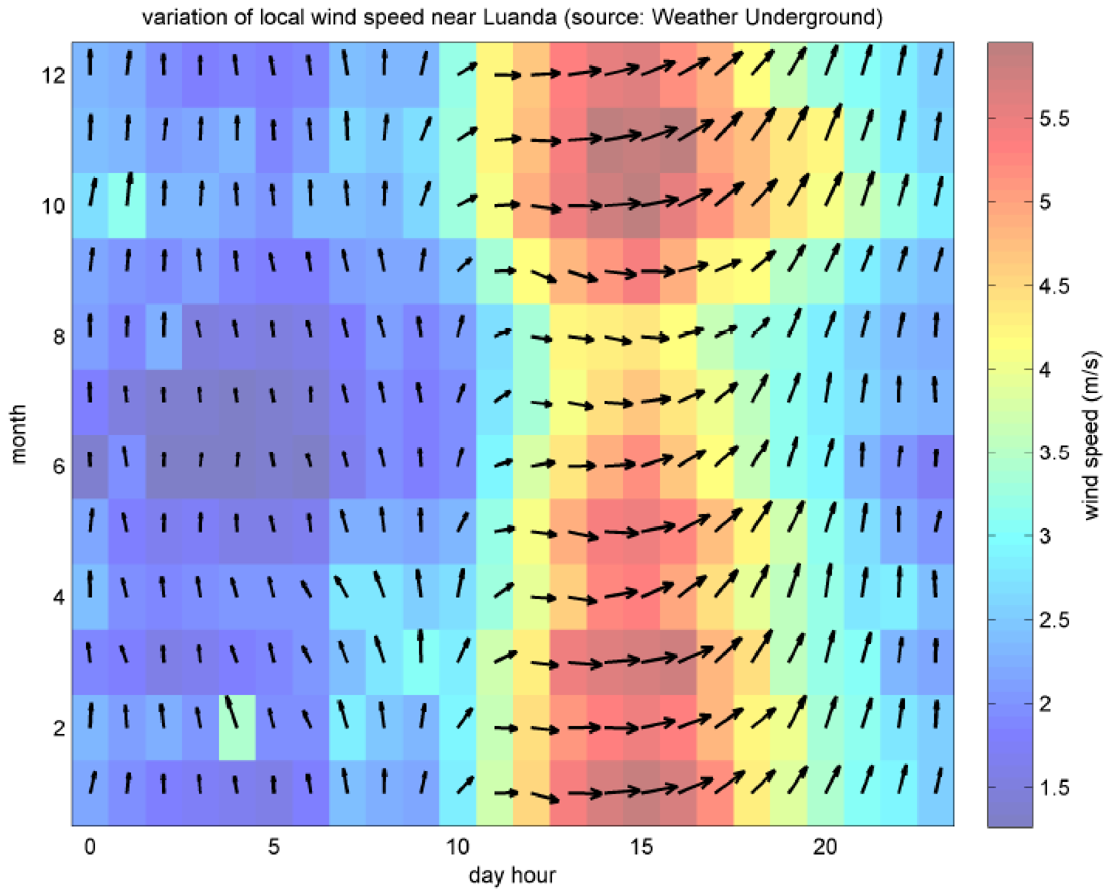

Figure 2.7: Variation of local wind speed near Luanda taken from Deltares [2013]

ocean is considered as the ‘main’ Longo River. The main source is the area near Caliliueke and has two major tributaries Nhia and Mugige.

- The Kwanza River (9°21’S; 13°9’E); shown in Figure 2.8, also known as Cuanzar or Kuanza River flows in the Atlantic Ocean 60 km to the south of Luanda at Barra do Cuanza and is the largest river in Angola. The catchment area is around 150,000 km^2 and the total length is about 960 km. The Kwanza River is dammed by the Cambambe which was built between 1958 and 1962 [5] in the province Cuanza Sul as well by a second dam known as the Capanda dam, which is located upstream of the Cambambe dam in the province Cuanza Norte.1984. The mean flow of the Kwanza River is about 58 m^3/s. The Kwanza River is not used for navigation due to shallow depth during the dry season and the shifting sandbar at the mouth. The Kwanza River is seen as an important sediment source for the Luanda area.
- The Bengo River (8°44’S; 13°24’E); shown in Figure 2.8, is located a couple kilometres north of the city of Luanda. Its source is mainly from the Crystal Mountains (northern Angola). The total length of the river is about 300 km and has a drainage area of 7370 km^2. The (averaged) discharge is 47 m^3/s. The Bengo River is also dammed at Kiminha.
- Dande River (8°28’S; 13°23’E); just north of the Bengo River. Its source is, together with the Bengo River, mainly from the Crystal Mountains it has a total length of (roughly) 285 km and a mean discharge of 50 m^3/s. The Dande River is dammed at Mabubas.

More to the north several rivers flow into the Atlantic Ocean which all comes from the river Logo, they are considered not to have a major influence on the Luanda coastal area.

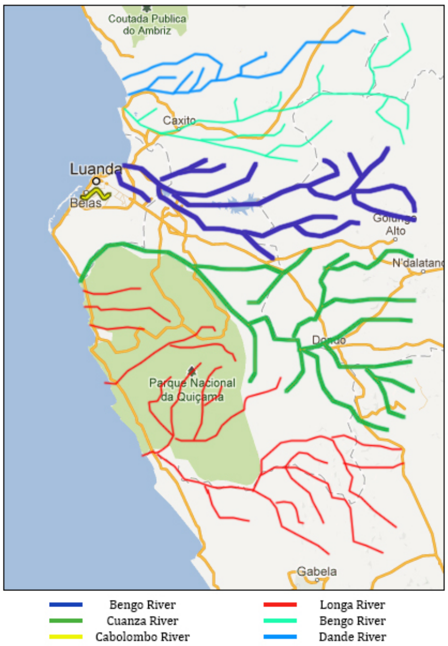

Figure 2.8: Main rivers in the Luanda area and there catchment areas

Luanda city

Luanda is the main capital of Angola and is founded in 1575 by the Portuguese. With a population of 5.2 million people (2012) it is the biggest city in Angola. A lot of coastal activities like dredging

[5]http://www.macauhub.com.mo/en/2010/12/07/second-phase-of-expansion-of-cambambe-dam-angola-to-begin-in-january-2011/

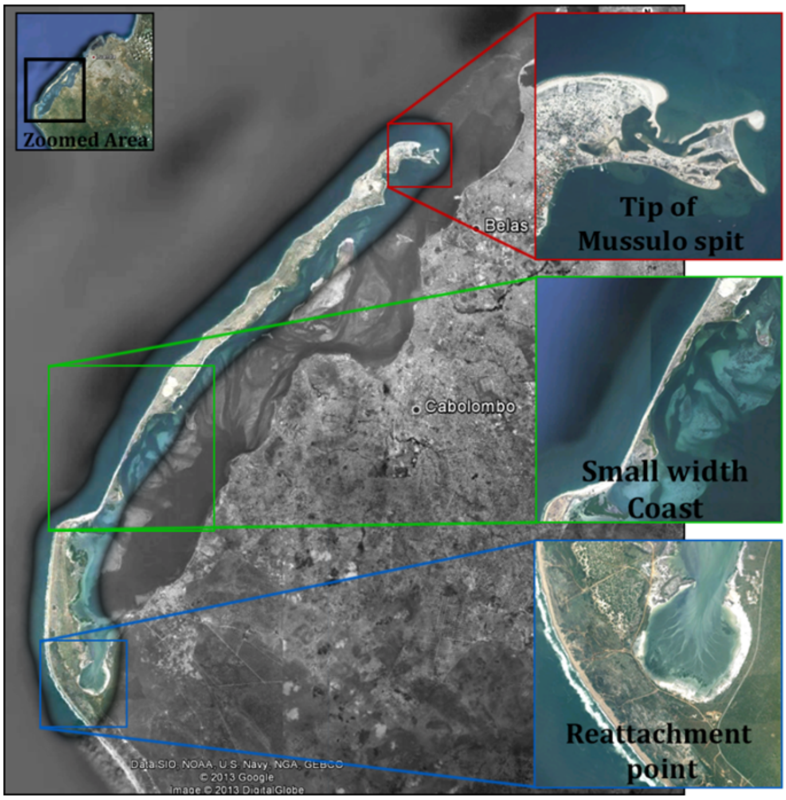

Figure 2.9: Island of Mussulo with its main features. Adjusted from Google Earth [2013]

and land reclamations are done, being done or are will start in the near future. The urban area consists of sand with exception of the north-east where expansive clay areas are found. The city of Luanda is located near two bays namely the Bay of Mussulo and the Bay of Luanda each enclosed by a spit called respectively the Island of Mussulo and the Island of Luanda.

Island of Mussulo

Mussulo Spit better known as the Island of Mussulo (or Ilha do Mussulo) is located to the south of Luanda as shown in Figure 2.9. It has a total length of about 32 km. At the tip of the Island of Mussulo sediment is expected to be transported to the north due to a net sediment transport towards the north, induced by "powerful south-westerly swells and predominant north flowing littoral drift", [Schwartz, 2006]. Furthermore it is thought that the Island of Mussulo was breached at least once, [Theron and Rossouw, 2008].

Bay of Mussulo

The Bay of Mussulo or the Baia da Corimba is a watermass protected by the Island of Mussulo. Three large islands are located within the bay; Ilha de Cazanga, Ilha do Desterro, Ilha dos Pássaros. A small river, the Cabolombo, flows in the Bay of Mussulo though not constantly.

Submerged shoal

At the entrance to the bay a shoal reduces the depth considerably. The shoal is in straight line with the orientation of the Island of Mussulo and the Island Luanda. It is therefore a possibility that the shoal once was part of the Island of Mussulo or the Island of Luanda and due to a coastal feature, breaching or shifting of opening to the bay, disappeared below water. Sediment is expected to be transferred along the shoal with the help of waves and into the Bay of Mussulo by

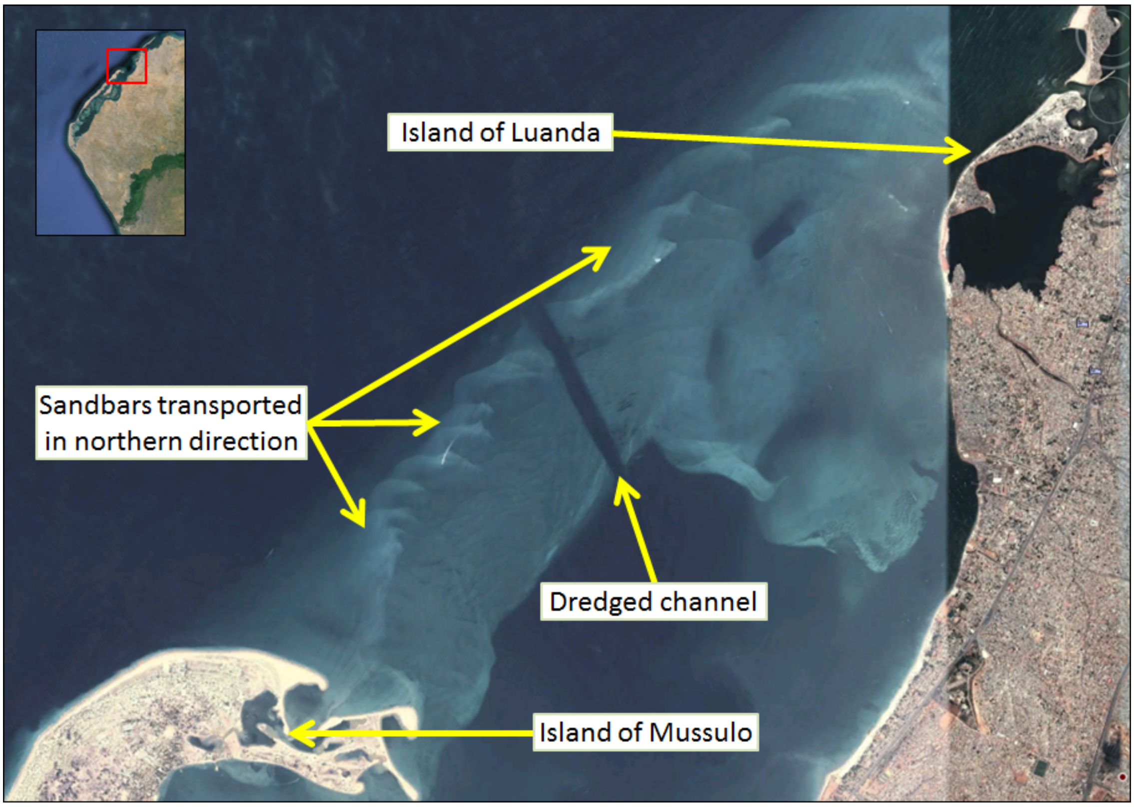

Figure 2.10: Main features at the entrance to the Bay of Mussulo. Adjusted from Google Earth [2013]

the tide. From aerial photographs sandbars are seen at the Atlantic side of the shoal. These bars tend to migrate northerly supposedly under the action of waves with the help of tide. All features are shown in Figure 2.10.

The shoal has been interrupted by a dredged channel which is needed in order to let ships enter/leave the Bay of Mussulo. Maintenance dredging is needed in order to maintain the depth of this channel. It is expected that this channel is interfering with the longshore sediment transport along the shoal.

Island of Luanda

The Luanda spit better known as the Island of Luanda or Ilha do Luanda (Ilha do Cabo) is located at the East of Luanda city and encloses the Bay of Luanda, see also Figure 2.11. The spit is highly developed with bars, hotels and other tourist facilities. Due to erosion and increasing tourism of the Island of Luanda numerous human interventions have been done during the last decades. Numerous groynes are constructed and land reclamations are done in order to mitigate erosion of the Island of Luanda. Stabilization of the coast as well as the tip of the Island of Luanda already occurred in the 1970's by using rock and concrete groynes. Nowadays even more plans are being investigated which will interfere with the hydrodynamics and morphology of the Island of Luanda.

Information about the sediment in the area of the Island of Luanda is given by HR Wallingford [2011]. A preliminary study is made of the coast between the Samba/Sodimo lagoon to the northern end of the Island of Luanda. The sediment characteristics are based on samples taken at several locations along the Island of Luanda and consist of medium to coarse sand with a limited amount of gravels or silt with most particle sizes between 2 mm and 63 microns.

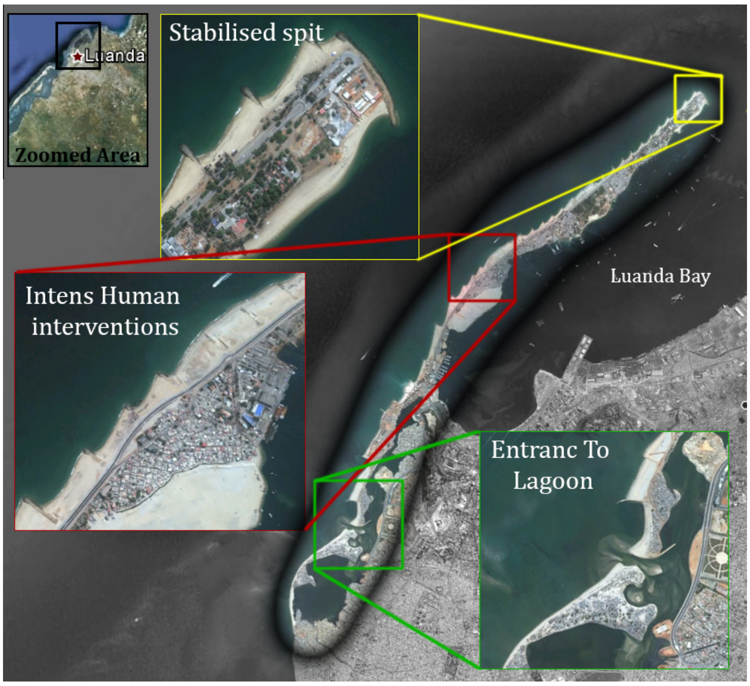

Figure 2.11: Main features of the Island of Luanda. Adjusted from Google Earth [2013]

Luanda Bay

Due to its natural depth the Bay of Luanda is the area where most shipping activities occur. Several large port facilities for the transshipment of all sorts of commodities are located in Luanda Bay and new projects are in development such as the “Luanda Bay Project.” Which main focus is on cleaning up pollution and silt from the bay and re-arrangement of the Luanda Marginal Avenue.

Southern area

The area between the mouth of the Kwanza River and the start of the Island of Luanda will be called Southern area in this thesis as it has no specific name at this moment. The Southern area consist of a coastal stretch of about 31 km. At the mouth of the Kwanza river a sandbar is present which disappear and reappear at random moments in time.

2.3 Historical shoreline changes

Historical shoreline changes indicates the effect of dominant processes over a longer period. Historical charts were collected and compared to determine these historical changes. The collected charts are used to define the shoreline changes in the last centuries as aerial images from Google Earth are used to determine the coastal changes for the last decade.

2.3.1 Shoreline changes during last centuries

Historical charts are scares and difficult to obtain. The available charts which are used are shown in Table 2.1. Two distinct periods are used for comparing the historical charts, namely

- Period I starting at 1876 to 1949 (67 years)

- Period II starting at 1949 to 2012 (63 years)

Table 2.1: Different historcal charts used for comparing coastlines.

nr	Title	year	Author	Scale
1	África Occidental Portugueza Angola planta territorio entre Loanda e Ambaca	1876	NA	1:500.000
2	Carta do Tracado dos caminhos de ferro e das estradas	1884	Grav. Palha e Samora	1:270.000
3	Ministério do Ultramar. Junta das Missões Geográficas e de Investigações do Ultramar. Lisboa. Oceano Atlântico Sul. África Ocidental Portuguesa (Angola).	1949	Des. F. Soares Pereira	1:100.000
4	Google Earth (Satellite images)	2010-2012	Google	Various

Period I, 1876 - 1949

Two maps are available for the period around 1876 and one map for the year 1949. These charts were compared with each other and the most important changes are shown in Table 2.2. As the charts from the year 1876 lack accuracy only large scale trends are made and no quantitatively conclusions.

Table 2.2: Main changes and similarities between the charts of 1876 and 1949 (period I).

Nr	**Changes**
1	Between the Point of Palmeirinhas and the mouth of the Kwanza river the coast lies landwards almost towards the mountain in the year 1876. In the year 1949 this “gap” has been filled and the location of the coast is (roughly) 240°
2	The Point of Palmeirinhas lies almost 4 km in the ocean at the year 1876. This bump has been flatten in the year 1949
3	The Bay of Mussulo has an extension at the (inside) southern end of the bay in the year 1876. This extension has disappeared in the year 1949
4	The entrance of the Bay of Mussulo is wider in the year 1949 compared to the year 1876
5	The Island de Cazanga within the Bay of Mussulo does not exist in the year 1876
6	In the year 1949 the island of Luanda is shifted more to the mainland where it almost attach to the mainland compared to the year 1876. Furthermore the Island of Luanda seems to be thinner in the year 1949 compared to the year 1876
	Similarities
1	The Island of Mussulo has the same configuration in both maps though the width may be less in the year 1949 compared to 1876

Comparing the charts it is concluded that between the year 1876 and 1949 a lot of large scale changes occur. The major trends are showed in Table 2.2 from which several hypotheses are obtained.

- Due to the numerous changes during this period it is thought that there was no equilibrium state during this period.
- Properly due to wave interactions the Point of Palmeirinha eroded. Sediment of this area is expected to moved northwards towards the Island of Mussulo and southwards towards the gap in the area between Point of Palmeirinhas and the Kwanza River.

- The Island de Cazanga lies in the area behind the opening in the Island of Mussulo as shown in the chart of the year 1876. The closing of the opening and the creation of the Island de Cazanga might be linked.

Period II, 1949 – 2012

The chart of the year 1949 is compared with nowadays aerial images obtained with Google Earth.

Table 2.3: Main changes and similarities between the charts of 1949 and 2012 (period II).

Nr	**Changes**
1	The Island of Luanda is nowadays connected to the main land and the northern part of the Island of Luanda is fully constructed with groynes. The southern part of the Island of Luanda is shifted towards the mainland
2	The Island of Mussulo has been extended in the north with 1.8 km^2. According to the sensitivity analysis in Appendix A the total accretion lies in the range between $1.4 \cdot 10^6$ en $4.1 \cdot 10^6$ which is over a time span of 63 years. The average rate of accretion lies between 21,000 $m^3/year$ and 65,000 $m^3/year$.
3	The sand bar which partly blocks the opening to the Kwanza River in the year 1949 does not exist nowadays
	Similarities
1	The submerged shoal has the same configuration nowadays than in the year 1949
2	The configuration of the Island of Mussulo, except for the northern spit tip, has not undergone any major changes during the last 60 years. It seems to have reached an equilibrium
3	The configuration of the area south of the Point of Palmeirinhas has not undergone any major changes. It seems to have reached an equilibrium
4	The Kwanza River does not differs significant between 1949 and 2012.

Comparing the charts concluded that between the year 1949 and 2012 no large scale changes occured. As the charts are more accurate compared to the chars used for the first periodit was possible to make beside qualitatively also quantitative conclusions. The following is concluded:

- The northern tip of the Island of Mussulo is accumulating sediment every year lies between 21,000 $m^3/year$ and 65,000 $m^3/year$, as shown in Figure 2.12.
- The Island of Mussulo and the area between Point of Palmeirinhas and the mouth of the Kwanza River do not change significantly and are considered to be stable. An equilibrium has been reached.
- Due to the fact that the Kwanza River is dammed upstream, construction finished in the year 1962, the amount of sediment is expected to decrease and erosion of the coast near the Kwanza River mouth is expected. No evidence of erosion confirms this idea, it is therefore possible that the Kwanza River does not have a significant influence on the amount of sediment.
- The Island of Luanda is eroding and without the constructed groynes might have been disappeared nowadays.

Conclusion

The first period is characterized by large scale changes along the coast. In contrary to the second period in which the coast seems to be stable. As old charts suffer from inaccuracy it was not possible to draw any quantitative conclusion for the first period. A graphical overview of the large scale changes is shown in Figure 2.13.

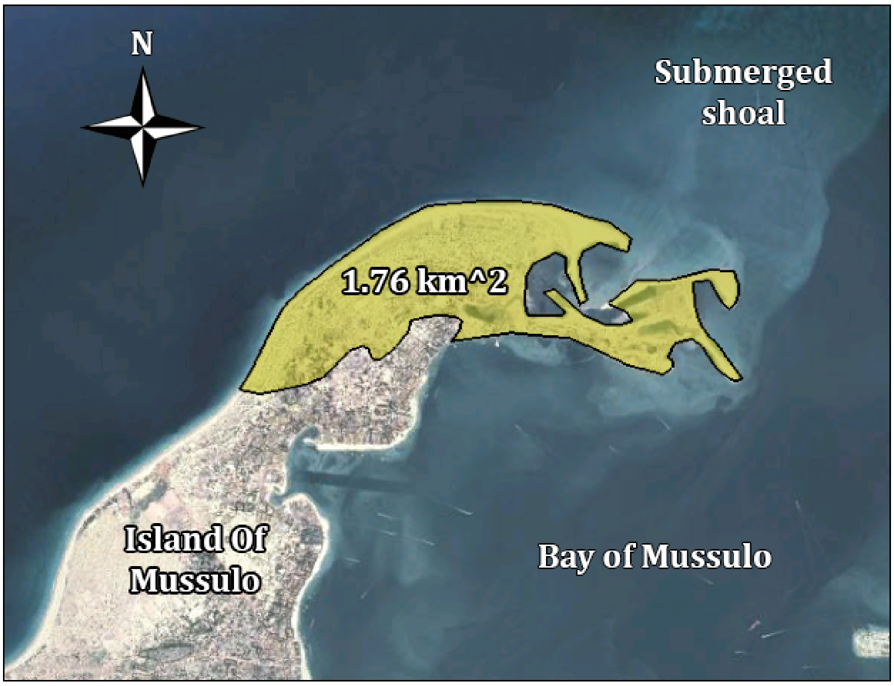

Figure 2.12: Accumulation of sediment between the years 1949 – 2013 (total of 64 years).

2.3.2 Shoreline changes during the last decade

Aerial images obtained from Google Earth are used to determine the coastal change during the last decade. As these images do not cover the entire Luanda area the images are split into three areas, as shown in Figure 2.14, namely:

- Southern area (#1 in Figure 2.14)
- Island of Mussulo (#2 in Figure 2.14)
- Island of Luanda (#3 in Figure 2.14)

The coastline regression/accretion is determined over times. In Figure 2.18, Figure 2.16 and Figure 2.15 the regression (negative) or accretion (positive) per year is shown.

Southern area

The southern area starts at the Kwanza River and ends 3.5 km East of the Kwanza River. Due to the lack of satellite images it was only possible to compare two aerial images. The yearly regression rate between the years 2006-2012 is shown Figure 2.15. From Figure 2.15 the following is concluded:

- There are two large areas where accretion occurs as well as two large areas where erosion occurs. Overal there is more accretion than erosion.
- At the the Kwanza River large erosion rates occur due to a large regression of the coast. A spit in front of the Kwanza River disappeared between the 2008 and 2012. This is considered to be the main explanation for the increased erosion rates.

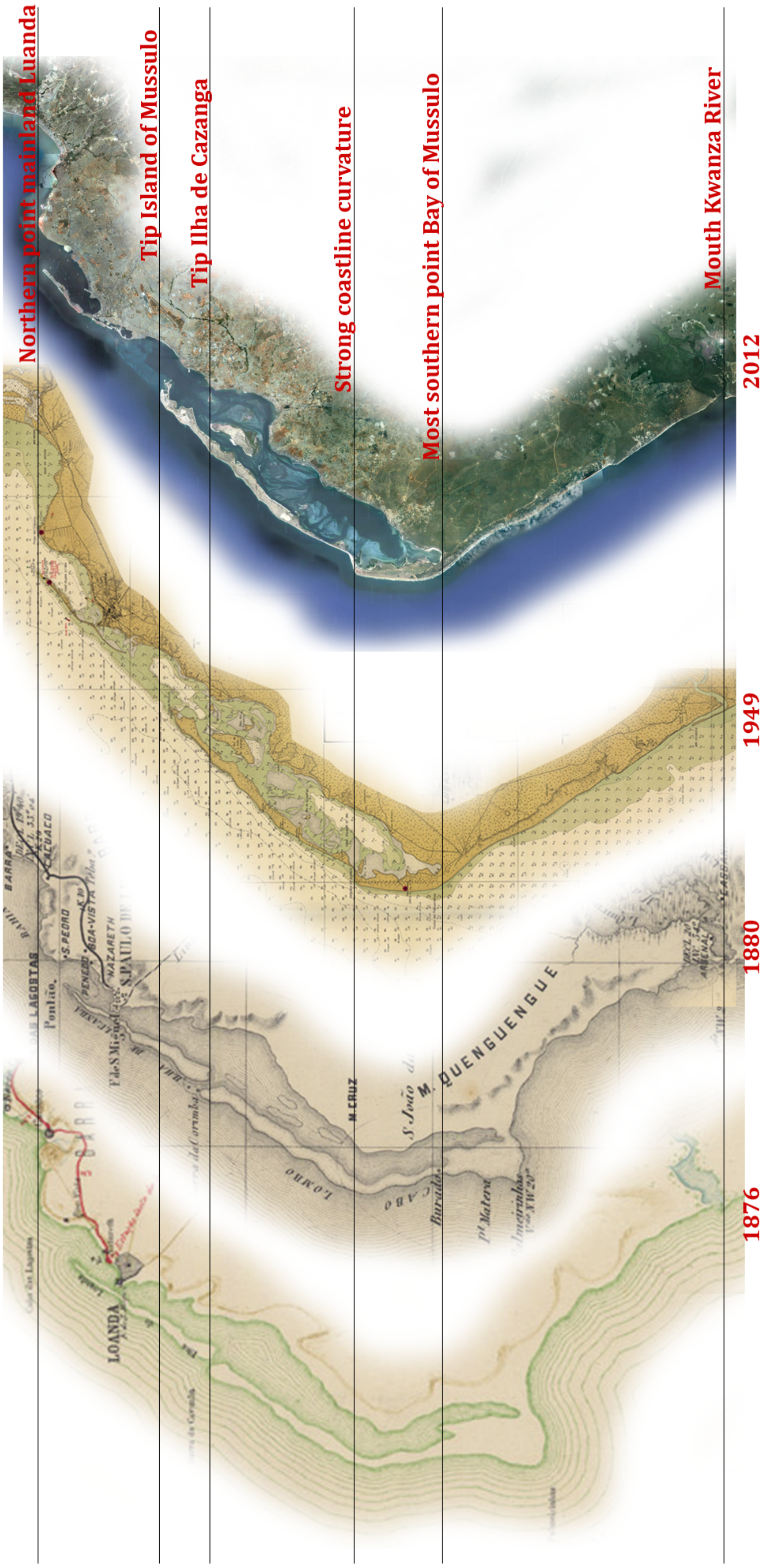

Figure 2.13: Available charts between 1876 and 2013 compared. Most distinct features are highlighted to detect large scale changes.

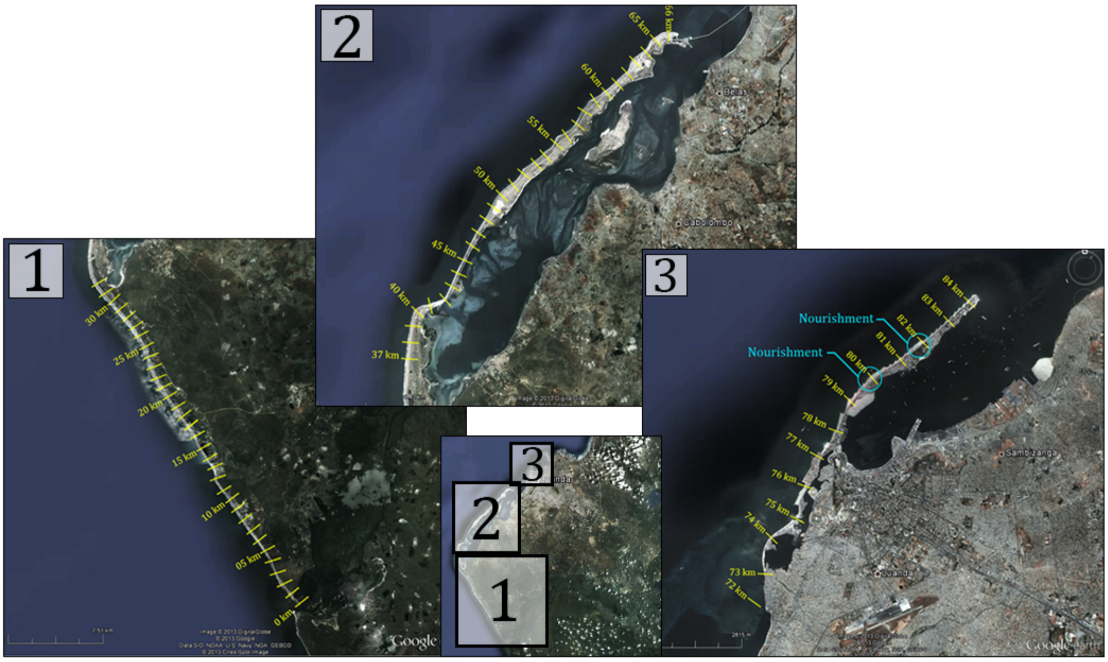

Figure 2.14: Different areas used for comparing aerial images. Area 1 represent the southern area, area 2 represent the Island of Mussulo and area 3 represent the Island of Luanda.

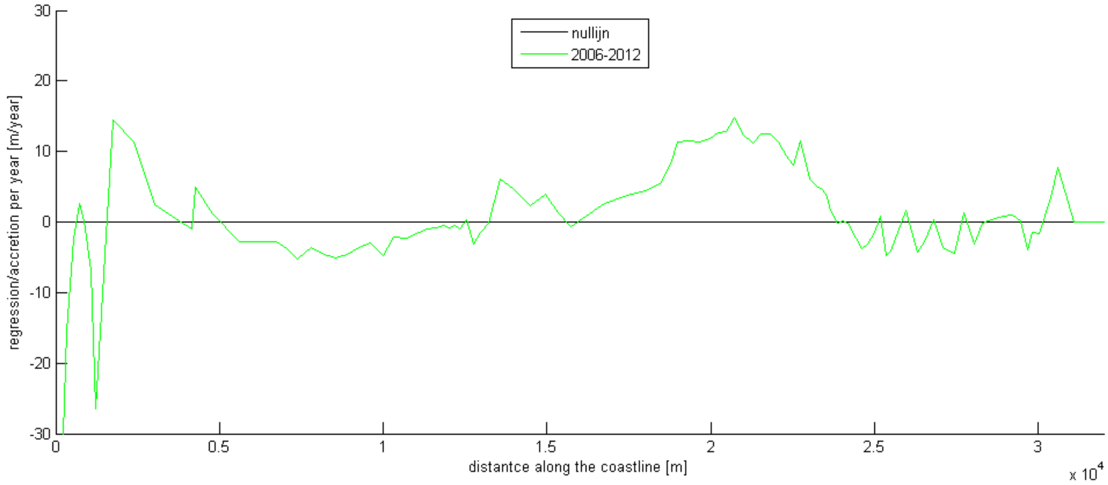

Figure 2.15: Yearly regression (positive)/accretion (negative) rates for area 1 in Figure 2.14.

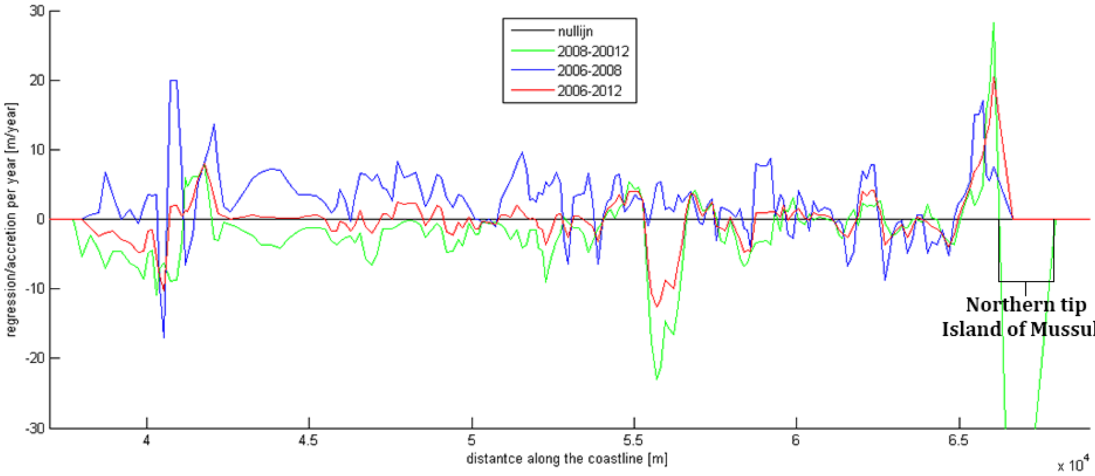

Figure 2.16: Yearly regression (positive)/accretion (negative) rates for area 2 in Figure 2.14.

Island of Mussulo

No large scale human interventions occur along the coast of the Island of Mussulo. In Figure 2.16 the erosion/accretion rate of this area is shown between the years 2005-2008 and 2008-2012. The following conclusions are made based on Figure 2.16.

- Between the years 2005-2008 more accretion than erosion occurred.
- After 2008 erosion becomes dominant in this area. It seems like the line of 2005-2008 has shifted downwards which mean that the longshore transport rates has increased with the same factor along the coast of the Island of Mussulo.
- Considering the timespan 2005-2012 most areas of the Island of Mussulo seems to be stable. Around $3.9{\cdot}10^4$ and $5.6{\cdot}10^4$ m erosion occurs.

Submerged shoal

The submerged shoal was formed between 1880 and 1949. In the last 60 years no large scale change where seen. Still small scale features might occur. In order to investigated this aerial images, taken from Google Earth, of the year 2005 and 2013 are compared. The location of the sandbars are shown in Figure 2.17. With the help of a simple calculation the amount of sediment transported per year by the sandbars are calculated. The width of a sandbar is taken and multiplied with the distance a sandbar shifts per year. This is multiplied with the height of a sandbar for which two values are taken a minimum depth of 1 m and a maximum depth of 2 m. The amount of sediment transport due to these sandbars are shown in Figure 2.17. From a dredging company it is known that an amount of 10,000 to 20,000 m^3 is dredged yearly to maintain the depth of the channel.

Island of Luanda

The Island of Luanda has been modified extensively during the last decades. Starting from the 1970's groynes were built and the northern tip was fixed. The following conclusions are drawn from Figure 2.16:

- The entrance of the lagoon (around $7.50{\cdot}10^4$ m in is stabilized by the construction of a jetty at the north side of the entrance to the lagoon. This has led to a decrease in the longshore transport rates and therefore accretion in the coastal area of the lagoon.

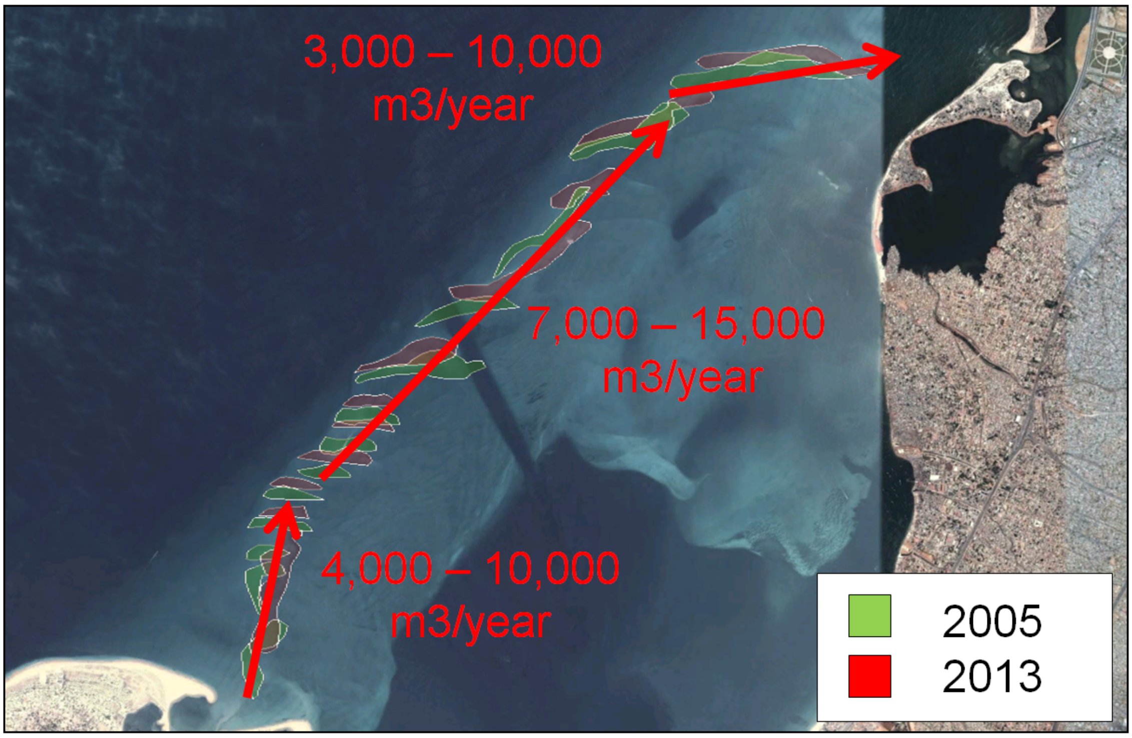

Figure 2.17: Sandbars at the submerged shoal for two different aerial images. In red the location of the sandbars in the year 2013. In green the location of the sandbars in the year 2005. The red arrows indicates the direction of the moving sandbars.

- New groynes were constructed along the coast (around $7.55{\cdot}10^4$ m until $7.70{\cdot}10^4$ m in Figure 2.16) which reduce the longshore transport rates and cause sediment to settle in these areas.
- There are two nourishment areas (around $7.95{\cdot}10^4$ m until $8.15{\cdot}10^4$ in Figure 2.16). Sediment is transported to the north during the year 2012 which explains a wider accretion area.
- Due to human intervention (nourishment, construction of groynes and stabilizing the lagoon) accretion occurs along the Island of Luanda.

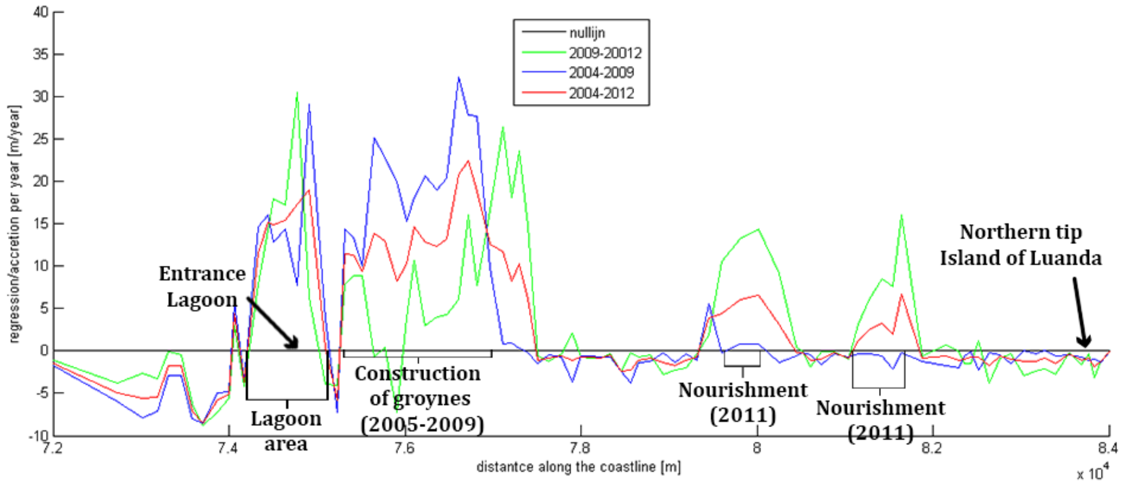

Figure 2.18: Yearly regression (positive)/accretion (negative) rates for area 3 in Figure 2.14.

2.4 Theories applied for coastal characteristics

To understand the global behaviour of a coast basic understanding of coastal processes is needed. This chapter will elaborate on that by introducing hydrodynamics and morphodynamics processes in the coastal zone.

2.4.1 Coastal hydrodynamics

Waves which propagate from deep into shallow water undergo several processes such as diffraction, refraction and shoaling. Where shallow water is defined as the area where the wavelength is two times larger compared to the depth. These processes are important for understanding the behaviour of the coastal area.

Shoaling

As one may know, surface waves increases in height when travelling from deep into shallow water. This phenomenon is called shoaling and is caused by the change in group velocity which is related to the change in water depth. Wave energy transport decreases with the reduction of water depth. This decrease in transport is compensated by an increase in energy density in order to maintain a constant energy flux. Shoaling is limited by dissipation induced by wave breaking.

Refraction

Waves approaching underwater contours at an angle will tend to approach the coast more perpendicular. Sections of the wave in deeper water will travel faster than the section in shallower water better known as refraction. Due to the coastline orientation of the Luanda area waves will refract towards the coast. At the Luanda area waves are mainly from the SW to SSW. These waves will be forced to approach the coast perpendicular. Though it is not expected for waves to adjust completely it is expected that an angle between the wave direction and the normal of the coastline will occur along the coastal stretch. The incoming waves will induce sediment transport due to this angle of incidence.

Diffraction

Turning of waves into the sheltered region of a surface piercing obstacle (e.g. breakwater or an island) is called diffraction. The impact of this effect is proportional to the wavelength i.e. a larger wave length leads to a larger spreading effect. Diffraction will have effect on the way waves will travel into the Bay of Mussulo and the Bay of Luanda.

Wave breaking

Shoaling forces waves to increases in height. Waves will increase in height until they start to break. Wave breaking occurs when wave crest becomes unstable due to exceeding of the velocity of the wave crest by the particle velocity.

2.4.2 Coast classification

The Luanda coast can be classified by means of different characters such as the beach state and the continental shelve width. This section will elaborate on the type of coast the Luanda area is.

Continental shelve width

The continent Africa lies in the middle of a continental plate. Due to the relative few mountains compared to North America less material can be transported towards the ocean. The edge of the coast of Africa is therefore called an Afro trailing edge coast. According to Bosboom and Stive [2012] the main feature is a coast which is trailing at both sides of the continent. Basic features are pronounced continental shelves and coastal plains.

The relationship between mean tidal range and wave height is an indication of the coastal character as determined in Hayes [1980] and Davis and Hayes [1984] e.g. tide dominated flats occur for large tidal ranges and small wave heights. The relative importance of tide and waves determines the coastal character, not the absolute tidal range. Davis and Hayes [1984] determined five different classes as shown in Figure 2.19. With an averaged significant wave height Hs of 1.25 m (between 1 and 1.5 m according to Deltares [2013]) and a mean tidal range of 1.05 m the coast shows a wave dominated character.

The relative strong wave climate is responsible for a strong alongshore transport and can also be seen as an incentive for spit formation, spit formation will be discussed later in this chapter.

Beach state

Micro tidal beach systems are assumed to be wave dominated, which have a low tide range that has a minor to negligible role in determining beach morphology [Short, 1996]. Shoaling surf and swash zones are assumed to be stationary. Beach types are defined by Masselink and Short [1993] by using the fall velocity:

$$\Omega = H_{\mathrm{b}}/w_{\mathrm{s}} * T \tag{2.1}$$

In which H_{b} is breaker wave height in m, w_{s} is the sediment fall velocity in m/s and T is wave period in sec. The classification is as follows:

- Ω >6, are called dissipative beaches characterized by fine sand, high wave energy and preferable short wave periods
- 1 >Ω >6, are called rip dominated intermediate beaches characterized by moderated to high waves, fine to medium sand and longer wave periods
- Ω <1, are called reflective beaches characterized by medium to coarse sand, low wave energy and is favoured by ong wae periods

The fall velocity is extracted from Figure 2.20 which shows a w_s of 0.025 m/s. A H_b of 1.25 is used with a period of 10 s. The coastal beach can be characterized as a rip dominated intermediate beach, tending to a dissipative beach, with a Ω of 5.

2.4.3 Formation of spits

Spits are morphological features which are typically formed when a coast makes a sudden change in orientation. According to Bosboom and Stive [2012] spits develop where the longshore transport capacity is diminished. The transport capacity is lost and sediment is able to settle, forming elongate spits, which grow in the direction of the predominant longshore drift. The main processes are wave induced alongshore and cross-shore sediment transport

Alongshore processes

Several theories are presented in order to explain spit formation. A possible situation is based on the erosion or accretion of a coast which occurs if gradients are present in the alongshore sediment transport. A decrease in gradient will lead to sediment accretion and an increase in gradient will lead to sediment erosion. According to Zenkovich et al. [1967], as shown in [Petersen et al., 2008], a spit is aligning at an equilibrium orientation. Zenkovich states that a spit will tend to bounce back to the equilibrium orientation i.e. when a spit moves towards the mainland the alongshore sediment decreases and sediment accumulation occurs and the spit will tend to bounce back, from P2 to P1 in Figure 2.21. Zenkovich concludes that the deposition necessary for the growth of a spit will only take place if the wave angle relative to the x-axis is larger than approximately 45°.

Instabilities of sediment drift ([Ashton et al., 2001] taken from Dan [2008]) can also be a cause of the formation of spit shape shoreline features. Under relative large offshore incidence angles irregularity on an uniform coast, a relatively straight coastline, can grow under a constant wave climate because of a positive feedback process. This concepts is also shown in sector A-B in Figure 2.21. This process may lead to the formation and development of spit-like coastal features which grows in an approximately cross-shore direction.

Cross-shore processes

Cross-shore transports reshape a spit constantly. Due to over-wash and wave action sediment erosion occurs at the sea side and deposition occurs at the bay side of the a spit if the width of a spit is not large enough.

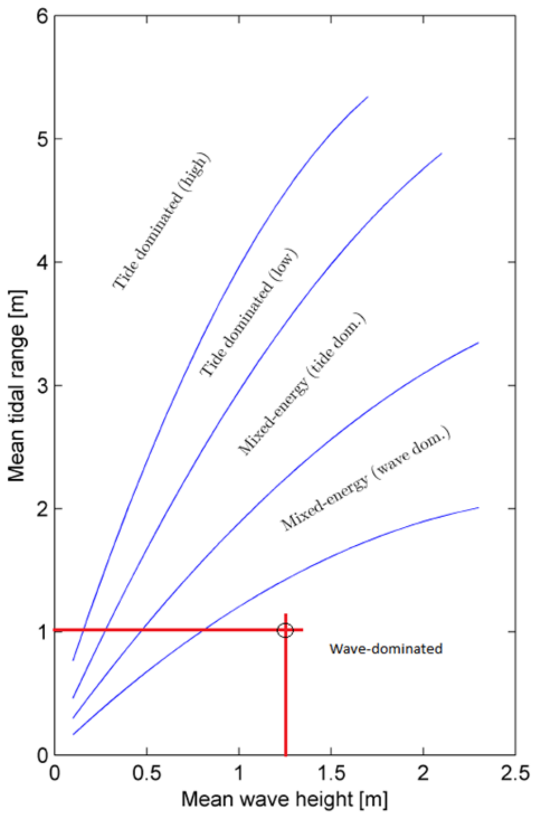

Figure 2.19: Relationship between mean tidal range and wave height. Taken from Bosboom and Stive [2012] adapted from Davis and Hayes [1984]

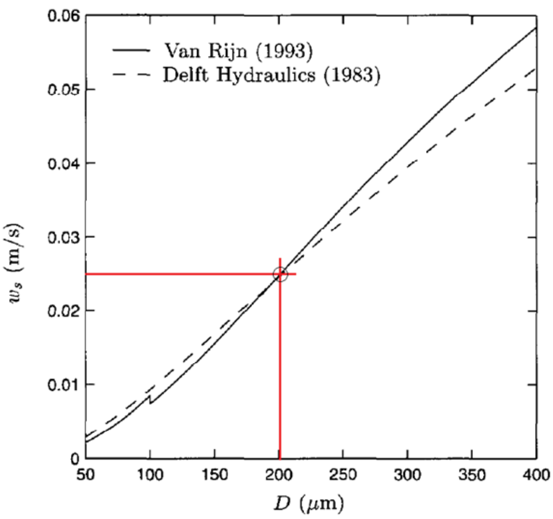

Figure 2.20: Fall velocities of sediment for fresh water with a temperature of 18°C determined with fall velocity formula of Van Rijn [1993] and Delft Hydraulics [1983] modified from Sistermans and van de Graaff [2002]

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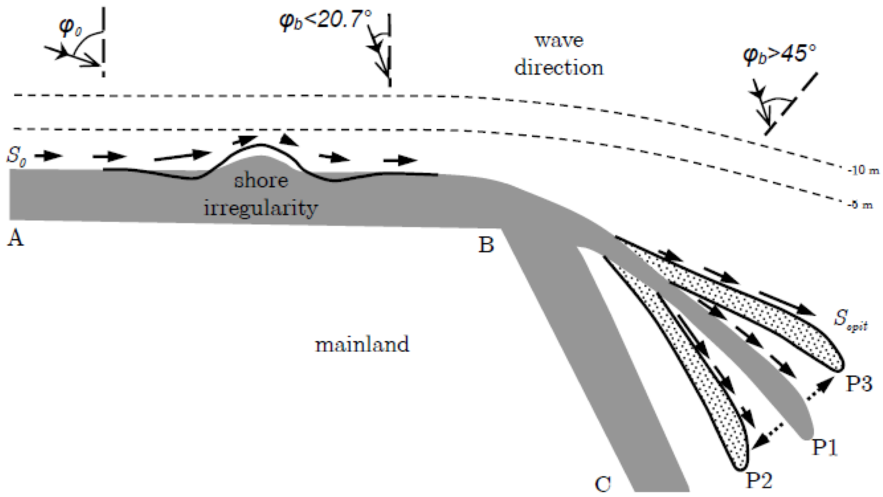

Figure 2.21: The generation (left side, modified after Ashton et al. [2001]) and the equilibrium position (modified after Zenkovich et al. [1967]) for a sand spit. The depth contours are parallel to shoreline for the sector A-B and not parallel to shoreline for the sector B-C. The wave angles φ_0 and φ_b correspond to offshore and breaking line position, respectively. The black arrows indicate the alongshore transport and their length is proportional with the transport magnitude. Taken from [Dan, 2008]

Chapter 3

Sediment transport of the various coastal areas

In this chapter the sediment transport of the various coastal areas are analysed. At first, the sediment transport between the Kwanza River and the tip of the Island of Mussulo is investigated. This is done with the one line model software package UNIBEST-CL+. Secondly, the sediment transport along and over the shoal between the Island of Mussulo and the Island of Luanda is investigated. This is calculated with the help of a tide model and with UNIBEST-CL+. Hereafter the sediment transport along the Island of Luanda is analysed with the help of UNIBEST-CL+. This chapter will end with a validation of the UNIBEST-CL+ model.

3.1 Model type

As seen in the previous section the Luanda coast is described as a wave dominant coast which indicates that waves are dominant over the tides. Longshore sediment transport rates give an indication whether accretion or erosion of a coast takes place. An one-line model, as described by Pelnard-Considère [1956], is often used to predict long time scales. As such an one line model is chosen to simulate the longshore sediment transport. The UNIBST-CL+ software package is often used for wave dominant coasts.

3.1.1 UNIBEST-CL+ software package

In this section the UNIBEST-CL+ software package is briefly explained and discussed. Longshore sediment transport capacities are modelled with the software package UNIBEST-CL+ which makes use of the one-line model principal as described by Pelnard-Considère [1956]. UNIBEST-CL+ determines the sediment transport capacities with a so called S-ϕ-curve. The S-ϕ-curves are used to determine the shoreline changes.

Wave-induced longshore sediment transport

One-line models are often used in order to get a first insight in the basic behaviour of a coast. It is often used to predict the morphological changes due to hydrodynamic processes occurring over a longer period. UNIBEST-Cl+ is a powerful tool to model longshore sediment transport and morphological changes of coastlines. This section will briefly handle the UNIBEST-CL+ model by describing important input and output parameters. A more detailed explanation can be found in Appendix A.

UNIBEST-CL+ is an acronym for **un**iform **be**ach **s**ediment **t**ransport and is used to model coastline changes along a coast on wave dominated longshore uniform coasts. It is developed by WL Delft Hydraulics nowadays known as Deltares. UNIBEST-CL+ consist of two modules.

- The Longshore Transport module (LT-Module); computes and schematizing the longshore sediment transport separately for a cross-shore profiles along the coast.
- The CoastLine module (CL-Module); The CL module models the coastline change after a certain time step. The output of the LT-module for a predefined cross-sections are used as an input in the CL module.

UNIBEST-LT+ Module

The setup of the LT module requires input parameters such as wave data, bathymetry and sediment characteristics.

Nearshore wave data

Wave data is modelled with SWAN (**S**imulating **WA**ves **N**earshore) also known as Delft3D-WAVE. SWAN is used to set-up a numerical wave model to calculate the nearshore wave conditions. SWAN makes use of nested grids, in this case four types of grids, to acquire the needed resolution in the area of interest. On the largest grid boundary conditions are used which are acquired from ERA-Interm (ERAI)data generated by the European centre for medium range weather forecast. The dataset has a timespan starting at the year 1979 and is still on-going. The model is compared with the WANE2 dataset which lies in the largest grid. More information can be found in Appendix B.

Bathymetry

Bathymetry data is needed for setting up the SWAN model and to determine the coastal profiles for the LT module. Multiple datasets are used which combined represent the bathymetry for the Luanda area. The following bathymetry data is used:

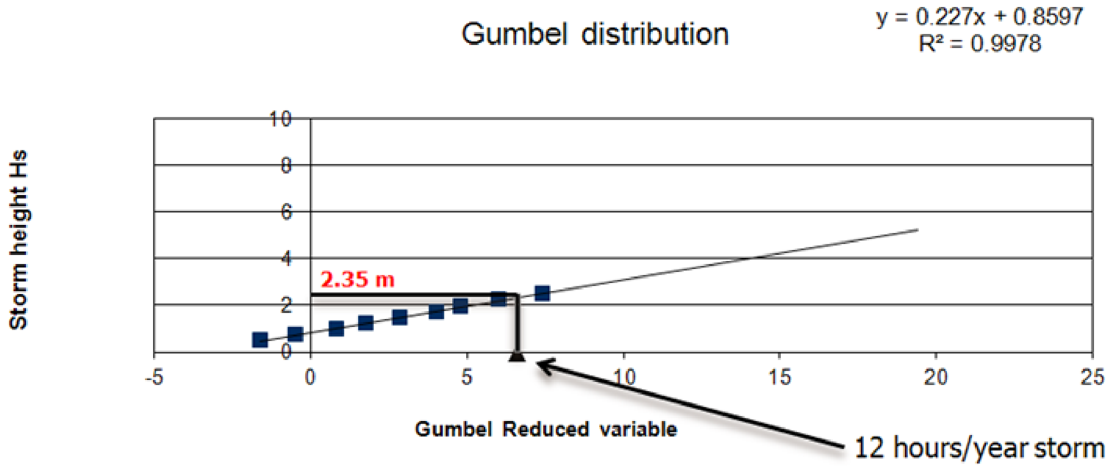

Figure 3.1: Gumbel distribution of the significant wave height used to determine the closure depth.

- GEBCO08; which is extracted from the OpenEarth tool "Delft Dashboard". For the bathymetry the GEBCO08 database is used. GEBCO is an international reference map of the sea-floor depth of the worlds oceans. It is produced under the auspices of the Intergovernmental Oceanographic Commission and the International Hydrographic Organization. GEBCO08 is a global 30 arc-second grid. In which the world (sphere) is divided into 360 degrees where each degree is subdivided into 60 minutes and every minute into 60 seconds. Therefore 30 arc-second is equal to 30/3600th of a degree.
- Admiralty Charts; in order to get a better insight in the contour lines Admirality Charts is used to improve bathymetry data.
- C-map; C-map data collected for the Luanda area is used to increase bathymetry detail at certain areas.

Sediment characteristics

The most accurate available data in this area is found in the report of Scott and Wilson [2005]. In here a D_{50} of 200 μm is taken as an average for the entire Island of Luanda. No sediment samples are available for the Island of Mussulo. The sediment characteristics found at the Island of Luanda are also used for the Island of Mussulo.

Closure depth

Beach profiles are extended to reach a depth which matches the location of the seaward boundary (dynamic boundary) which is the closure depth separating the active and inactive zone. A basic rule of thumb states that the closure depth is around 2 to 3 times the highest H_s. Considering a H_s of 2 m, as found in Scott and Wilson [2005], in this area the closure depth is set to 6 m. A more accurate approach to calculate the closure depth is to define the 12 hours per year storm and multiply this with 1.57 [Hallermeier, 1983]. The 12 hours per year storm is calculated with a Gumbel distribution as shown in Figure 3.1. A closure depth of 3.7 m is calculated. Compared to the rule of thumb, which is often used, the calculated closure depth is considered to be relative low. As a first estimation the rule of thumb is used and with a sensitivity analysis the difference between the calculated closure depth and the rule of thumb is investigated.

Sediment transport formulas

There is a variety in sediment transport formulas which can be used in the LT module. The two sediment transport formulas used in this report are Bijker and CERC. CERC is chosen as it is used to compare sediment transport capacities in similar studies such as Scott and Wilson [2005] and Wallingford [2011]. CERC is a bulk formula which does not take into account the characteristics of sediments. The alongshore sediment transport rate depends only on the alongshore component of energy flux in the surf zone. CERC assumes the conservation of energy flux in shoaling waves, using the small amplitude theory and than evaluate the energy flux in the surf zone. Unlike CERC, Bijker does include characteristics of sediment such as grain size and fall velocity of the sediment. Bijker is often used within Deltares and has therefore gained a certain trust. By integrating the product of the concentration and velocity profiles along the vertical the suspended load and bedload are calculated.

Beach profile

Bathymetric data near the beach is not accurate enough to determine the beach slopes needed for the LT module. In order to calculate the longshore sediment transport (LST) a so called Dean profile is used as described in Dean [1991]. The coastal profile tends to have an average characteristic form also called a theoretical equilibrium profile. The equilibrium profile has been defined as "a statistical average profile, which maintains its form apart from small fluctuations, including seasonal fluctuations". The depth in the equilibrium profile increases exponentially with the distance x in meters from the shoreline according to the equation. The depth d in meters is defined as follows:

$$d = A \cdot x^m \tag{3.1}$$

In which A is the dimensionless steepness parameter which is related to the sediment fall velocity and m is a dimensionless exponent of which Dean [1991] has suggested an average value of 0.67. The Dean profile definition is used in this model as detailed up to date bathymetric data is not available.

subsections

The model is divided into three distinct coastal areas.

- Area one; Kwanza River till the end of the Island of Mussulo. This area starts at the Kwanza River till the end of the Island of Mussulo.
- Area two; submerged shoal. The submerged shoal has a different interaction with the surrounding compared to Area one. Besides waves, the tide is also expected to have influence on sediment transport in this area.
- Area three; the Island of Luanda. The Island of Luanda has highly been influenced by human interventions. Multiple groynes are constructed and the tip of the Island of Luanda has been fixed.

The different areas are chosen based on expected related hydrodynamics.

3.2 Area one; Kwanza River till the end of the Island of Mussulo

This section will cover the coastal area starting at the Kwanza River till the tip of the Island of Mussulo. The UNIBEST-CL+ software package is used to calculate the longshore sediment transport and will first be discussed briefly after which the relevant wave conditions, extracted from the SWAN model, are analysed. With help of the UNIBEST-CL+ model the longshore sediment capacities along the coast between the Kwanza River and the Island of Mussulo are determined and a sediment budget is made.

3.2.1 Wave-induced longshore sediment transport capacity

Wave data is extracted from the SWAN model for 15 locations at the 8 m depth contour line along the Island of Mussulo, shown in Figure 3.2(a). The extracted wave data consist of 58 wave conditions which represent a whole wave pattern of a year. The wave data is used as an input in the UNIBEST-LT module in order to calculate the LST. The LST capactity varies per conditions. Which wave condition is important, i.e contributes more to the LST capacity, is investigated.

For every ray and every wave condition the LST capacity is calculated. The relative contribution of each wave condition (rel.LST) is calculated by taking the LST capacity of wave condition [n,m] (in which n is the ray number, and m the wave condition number) and divide this by the sum of all LST capacities in ray n. The absolute contribution of each condition is the LST capacity at a specific condition.

$$rel.LST_{(\mathrm{n,m})} = \frac{abs.LST_{(\mathrm{n,m})}}{\sum_{m=1}^{58} abs.LST_{(\mathrm{n,m})}} \tag{3.2}$$

The results are shown in Figure 3.2. Looking at the relative sediment transport per condition it is shown that the wave conditions which have a duration of 3 days or longer are dominant in inducing LST, as these have the most LST capacity in percentage, compared too the durations which occur less then three days. When looking at the absolute sediment transport per condition the southern rays have a higher LST capacity compared to the north. This is as expected as the wave height reduces in northern direction. A lower wave height will result in less stirring up of sediment and therefore less sediment to be transported, i.e. reduction in LST capacity.

Wave height, wave period and direction

A similar analysis as for the wave conditions is made but now related to the wave period, wave height and direction. The results are shown in Figure 3.3. It is concluded that the wave height is reduced from the south to the north and waves which induce sediment are rotating, due to refraction, clockwise in the north compared to the south.

The LST capacity determined with the Bijker sediment formula for the most northerly area (northern part of the Island of Mussulo, Ray 13-15) has very low values. Especially compared to the CERC formula. As a check a sensitivity analysis is made in which the cause of these low values is determined to be a combination of very steep slopes, on average 1/20, and low significant wave heights. More information can be found in Appendix A.

3.2.2 Wave-induced longshore sediment transport

With help of UNIBEST-CL module a computation for the sediment budget is made for the Island of Mussulo. In Figure 3.4 the longshore sediment is shown for the entire coastal stretch as calculated with the CERC and Bijker sediment formula. The CERC calculation has a larger LST compared to the Bijker calculation. The trend of the LST is from Ray 1 until Ray 9 similar for Bijker and CERC. Both calculations have a small gradient. From Ray 9 to Ray 15 the decrease in LST is larger for CERC compared to Bijker, as the level of erosion/accretion depends on this the CERC calculations will have more accretion in this area compared to the Bijker calculation. This is also confirmed in the middle graph of Figure 3.4 which shows the coastline changes in 50 years along the coast calculated with CERC and Bijker. As validation is difficult due to the limited availability of data the sensitivity of the input parameters is important. As such a sensitivity analysis has been made in order to get an insight in the robustness of the model. This is only done for the LST capacity calculation of the Bijker sediment transport formula as it includes parameters which have a certain degree of uncertainty. The CERC sediment formula has less input factors and is therefore not expected to differ much from the outcome which is calculated already. The input parameters

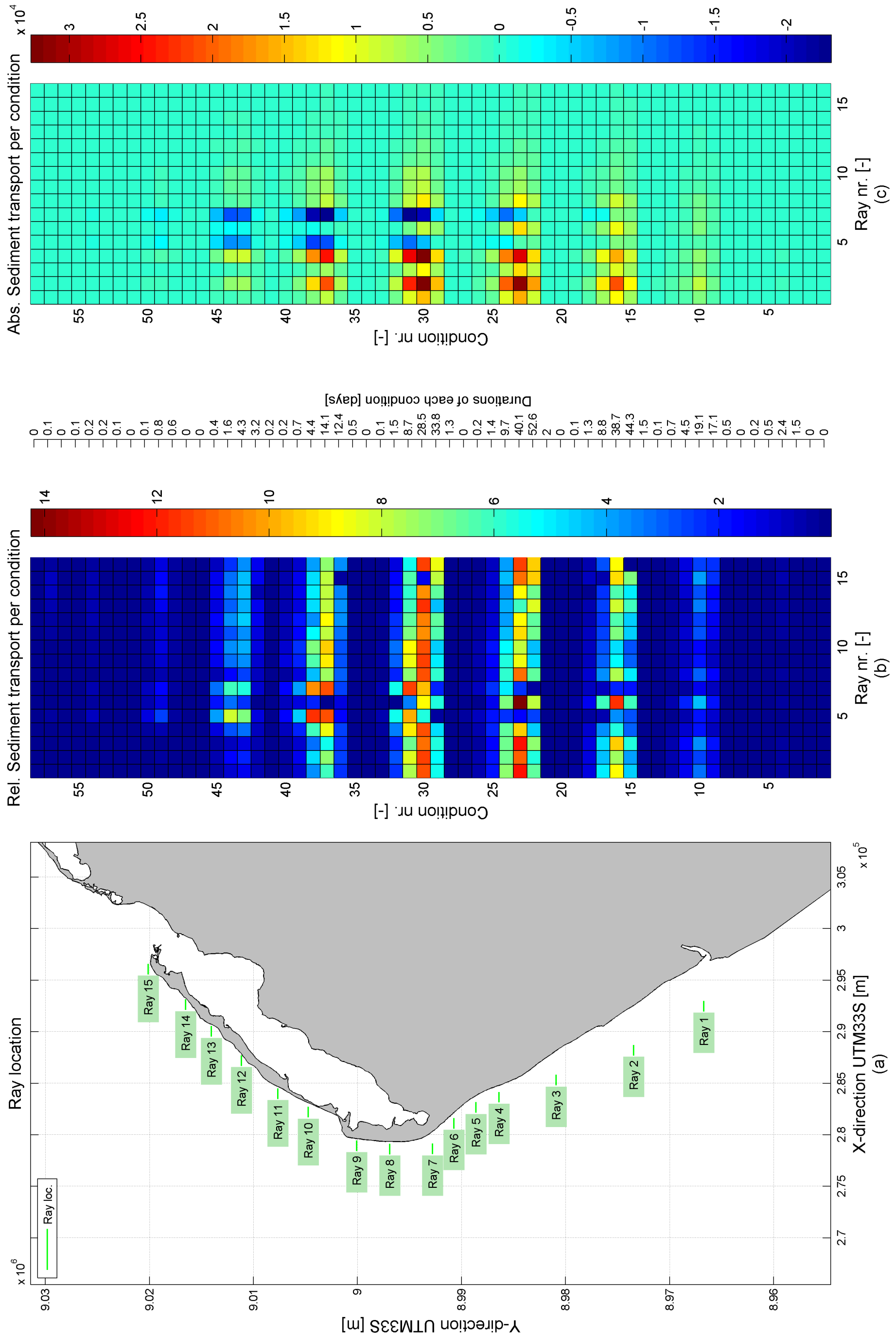

Figure 3.2: Wave conditions for different rays. Each ray represent a location over which the LST is modelled. An overview of the area is shown in (a). Relative sediment transport shown in (b) is relative over a ray number. Figure (c) shows the absolute sediment transport per condition.

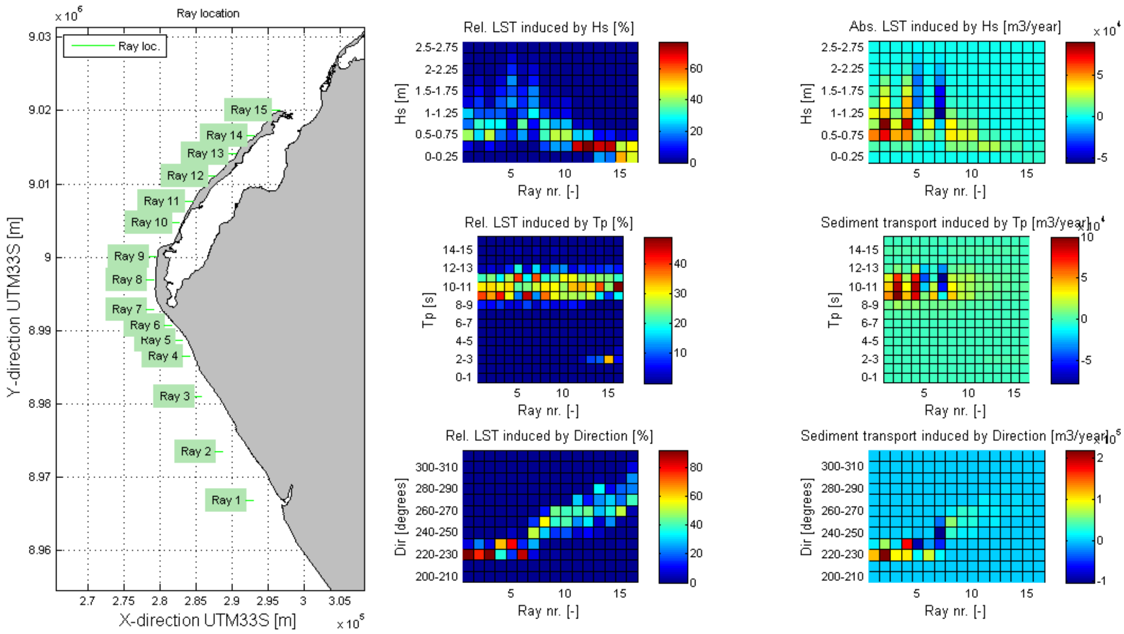

Figure 3.3: Longshore sediment transport capacity related to the wave period, wave height and wave direction.

are differed with 30 percent and the outcome is compared to the base case. Furthermore the calculated LST at the northern tip of the Island of Mussulo matches with other studies.

The outcome of this analysis shows that the fall velocity and the D_{50} are the most sensitive parameters in this model. With the help of this sensitivity analysis an upper limit and a lower limit is defined. Overall the upper limit is 1.9 times the base case and the lower limit is 0.5 times the base case. A sediment budget is made with the different limits of Bijker and the CERC sediment transport formulas, which is shown in Figure 3.5. A more detailed explanation about the sensitivity analysis is described in Appendix A.

3.2.3 Validation

To validate the model made with UNIBEST-CL+ the outcome of the coastline changes per year is compared with observations as observed on aerial images obtained from Google Earth used in Chapter 2. The changes in coastline for a certain timespan is shown in Chapter 2.3.2. The data is smoothed in Figure 3.6 (a) to show the large scale trend. In Figure 3.6 (c) the outcome of the model considering the coastline changes per year is added together with the smoothed Google Earth observation.

The coastline changes observed with Google Earth shows higher rates compared to the rates calculated with Bijker and CERC. No obvious reason is found for this difference. Note is made regarding the Google Earth observations which may have an error due to the short timespan on which the coastline changes are based on. Also no tide compensation was done.

Furthermore the spit grown in the last decade is compared with the outcome of the model. The spit end grows with $21{\cdot}10^3$ to $65{\cdot}10^3$ $m^3/year$ as is shown in Chapter 2.3.2. The LST in the northern part of the Island of Mussulo must be sufficient to provide this amount of sediment to the spit tip for letting the spit grow. The most northern part shows a LST of $65{\cdot}10^3$ $m^3/year$ (CERC) to $2{\cdot}10^3$ $m^3/year$ (Bijker), see also Figure 3.5. The CERC sediment formula fits better considering the sediment accumulation of the spit tip compared to the Bijker sediment formula.

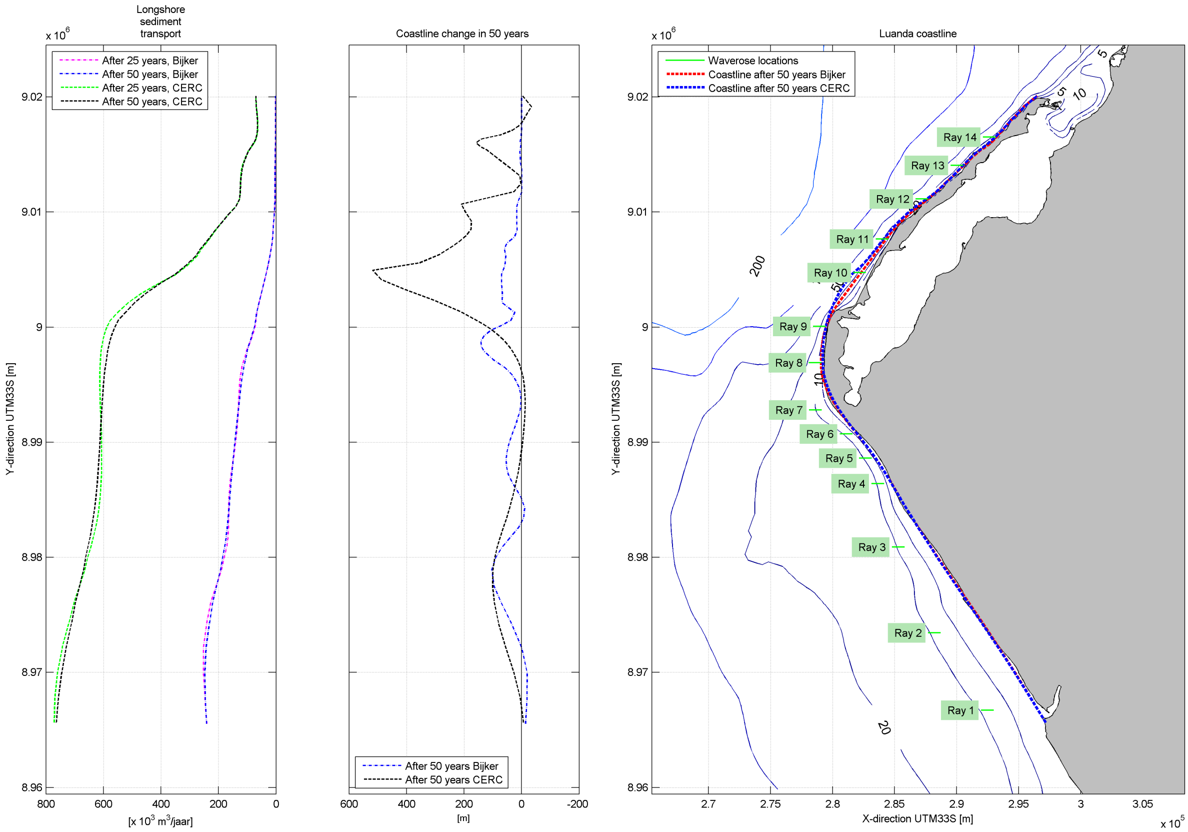

Figure 3.4: Longshore sediment transport calculated with Bijker and CERC. Left: Longshore sediment transport along the coast in $10^3\ m^3/year$. Middle: Coastal change along the coast in meters per 50 years. Right: Overview of the area with in the south the Kwanza river and in the north the opening of the Bay of Mussulo.

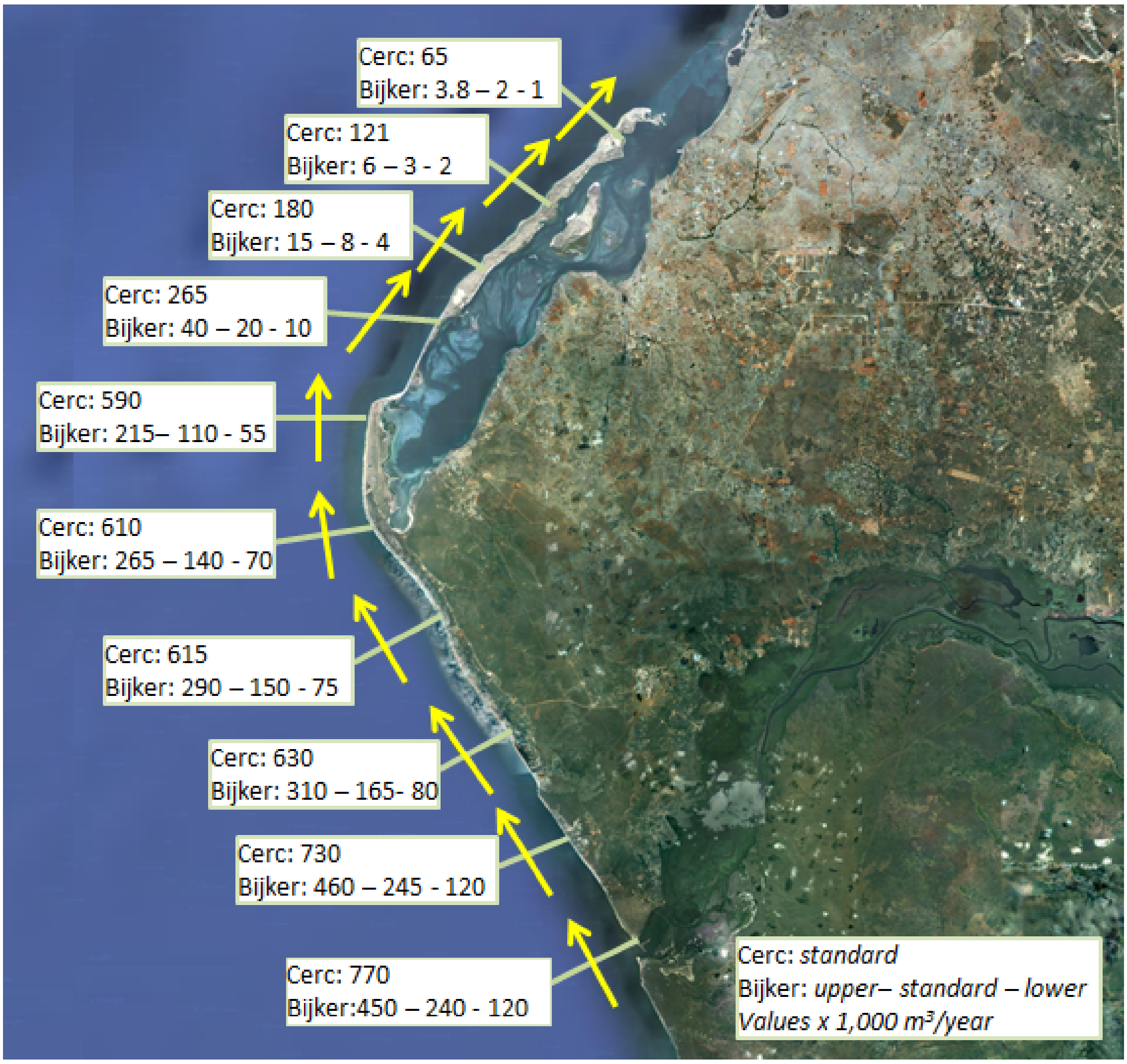

Figure 3.5: Sediment budget made with UNIBEST-CL+ model outcome for the Island of Mussulo. Values are in 1,000 $m^3/year$

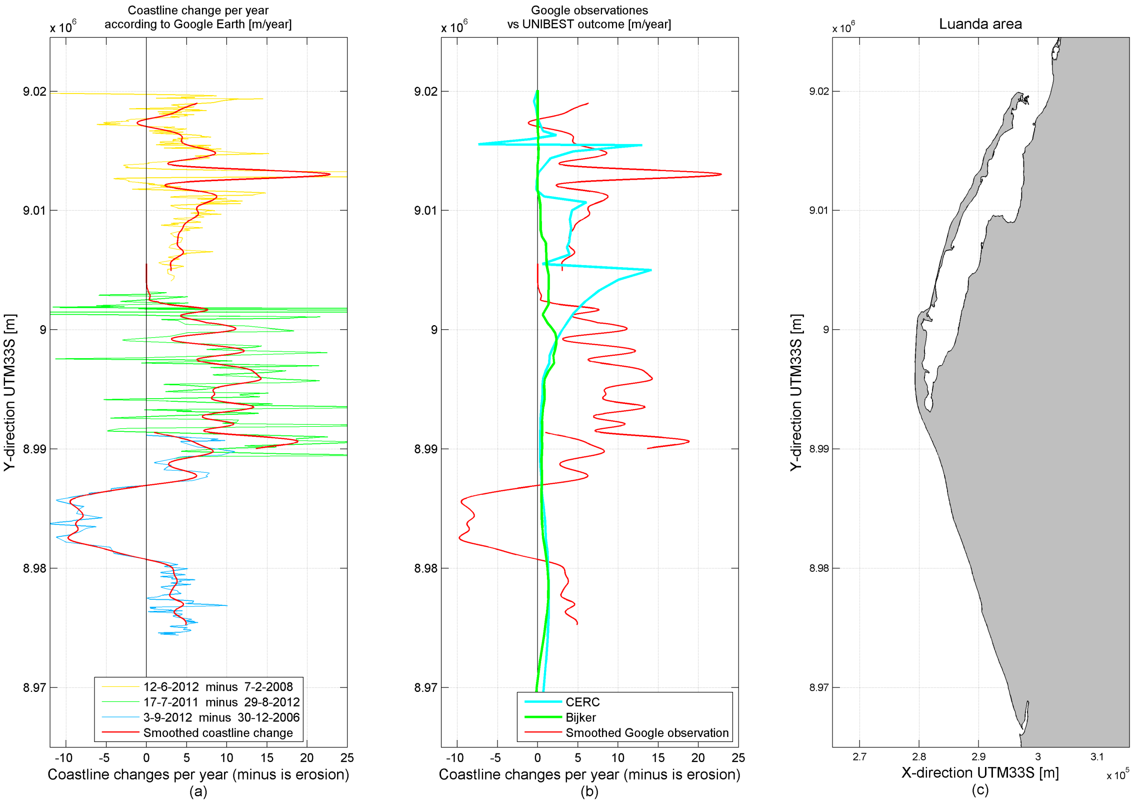

Figure 3.6: The coastline change per year calculated with the UNIBEST model compared to the observation made with Google Earth. Left: The coastline change observed with aerial images obtained from Google Earth. Middle: Coastline changes obtained with Google Earth compared to the coastline changes modelled with UNIBEST-CL+. Right: Overview of the area.

3.2.4 Conclusion and discussion

A one-line model is simulated with UNIBEST-CL+ for the area between the Kwanza River and the tip of the Island of Mussulo area. The main conclusion are:

- Only the wave conditions which last a couple of days or more have a significant effect on the sediment transport capacity.
- The wave height is reduced in northern direction starting at 0.5-1.25 m to 0-0.5 m
- The direction of the incoming waves is rotated clockwise starting at 225° in the south to 280° in the north.
- The period of the waves stays between 8-12 s.
- The longshore sediment transport is decreasing from north to south.
- Validation is done by comparing coastal changes observed with Google Earth images and coastal changes modelled with UNIBEST-CL+. No clear similarities could be extracted from this analysis.

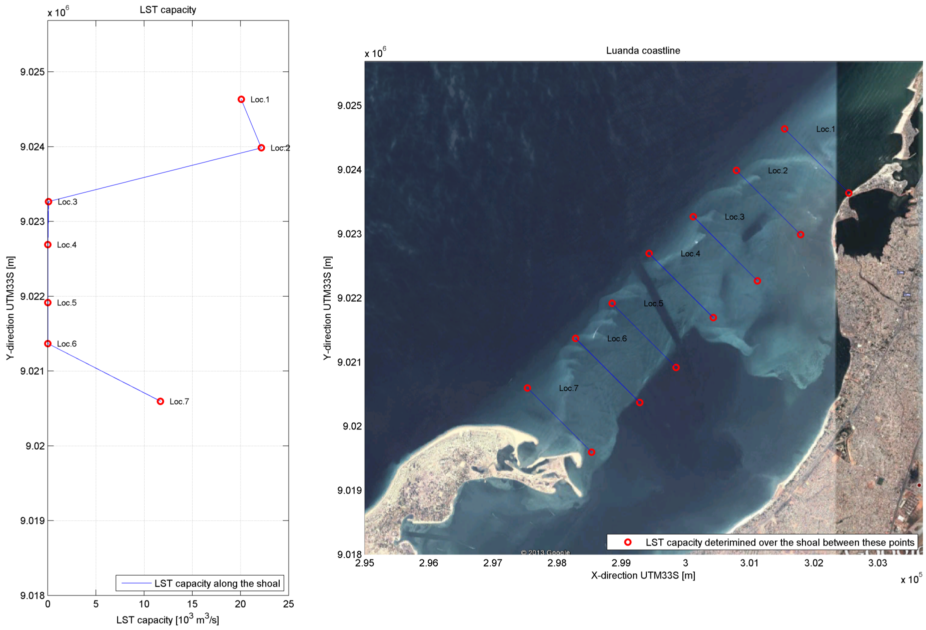

Figure 3.7: LST capacity determined with the LT module of the UNIBEST package. Left: the longshore sediment transport capacity at different cross-sections. Right: Overview of the locations of the different cross-sections.

3.3 Area two; submerged shoal

The submerged shoal is located in area two. Sediment transport is expected to be transferred from the Island of Mussulo to the Island of Luanda via the submerged shoal. This is investigated by modelling the longshore sediment transport rates at the submerged shoal. Firstly the longshore sediment transport is calculated with the UNIBEST-CL+ model as is done with area one. Secondly, a tide model is used of which the tide induced currents are used as an input for the Soulsby van Rijn sediment transport formula, as described in Soulsby [1997].

3.3.1 Wave induced sediment transport

The LT module is set up just as the other models only now for the locations which are shown in Figure 3.7. In total seven cross-sections at the shoal are used to calculate the LST. The orientation which is used to determine the LST is derived from Google Earth and set as such that a cross-sections is perpendicular to the main orientation of the shoal. The LST capacity varies between $0.1 \cdot 10^3\ m^3/year$ in the middle of the shoal to $15{\cdot}10^3\ m^3/year$ to $20{\cdot}10^3\ m^3/year$ in the northern and southern area of the shoal. The difference between the LST in the middle area and the areas at location 1, 6 and 7 are due to the fact the depth at these locations are up to the beach and, as seen in the LT-module, most of the sediment transport capacity is formed in the area where the water depth is 1.5 m or less. The minimum depth in the middle at the shoal is around 2 m or more which explains the difference in LST capacity. As the UNIBEST model only takes wave induced currents into account it is missing currents induced by tide. It is expected that at the shoal some sediment will be transported by these tide induced currents. In order to investigated a tide model is used and combined with the Soulsby van Rijn sediment transport formula to calculated these transports.

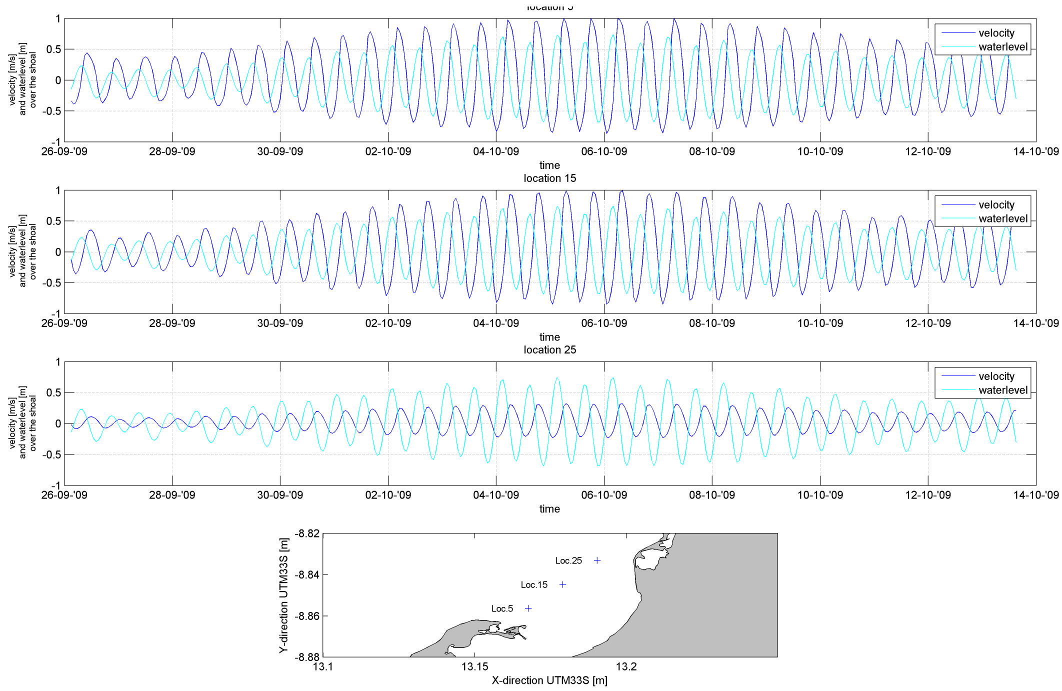

Figure 3.8: Water level and velocity during one spring-neap cycle. For shoal locations 5, 15 and 25, as shown in the lower figure.

3.3.2 Tide induced sediment transport

To predict sediment transport over the shoal a tide model as used in the report of Deltares [2013] is used in order to calculate the flow velocity during a tide over the shoal. The tide model used is part of a nation wide model to describe the tide along the Angola coast. The model uses the new computational core of Delft3D, called D-Flow FM (FM stand for Flexible Mesh). D-Flow FM has certain advantages, one of them is that D-Flow can easily be extended by locally applying a high resolution without affecting the resolution in the offshore areas. The tidal boundary conditions are extracted from the global tide model TPXO 7.2, consisting of 13 varying constituents. Bathymetric data are obtained from the global GEBCO database. More detailed information is found in Appendix C.

In Figure 3.8 the velocity and the water level are plotted for several locations along the shoal. For all locations the horizontal tide, which represent the velocity, is lacking compared the vertical tide, which is represented by the water level. There is a phase lag of about 3 hours.

Soulsby van Rijn sediment formula

The location of the cross-sections are similar to the cross-sections as used in Figure 3.7. The sediment transport is calculated for four locations per cross-section. Over a cross-section sediment transport will vary due to varying water depths. The sediment transport profiles over the shoal are investigated to determine which part of the shoal is responsible for sediment transport. The sediment transport formula is calculated with:

$$q_t = A_s \bar{U}[(\bar{U}^2 + \frac{0.018}{C_D} U_{rms})^{0.5} - U_{cr}]^{2.4}(1 - 1.6 tan\beta) \quad (3.3)$$

In which the tide induced velocity ($\bar{U}$), as extracted from the tide model, is used as the transport velocity. The concentration of sediment in a water column is determined by a combination of the wave orbital velocity (U_{rms}, extracted from the SWAN model) and the velocity of the tide ($\bar{U}$).

The results of the model are shown in Figure 3.9. On the left graph of Figure 3.9 the longshore sediment transport are shown. Positive value on the x-axis means transport in north east direction. At all locations along the shoal the longshore sediment transport is in north east direction. In the middle graph of Figure 3.9 the sediment transport in cross-shore direction is shown. Positive on the x-axis means landwards, negative means seawards. The results shows a mainly negative sediment transport value which indicates that sediment is transported in north west direction.

Values in both direction, longshore and cross-shore, are low. Taking the sum of both sediment transport axis for a location results in a net sediment transport in northern direction. This mechanism could feed the sandbars at the seaside with sediment but there is not enough sediment transport to fully explain the shifting sandbars.

3.3.3 Conclusion

Wave induced sediment transport calculated with UNIBEST-LT module are low in the order of 100 $m^3/year$. Tides are expected to have influence on the sediment transport at the shoal, therefore a tide model is used in order to calculate tide induced velocity. Sediment transport induced by tides are limited, but could (partly) feed the sandbars at the seaside with sediment.

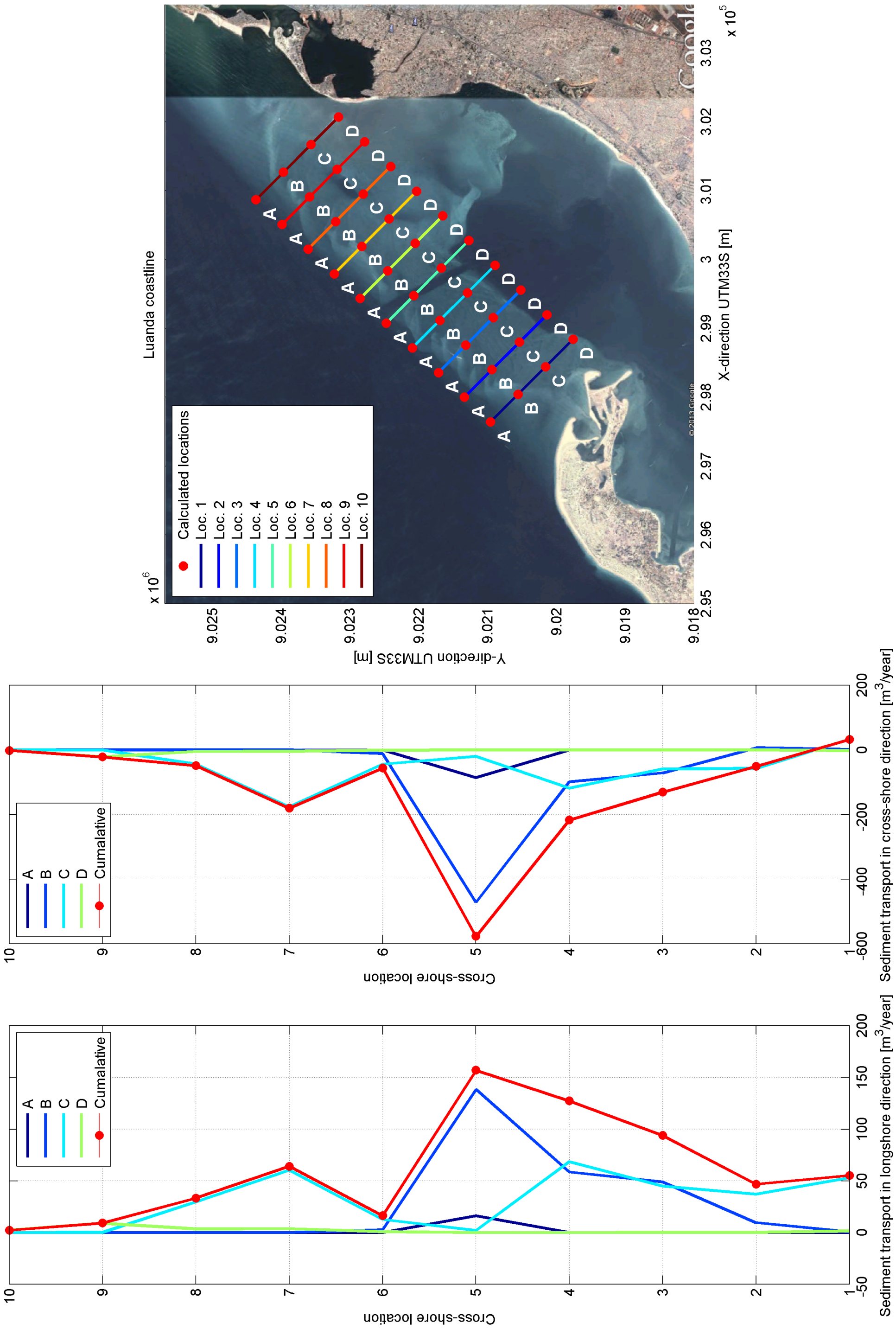

Figure 3.9: Sediment transport modelled for different locations in cross-shore and longshore direction. Left: Longshore sediment transport. Middle: Cross-shore sediment transport. Right: overview locations.

3.4 Area three;the Island of Luanda

This section will cover the analysis of the Island of Luanda in which firstly the wave climates of the SWAN model are analysed in order to determine the important wave conditions. After which the sediment transport capacities will be modelled with UNIBEST-CL+ which will be used to determine the sediment budget.

3.4.1 Wave-induced longshore sediment transport

Wave data is extracted from the SWAN model at seven locations in front of the coast at the Island of Luanda at the 8 m depth contour line, coordinates are shown in Table 3.1 and the locations are shown on the map in Figure 3.10 (a).

Table 3.1: Coordinates for each ray number used to extract wave data from SWAN at the Island of Luanda as a input for the UNIBEST-LT module.

Ray nr.	x-coordinate	y-coordinate
1	$3.0803715 \cdot 10^5$	$9.0312011 \cdot 10^6$
2	$3.0650653 \cdot 10^5$	$9.0300454 \cdot 10^6$
3	$3.0530644 \cdot 10^5$	$9.0290583 \cdot 10^6$
4	$3.0445462 \cdot 10^5$	$9.0280756 \cdot 10^6$
5	$3.0350591 \cdot 10^5$	$9.0266715 \cdot 10^6$
6	$3.0230671 \cdot 10^5$	$9.0255421 \cdot 10^6$
7	$3.0111557 \cdot 10^5$	$9.0242368 \cdot 10^6$
8	$3.0133733 \cdot 10^5$	$9.0231821 \cdot 10^6$

For every location it is calculated which condition contributes the most to the LST capacity. The results are shown in Figure 3.10. The conditions which have a longer duration induce the most LST e.g. wave condition 30 in Figure 3.10(b), induces more LST than wave condition 28. Furthermore the LST is increasing in southern direction as is shown in Figure 3.10 (c).

The wave characteristics which induce LST are shown in Figure 3.11. The relative contribution of a wave height in a ray is mostly induced by a wave height of 0.25-0.5 m, as is shown in Figure 3.11 (b.1) and (c.1). The wave height is increasing to the south except for Ray 8 which has to do with the location at the shoal (waves reduce height due to breaking on the shoal). The period of the waves lies between 9 and 13 s. The direction of the waves are slightly more from the SE in the south then in the north, as is shown in Figure 3.11 (c.3).

The longshore sediment transport is shown in Figure 3.12 (a). The LST is given as it is calculated with the sediment transport formulas Bijker and CERC. As seen earlier, the modelled sediment transports with CERC are higher compared to the ones modelled with Bijker. The gradient in the southern area is larger with CERC compared to Bijker which will result in more erosion as can be seen in Figure 3.12 (b). Erosion of the southern area seems to be in agreement with the trend seen on the old maps in which the Island of Luanda was not yet connected to the mainland and slowly (between 1870 and 1949) migrates in the direction of the mainland.

3.4.2 Sediment budget

The sediment budget is made with the Bijker and CERC values which are calculated with UNIBEST-CL+. The Bijker values are divided into a upper, standard and lower value with the distribution as is described in Appendix A. In Figure 3.13 the sediment budget is shown. The values are taken from the model after a run which simulates a timespan of 50 years. CERC shows a increase in

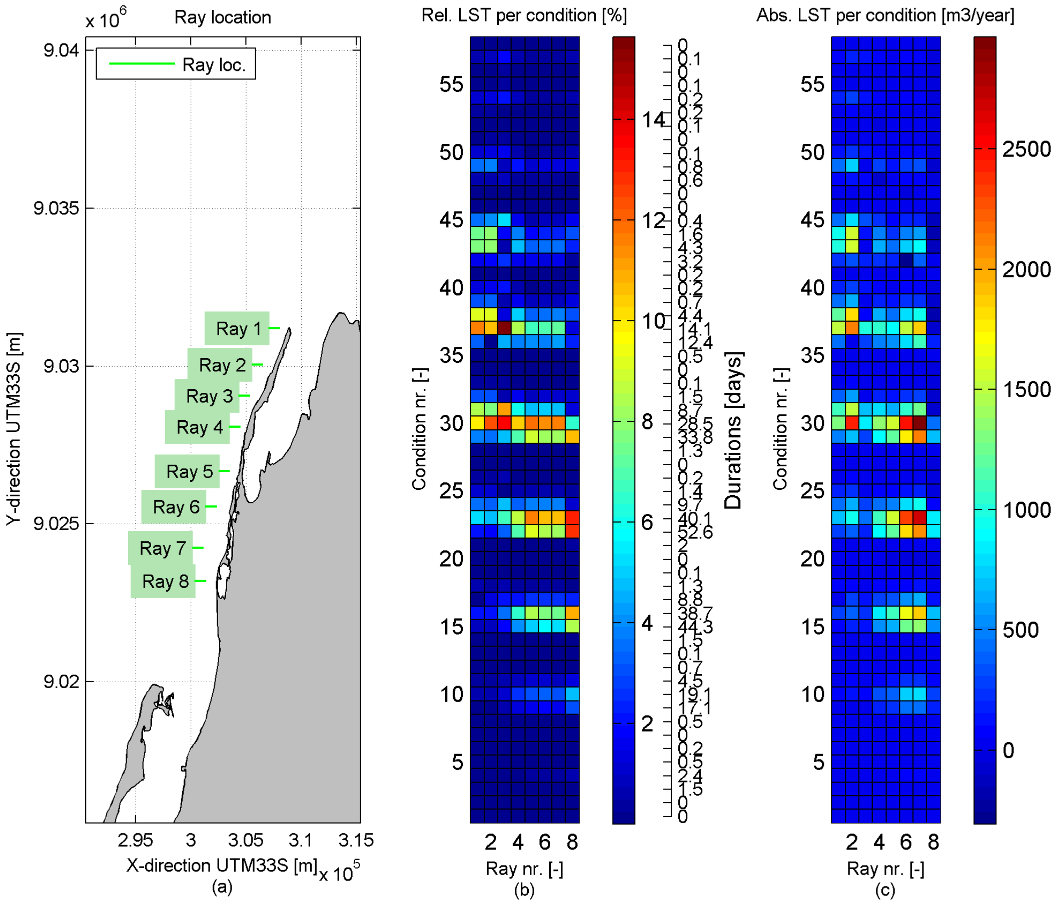

Figure 3.10: Wave characteristics along the Island of Luanda for each wave condition. The durations correspond with each condition. Left: area overview. Middle: Relative LST per condition. Right: Absolute LST per condition.

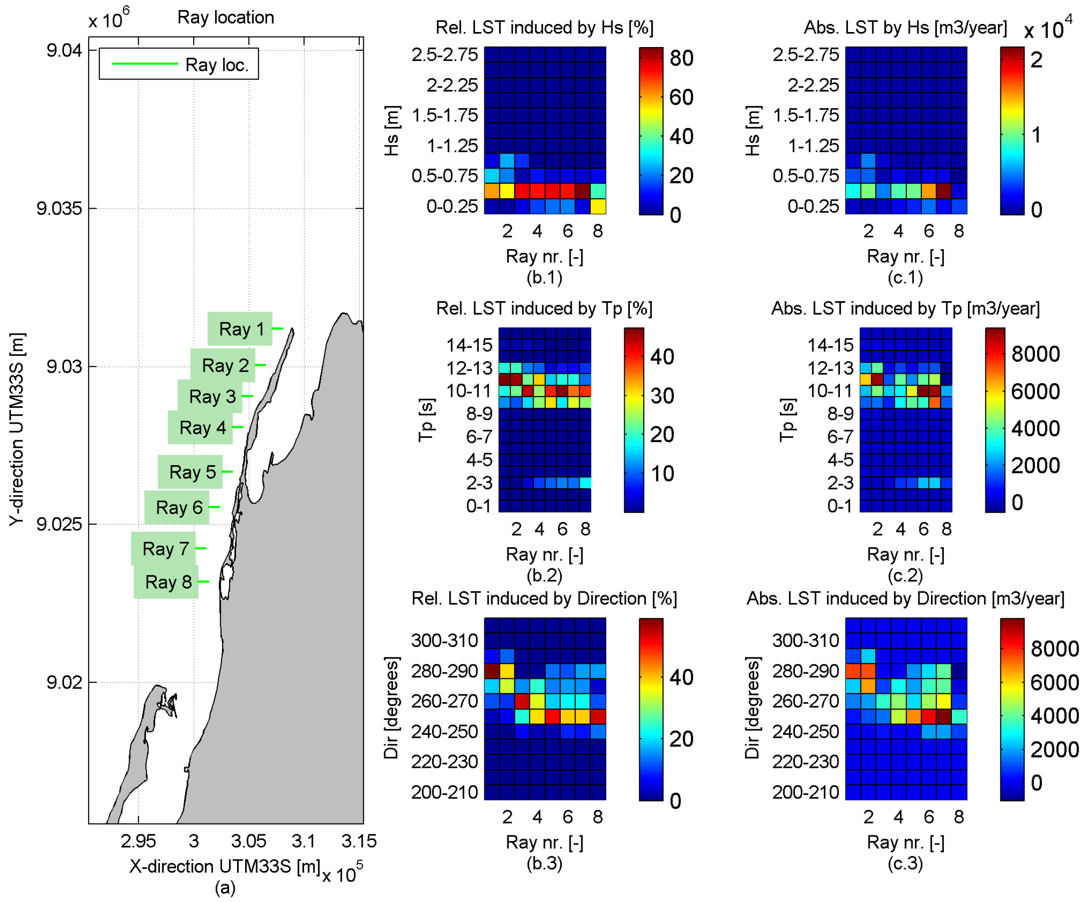

Figure 3.11: Wave characteristics for the Island of Luanda. Left: area overview. Middle row: Relative LST for H_s, T_p and the direction for the extracted wave condition. Right row: Absolute LST for H_s, T_p and the direction for the extracted wave condition.

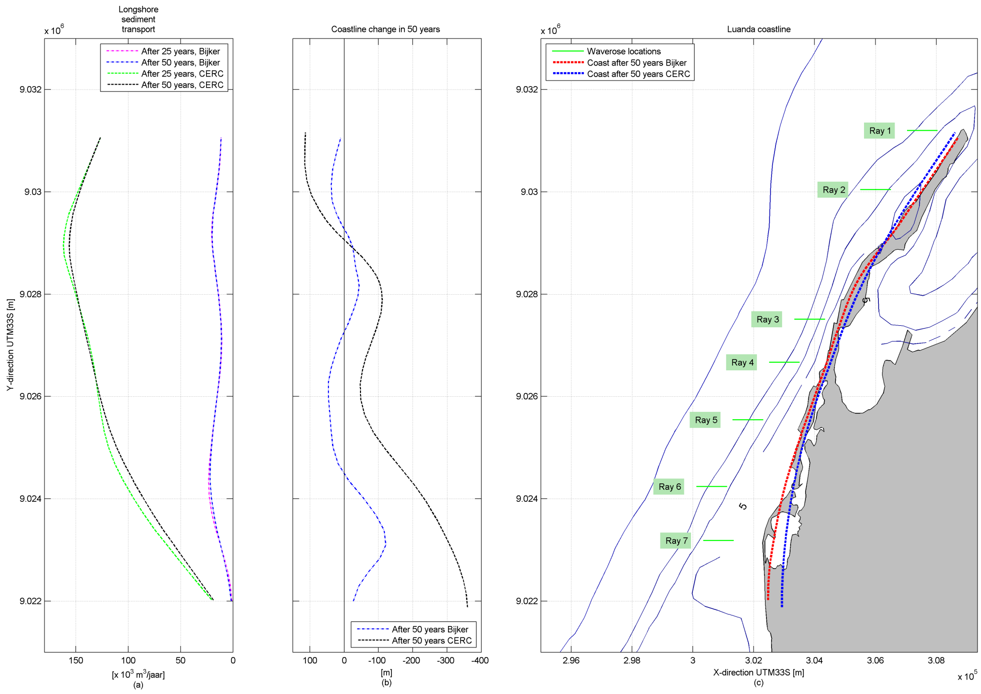

Figure 3.12: Longshore sediment transport and coastal change in orientation when simulating 50 years. Left: LST. Middle: Coastline change. Right: Area overview.

sediment transport in northern direction. Bijker does not increase as much as CERC in northern direction and even decreases slightly midway the Island of Luanda.

3.4.3 Conclusion and discussion

The following is concluded in this chapter

- Only conditions which occur one or more days are responsible for sediment transport.
- Wave height is 0 - 0.5 m. The Direction of the incoming waves are turned counter-clockwise towards the south starting at 280 - 290 ° in the north to 250 - 260 ° in the south of the Island of Luanda. Period of the waves lies between 9 - 12 s.
- Sediment transport increase from north to south starting at $19 \cdot 10^3$ $m^3/year$ (CERC) , $2 \cdot 10^3$ $m^3/year$ (Bijker) in the south to $130 \cdot 10^3$ $m^3/year$ (CERC) - $12 \cdot 10^3$ $m^3/year$ (Bijker) in the north.

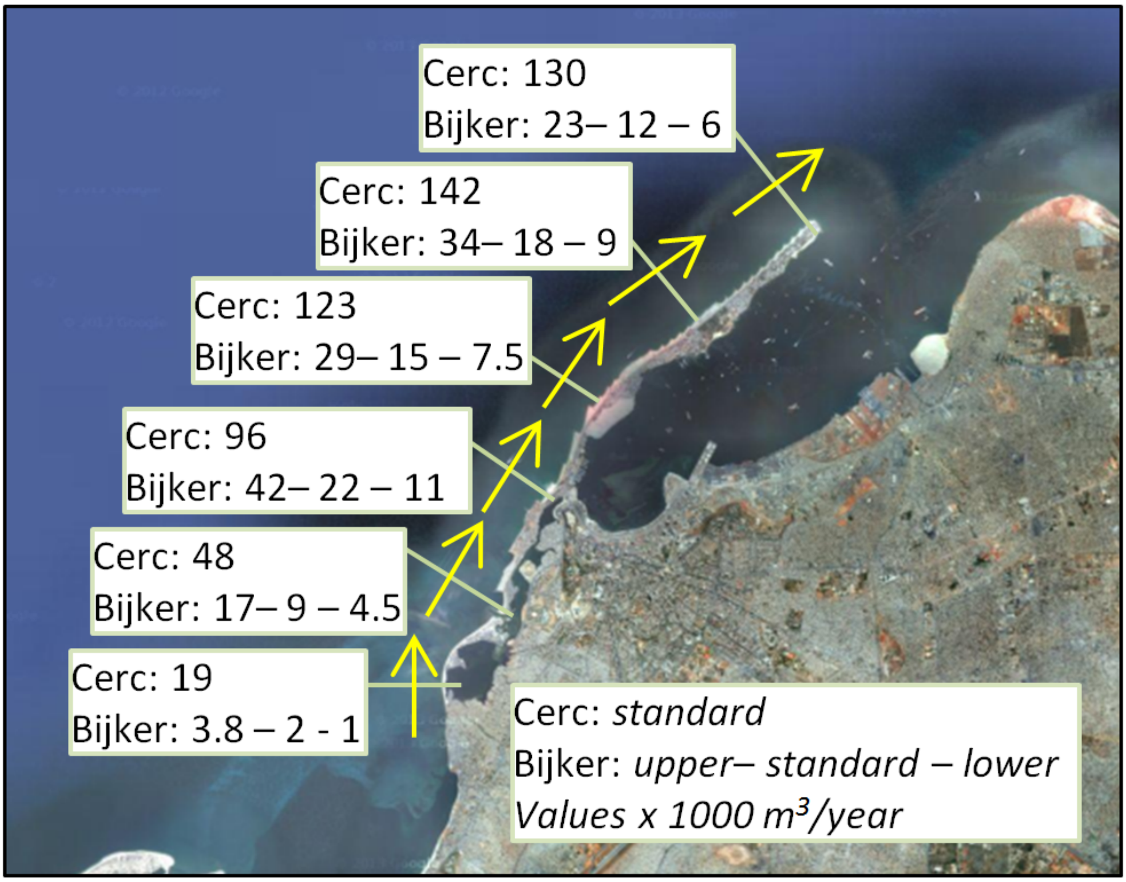

Figure 3.13: Sediment budget as calculated with UNIBEST-CL+ for the Island of Luanda. Values are in 1,000 $m^3/year$. The Bijker values is divided in an upper - standard - lower value.

3.5 Validation of the UNIBEST model with other reports

To validate the UNIBES-CL+ model two earlier studies are used, namely:

- Wallingford [2011]. Preliminary coastal process study by HR Wallingford.
- Scott and Wilson [2005]. Hydraulic Modelling Study- Phase I Report by Scott Wilson

HR Wallingford

The first report is focusing on the Island of Luanda. HR Wallingford has been commissioned by Marine and Port Services to undertake a high level study to assess the coastal processes along the Island of Luanda. The scope of work consist of a review of existing data and project appreciation, wave modelling, desk assessment of flows at the site and an assessment of sediment transport.

For the wave modelling HR Wallingford uses the TELURAY wave model which predicts the near shore wave activity by representing the refraction and shoaling on all components of a given offshore spectrum. HR Wallingford calculates wave climates at four locations in front of the Island of Luanda. After this is done HR Wallingford calculates the net sediment transport at the coast at these four specific locations. Validation is done by comparing the results of the report of HR Wallingford with the results calculated with UNIBEST-CL+ for the same loctions.

Table 3.2: Longshore sediment transport according to HR Wallingford for four locations at the Island of Luanda

Locations number	Easting (E)	Northing (N)	Sediment transport rates $m3/year$(CERC)
1	302647	9025726	x
2	303874	9026973	x
3	306653	9029674	90,000 – 215,000 North
4	308699	9031475	140,000 – 330,000 North

The values calculated by HR Wallingford are shown in Table 3.2, the sediment transport rates differs as HR Wallingford used two different sizes for the median grain size, 200 microns and 600 microns. The sediment transport rates calculated with the UNIBEST model for the same four locations are shown in Table 3.3. For the sediment transport formula in the UNIBEST-CL+ model CERC and Bijker are used, with a median grain size of 200 microns.

Table 3.3: Longshore sediment transport according to UNIBEST at the locations as used in HR Wallingford

Location number	Sediment transport rates m3/year (CERC)	Sediment transport rates m3/year (Bijker)
1	100,000 North	20,000 North
2	100,000 North	15,000 North
3	175,000 North	30,000 – 40,000 North
4	120,000 North	18,000 – 23,000 North

As there are no sediment transport rates for the locations 1 and 2 these will not be discussed further. The sediment transport rates at location 3 in the UNIBEST-CL+ model, with the CERC formula, resembles quiet well to the results of the HR Wallingford investigation. At location 4 the UNIBEST-CL+ model is underestimating the sediment transport rates compared to the outcome

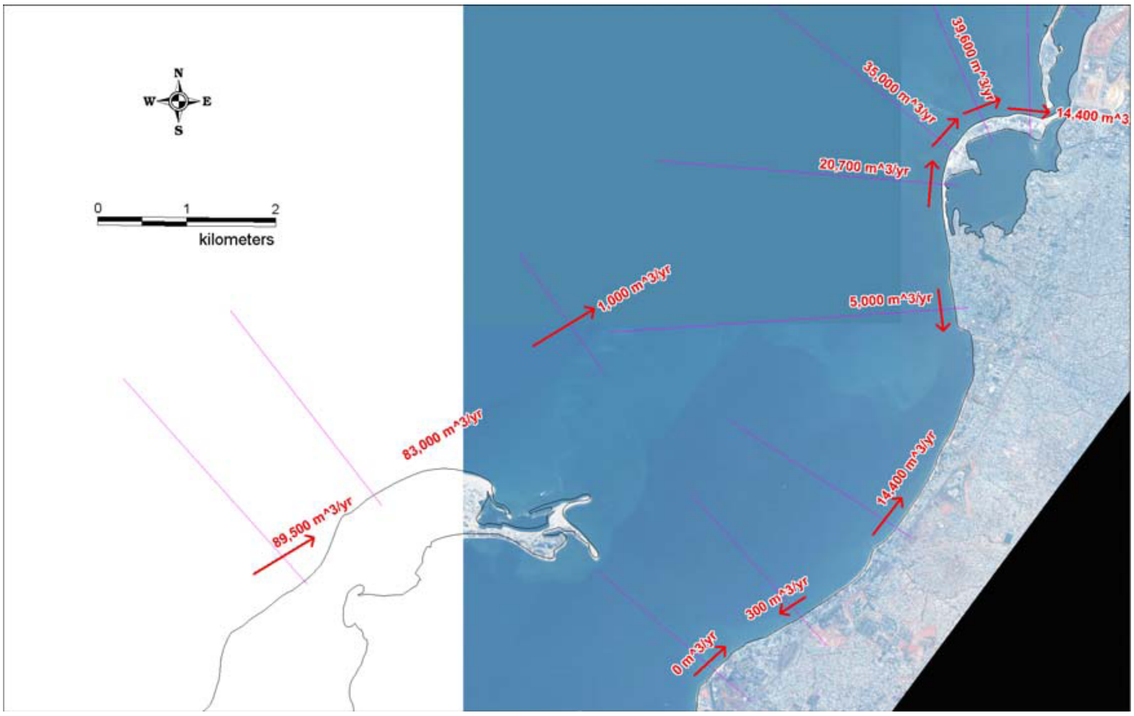

Figure 3.14: LitDrift Calculation Cross Sections and Annual Net Drift. Taken from Scott and Wilson [2005] Corimba Coastal Development - Hydraulic Modeling Study – Phase I Report

of HR Wellingford. The Bijker formula in the UNIBEST model is 5 to 6 times less compared to the CERC formula in UNIBEST-CL+ though more confidence is put from the Bijker formula compared to the CERC formula.

The results calculated with the CERC formula in UNIBEST-CL+ and in the report of HR Wallingford do not differ significant. The UNIBEST-CL+ model is therefore considered to be valid compared to the report of HR Wallingford.

Scott Wilson

The report of Scott and Wilson [2005] is focusing on a hydraulic modelling study of the Corimba Bay in collaboration with Sonangol. Offshore wave conditions were transformed onshore using the numerical wave model MIKE21 Nearshore Spectral Wave module, which is developed by Danish Hydraulic Institute (DHI). The wave model is used as an input in the LitDrift Model which is used for predicting longshore sediment transports in the littoral zone. The littoral drift is calculated at nine locations shown in Figure 3.14. The median sediment grain size used is 200 μm.

The exact locations with the corresponding sediment transport rates of the LitDrift calculations are shown in Table 3.4. The results of the UNIBEST model are shown in Table 3.5.

The sediment transport rates in the UNIBEST-CL+ calculation with the CERC formula resembles quiet well to the LitDrift calculations only location seven differs a lot, this might be due too local bathymetry). The Bijker formula in the UNIBEST-CL+ model is underestimating sediment transport rates compared to the LitDrift calculation, except for location three. The CERC formula generates approximately 7 - 9 times more sediment transport than the Bijker formula. The CERC formula has the most similarities with the LitDrift model still there are deviations which are not expected. At this moment these anomalies are likely caused by differences in the bathymetry.

Table 3.4: Sediment transport according to Scott Wilson at different locations along the Island of Luanda predefined by Scott Wilson.

Location number	Easting UTM 33S	Northing UTM 33S	Sediment transport rates m3/year (CERC)
1	$2.9506{\cdot}10^5$	$9.0187{\cdot}10^6$	89,500 North
2	$2.9587{\cdot}10^5$	$9.0197{\cdot}10^6$	83,000 North
3	$3.0024{\cdot}10^5$	$9.0187{\cdot}10^6$	300 North
4	$3.0148{\cdot}10^5$	$9.0195{\cdot}10^6$	14,400 North
5	$3.0136{\cdot}10^5$	$9.0216{\cdot}10^6$	5,000 South
6	$3.0133{\cdot}10^5$	$9.0231{\cdot}10^6$	20,700 North
7	$3.0158{\cdot}10^5$	$9.0240{\cdot}10^6$	35,000 North
8	$3.0192{\cdot}10^5$	$9.0248{\cdot}10^6$	39,600 North
9	$3.0249{\cdot}10^5$	$9.0253{\cdot}10^6$	14,400 North

Table 3.5: Sediment transport rates according to UNIBEST at the locations along the Island of Luanda predefined by SCott Wilson.

Location number	Sediment transport rates m3/year (CERC)	Sediment transport rates m3/year (Bijker)
1	62,500 North	7,000 North
2	105,000 North	12,000 North
3	9,000 North	800 North
4	29,000 North	3,500 North
5	2,000 South	0
6	38,000 North	6,000 North
7	140,000 North	22,500 North
8	55,000 North	8,000 North
9	0	0

Chapter 4

Model validation with observations

Simulations done in the previous chapter are checked in this chapter. This is done by taking observation as discussed in Chapter 2 and compare them with results of the model simulations. Each area (Kwanza river till end of the Island of Mussulo, the shoal and the Island of Luanda) is taken separately.

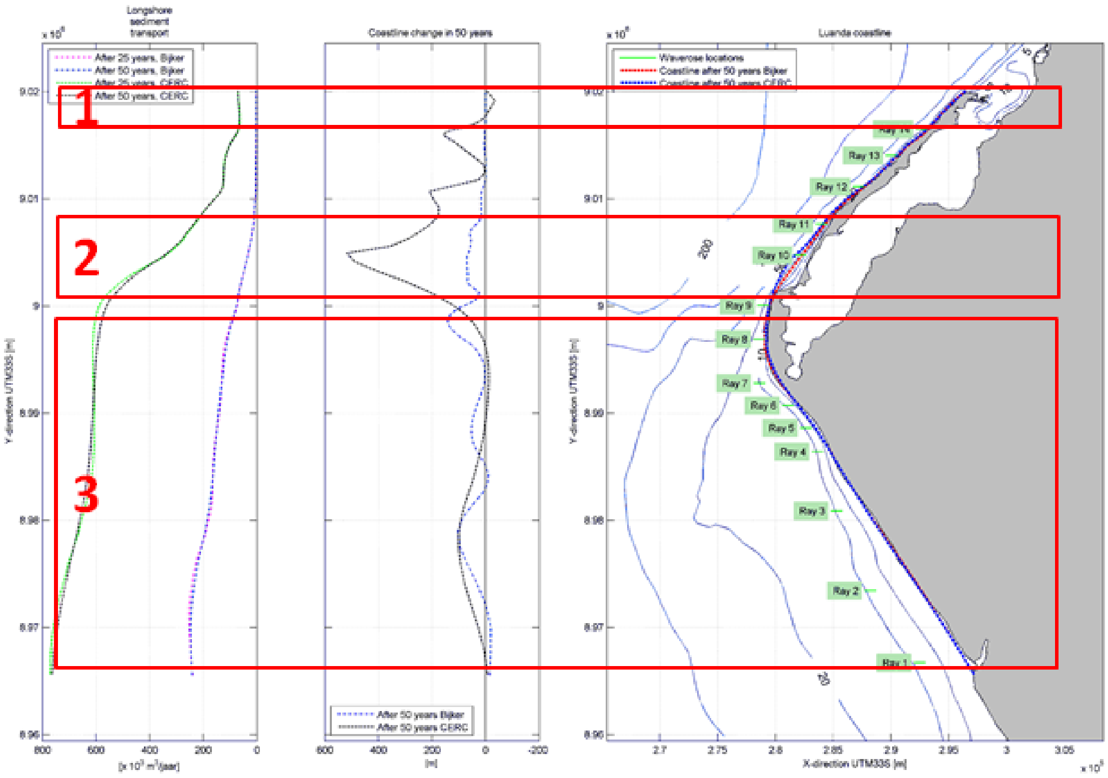

Figure 4.1: UNIBEST model for area one, Kwanza river till end of the Island of Mussulo. Three distinct areas are used to compare simulations with observations. 1. end of the Island of Mussulo. 2. The Buraco area. 3. Southern area.

4.1 Area one; Kwanza River till end of Island of Mussulo

Simulations as done in the Chapter 3 are discussed in this chapter by comparing results with observations made in Chapter 2. Results of the UNIBEST-CL+ model for area one shows a difference in LST between the CERC sediment transport formula and the Bijker sediment transport formula. Whether Bijker is more accurate than CERC, or vice versa, is checked by comparing simulation results with observations. For area one this is done by dividing the area into three different areas as shown in Figure 4.1.

4.1.1 End of the Island of Mussulo

The tip of the Island of Mussulo is investigated in Chapter 2. Based on old and new maps it was concluded that the Island of Mussulo is accumulating sediment at the end of spit. The amount of sediment it yearly accumulates is calculated to be between 21,000 $m^3/year$ till 65,000 $m^3/year$.

The LST in area one of Figure 4.1 has to be sufficient to provide the spit tip with the necessary amount of sediment. The LST of the CERC sediment transport formula at the end of the spit lies around 65,000 $m^3/year$ and the Bijker sediment transport formula lies around 2,000 $m^3/year$. The LST calculated with the CERC formula lies in the range of the required sediment supply needed to let the end of the Island of Mussulo grow. The LST calculated with the Bijker formula is insufficient to let the end of the Island of Mussulo grow as calculated earlier. The LST calculated with the CERC formulation is therefore considered to be more reliable compared to the Bijker sediment transport formulation for this area.

An explanation for the low LST values is the slopes of the bed profile in this area. The Bijker sediment transport formula is affected by the steep slopes as described in Appendix A. Though even with more gentle slopes the LST is not in the range needed to fill the tip of the Island of Mussulo as observed. Another possible explanation of the low LST calculated with the Bijker sediment transport formula in this area might be the extreme oblique waves which are mainly from WSW. The Bijker formula might be affected by these wave and underestimating the LST. Further research is not done as this was not in the scope of this research.

4.1.2 Buraco area

At the Buraco area, area two in Figure 4.1, the coastline makes a sharp change in coastline orientation. Such a feature is difficult to model in UNIBEST-CL+ and an error was therefore made. This error is shown in the middle graph of Figure 4.1 which shows the coastline changes in 50 years. In the model the area of Buraco, which hardly changes in the last 50 years, shows a large accretion area.

As the model simulates this area poorly the LST within this area could not be used. As such this area was seen as a black box. At this black box a certain LST arrives from the south and a certain LST is leaving to the north. Both sediment transport formulas show a difference in LST arriving at the area of Buraco and leaving the area of Buraco. LST is decreasing within this black box without causing accretion.

An explanation for this reduction is found in bathymetric charts, as seen in Figure 4.2. A sudden increase in depth close to the beach located at the sharp change in coastline orientation. This remarkable feature might act as a sand-trap removing sediment out of the coastal area and reducing the LST in this area without causing accretion.

4.1.3 Southern area

The southern area starts about 1 km south of Buraco area and covers the coastal area till the Kwanza River. Both the CERC and Bijker sediment transport formulations shows a quiet stable coast in this area. Coastline changes are relative small as seen on maps analysed in Chapter 3. The orientation of the coast south of the Kwanza River is similar to the coastline orientation north of the Kwanza River as such the LST south of the Kwanza River is expected to be similar as at the north side of the Kwanza River. This indicates that the sediment input by the Kwanza river must be relative small compared to the LST considered large scale accretion is not seen around the Kwanza River. Another indication for this is that no erosion is seen due to the fact that the river has been dammed twice. Damming of a river often reduces the supply of sediment to the coast and therefore causing erosion. Erosion was therefore expected but is not seen on observations.

4.1.4 Conclusion and discussion

Comparing the results of the UNIBEST-CL+ model with observations as described in Chapter 2 the two sediment transport formulas, CERC and Bijker, are validated. The LST at the end of the Island of Mussulo was compared to the sediment needed to let the end of the spit grow. The CERC formulation seems more reliable as it lies in the range of the needed amount of sediment. At the area of Buraco both sediment transport formulas decrease significant. A possible explanation was found in bathymetric charts which shows a sudden deepening in the area just offshore south of the area of Buraco. The LST for the southern area does not shows any major changes in the coastline which is in agreement with the analysis made in Chapter 2. Furthermore the sediment input by the Kwanza River is relative small as no changes where seen in the coastline after damming of the river.

Figure 4.2: Bathymetric chart for the Buraco area. The red arrow indicates a sudden deepening of the bathymetry which seems to act as a sandtrap and can explain the decrease in LST as seen in the results of the UNIBEST-CL+ run.

4.2 Area two; submerged shoal

Simulations done for area two are discussed in this part. Two types of simulations were done for this area. First the UNIBEST-CL+ model was used to determine the LST. As it was expected that sediment transport is also influenced by tide induced currents a tide model was used and with the Soulsby van Rijn sediment transport formula the sediment transports were calculated.

4.2.1 Tide induced vs wave induced

Sediment transport amounts calculated with UNIBEST-CL+ and with the Soulsby van Rijn formula are relative low. As the UNIBEST-CL+ model is lacking tide induced currents one might expect a higher amount of sediment transport when taking tide induced currents into account. The tide model is excluding wave induced currents. The results of the Soulsby van Rijn calculation is influenced when wave induced current are added. When considering the direction of the waves an increase in the sediment transport capacity to the north east is expected. Unfortunately it was not able to simulate this properly. Another effect which could not be simulated properly where the moving sandbars as accurate bathymetry data is lacking.

4.2.2 Sandbars

The amount of sediment dredged yearly to keep the channel in the shoal at a certain depth is between 10,000 to 20,000 as stated by the responsible dredging company. The tide induced, even combined with the wave induced currents, are not sufficient to transport this amount of sediment

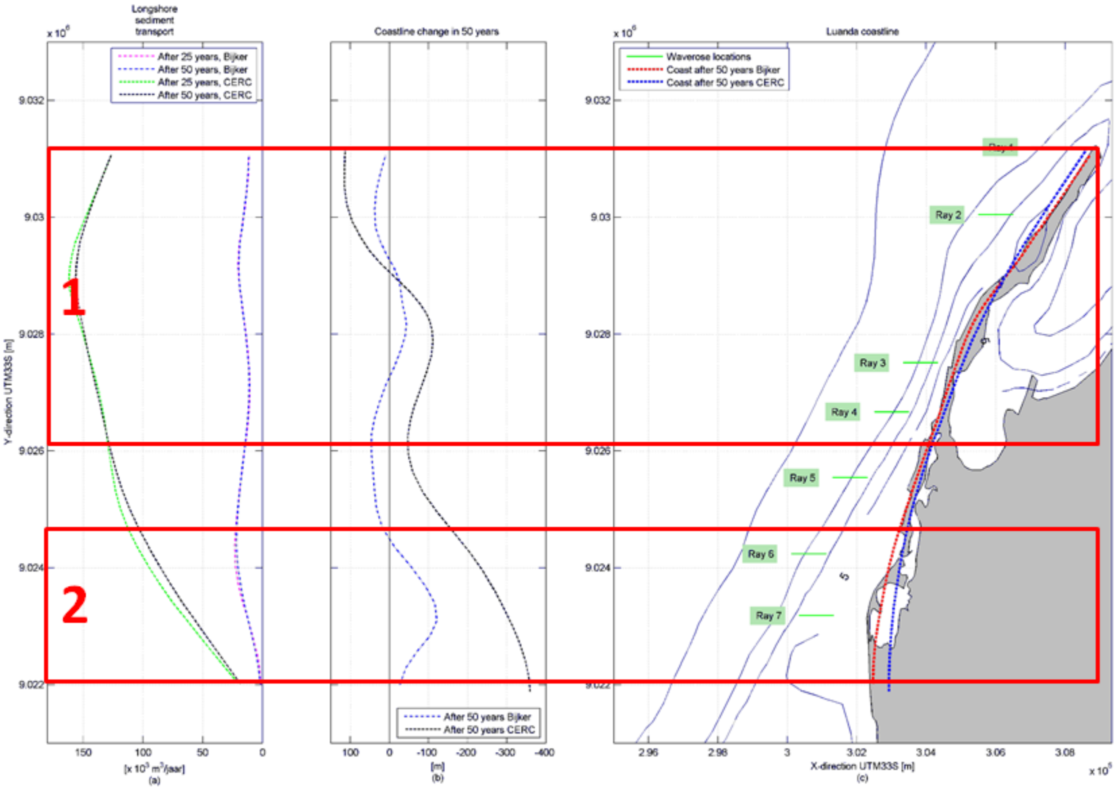

Figure 4.3: The Island of Luanda divided into two areas. 1. The northern area, consisting of multiple groynes. 2. The southern area, consisting of the Corimba area.

into the channel. As stated in Chapter 2 sandbars travel from the end of the island of Mussulo to the Island of Luanda via the shoal. The amount of sediment transported by these sandbars are sufficient to deliver enough sediment to match the dredged amount of sediment. The sandbars are therefore seen as the main mechanism driving the sediment transport from the Island of Mussulo to the Island of Luanda. As seen on aerial images these sandbars are forced by breaking waves and reattach to the mainland at the south of the Island of Luanda also known as the Corimba area.

4.2.3 Conclusion and discussion

The LST calculated with UNIBEST-CL+ and the Soulsby van Rijn formulation are relative low compared to the amount of dredged sediment every year. The sandbars, as shown an aerial images, are considered to be the main mechanism driven by waves transporting sediment from the Island of Mussulo to the Island of Luanda.

4.3 Area three; Island of Luanda

An UNIBEST-CL+ model is also made for the Island of Luanda which will be compared with observations made and analysed in Chapter 2. The Island of Luanda is divided in two areas: northern and southern area. Both areas are compared with observations.

Figure 4.4: The coastline change of the area between the groynes in the red box gives an indication of the minimal required LST in this area.

4.3.1 Northern area

The LST in the northern area, indicated with number one in Figure 4.3, is compared with aerial observations which shows the coastline between the groynes. With the help of several nourishments along the Island of Luanda and the coastline changes between groynes near the nourishment an indication of the minimal LST was made. An example is shown in Figure 4.4. The increase in the area is around 9,000 $m^2/year$. Considering a closure depth of 6 m a minimum of 54,000 $m^3/year$ is needed to fill this area with sediment. This is done for two more locations. The red dots in Figure 4.5 shows the results.

4.3.2 Southern area

The CERC and Bijker sediment transport formulas in the southern area, area number two in Figure 4.3, shows both an increasing LST towards the north. This results in an eroding coast as is seen in Figure 4.3 and is in agreement with the changes as seen between old and new maps. The erosion is expected to be less than the CERC formulation as sediment is brought into the system at the Corimba area via the sandbars coming from the submerged shoal. The LST is expected to be higher then the LST calculated with Bijker formula as the sediment supply of the sandbars will accrete this area when using the Bijker formula which is not the case. Combining these observations with the knowledge of the northern area a more realistic LST for the Island of Luanda is shown in Figure 4.3.

4.3.3 Conclusion and discussion

The simulated LST with CERC and Bijker are validated with observation. The LST calculated with CERC seems to be a bit overestimated in contrast to the LST calculated with the Bijker formula which seems to be underestimated. An expected LST is made with the help of observations and shown in Figure 4.3.

4.4 Conclusion and discussion

The three different areas are validated with observations obtained in Chapter 3. The CERC formula seems to be more realistic for the area between the Kwanza River and the Island of

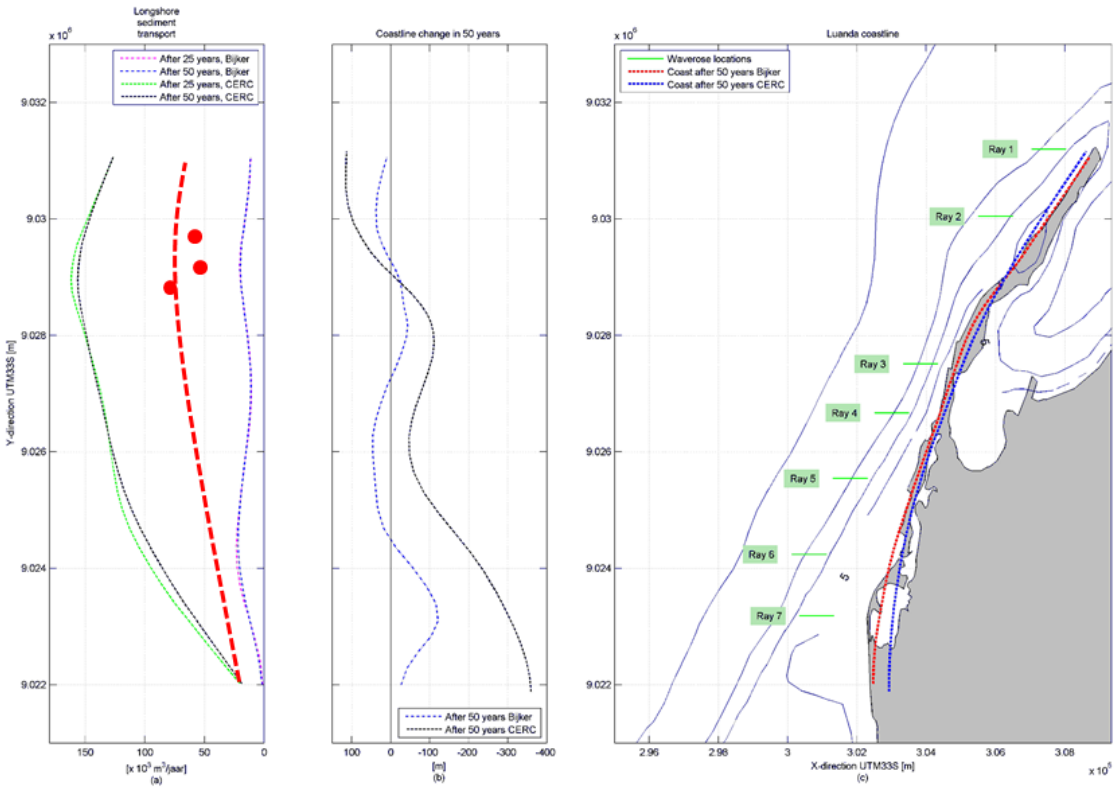

Figure 4.5: The LST for the Luanda area. In the red arrows are the calculated LST with the coastline changes between groynes. In the red dashed the expected LST is shown which takes observations and calculations into account.

Mussulo, at least for the most northern part. The LST at the area of Buraco has to decrease in order to be in agreement with observations. A sudden deepening in the bathymetry is seen as a possible explanation for this. The main sediment transport mechanism between the Island of Mussulo and the Island of Luanda are the sandbars which are wave driven and travel at the seaside of the shoal. The LST for the Island of Luanda is between the modelled LST for the Bijker and CERC sediment transport formulas.

By combining observations with simulations a validation step was made. As there are still uncertainties a more qualitatively model will be made in the next chapter in which we use the knowledge of this chapter.

Chapter 5

Conceptual overview of the Luanda area

In this chapter a conceptual model for each separate area is made. Observation data from Chapter 2 and insight gained in Chapter 4 are combined and used to make a conceptual figure of the longshore sediment transport of an area. The conceptual overviews are combined and used to qualitatively describe the interaction between the Island of Mussulo and the Island of Luanda. With help of this analysis the effects of the dredged channel at the shoal are investigated.

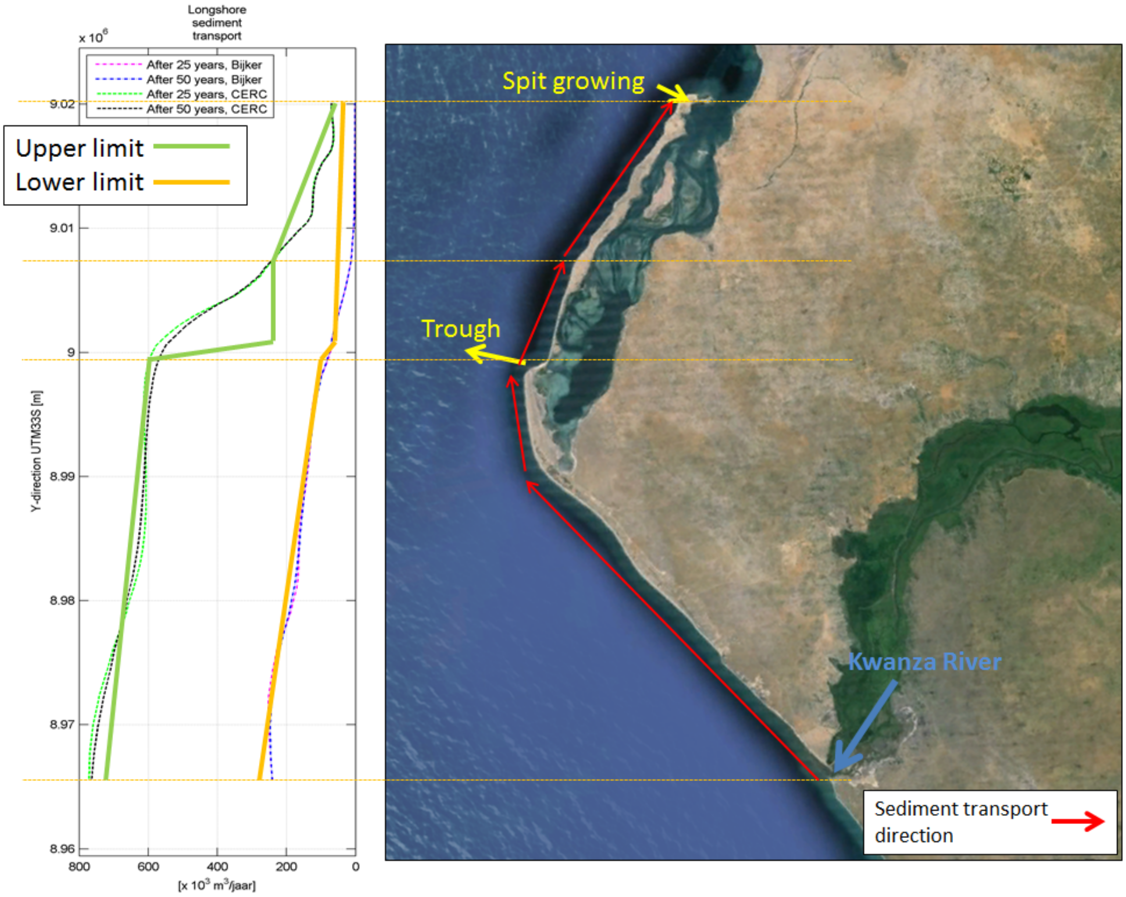

Figure 5.1: Conceptual LST for the area one, the Kwanza River till the end of the Island of Mussulo. The LST, left graph, has an upper and lower limit representing a range within the real LST is expected to lay in.

5.1 Overview of each separate area

Simulations done in Chapter 3 are validated with observations obtained from Chapter 2. With the insights obtained in the previous chapters a conceptual overview will be made. Goal of this chapter is to connect the different areas with each other and qualitatively describe the Luanda coastal area.

5.1.1 Conceptual overview of area one

With the help of Chapter 4 a conceptual overview of area one, the area between the Kwanza river and the end of the Island of Mussulo, is made as shown in Figure 5.1. The direction of the LST is shown by the red arrows. Sediment is transported in northern direction. The left graph in Figure 5.1 shows the LST. An upper and lower limit is determined to create a range in which the LST is expected to lay in. At the area of Buraco the LST drops significantly. A trough in this area is seen as a sink causing this reduction in LST. The LST at the end of the Island of Mussulo lies beteween 65,000 $m^3/year$ and 15,000 $m3/year$. The LST has to be in the range which is minimal required for the growth of the end of the Island of Mussulo. As such the LST for the lower limit is set to 15,000 $m^3/year$ and not the 2,000 $m^3/year$ modelled with the Bijker formula.

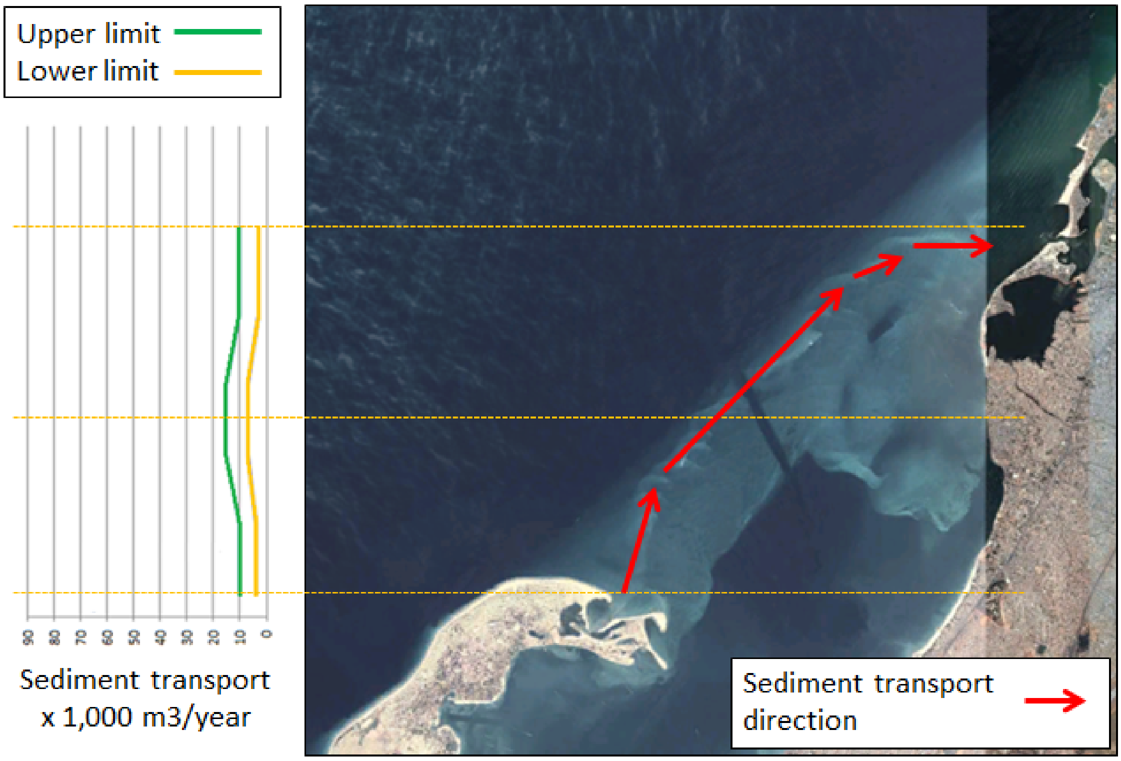

Figure 5.2: The conceptual overview of the submerged shoal. The LST is shown in the left graph.

5.1.2 Conceptual overview of area two

Sediment transport of area two, the submerged shoal, is mainly done by the wave driven shifting sandbars, as stated in Chapter 4. A conceptual overview is made and shown in Figure 5.2. The left graph of Figure 5.2 shows the range, bounded by an upper an lower value, in which the LST is expected to lay in. The upper and lower boundary are extracted from the calculations made based on the amount of sediment the sandbars transport during a year. In the southern part the LST has a value between 4,000 $m^3/year$ and 10,000 $m^3/year$, the LST in the middle part of the submerged shoal is between 8,000 $m^3/year$ and 15,000 $m^3/year$ and the LST in the northern part of the shoal is between 3,000 $m^3/year$ and 10,000 $m^3/year$.

5.1.3 Conceptual overview of area three

As stated in Chapter 4 the CERC formula is overestimating and the Bijker formula is underestimating the LST at the Island of Luanda. The expected LST was determined by validating the model with observations. By taking a range of 20 percentage around the expected LST a range is created in which the LST for this area is expected to lay in. Furhtermore the LST at the southern boundary is expected to be the same as the CERC formula. The conceptual overview of the Island of Luanda is shown in Figure 5.3. The left graph in Figure 5.3 shows the LST. Sediment is transported from south to the north. Sediment transport to this area via the sandbars is spread over a larger area. As such no jump in the LST is expected but a milder slope of the LST. Sediment is leaving the system in the south at the end of the spit.

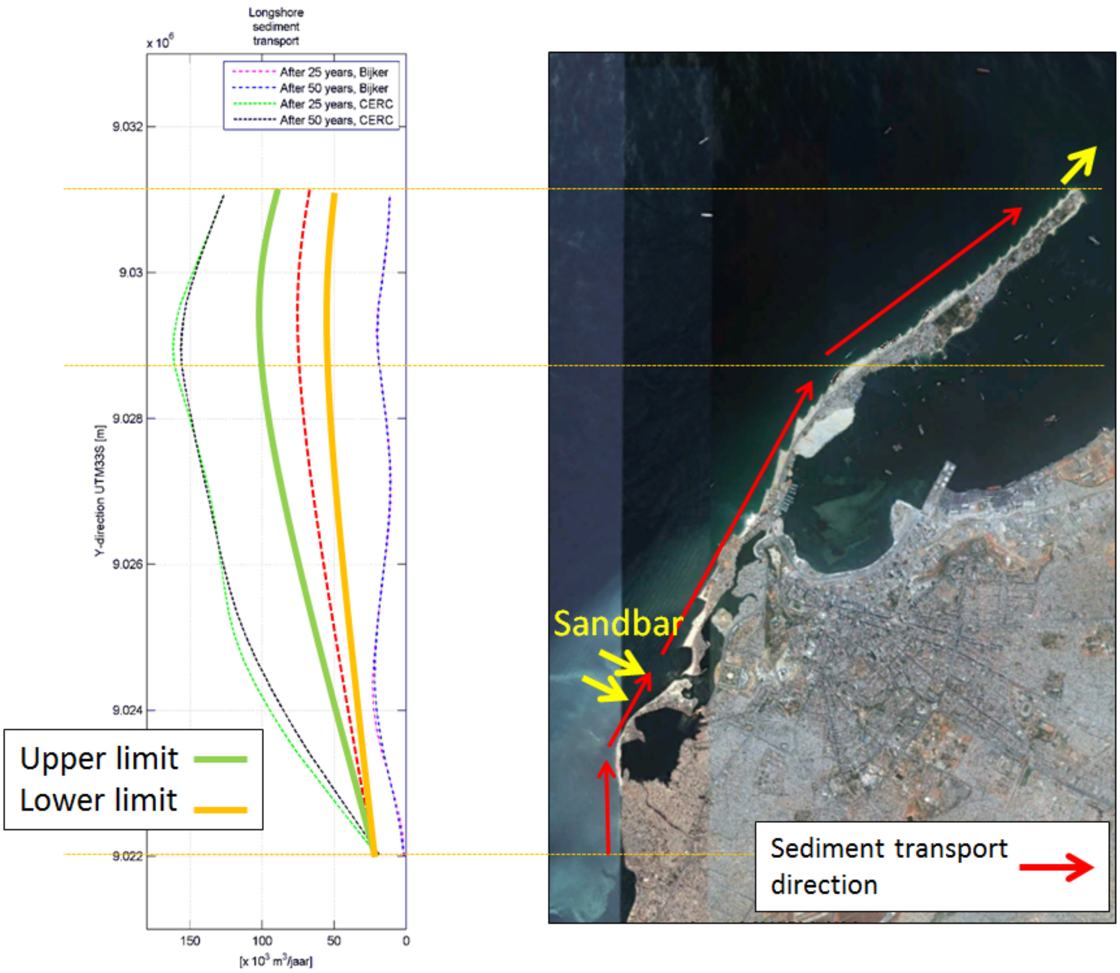

Figure 5.3: A conceptual overview of the Island of Luanda. The left graph shows the LST along the Island of Luanda with an upper and lower limit creating a range in which the LST is expected to be in.

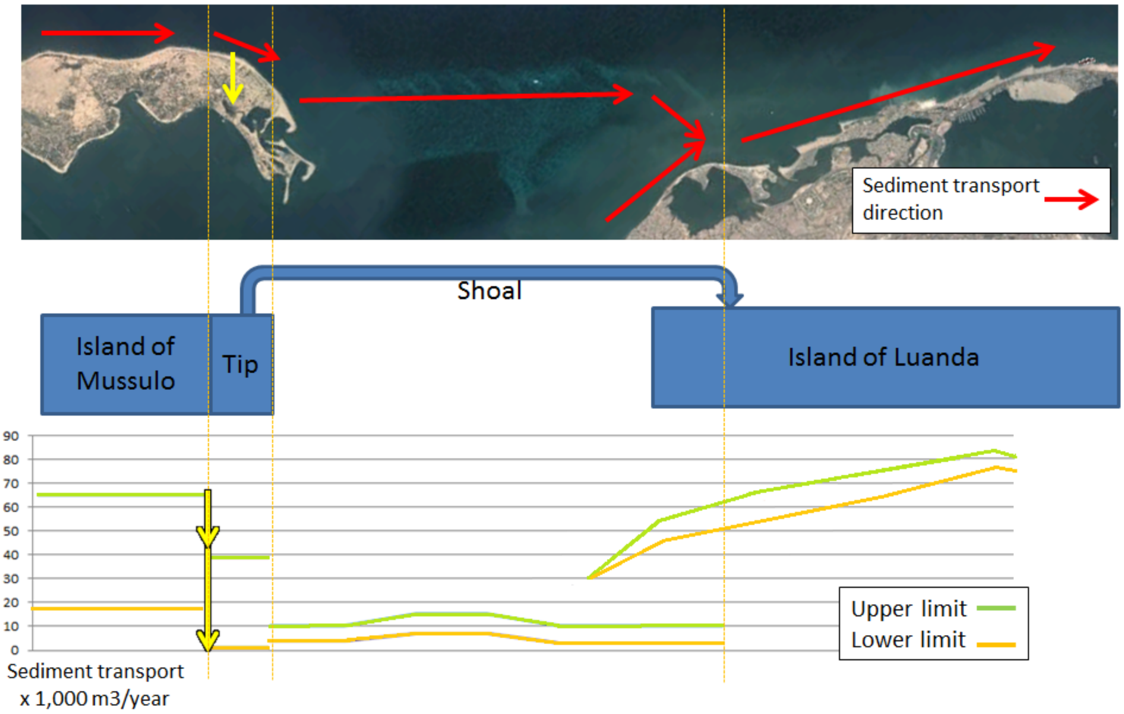

Figure 5.4: Conceptual overview of the connection between the Island of Mussulo and the Island of Luanda. The lower graph shows the LST along this connection in which a range is determined in which the real LST is expected to be in.

5.2 Connection between the Island of Mussulo and the Island of Luanda

The transport of sediment from the Island of Mussulo to the Island of Luanda is complex as three different types of areas are interacting with each other. The Island of Mussulo which accumulates sand at the end of the spit, the shoal which has wave driven sandbars and the Island of Luanda which is highly influenced by human interventions. Based on the conceptual overview of each separate area an overview of the sediment transport between the Island of Mussulo and the Island of Luanda is made and shown in Figure 5.4. The LST at the Island of Mussulo is between 15,000 $m^3/year$ and 65,000 $m^3/year$. Due to accumalation of sand at the end of the Island of Mussulo the LST drops to range of 0 $m^3/year$ to 40,000 $m^3/year$. Sediment is picked up by the sandbars and transported via the shoal to the Island of Luanda with a LST of about 4,000 $m^3/year$ to 15,000 $m^3/year$. Sediment of the sandbars is transported into the area of the Island of Luanda. The LST is increasing along the Island of Luanda from south with a value of 30,000 $m^3/year$ to around 80,000 $m^3/year$ in the middle of the Island of Luanda.

5.2.1 Effect of the dredged channel

As stated earlier a channel was dredged in the shoal for navigational purpose. The effect of the dredged channel is evaluated with the help of the conceptual model shown in Figure 5.4. The amount of sediment transported into the dredged channel is between 7.000 $m^3/year$ and 15.000 $m^3/year$, which is in agreement with the 10,000 $m^3/year$ to 20,000 $m^3/year$ dredged yearly in order to keep the channel at the appropriate depth. The moving speed of the sandbars is relative small, 10 to 15 $m/year$. The effect of the dredged channel is expected to be minimal for the surrounding area on the short term. Still after a longer period the sandbars north of the dredged channel will disappear due to a lack of sediment supply from the south. An effect of the disappearing sandbars is the increase of wave energy at the coast behind these sandbars. Waves which previously lost energy on these sandbars, due to wave breaking, can now freely propagate to the coast and induce more sediment as the waves have more energy. This increases the LST at this area and erosion is expected to occur at the coast behind the disappearing sandbars due to the dredged channel. In time an erosion wave will be transported to the north as this coast is not sheltered no more by the sandbars. Reduction of sediment supply to the Island of Luanda by the sandbars is also expected to reduce after a longer period. Combining this with the expected erosion wave from the coast at the south it is expected that the Island of Luanda will suffer from large scale erosion. This process can be mitigated or even stopped if dredged material is dumped at the sandbars north of the dredged channel.

5.3 Conclusion and discussion

A conceptual overview was made in order to get a clear view on the LST along the different coastal areas of Luanda. At first a concept overview was made of the individual areas. The LST for each area was bounded by an upper and lower limit. This created a range in the LST in which the real LST must lay in. The individual conceptual overview are used to schematize the interaction between the Island of Luanda, shoal and Island of Mussulo. The LST of each individual area has to be in agreement with the next/previous area. With help of the overview of the interaction between the Island of Mussulo and the Island of Luanda the effect of the dredged channel could be described. The dredged channel will not have an effect on the short term but can have a major effect on the long term if no mitigation measures are taken into account.

Chapter 6

Conclusion and Discussion

With the help of the information gained in the previous chapters an answer is formed for the questions as asked in Chapter 1. Furthermore, recommendations for further research are given.

6.1 Conclusion

By combining the different analysis of the investigated coastal areas the following answers are formed for the research question as stated in Chapter 1.

What are the main features of the coastal system in the area of interest?

The Luanda area consist of two spits (the Island of Luanda and the Island of Mussulo), two bays (the Bay of Mussulo and the Bay of Luanda) and a submerged shoal at the entrance to the Bay of Mussulo. The Kwanza River was seen as one of the sources for the Luanda area but its relative contribution of sediment to the Luanda coastal area is considered to be minimal. Maps and aerial images were compared and it was shown that the Island of Mussulo was accumulating sand at the spit end. Furthermore the Island of Luanda showed structural erosion. Sandbars on which waves break are shown at the seaside of the shoal and a channel was dredged in the shoal for navigational purposes between the year 2005 and 2008.

What drives the longshore sediment transport drift and how does the longshore sediment transport changes along the coastal stretch?

The littoral drift is driven by dominant waves which hardly differ in direction. As seen in Chapter 3 wave energy decreases in northern direction. The incoming waves are mostly all coming from 210° to 220°. Due to these waves the longshore sediment transport along the coast is in northern direction. Waves vary between 0.5 m to 1.25 m at the Kwanza River, 0 m to 0.5 m tip of the Island of Mussulo and 0 m to 0.75 m at the Island of Luanda. The direction of the incoming waves varies between 220° at the Kwanza River from where they, when going in northern direction, turn clockwise to about 280° at the tip of the Island of Mussulo. In the south of the Island of Luanda waves are approaching from 250° to 260° and turns clockwise to the north till about 290°. The period of the incoming waves are along the coast do not differ along the coast and are between 9 s to 13 s.

What is causing coastline changes and what is the large scale evolution of the coastline?

Sediment transport along the Luanda coast is dominated by waves. Most waves are approaching the Luanda area under a similar orientation (SW to SSW). These waves induce a wave driven longshore sediment transport, mainly to the north. The south of the Island of Luanda suffers from erosion due to wave driven sediment transport. Sediment supply from the shoal and southern beach area are limited and not sufficient to compensate the longshore sediment transport at the Island of Luanda. This event seems to occur for quite some time as historical maps show that the Island of Luanda has shifted onshore during the last century. The Island of Mussulo does not show large scale changes except for the tip of the spit. The tip of the Island of Mussulo is accumulating sediment with an amount of $21{\cdot}10^3$ $m^3/year$ to $65{\cdot}10^3$ $m^3/year$. At the Buraco area sediment is expected to be extracted from the coastal system via a trough. This might also explain the sharp change in coastline orientation at this location.

What is the long term development of the shoal and what is the effect of the dredged channel?

The shoal changed drastically between the year 1870 and the year 1950 as the nowadays submerged shoal was complete above waterlevel during the year 1870. No large scale changes were observed during the last 50 years and the shoal is considered to be quite stable now. The shoal has recently been interrupted by a dredged channel (between 2005-2008). The LST capacity along the shoal was modelled with different approaches. No large LST were found with these models. Another mechanism is held responsible for the transport of sediment from the Island of Mussulo to the Island of Luanda. From aerial images sandbars were observed at the seaside of the shoal. The sandbars moved with a distance of about 10 $m/year$ to 15 $m/year$ as waves break on them. The sandbars are seen as the main mechanism driving the sediment transport from the Island of Mussulo to the Island of Luanda. The dredged channel will not have an effect on the short term due to the relative slowly propagation speed. On the long time waves which broke on the sandbars will be able to propagate freely to the coast as the sandbars disappeared due to a lack of sediment supply from the south. These energetic waves will cause erosion at the coast behind the shoal. Furthermore the sediment supply to the Island of Luanda by the sandbars will stop if no mitigation measures are taken. Causing even more erosion to the Island of Luanda. Dredged material can be used to supply the sandbars in order to prevent them from eroding.

How does the interaction, with respect to the sediment distribution, works between the Mussulo Bay, Atlantic Ocean, Island of Mussulo and Island of Luanda works?

The transport of sediment from the Island of Mussulo to the Island of Luanda is complex as three different types of areas are interacting with each other in this area. The Island of Mussulo which accumulates sand at the end of the spit, the shoal which has wave driven sandbars and the Island of Luanda which is highly influenced by human interventions. Based on the conceptual overview of each separate area an overview of the sediment transport between the Island of Mussulo and the Island of Luanda is made. The LST at the Island of Mussulo is between 15,000 $m^3/year$ and 65,000 $m^3/year$. Due to accumulation of sand at the end of the Island of Mussulo the LST drops to range of 0 $m^3/year$ to 40,000 $m^3/year$. Sediment is picked up by the sandbars and transported via the shoal to the Island of Luanda with a LST of about 4,000 $m^3/year$ to 15,000 $m^3/year$. Sediment of the sandbars is transported into the area of the Island of Luanda. The LST is increasing along the Island of Luanda from south with a value of 30,000 $m^3/year$ to around 65,000 $m^3/year$ in the north.

Main question

What are the main characteristics which influence the coastal systems of the Island of Mussulo and the Island of Luanda and how differs the longshore sediment transport along the Luanda coast in particular at the area between the Island of Mussulo and the Island of Luanda?

The sediment transport along the coast is mainly driven to the north by waves approaching from the south-west. The Kwanza River is not seen as a main sediment supplier for the present Luanda area. Sediment supply at the south is mainly expected to be from the coastal area south of the Kwanza River. Part of the sediment transported along the tip of the Island of Mussulo will be transported to the shoal and partly to the tip of the Island of Mussulo where it will settle. The tide has a relatively small influence on the interaction between the shoal and the Bay of Mussulo. The dredged channel in the shoal will act as a sand trap and reduce sediment to be transported to the north. This will not have a large effect and a short time scale but can have a major impact on the long term. The LST by the sandbars via the shoal supplies the Island of Luanda with sediment as well as sediment transport from the coast south of the Island of Luanda. The Island of Luanda suffers from structural erosion as the supplied sediment is not enough in order to keep up with the LST. The erosion is nowadays compensated with beach nourishment and coastal structures such as groynes.

6.2 Recommendations

A conceptual model is made in which the main coastal interactions of the Luanda coast are investigated by looking at longshore sediment transports. Still there are a lot of smaller scale processes which are not investigated but can contribute in better understanding the Luanda coastal area. Furthermore simulations were limited by the model capabilities.

Data gathering.

As always one wants as much field data as possible. Validation was difficult as data was limited. E.g. sediment transport rates are checked with other reports in which the sediment transport rates are based on observations seen on maps which have certain errors and uncertainties. For future researches it is highly recommended to undergo a field research in order to collect validation data and/or input data for numerical models. The following data is suggested to be useful to collect on a field trip.

- Nearshore bathymetry data; bottom profiles were estimated with a Dean profile as accurate nearshore bathymetry data was lacking. Dimension of the trough seen on bathymetric charts at the Buraco area are interesting to confirm whether or not this could be a sediment sink.
- Sediment characteristics; with the help of sediment samples a more accurate prediction can be made as the model uncertainties reduces.
- Long time survey of the bathymetry; by doing a survey of the bathymetry for a longer period the net sediment transport can be calculated which can be used for validation of the model. I.e. a survey of the sandbars over a longer period. With a more precise depth and shape of the sandbars, over a longer period, a more accurate calculation of the sediment transport by the sandbars can be made.
- Sediment transport by the Kwanza River; sediment volumes delivered by the Kwanza River can prove the statement that the River Kwanza is not a main supplier for the Luanda area.
- More accurate dredging and nourishment values; these values can be used to validate the model.

Different model software

The software, UNIBEST-CL+ package, as used in this report is based on the single line theory of Pelnard-Considère [1956]. The UNIBEST-CL+ package is often used as a first model tool in order to predict long-scale changes for a larger area. In a future study a more complex model is recommended in order to model more complex processes which could not be modelled with the UNIBEST-CL+ model. The subjects which might be interesting to look into are:

- Modelling of the interaction of wave and sediment over the shoal including the sandbars; a simple calculation was done in order to get an insight in the behaviour of the shoal the sandbars were not included as they were not shown on available bathymetry data.
- Dumping of dredged material, gathered from the dredged channel in the shoal, north of the dredged channel.
- Numerical model of a breach at the Buraco area.
- Implementation of the groynes at Island of Luanda, this was not done in the UNIBEST-CL+ model as the model could not handle this correctly.
- Simulation of the accumulation at the end of the Island of Mussulo. This will increase the understanding of the LST at this area and the interaction with shoal and the sandbars can be investigated by adding this into a model.

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Appendix A

UNIBEST-CL+ model

This appendix covers the one line model software package UNIBEST-CL+. The different modules used in UNIBEST-CL+ are discussed and the basic parameters are described. Furthermore a sensitivity analysis is made for the Bijker sediment transport formula as well for the steepness of the used profiles and the accretion rate at the tip of the Island of Mussulo.

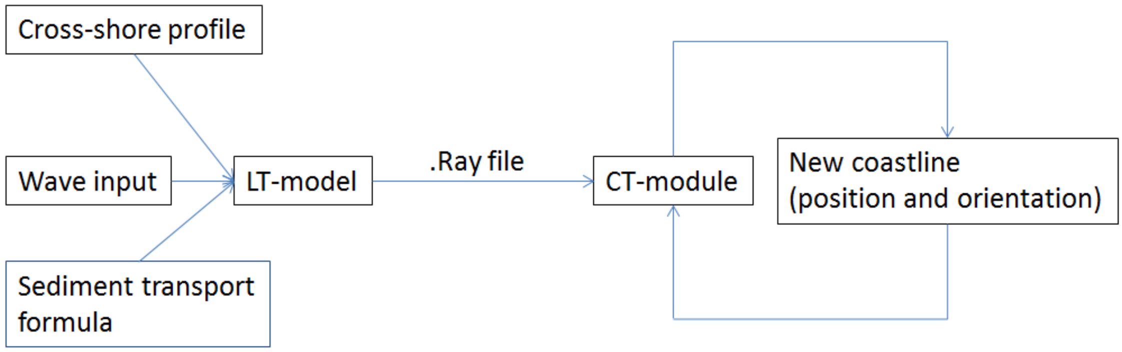

Figure A.1: Connection LT and CT module

A.1 Model set up

UNIBEST-CL+[1] is designed for simulating the coastline changes as an effect of the gradients in the longshore sediment transport induced by wave and tide driven longshore currents. UNIBEST-CL+ consist of two integrated modules, which are:

- Longshore Transport (LT) module
- Coastline Model (CL) module

The LT module is used to compute tide. wave induced longshore currents and resulting sediment transport at a specific cross-shore profile. It is assumed that the beach is uniform in alongshore direction. Principal processes of linear refraction, non-linear dissipation by wave breaking and bottom friction are taken into account with a built in random wave propagation and decay model within the LT module.

The coastline changes due to gradients in the longshore sediment transport, which are calculated in the LT module (see Figure A.1), are induced in the CL module. The CL module is based on the single line theory first presented by Pelnard-Considère [1956]. The single line theory gives the basic equations describing the morphological processes of coastline evolution due to longshore sediment transport gradients. This is done with the basic assumption that the shape of the cross-shore profile does not change in time. If the coast erodes or accretes the entire profile moves seaward or landward.

Along the modelled coastline certain aspects can be added such as sources and sinks to represent e.g. sediment brought by a river (source) or sediment extracted from the system due to a trough (sink). Morphological impacts such as headlands, groynes and revetments can also be modelled.

A.2 LT module

Several cross-sections are used in the LT module in order to simulate the different wave conditions along the Luanda coast. Every cross-section has the following characteristics:

- Cross-shore Profile; is needed to determine the cross-shore distribution of the longshore transport

[1] Chapter mainly based on UNIBEST-CL+ manual, Manual for version 7.1 of the shoreline model UNIBEST-CL+, Deltares, 2011

- Transport Parameters; the coefficients are important in order to determine the behaviour of sediment
- Wave Parameters; are used to define breaking, bottom friction and bottom roughness
- Wave Current; is needed to determine the S-ϕ curve as it is a wave driven current

This information is used to determine the S-ϕ curve which determines the longshore sediment transport as function of the wave angle. This data is stored into a file (.RAY file) which is used for the CT-Module in which parameters such as the sediment transport and the sediment transport distribution in cross-shore direction are stored.

A.2.1 Cross-shore profile

The cross-shore profiles are determined with the help of GEBCO and Nautical Chart information. The coastal orientation of the coast is determined with the help of aerial images obtained from Google Earth [2013]. The profiles are extended to reach a depth which matches the precise location of the seaward boundary (dynamic boundary) which is the closure depth separating the active and inactive zone.

A rule of thumb states that the closure depth is roughly three times larger than the largest wave heights. Which is in this case about 2 meters. Therefore a closure depth of 6 meters is defined as a first estimate.

As shown in Hallermeier [1983], the following formula which gives “a reasonable closure estimate” is based only on the wave height, $\mathrm{H_e}$.

$$d_{\mathrm{c}} = 1.57 \times H_{\mathrm{e}} \tag{A.1}$$

In which $\mathrm{H_e}$ is the nearshore storm wave height which is exceeded only 12 hr/yr.

With help of a Gumbel Distribution the 12 hr/yr is calculated, which is 2.35 m, as is shown in Figure A.2. The closure depth is therefore $\mathrm{d_c}$ = 3.7 m. Compared to the rule of thumb, which is often used, the calculated closure depth is considered to be relative low. As a first estimation the rule of thumb is used and with a sensativity analysis the difference between the calculated and the rule of thumb is investigated.

Beach profile

Bathymetric data is not accurate enough near the beach to determine the beach slopes needed for the LT module. In order to calculate the LST a so called Dean profile is used as discussed in Dean [1991]. The coastal profile tends to have an average, characteristic form, also called a theoretical equilibrium profile. The equilibrium profile has been defined as ”a statistical average profile, which maintains its form apart from small fluctuations, including seasonal fluctuations”. The depth in the equilibrium profile increases exponentially with the distance x in meters from the shoreline according to the equation. The depth d in meters is defined as follows:

$$d = A \cdot x^m \tag{A.2}$$

In which A is the dimensionless steepness parameter which is related to the sediment fall velocity and m is a dimensionless exponent of which Dean [1991] has suggested an average value of 0.67. The Dean profile definition is used in this model as detailed up to date bathymetric data is not available. The profiles used in the different coastal areas, as explained in Chapter 3, are shown in Figure A.3.

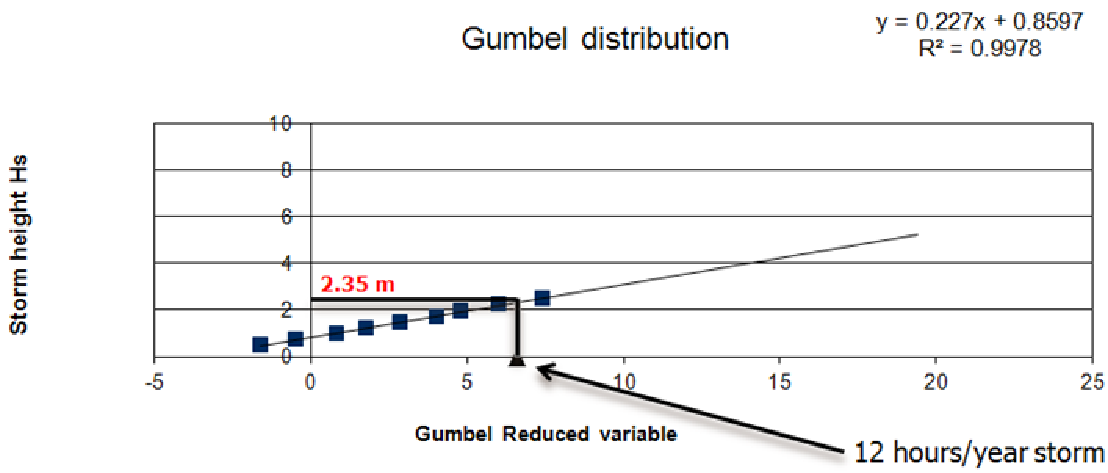

Figure A.2: Gumbal distribution (aanpassen)

A.2.2 Transport parameters

Transport of sediment is calculated for every ray and can be modelled with the help of a variety of sediment transport formulas which are implemented in the UNIBEST package such as Cerc, Bijker and Van Rijn and Van der Meer-Pilarczyk. In this report the formula of CERC and Bijker are used.

Cerc

The longshore transport according to CERC is related to the energy component of the wave action parallel to the coast, the surfzone. The analytical approach the CERC transport S_c $[m3/s]$ is defined as:

$$S_{\mathrm{x}} = AH_{\mathrm{b}}{}^2 n_{\mathrm{b}} c_{\mathrm{b}} cos\phi_{\mathrm{b}} sin\phi_{\mathrm{b}} \tag{A.3}$$

Where:

S_x = longshore sediment transport $[m^3/s]$

A = dimensionless coefficient $[-]$

H_b = wave height at breaker depth $[m]$

n_b = ratio of wave propagation speed and wave group celerity at breaker depth $[-]$

c_b = wave celerity at breaker depth $[m/s]$

b = angle of wave approach at breaker depth $[m/s]$

A depends on the type of wave height which is used, 0.08 when root mean square wave height is used and 0.04 for a significant wave height.

Within Unibest LT the formulation of CERC is defined as:

$$S = AH_{\mathrm{s0}}{}^2 2C_{\mathrm{g0}} sin\phi_{\mathrm{b}} cos\phi_0 \tag{A.4}$$

Where:

H_{s0} = significant wave height at deep water $[m]$

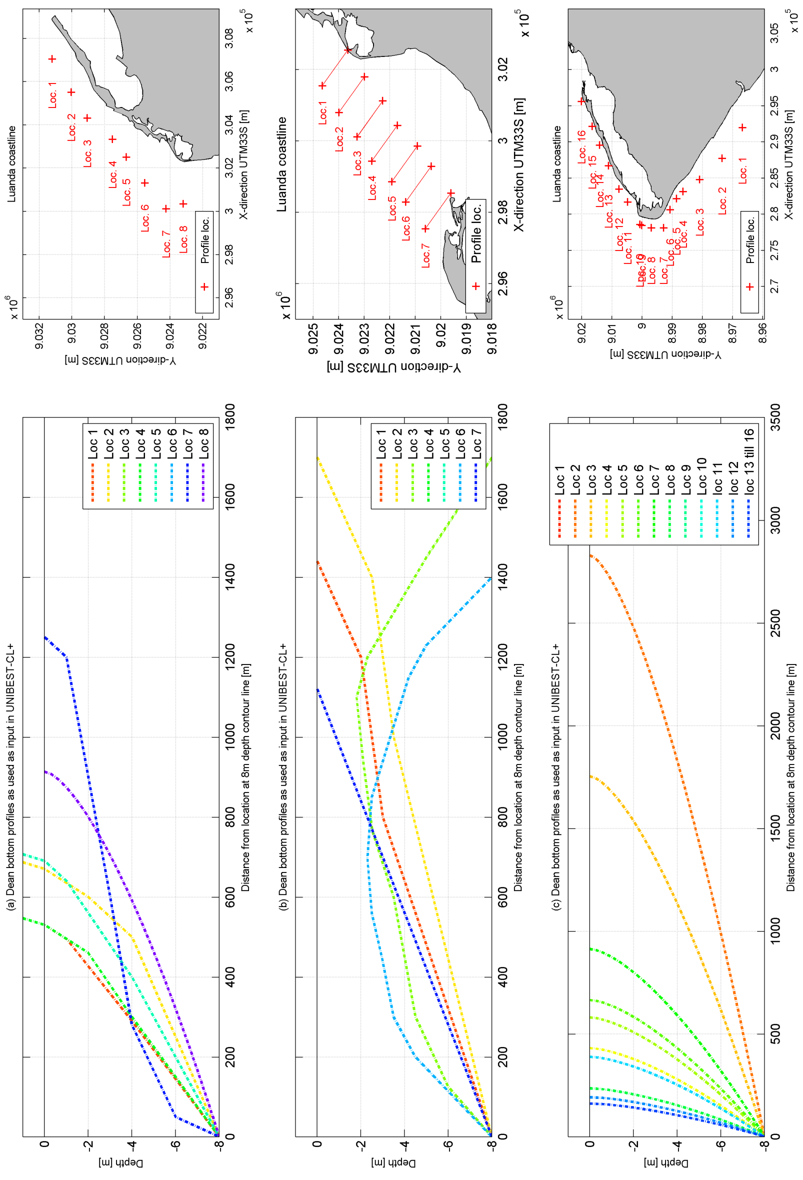

Figure A.3: Beach profiles used in UNIBEST-CL+ for (a) the Island of Luanda, (b) the shoal at the entrance to the Bay of Mussulo and (c) the Island of Mussulo till the Kwanza River.

C_g = group velocity waves at deep water $[m/s]$

C_{g0}=$n \cdot C$

ϕ_0= wave angle at deep water [°]

ϕ_b=wave angle at breaker depth [][°])

The breaker depth h_b is defined by the relation $\gamma \times h_b = H_{s0}^2$

Point of considerations

- CERC-formula does not account for differences in grain-size.
- CERC-formula is only valid for relatively long and straight beaches where the longshore differences in the breaking wave heights are only small
- CERC-formula does not account for currents which are not generated by breaking waves, such as tidal currents

Bijker

Bijker formula is based upon the formula of Kalinske-Frijling for bed load due to currents only which is compensated with a formulation in the increase of the bottom shear stress.

The formula of Kalinske-Frijling, which Bijker [1968] refers to as a starting point, was written in the form:

$$\frac{S_\mathrm{b}}{f(D^{3/2}g^{1/2}\Delta)} = f(\frac{\Delta D}{\mu h I}) \tag{A.5}$$

The first term is called by Bijker [1968] “the transport parameter” and the ”the exponent of e in the second term “the stirring ’parameter’. A mean resultant bed shear of the combination of waves and current is introduced in the bed shear in the stirring parameter by Bijker. This will stir op the sediment which will be transported by normal currents. By adjusting the new formula with available data the sediment transport of a combination of waves and currents is written by Bijker as shown in Hallermeier [1983] as follow:

$$S_\mathrm{b} = bD(\tau_\mathrm{c}/\rho)^{1/2}e^{-0.27\frac{\Delta\rho g}{\mu\tau_\mathrm{r}}} \tag{A.6}$$

Or as formulated in the UNIBEST-CL+ manual:

$$S_\mathrm{b} = bD_{50}\frac{v}{C}g^{1/2}e^{(}\frac{-0.27\Delta D_{50}C^2}{\mu v\{1+\frac{1}{2}\zeta\frac{u_\mathrm{b}}{v}\}^2}) \tag{A.7}$$

Where:

$D_(50)$ = median grain diameter $[m]$

D_{90} = 90% grain diameter $[m]$

Δ = relative density $[-]$

r_c = bottom roughness (0.5-1.0 times ripple height) $[m]$

ρ_s = sediment’s density

w = sediment’s fall velocity $[m/s]$

$\mathrm{u_b}$ = orbital velocity near the bottom $[m/s]$

ω = wave frequency $[rad/s]$

Bijker [1968] added to the bed load a distribution of the suspended load, which is based upon the Einstein-Rouse concentration vertical, the total transport is described as:

$$S = S_{\mathrm{b}} + S_{\mathrm{s}} \tag{A.8}$$

In which S_s is formulated as:

$$S_{\mathrm{s}} = 1.83 S_{\mathrm{b}} \{ I_1 ln \left(\frac{33h}{r} \right) + I2 \} \tag{A.9}$$

With:

$$I_1 = 0.216 \frac{(a/h)^{\text{z-1}}}{\left(1 - \frac{a}{h}^z\right)} \int_{a/h}^{1} \left(\frac{1-y}{y} \right)^z dz \tag{A.10}$$

$$I_2 = 0.216 \frac{(a/h)^{\text{z-1}}}{\left(1 - \frac{a}{h}^z\right)} \int_{a/h}^{1} \left(\frac{1-y}{y} \right)^z lnydz \tag{A.11}$$

Point of considerations

- Bijker formula overestimates transport rate for low transport capacities.
- Data for perpendicular wave attack and those for oblique wave attack have no systematic differences.

Wave Parameters

For each ray there are different wave conditions. Wave conditions are modelled with SWAN (Delft3D Wave) as described in Appendix B, in which the offshore wave and wind data is translated to nearshore wave data. The wave data is extracted for locations which are used as a starting point in the cross shore profiles.

A.2.3 CT-Module

The CT module calculates the gradient in the alongshore transports and determines whether erosion or accretion occurs. The S-ϕ curves of the rays determined in the LT module are used to calculate the longshore sediment transport capacity of each ray.

The actual coastline is described in the Basic Model. The coastline (x-direction) is schematised by means of a curved line the normals perpendicular to this lines are the y-axis. Certain entities can be used to define the characteristics of a coastline stretch such as boundary conditions, sources and sinks.

Boundary conditions

These conditions describe the behaviour of the model at the two model boundaries the four possible options are:

- Coastline position Y remains constant
- The coastal angle remains constant
- Transport Qs is a user-defined constant value
- Transport Qs is a user-defined function of time

Coastal structures

There are several coastal structures which can be implanted in the coastline which are:

- Groynes; these are defined by the position in x-direction, the position of the top in y-direction and the percentage of blocking.
- Offshore breakwaters; these are simulated by series of transport rays which describe the local transport behind the breakwaters
- Revetments; these will stop erosion when the shoreline reaches a predefined line

Sources and sinks

Sediment input due to i.e. a river or sediment extraction due to i.e. a trough are schematised by adding sources and sinks in the model. Sources and sinks are used when simulating a breach in the Island of Mussulo.

A.3 Sensitivity Analysis

In order to test the reliability of the outcome of the LT module a sensitivity analysis is made. The Bijker sediment transport formula is tested as this has by far the most parameters which can influence the S-ϕ curve calculated in the LT module.

For every ray the sediment parameters are changed with a 30%, as is shown in Table A.1.

Table A.1: Parameters which are tuned

	lower limit	standard	upper limit
Bottom roughness [m]	0.035	0.05	0.065
Criterion deep water [-]	0.049	0.07	0.091
Criterion shallow water [-]	0.042	0.06	0.078
Sediment fall velocity [$^m/_s$]	0.014	0.02	0.026
D_{50} [μm]	140	200	260
D_{90} [μm]	560	800	1040

For every parameter the longshore sediment transport capacity at the existing coastline orientation for that specific ray is extracted from the S-ϕ curve. For example Figure A.4, in this figure the dotted line represent the coastline orientation at this specific location, Ray 12. For this location the upper, lower and standard value of the paramater D_{50} differ.

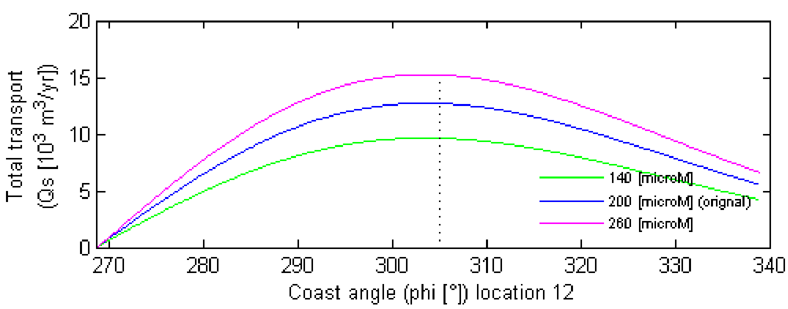

Figure A.4: S-ϕ curve at different D_{50} settings

All the parameters are calculated in this way and added together to define a upper and lower boundary for the Bijker sediment transport formula. In the middle figure of Figure A.5 the absolute values of the different parameters are shown. As can be seen the LST capacities in the north do not differ much compared to the standard calculation. The absolute difference increases from north to south. When looking at the relative difference of the upper and lower limit compared to the standard case, as shown in the left figure in Figure A.5, we see that the lower boundary is 50% less than the standard case and the upper boundary is (on average) 80% more than the standard case.

A.3.1 Steepness profile

A difference between the Bijker formula and the CERC formula is observed, as is shown in Figure A.6. The ratio CERC/Bijker for the LST is about 3-3.5 in the south and increases rapidly at the Island of Mussulo to about 38. This increase can not be explained by the sensitivity analyses done on the parameters of the sediment transport formula of Bijker. Another uncertainty in this area is the bottom profiles which is first estimated with a Dean profile. The northern profiles are replaced with a more gentle bottom profile. After reduction of the northern profiles the ratio of the LST of CERC/Bijker is reduced in the south to about 8 to 9, as is shown in Figure A.7. The ratio in the coastline changes between CERC and Bijker is almost the same as in the case of the earlier Dean profiles.

A.3.2 Accretion tip Island of Mussulo

Volumes about the accretion of the Island of Mussulo tip can differ. In order to present a range in which these accretion values can lie a sensitivity analysis is made. An increase in surface area of the spit end is determined with help of an old map dated from 1949[2] which is compared with nowadays Google Earth images. A surface area of 1.76 km^2 is calculated as shown in Figure A.8. An error of $+/-$ 5 percentage is expected for the surface area. The depth around this area differs from 0.5 to 2.5 m. An average range differs between 0.8 m to 2.2 m which had to be filled in to extend the spit tip.

Table A.2: Sensitivity volumes Mussulo tip extension

	Minimum value surface area 1.67 km2	**Maximum value surface area 1.85 m2**
Min. depth value 0.8 m	1,336,000 m3	1,480,000 m3
Max. depth value 2.2 m	3,674,000 m3	4,070,000 m3

The total accretion lies in the range between $1.4 \cdot 10^6$ en $4.1 \cdot 10^6$ which is over a time span of 63 years. The average rate of accretion lies between 21,000 $m^3/year$ and 65,000 $m^3/year$.

[2]Ministério do Ultramar. Junta das Missões Geográficas e de Investigações do Ultramar. Lisboa. Oceano Atlântico Sul. África Ocidental Portuguesa (Angola) - 1949 Des. F. Soares Pereira scale 1:100.000

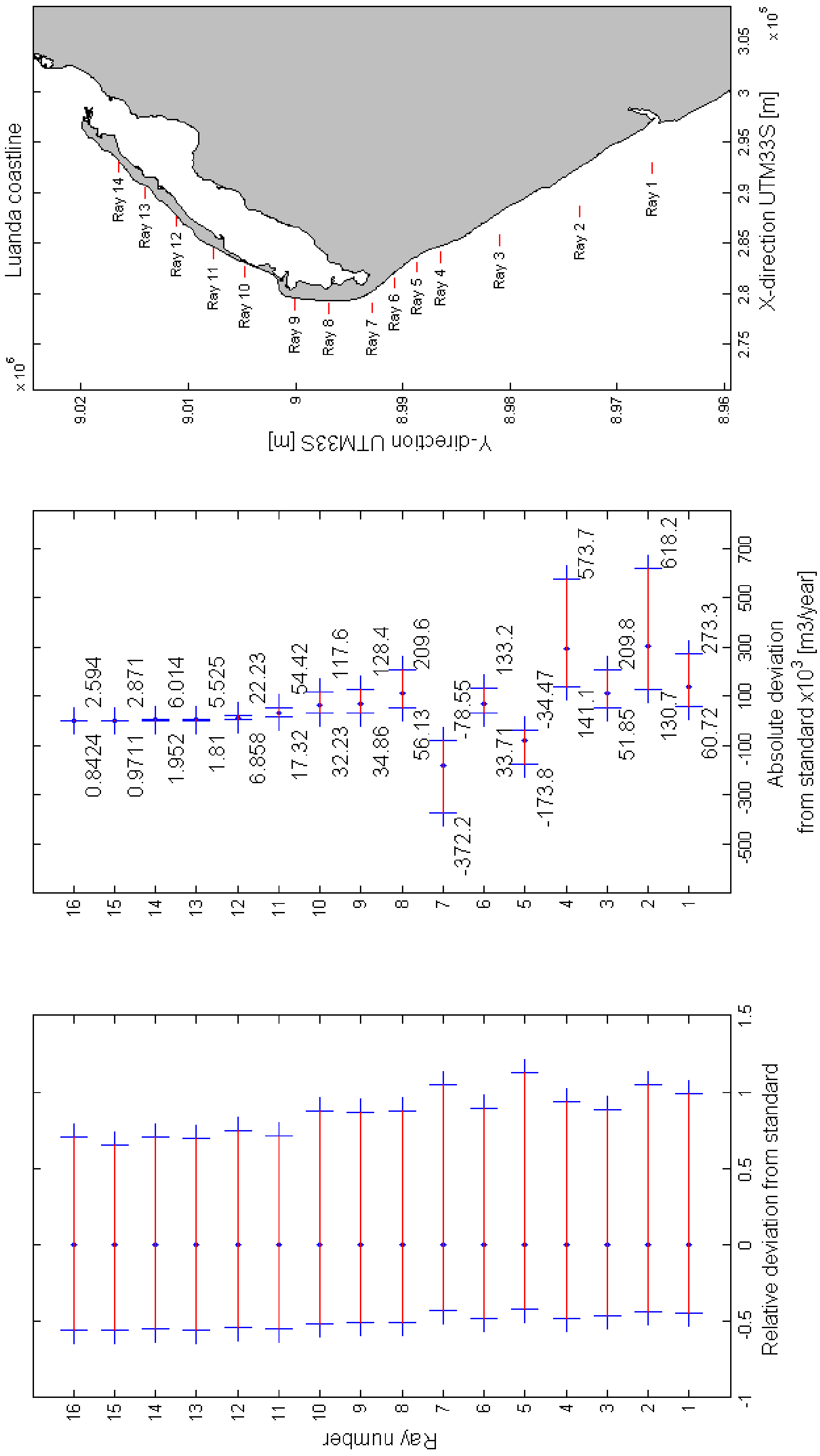

Figure A.5: Sensitivity for all parameters for the locations along the Island of Mussulo

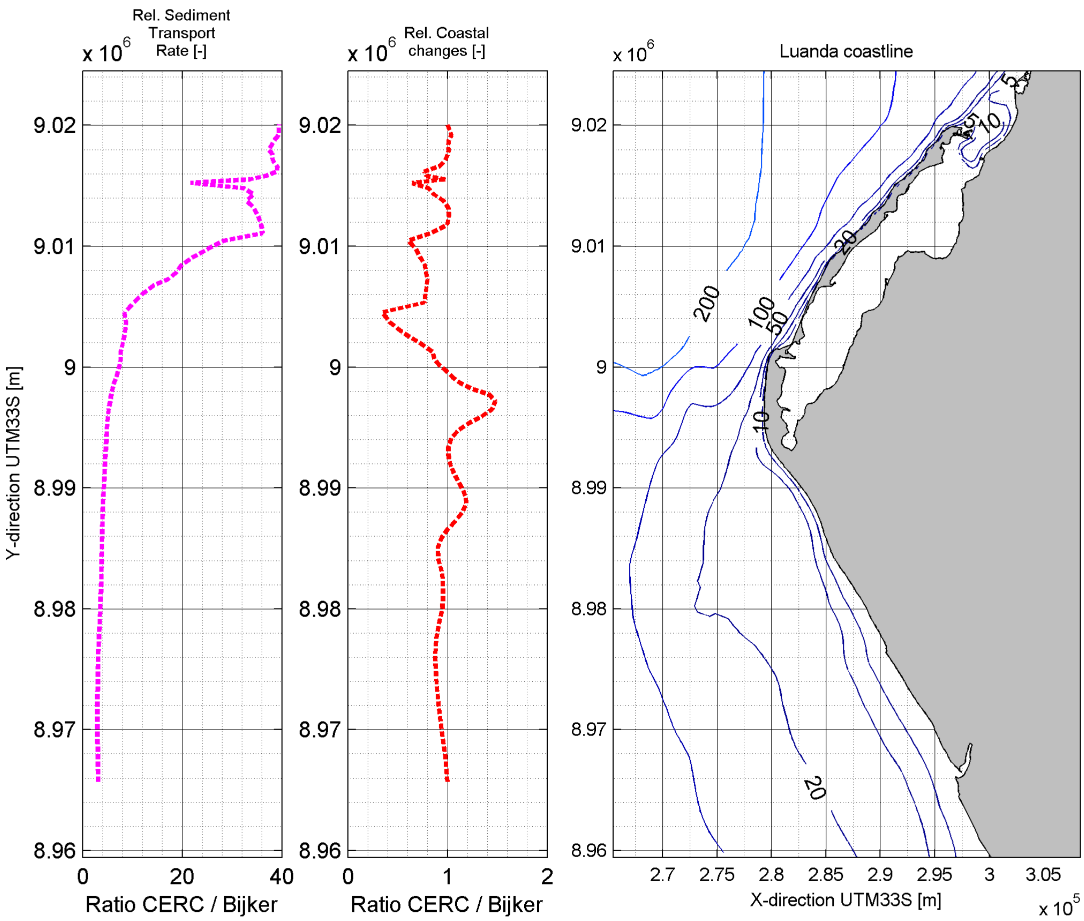

Figure A.6: Relative difference between the sediment transport formula of CERC and Bijker along the Island of Mussulo

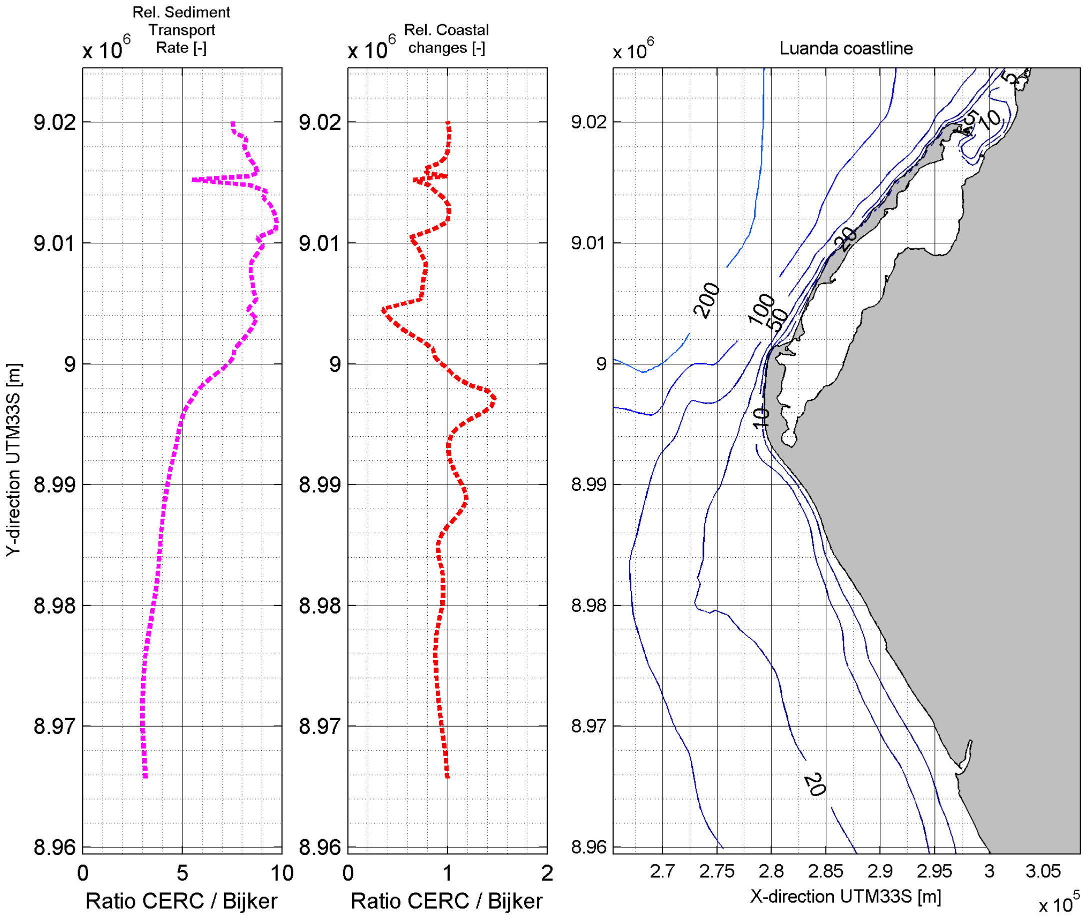

Figure A.7: Relative difference between the sediment transport formula of CERC and Bijker along the Island of Mussulo when using a less steep slope in the northern area of the Island of Mussulo

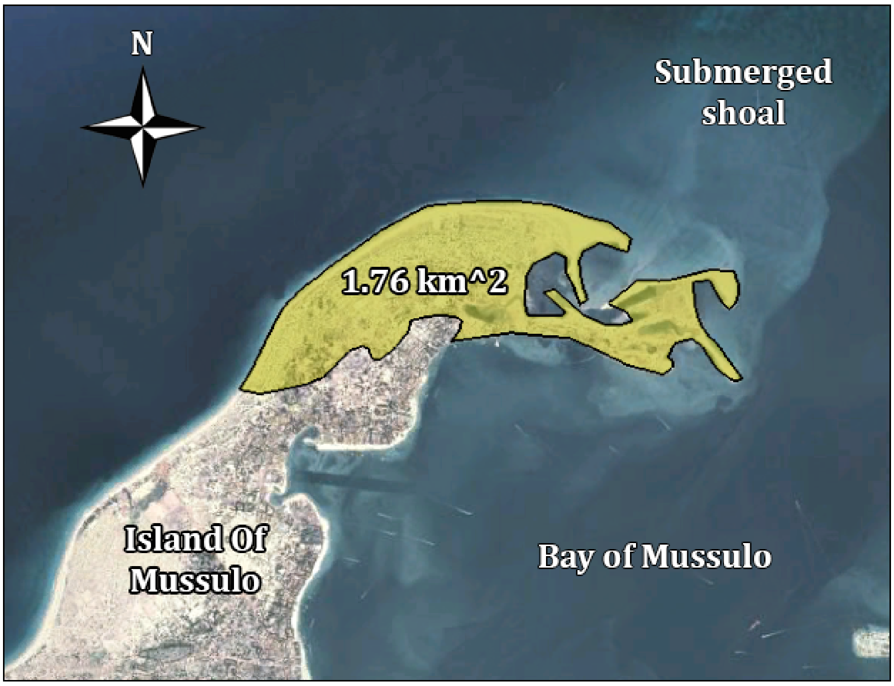

Figure A.8: Spit increase between the years 1949 – 2013 (64 years)

Appendix B

Wave climate simulation

The SWAN (Simulating WAves Nearshore) model is used to determine the nearshore wave climates. SWAN is a third generation numerical model to compute random short-crested waves in coastal regions with shallow water and is developed by the Delft University of Technology. Processes such as refraction, diffraction, dissipation processes and wave-wave interactions are possible to take into account. The wave climates used are extracted from a database used in "Angola Coastal Studies, Evaluation of the Futungo beach widening scheme" by Deltares. In this appendix the basic settings are elaborated on, such as the grid, bathymetry and boundary conditions. The model outcome and validation is also discussed.

B.1 Grid

In order to require an accurate result four kinds of grids are used which differs in overall size, cell size and location. From overall grid to detailed coastal grid:

- Overall grid; The boundary conditions are imposed on the boundary of this grid. The total grid extends from approximately -4.5° to -18° North and 10.5° and 12° East with an grid size of around 5,400 m with a total area of 377,244 km^2.
- Large grid; The large grid is nested inside the overall grid and has a grid size of approximately 1100 m and covers an area of approximately 54,615 km^2. The grid is slightly tilted in order to have the same orientation as the coast.
- Intermediate grid; The intermediate grid is nested within the large grid and covers an area of approximately 7,344 km^2 with a grid size of 400 m.
- Detailed coastal grid; the detailed coastal grid is a curvi linear grid in order to reduce the numerical errors nearshore. The grid size differs from 55 x 155 (4/5 of the grid) furthest from the coast and 30 x 90 m (1/5 of the grid) nearshore.

B.2 Boundary conditions

Two datasets were available for setting up the boundary conditions.

- WANE2; The WANE2 data (West African Normals and Extreme Update) which was provided by Draimar Ltd is a 3-hourly hindcast data set for a period of 15 years, 1992 to 2006, on a 0.125 by 0.125 degree grid. The model is an update of the WANE hindcast study by Ocean Numerics which is a joint venture between Oceanweather Inc. and GEOS. This dataset is can only be used for the Luanda coastal area.
- ERA-interim (ERAI); The ERAI data is generated by the European centre for medium range weather forecast (ECMWF). The dataset has a resolution of 1° x 1° from 1979 and is still ongoing. This dataset can be used for the entire Angolan coast.

The two datasets were compared for a location offshore and it was shown that the datasets were comparable. The ERAI dataset is used as this datasets covers the whole Angolan area, which was a requirement for the Deltares study.

The ERAI dataset is reduced into 58 separate scenarios in which the data point at -9 North, 10.5 East is used as reference point for the determination of the wind and wave climate for the wave model. The joint occurrence of the 58 scenarios are shown in Figure B.2.

B.3 Bathymetry

Bathymetry data consist of three kinds of datasets which have different quality of accuracy. The most accurate one is used a basis and areas which are not included in this bathymetry are filled up with coarser bathymetries.

- C-map; C-map data collected for the Luanda area is used to increase bathymetry detail at certain areas.

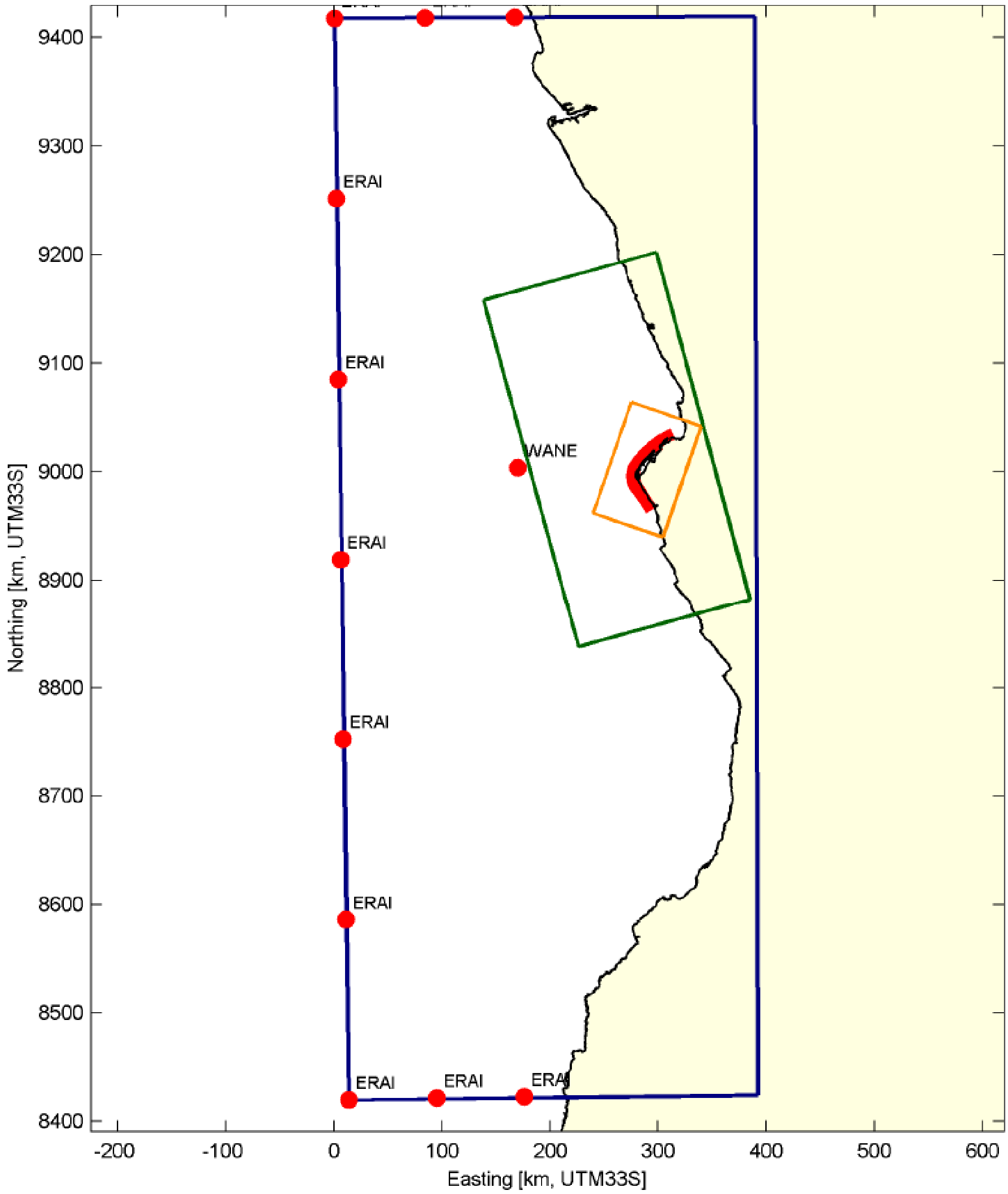

Figure B.1: Outlines of computational grids used (blue: overall grid, green: large grid, orange: intermediate grid and red: detailed coastal grid). Red dots represent the ERA-interim points used to determine the wave scanarios, the WANE data point at Lat 9S, Lon. 12.5E is also indicated. From: Angola Coastal studies – Evaluation of the Futongo beach widening scheme. Deltares

Significant wave height	350.0-180.0	180.0-190.0	190.0-195.0	195.0-200.0	200.0-205.0	205.0-210.0	210.0-215.0	215.0-220.0	220.0-225.0	225.0-230.0	230.0-240.0	240.0-260.0	
>6.0													
5.0-6.0													
4.5-5.0													
4.0-4.5													
3.5-4.0				0.00	0.01	0.00							0.02
3.0-3.5		0.01	0.03	0.04	0.05	0.03	0.04	0.00					0.20
2.5-3.0		0.04	0.18	0.35	0.38	0.41	0.20	0.10	0.00				1.68
2.0-2.5		0.14	1.24	2.41	2.65	2.37	1.19	0.43	0.04				10.47
1.5-2.0	0.00	0.66	5.23	10.60	10.98	7.80	3.85	1.17	0.23	0.04	0.00	0.00	40.59
1.0-1.5		0.40	4.68	12.13	14.40	9.27	3.41	0.89	0.16	0.05	0.03	0.03	45.42
0.5-1.0		0.01	0.12	0.41	0.53	0.34	0.13	0.05	0.00	0.01			1.62
0.0-0.5													
Entire dataset	0.00	1.26	11.48	25.93	29.00	20.22	8.83	2.65	0.44	0.11	0.03	0.03	100.00
													Total

Figure B.2: Joint occurrence table for significant wave height and mean wave direction for the ERA-interim. From: Angola Coastal studies – Evaluation of the Futongo beach widening scheme. Deltares

- Admiralty Charts; in order to get a better insight in the contour lines Admirality Charts is used to improve bathymetry data.
- Gebco 08, which is extracted from the OpenEarth tool “Delft Dashboard”. This is the coarsest bathymetry data which is used. GEBCO is an international reference map of the seafloor depth of the worlds oceans. It is produced under the auspices of the Intergovernmental Oceanographic Commission and the International Hydrographic Organization. GEBCO 08 is a global 30 arc-second grid. In which the world (sphere) is divided into 360 degrees where each degree is subdivided into 60 minutes and every minute into 60 seconds. Therefore 30 arc-second is equal to 30/3600th of a degree.

In Figure B.3 the bathymetry which is used for the detailed coastal grid is showed.

B.4 Wave model outcome

The nearshore significant wave height are calculated with SWAN for every of the 58 wave conditions. The local nearshore significant wave height for specific locations used in the UNIBEST-CL+ model is extracted from the SWAN model.

B.5 Validation

The validation of the ERA-Interim data has been done on deep water with the WANE data. The SWAN output at the location of the WANE data is comparable. For shallow water there is less validation data available. The SWAN model outcome is compared with the wave climates which are calculated in the report of HR Wallingford. HR Wallingford calculated for four locations the wave climates. The results are shown in Figure B.4.

The wave climates of the SWAN model are more modest at all locations. This can clearly be seen when comparing the H_s which are below 0.3 m. More validation is preferable as there is a difference between the two wave data outcomes.

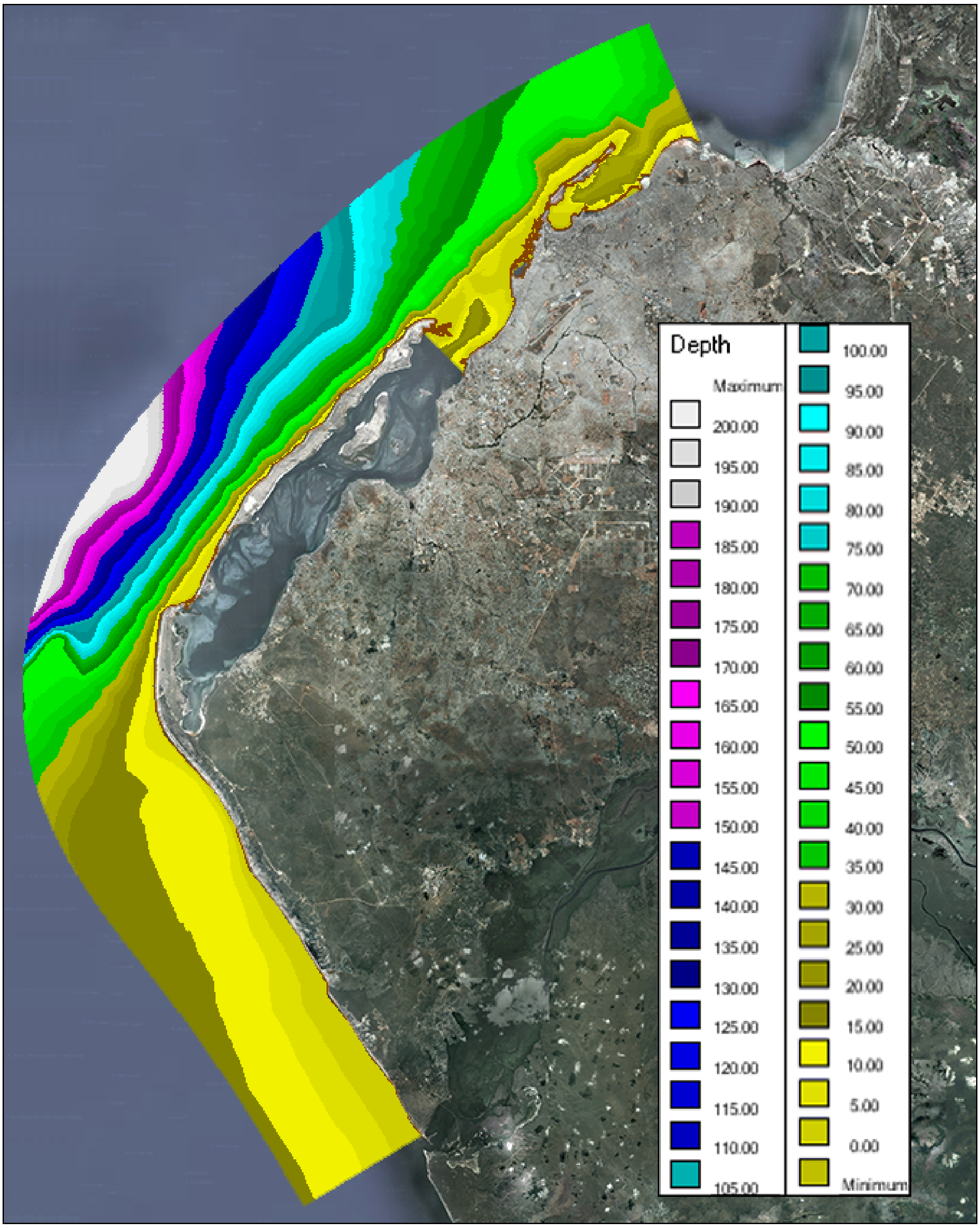

Figure B.3: Bathymetry of the detailed coastal grid

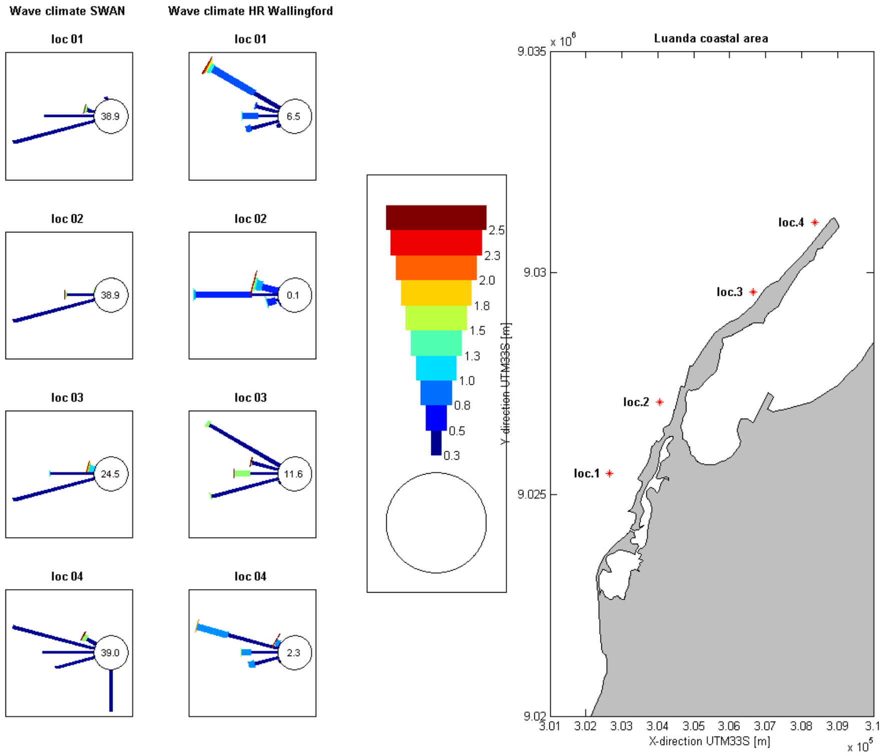

Figure B.4: Wave climates compared. SWAN vs. HR Wallingford. Wave climates are located at 5 m depth contour lines.

Appendix C

Tide analysis

A tide model, with the help of the software package Delft3D, is used to calculate the velocities due to tides. This appendix will first elaborates on the model set-up. Secondly, this appendix will describe the used sediment transport formulas in combination with the tide model.

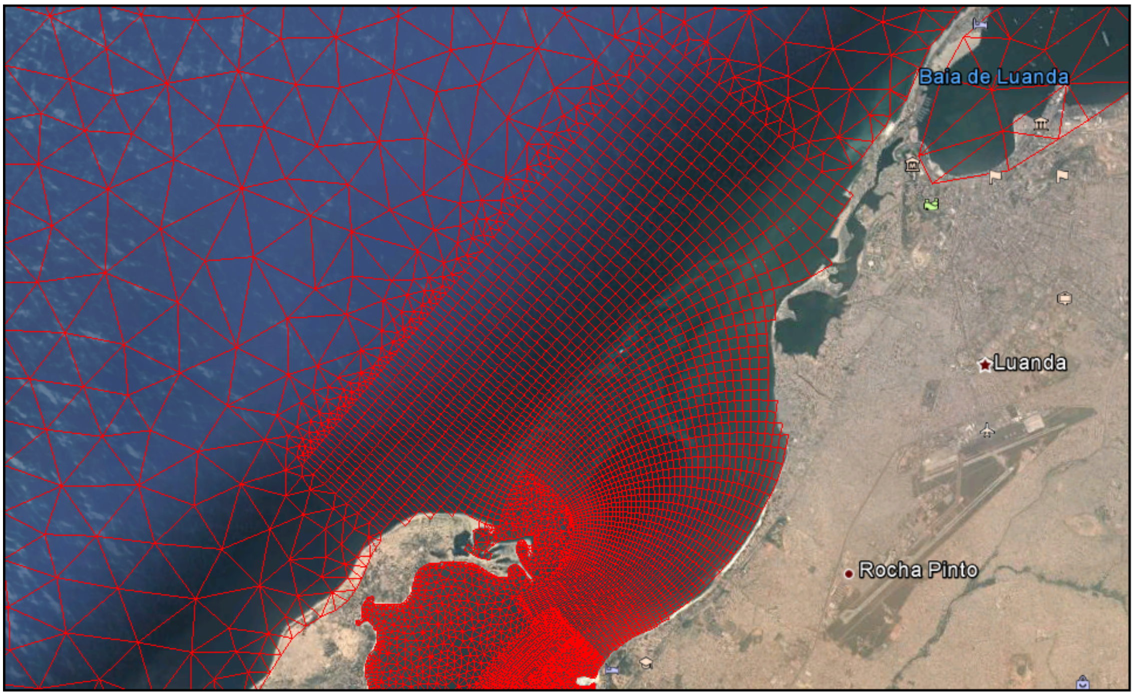

Figure C.1: Mesh used by Delft3D in combination with D-Flow FM, spatial domain at the shoal.

C.1 Tide model set-up

Tide is simulated with Delft3D in combination with a newly developed software engine D-Flow FM (FM stands for flexible mesh) which makes use of unstructured grids. Besides the familiar curvilinear meshes known in Delft3D the unstructured grid can consist of triangles, pentagons and more[1].

In order to simulate the tide, the tide constituents as shown in table C.1 are used.

Table C.1: Tidal constituents used in Delft3D to simulate tides

Diurnal		Semi-Diurnal		Long period	
M2	Principal lunar	O1	Principal lunar	MF	Foitnightly
S2	Principal solar	P1	Principal solar	MM	Monthly
N2	Lunar elliptical	Q1	Lunar elliptical	M4	Principal lunar
K2	Lunar-solar declinational			MS4	Compound tide of M2 and S2
K1	Lunar-solar declinational (diurnal)			MN4	Shallow water quarter diurnal

The tide model makes use of the nation wide grid used for the wave simulation as described in Appendix B. This is altered with an increasing spatial resolution within the bay which is used to increase the accuracy of the model. The spatial domain in the area of the shoal is shown in Figure C.1. A period of one year is modelled starting at the first of January till the end of December 2009. The model is validated with observed data acquired within the Bay of Mussulo[2].

[1] For more information about D-Flow FM please consult the D-Flow Flexible Mesh - User Manual by Deltares
[2] More information about the validation of the tidal model is found in Deltares [2013]

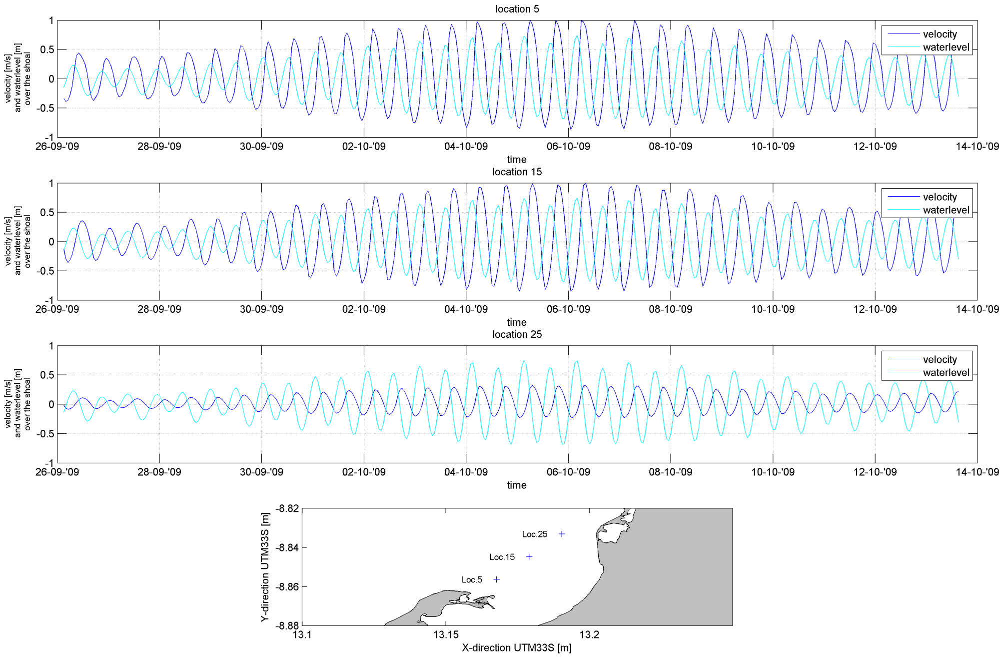

Figure C.2: Velocity cycle for spring-neap cycle

C.2 Sediment transport

The sediment transport is related with the velocity (wave induced and tide induced). With help of a sediment transport formula an indication of the velocity can be given. The sediment transport formulas used is Soulsby van Rijn.

Soulsby van Rijn

The sediment transport formula as used in the Soulsby van Rijn formulation applies on the total sediment transport i.e. suspended and bedload sediment transport. The sediment transport formula is based on Van Rijn [1993] and described in Soulsby [1997] as follows:

$$q_t = A_s\bar{U}[(\bar{U}^2 + \frac{0.018}{C_D}U_{rms})^{0.5} - U_{cr}]^{2.4}(1 - 1.6tan\beta) \qquad \text{(C.1)}$$

In which:

$A_{sb} = \frac{0.005h(d_{50}/h)^{1.2}}{[(s-1)gd_{50}]^{1.2}}$

$A_{ss} = \frac{0.012d_{50}D*^{0.6}}{[(s-1)gd_{50}]^{1.2}}$

$A_s = A_{sb} + Ass$

$\bar{U}$ =depth averaged current velocity

$U_{rms} = \sqrt{2}\frac{\pi H_{rms}}{T_p \sinh kH}$ =root mean square wave orbital velocity in which:

$H_{rms} = Hs/2$

$k = \frac{2\pi}{L} = \frac{4\pi^2}{gT_p}$

$C_D = \left[\frac{\kappa}{ln(h/z_0)-1}\right]^2$ = drag coefficient due to current alone

$\bar{U}_{cr}$ =threshold current velocity in which:

$$\bar{U}_{cr} = 0.19 d_{50}^{0.1}\ log_{10}\left(\frac{4h}{d_{90}}\right) for\ 0.1 \le d_{50} \le 0.5\ mm$$

$$\bar{U}_{cr} = 8.5 d_{50}^{0.6}\ log_{10}\left(\frac{4h}{d_{90}}\right) for\ 0.5 \le d_{50} \le 2\ mm$$

β =slope of bed in streamwise directon, positive if flow runs uphill

h =water depth

d_{50} =median grain diameter

z_0 =bed roughness length = 0.006 m

s = relative density of sediment

g = acceleration due to gravity

ν = kinematic viscosity of water

$D* = \left[\frac{g(s-1)}{\nu^2}\right]^{1/3} d_{50}$

The coefficient 0.018 was obtained by calibration against the curves plotted by Van Rijn [1993]. The values of the different parameters used are described in Table C.2

Table C.2: Values of parameters used in the Soulsby van Rijn formulation

Parameter	Value
d_{50}	$200 \cdot 10^{-6}\ m$
κ	0.3
d_{90}	$900 \cdot 10^{-6}\ m$
z_0	$0.006\ m$
g	$9.81\ m/s^2$

The SWAN model in combination with the tide model produce the input for the Soulsby van Rijn formula. A description of the procedure is given. At first, the SWAN model is used to extract the H_s which is than rewritten to H_{rms} this will be done with 58 conditions which represent the wave climate of a year. Secondly, a location is chosen where the sediment transport will be calculated. At this location the tide model is used in order to extract the tide induced velocities at this specific location. The tide velocity over a year is combined with a condition. As this condition is 1 of the 58 and does not represent a total year the calculated sediment transport is multiplied with the duration a condition has, the duration is extracted from the SWAN model. By taking the sum of all the 58 conditions, which represent the wave climate of a year, the total sediment transport for a year is calculated.