Project South Durban
Understanding the Sediment Transports and Budgets around the Durban DigOut Port, South Africa

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MSc Thesis - F.C. Habets

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- *Understanding the Sediment Transports and Budgets around the Durban DigOut Port, South Africa* -

26th of October 2015, Delft

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Executive summary

Title

Project South Durban - *Understanding the sediment transports and budgets around the Durban DigOut Port*

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Executive Summary

Durban is located on the east coast of South Africa in the province of KwaZulu-Natal. It is one of South Africa’s biggest cities and has one of the busiest ports in Africa. To maintain Durban’s current economic position the Durban Port has to expand, which is problematic due to a lack of space. A solution is to develop a completely new port: the Durban DigOut Port. The past has taught us that significant erosion/accretion patterns are likely to occur around the breakwaters of the new port, as has happened at the Durban Port. In the long run climate change could also lead to alterations in shoreline behavior of the South Durban coast. The problem definition reads: *“Currently, it is not fully known how the coastal system of South Durban functions and what the future state of the system will be under influence of climate change and after construction of the Durban DigOut Port.“* The goal of this research is to understand the sediment transports and budgets along the South Durban coast both now and in the future. To do this it is necessary to predict and assess future shoreline behavior, in response to anthropogenic interventions, like the Durban DigOut Port, and to climatic changes such as sea level rise and changing wave conditions. The time scope is confined to the coming 40years. For this research use has been made of two numerical models. The equilibrium based Unibest-CL+ model is used to create a 1D shoreline model to model long-term shoreline behavior. The process-based SWAN (or Delft3d-Wave) model is used to model wave propagation on the continental shelf and in the nearshore of the South Durban coast. Waves approach the coast from a predominantly south-eastern direction. The annual wave climate consists of south-southeastern swell waves and wind-waves approaching from all directions. It provides a net northward longshore sediment transport for the South Durban coast, which is modeled to be 700,000m^3/year at the Durban Bluff. A gradient in longshore sediment transports is found over the area from Amanzimtoti to the Durban Bluff. This results in coastal erosion, because sediment input from rivers is lacking. Research into the longshore sediment transports for the South Durban coast shows that the coastline lies close to its equilibrium position and that maximum potential sediment transports are high (order of 1.5 to 3million m^3/year). This leads to significant erosion/accretion patterns around the Durban DigOut Port. The maximum shoreline retreat on the lee side of the port is modeled to be 500meters, 30years after construction of the breakwaters. A bypass system of 550,000m^3/year reduces shoreline retreat to a maximum of 30meters. In addition a local groyne system is proposed to prevent coastal retreat at the Sapref Refinery area. The calculated coastal retreat can be viewed as an extreme prediction, because a uniform sandy coast is assumed for the modeling, which is not realistic given the rocky formations along the South Durban coast. Changes in the average wave climate are found from literature; the average wave direction is likely to rotate clockwise and wave periods are expected to increase during winter. When these changes are included in the shoreline model, gradients in longshore sediment transports along the coast are enhanced, leading to additional coastal erosion. Sand supply from rivers is reduced due to sand mining, which leads to structural coastal erosion over the total system as well.

Project South Durban

- *Understanding the Sediment Transports and Budgets around the Durban DigOut Port, South Africa* –

By Francisclus Clemens (Frank) Habets

26th October 2015

This research is undertaken in partial fulfillment of the requirements
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Preface

In this report my MSc thesis is presented, which concludes my academic carrier as a student at the Faculty of Civil Engineering & Geosciences at the Delft University of Technology. I have followed the Hydraulic Engineering master program, with the emphasis on Coastal Engineering. With passion and interest, I have studied the physics of the sea surface and the dynamical processes in the coastal zone. A basis has been created to take with confidence my first step in the engineering world.

The topic of this MSc Thesis is formed by the Council of Scientific Industrial Research (CSIR), Deltares and Delft University of Technology. By researching the sediment transports and budgets around the Durban DigOut Port, information is gained about future shoreline behavior at the South Durban coast. Researching this topic suits me, due to my interest in long-term and large scale morphological development of coastal systems. Modeling of these coastal systems, interpreting the outcomes and managing an international research process, are the main lessons of my thesis, which I take with me in my future carrier.

I have completed my thesis for a large part at Deltares in Delft, The Netherlands. Deltares is an independent research and knowledge institute in the field of water, subsurface terrain and infrastructure. They have provided me all tools and necessities to fulfill this thesis, for which I am very grateful. I appreciate the open interaction between experts of the company and students to solve problems together. I have experienced this myself, through meetings with Dirk-Jan Walstra, Bas Huisman and Arjen Luijendijk, who all work for Deltares. I would like to thank Dirk-Jan for his support and advice during my total process and Bas for helping me out with the modeling part and setting up the report. I would also like to thank the other members of my graduation committee, Chairman Marcel Stive, Jill Slinger and Arjen Luijendijk, where I had valuable discussions with, which in turn has led to a better understanding of the problem and effective process.

During three months of my thesis I have worked at the CSIR in Stellenbosch, South Africa. The CSIR is one of the leading scientific and technology research, development and implementation organizations in Africa. I have stayed at the company and went with them to Durban to view the project site and investigate the coast of South Durban. I would like to thank them for giving me the opportunity to work in an international environment on an interesting contemporary topic about the South African East Coast. I would like to thank, Christo Rautenbach and Andre Theron, for sharing their expertise with me during the fruitful discussions at my stay.

This thesis project is carried out with the support of the Marie Curie funding. The Marie Curie fund supports the transition of knowledge between European and African research institutes. Discussions about the complex coastal system along the coast of East Africa and sharing of expertise on long-term shoreline modeling with researchers of the CSIR, South Africa are results of the usefulness of such a program.

I would like to acknowledge the EThekwini Municipality for supplying me the information about historical beach profiles and the Transnet Port Authority (TNPA) for supplying the necessary wave data.

Finally, I would like to thank my parents, family and friends for believing in me and supporting me throughout my entire study.

Franciscus Clemens (Frank) Habets

Delft, October 2015

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1. Introduction

1.1 Problem description

Durban is located on the east coast of South Africa in the province of KwaZulu-Natal. It is one of South Africa's biggest cities and has one of the busiest ports in Africa. Due to Durban's strategic port location, it is an important economic center for South African's import and export. Durban also boasts spectacular recreational beaches and is a very popular tourist destination and surfing area.

The Durban coast has been subjected to interventions by humans over the past 100years. The main focus of these interventions has always been the Durban Bight, which is the heart of the city, see Figure 1-1. The shoreline of the Bight has retreated significantly following the construction of the Durban Port, due to the interruption of the net northward sediment current by an extensive breakwater. It has resulted in significant erosion on the lee side of the port, which nowadays is controlled by an artificial bypass system. Contrary to the valuable Durban Bight, the coast of South Durban hasn't been a major topic of research. However, this is now changing due to the planned Durban DigOut Port.

To maintain Durban's economic position the current Durban Port has to expand (Mather, 2013). In its current situation this is problematic due to a lack of space, mainly because of the rapid expansion of the city in the past decades. A solution, developed by EThekwini Municipality, Transnet Port Authority and the South African Government, is to develop a completely new port: the Durban DigOut Port. The location of the DigOut Port is selected to be the old site of the International Airport located in South Durban, see Figure 1-1. Although construction works haven't started yet, it is eminently feasible that plans will come to fruition and be executed. The latest news is that the port will be operational in 2025.

In this research the effect of the DigOut Port on the coastal system is researched, focusing on shoreline behavior. The past has taught us that significant erosion/accretion patterns are likely to occur around the breakwaters of the port. These breakwaters are necessary to provide a calm navigation channel for ships and to protect the port from the energetic wave climate on the east coast of South Africa.

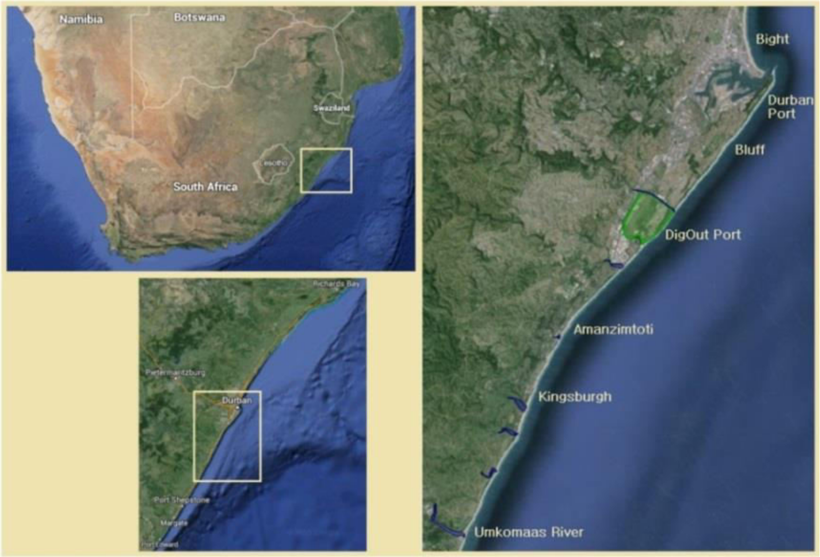

Figure 1-1 Project location (GoogleEarth, 2015)

The current coastal system of South Durban is not fully understood, because it has never been a major topic of research. Current and historical trends in shoreline behavior need to be identified, to determine the current state of the coast. The longshore sediments transports and budgets along the coast of South Durban are investigated to be able to predict shoreline translations. Gradients in these longshore sediment transports could lead to a reaction of the shoreline, manifesting in erosion or accretion. Sediment budgets and transports are therefore investigated to understand how the system functions.

In the long run climate change could lead to alterations in shoreline behavior of the South Durban coast. Static changes in ocean levels, such as sea level rise, but also dynamic changes, like changing wave climates could have an effect on the shoreline behavior in the future. For example, a shift in the average wave direction or an increase in average wave height will lead to different hydrodynamics in the nearshore, initiating differences in sediment transports. Knowledge is lacking about the effects of possible changes in the wave climate along the South Durban coast. Another secondary effect of the rapid expansion of the city is the sand extraction of rivers. Most of the rivers have already been dammed, blocking sediments from discharging into the coastal zone. Mining of rivers, which has intensified in the last decade, will decrease the input of sediments. Less sediment input leads to structural coastal erosion. Until now, not much is known about the effect of these mining activities on the coast. The changes in these, so called, environmental variables will influence to the DigOut Port and its effects on the coast. These effects need to be researched to come up with effective mitigation measures for the DigOut Port.

The Durban coast can be classified as a vulnerable coastal system. The March 2007 storm showed for example that numerous parts of the coast could not handle a one-in-five-hundred-year event (Corbella & Stretch, 2012a). Many erosion spots occurred and houses and rail tracks were destroyed[1]. The city is now closer to the ocean due to a rapid expansion and so potential consequences for people in the hinterland have become worse. Taking into account that the current coast is less flexible to repair after a storm event, means that the situation is increasingly risky. In order to take effective measures with regard to possible future developments, like the Durban DigOut Port, at an early stage, it is necessary to understand the behavior of the coast of South Durban, now and in the future.

Figure 1-2 Durban Port and Durban Bluff[2]

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[1] Hunter, I. (2007). Extensive Flooding and Damage to Coastal Infrastructure along the KwaZulu-Natal Coast. Retrieved November 11, 2014, from http://ports.co.za/shippingworld/article_2007_03_21_3337.html

[2] GrantPitcher. (n.d.). Grant Pitcher Photography | The Bluff. Retrieved August 11, 2015, from http://www.grantpitcher.com/product/the-bluff/

1.2 Project definition

1.2.1 Problem definition

The problem definition is formulated as:

"Currently, it is not fully known how the coastal system of South Durban, South Africa, functions and what the future state of the system will be under influence of climate change and after construction of the Durban DigOut Port. "

1.2.2 Goal

The goal of the present research is to understand the sediment transports and budgets around South Durban both now and in the future. To do this it is necessary to predict and assess future shoreline behavior, in response to anthropogenic interventions, like the Durban DigOut Port, and to climatic changes such as changing wave conditions. The time scope is confined to the coming 40years.

1.2.3 Research questions

The focus of the present research is defined with the formulation of the following research questions, which are divided into three main research topics: understanding the current coastal system, evaluation of the shoreline responses due to the Durban DigOut Port, and evaluation of the shoreline responses due to changing environmental conditions.

A. Understanding the current coastal system of South Durban

- *A.1.* Are currently any trends in the translation of the shoreline identifiable and what could be the cause of these trends? What is the current state of the coast, accreting or eroding?
- *A.2.* What is the interaction between the waves and the bathymetry of the continental shelf of South Durban; how do waves propagate towards the coast and what is the relation with the longshore sediment transport rates along the coast?
- *A.3.* What are anthropogenic and natural features along the coast of Durban? Do they have a significant influence on the sediment balance or trigger sediment gradients? Are they quantifiable?
- *A.4.* What are the boundaries of the system and what characterizes them as a boundary?
- *A.5.* How are net and gross longshore sediment transports distributed along the South Durban coast?

B. Evaluation of shoreline responses to the Durban DigOut Port

- *B.1.* What is the direct effect of the protruding breakwaters of the DigOut Port on the adjacent shoreline? What is the effect of different breakwaters lengths?
- *B.2.* How will appropriate mitigation measures function to diminish possible negative effects on the shoreline?
- *B.3.* How are longshore sediment transports adapting to a new situation with the DigOut Port and mitigation measures, considering for example the sand trap near the Durban Port, which is crucial for a stable shoreline of the Durban Bight?
- *B.4.* How critical is the shoreline response of the DigOut Port with and without mitigation measures with respect to the Durban Bluff?

C. Evaluation of shoreline responses to environmental variables, like climate change and river mining

- *C.1.* How does climate change influence the current wave climate; could any trend be identified?
- *C.2.* What is the effect of a changing wave climate on the longshore sediment transports?
- *C.3.* What is the prognosis on sediment inputs by rivers and what is the effect of a decreasing sediment budgets by rivers on the South Durban shoreline?
- *C.4.* What are the most vulnerable locations along the coast considering climate change?

1.3 Project approach

In the following paragraph the approach of the project is described by which answers to the research question will be obtained and the goal of this research fulfilled. The approach is divided into five sections, which detail the line of argument of this report.

1.3.1 Analysis of the coastal environment

Understanding the current coastal environment is important before predictions are made for future situations. The coastal environment is characterized by environmental conditions, the current state of the coast itself and other economic and recreational functions. All different aspects are studied carefully by analyzing data and reviewing literature. For this research the coast of South Durban is defined to be bounded in the south by the Umkomaas River and in the north by the Durban Port. The main focus lies on the Durban DigOut Port location, just south of the Durban Bluff.

Part of understanding the coastal environment covers the understanding of the environmental conditions, like the predominant wind and wave climates, the bathymetry and water-levels. Wind and wave climates are studied to get to know how waves approach the coast and what their effect is on the longshore coastal processes of the South Durban coast. Longshore sediment transports are firstly researched by reviewing literature, but will be modeled in a later stage. Uninvestigated sources of sediment, such as river inputs, offshore sinks and others, do not form a topic of research; therefore well considered assumptions are made. A study of the coastal characteristics is done to map and analyze their effect on the shoreline. Other environmental conditions studied are the bathymetric data, ocean currents and water-levels. An extensive literature study is done to investigate the variation of the environmental conditions over time. Climate change is nowadays a major concern. For this research the effect of a changing climate on the average wave climate is researched to investigate future differences in longshore sediment transports.

The historical situation is analyzed by identifying trends in shoreline behavior to understand and classify the current coastal state. Available information consists of beach profile measurements from CSIR, aerial satellite photographs from Google Earth and literature about the Durban coast. Unfortunately no long-term data sets are available, because the coast of South Durban hasn't been a focus of research. Causes of the trends are investigated by reviewing literature.

By these steps the physical conditions of the coastal environment are studied. Target values are formulated from the analysis to characterize the current coastal system. The 1D shoreline model is expected to meet the target values. If the model can mimic the targets, the model is said to be validated and can be used to predict future shoreline behavior

The Durban DigOut Port is anticipated to be part of the coastal system in the future. The current design of the port entrance with its breakwaters is reviewed and expected preliminary designs are used to investigate the effect on the shoreline. In this research no new design is made of the port layout, including the location of the port entrance. Other economic, recreational and domestic functions in the area around the port are studied as well. Key locations and related actors are mapped to assess potential impacts on them due to the Durban DigOut Port or climate change effects at a later stage.

1.3.2 Waves and shoreline modeling

The understanding of the coastal system gained by analyzing available data and reviewing literature is used to create a 1D shoreline model that predicts shoreline behavior in the future. First, a wave study is carried out to get a better understanding about the propagation of waves towards the shore. The interaction between the waves and the bathymetry is modeled using the process-based SWAN model (SWAN, 2014).

Refraction, shoaling and diffraction processes of waves are analyzed to understand how different wave conditions behave on the continental shelf and approach the nearshore.

In this research long-term coastal behavior is studied and therefore the average wave conditions are important, rather than the extremes. An annual average wave climate is obtained by reducing an existing wave record, gaining computational efficiency. This needs to reflect to the target points formulated from literature for validation.

In order to calculate longshore sediment transports a transport formula is used. An analysis is done to obtain the best performing sediment transport formula for the Durban region. Sediment transports are calculated at different location along the coast, which provide input for the 1D shoreline model. The mentioned calculations and shoreline translations are modeled with the UNIBEST-CL+ model (Deltares, 2011). The 1D shoreline model is an equilibrium-based model and is based on the single line theory. It assumes a sediment balance over a defined coastal stretch and an equilibrium profile which doesn't change in time. By using the 1D shoreline model information is obtained about the shoreline behavior and the longshore sediment transport gradients of the current coastal system in time. The model is required to meet the set targets from data analysis and literature review. This generates confidence in the model performance for the next phase.

At the end of this phase an overview is given about the gross and net longshore transports over the defined coastal stretch to understand how the system functions and is expected to react to changes under the current conditions. A conclusion is given about how the model performs, which is critical for interpretation of the results in the next phase.

1.3.3 Evaluation of shoreline behavior due to Durban DigOut Port

With the setup of the 1D shoreline model the effect of the Durban DigOut Port on the shoreline of the South Durban coast can be evaluated. The location of the port entrance is assumed to be predetermined, based on reviewed literature. The breakwaters protrude through the surf zone into deeper water and will initially block the longshore drift. The magnitude of erosion/accretion patterns and their development in time are studied. Based on the studied effects possible mitigation measures are conceived and tested by modeling. The 1D shoreline model is used to investigate their effectiveness in protecting the coast from possible erosion.

1.3.4 Evaluation of shoreline behavior due to environmental variables

The environmental conditions in the coastal environment of South Durban are changing in the future due to climate change. Trends in the average wave climate are studied in the analysis of the coastal environment. The effect of these changes on the shoreline is investigated using the 1D shoreline model. Firstly, the individual effect of the environmental variables on the coastal system is studied. Later a setup of different climate change scenarios is created, representing reasonable ranges of future changes in wave climate. Sea level rise is not taken into account in this research, but could be added to the outcomes of this research by using the Bruun rule (Bruun, 1962). Rivers deposit sediments into the coastal system. Due to river damming and mining the input of sediments is likely to decrease further in the future. The impact of this decrease in sediments is investigated. Hydrological changes are excluded from the scenarios, meaning that possible changes in precipitation rates feeding river discharges are not considered. Neither water quality issues are considered.

1.3.5 The state of the coast of South Durban now and in the future

Results are obtained of possible future states of the South Durban coast due to anthropogenic interventions and climate change. Relations between the results are researched by combining most probable future situations. With this information possible alternatives are created to ensure a sustainable coast of South Durban in the future. An assessment of the local impact on the shoreline of the Bluff is done for different situations after construction of the Durban DigOut Port with different mitigation measures, including the expected changing environmental conditions. Key locations are used for the assessment, determined in the analysis of the coastal environment. They are obtained after a stakeholder and field analysis, and provide valuable information for policy decisions. The study concludes by explaining how the coastal system of South Durban functions. Answers on the predetermined research questions are given. Effects of the Durban DigOut Port and changing environmental variables on the future state of the coast are explained and described. Recommendations are made regarding alternative designs and the identified knowledge gaps, to provide input for future modeling of the Durban coast.

1.4 Structure of the report

In the second chapter, 'Coastal environment', the ins and outs of the current situation of the Durban coastline are explained. Historical shoreline behavior is analyzed together with all other characteristics of the coast, like the wave climate. Economic functions in the coastal zone are identified and mapped. A prognosis is made for changes in the oceanic wave climate due to climate change. After the system has been analyzed and identified, in chapter three, 'Wave and shoreline modeling', the coastal system is studied in more depth. This includes the wave modeling part and the setup of the long-term coastal morphology models. In chapter four, the 'The impact of the Durban DigOut Port', the obtained 1D shoreline model is used to predict future shoreline behavior around the Durban DigOut Port. In chapter five, 'The impact of changing environmental conditions', understanding of the shoreline behavior due to changing wave climates and changing river inputs is obtained. In chapter six, 'The impact on the Durban Bluff', an assessment is done about the local impact of the most likely futures, explaining the interaction between alternatives for the DigOut Port and environmental variables. In chapter seven, 'Conclusion and Recommendations', research questions are answered and alternatives for a sustainable South Durban coast are formulated for decision making by policy makers. A list of references is provided at the end.

2. Coastal environment

In order to achieve the project goal the current coastal system has to be understood. In this chapter all relevant characteristics of the coastal environment are analyzed, such as environmental conditions, the historical development of the coast of South Durban and other economic functions in the coastal environment, like the plans for the Durban DigOut Port.

2.1 Environmental conditions

2.1.1 Introduction

Environmental conditions, such as wind and wave climates, varying water levels, ocean currents and bathymetry are the main contributors to coastal processes in the coastal zone. For the coast of Durban waves are the main initiator of coastal dynamics, generating longshore sediment transports. The Durban coast has an energetic wave climate due to its exposure to the Indian Ocean, where waves propagate from the deep ocean into shallower waters towards the Durban coast. Waves originating from the wind fields of different weather systems provide a broad wave spectrum with a predominant south-southeast direction. This will be explained in the first paragraphs. The bathymetric data is studied to understand wave propagation. Information about the current coastal characteristics, such as sediment grain sizes, longshore sediment transports and sediment input by rivers is researched to understand the physical characteristics of the coastal environment. Other environmental conditions are water-levels, tides and ocean currents, which will be elaborated on as well to understand their effect on long-term coastal morphology of the Durban coast. Environmental conditions are changing in time due to climate change. By a literature study trends in changing wave climates are investigated related to climate change.

2.1.2 Meteorological climate

The South African weather system is significantly dependent on the global air circulation patterns. South Africa lies in the Southern Hemisphere subtropical high pressure belt at 30degrees Latitude. East and West of the country lie two air mass sources in the Atlantic and Indian Ocean; both are called Marine Tropical sources (MacHutchon, 2006). These high pressure systems turn anti-clockwise and provide the main wind patterns. From the major atmospheric weather systems three main patterns can be identified for the east of South Africa, which create most of the larger wave events (Corbella & Stretch, 2012a). These systems are cold front systems, cut-off low systems and tropical cyclones, see Figure 2-1. It is important to understand these systems, because the wind fields generate waves by blowing over the oceans water surface. Waves are the main driver of coastal morphology for the Durban coast.

2.1.2.1 Cold front systems

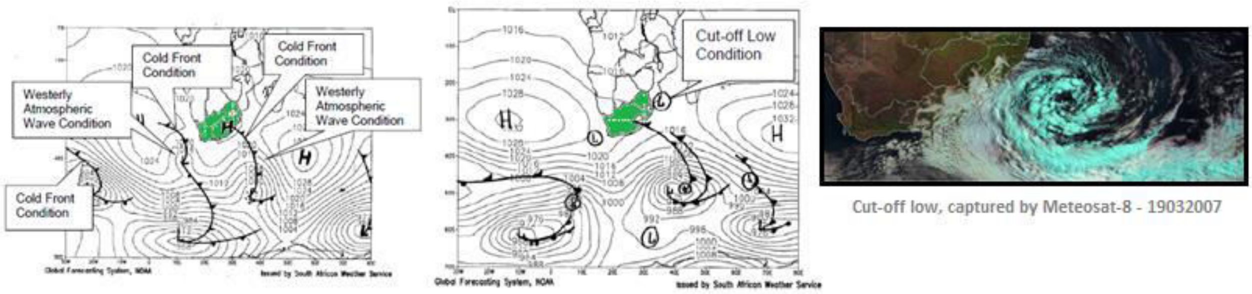
Cold fronts are associated with the temperate influence of low pressure systems from the south. They transport cold air from the south and south-west and are characterized by westerly winds. The cold air front moves in an easterly direction and lies closer to the coast creating relatively smaller wave heights and periods than the other systems. Cold fronts are the most frequent occurring mechanism that leads to storms in South Africa. They vary in strength. Severe cold fronts can create significant swell from the south.

2.1.2.2 Cut-off low systems

Cut-off lows are cold low depressions, where air of polar origin is cut off from the main sub-polar belt of low pressure. It usually begins as a trough in the upper-air flow, which becomes a closed circulation and sinks down to the Earth's surface (MacHutchon, 2006). If they remain stationary for a certain period, a large storm with severe swell is generated, like the 2007 storm, see Figure 2-1. Cut-off lows are formed offshore in the Indian Ocean. In the Southern Hemisphere low pressure systems turn clockwise, which results in waves from a south-eastern direction for the Durban area. They are most likely to occur during the winter. Cut-off lows can lead to major rainfall events as well.

2.1.2.3 Tropical cyclones

Tropical cyclones are usually associated with the easterlies in the Inter-Tropical Convergence zone. For South Africa they are quite rare, see the seven observations between 1962 and 1995 (Corbella & Stretch, 2012a). They generally produce swell waves from the north-east.



Cut-off low, captured by Meteosat-8 - 19032007

Figure 2-1 Cold front, Cut-off Low (MacHutchon, 2006) **and Cut-off low March2007** (Hunter, 2007)

2.1.3 Wind Climate

The wind climate of Durban is related to the weather systems described in the previous paragraph. In Figure 2-2 on- and offshore wind climates are given obtained from an onshore measuring point at the Durban Port Control (CSIR) and from satellite data, called NCEP data (NOAA). In Appendix A.1.1.2, Figure A-3 the location of both measuring points can be found. A local wind climate is shown to explain the local wind climate close to the shore. The offshore wind climate, located 25 kilometers out of the coast and the onshore climate show reasonable similarities. The wind climates are related to the cold front systems, which propagate along the shoreline of South Africa. These wind fields provide wind waves from the north-east and south-west. How these wind fields are related to the waves is explained in the next paragraph.

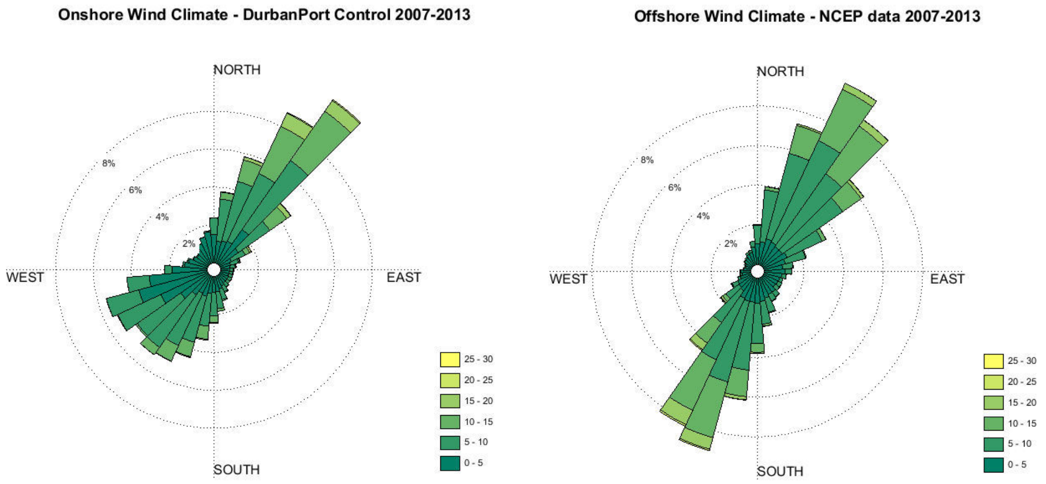


Figure 2-2 Onshore (left) and Offshore (right) Wind climate

2.1.4 Wave Climate

2.1.4.1 Wave data

Waves are one of the main drivers for coastal dynamics. In order to model the net yearly longshore sediment transports along the coast of Durban an average annual wave climate is necessary. Understanding the variation in waves over the years is important before an average wave climate can be obtained. Therefore wave records are analyzed to get to know the dominant patterns and the seasonality of the waves. In the previous paragraph the wind fields close to the Durban coast are given, these are related to the generation of waves by blowing over the sea surface.

The wave climate for the east coast of South Africa and the EThekwini coastline in particular is analyzed using the observations of the Waverider Buoy. The buoy is located at 30meters depth at 29.884, 31.07067 (Latitude, Longitude), which is 1.25kilometers offshore of the Durban Bluff coastline, at the height of the southern breakwater of the Durban Port. The shore normal at this point is approximately 128degrees north, which is given as a reference for the direction of the waves. The buoy measures the wave conditions of the sea constantly and outputs every three hour, the significant wave height, peak period and mean wave direction. A six year dataset is used from 01-11-2007 till 01-11-2013. By studying this dataset, information is obtained about the wave climate, such as the seasonal variety, directional spreading and the ratio between sea and swell. The buoy lies at 30meters water depth, which is for waves with larger swell components already a sensitive area in terms of wave refraction. This could lead to a distorted interpretation of the wave climate and therefore first is sought for more wave data sources. Besides the wave buoy another wave data source is available, namely the numerical model named WaveWatch3 (NOAA, n.d.). The data (NCEP data) is obtained by a numerical model, which is fed by hind casts of the global wind fields measured throughout the ocean. Through a sub-study at my own initiative is found that the data is not applicable for the Durban coast, see Appendix A.1.1. Especially, swell conditions from the south-east do not correspond with measured data from the buoy. Therefore the Waverider Buoy data is used in the rest of this study. Another reason for using a wave source close to the coast is the existence of a strong ocean current in front of the Durban coast. This current is the Agulhas, which is highly related to the waves due to wave-current relations and local wind-wave climate, what makes deep water wave modeling in this region complex.

In this study the average wave conditions are important rather than the extreme conditions. However, whether these extreme conditions influence the average climate still needs to be investigated. An analysis on the extreme wave conditions can be found in Appendix A.1.2.

2.1.4.2 Seasonal climate

As can be seen in Figure 2-3, the wave climate differs over the seasons, which corresponds with the meteorological changes over the seasons, discussed in the previous paragraph. The seasons are divided into the following months, see Table 2-1.

Table 2-1 Seasons South Africa

Seasons	
Winter	June-August
Autumn	September-November
Winter	December-February
Spring	March-May

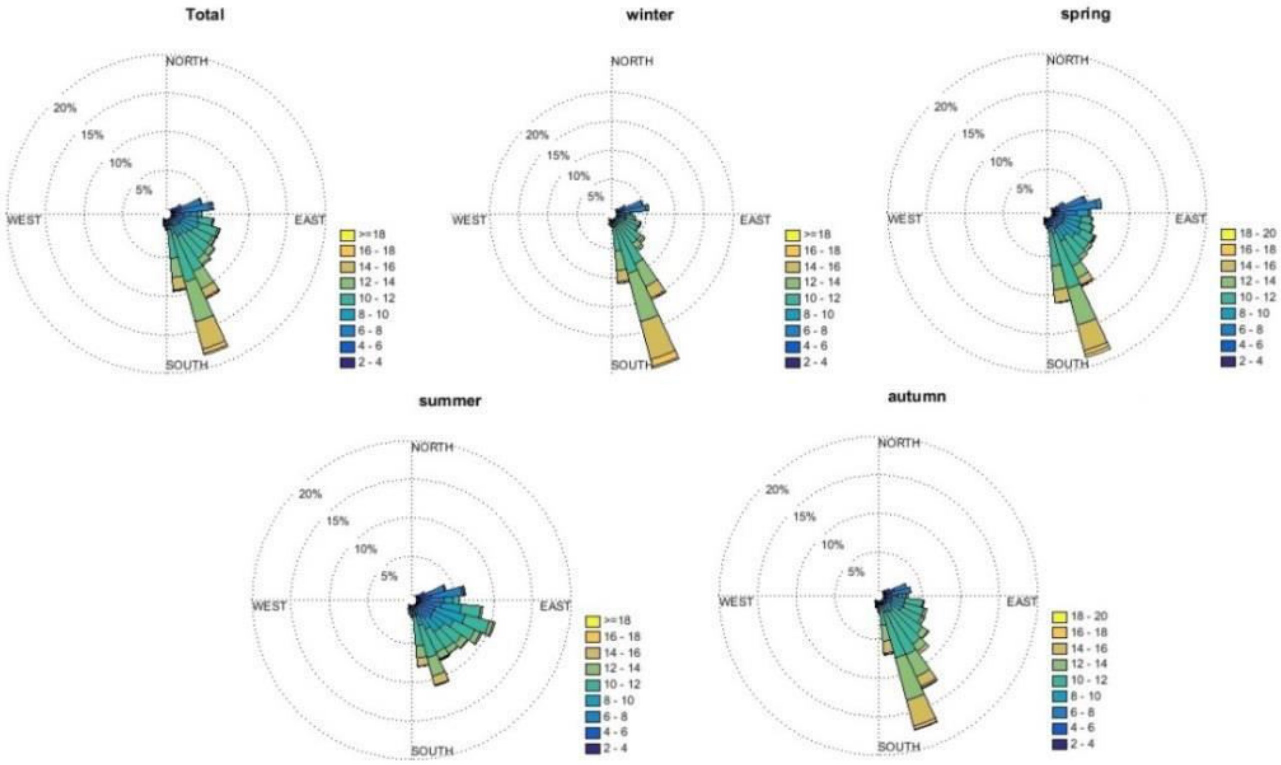


Figure 2-3 Wave period over wave direction –Waverider buoy 2007-2013

At the top left wave rose, in Figure 2-3, the total wave climate of the six year dataset is shown. A clearly dominant south-southeast direction of the waves is observed. A large part of these waves consist of large wave periods and are defined as swell generated by offshore cut-off lows and cold fronts from the south. A part of these swell waves are generated far offshore and cannot be related to the local wind fields. They mostly occur during austral winter, as can be seen in the top-middle wave rose. In the Figure 2-4 one can see the variation of the significant wave height (Hs) and the Peak Period (Tp) over the directions. Locally generated wind waves and swell are separated by a wave period of nine seconds. The larger the wave heights, the larger the period becomes, as can be observed in the left figure. Significant wave heights of one to four meters high are observed for swell waves from the south-southeast. During summer, waves are locally generated by local thermal fronts. These waves have smaller wave periods and can have significant wave heights, as can be observed in Figure 2-4. They are related to the local thermal winds along the coast during summer. These locally generated wind waves will not exceeds wave heights of approximately 3.5meters and enter mostly from the east-northeast to south-southeast directions. These waves are also related to the wind fields found in the wind analysis. In spring and autumn a transition of the seasons can be observed. Characteristic waves during winter such as the large swell from the south-southeast and characteristic local wind waves during summer are both observed in these seasons.

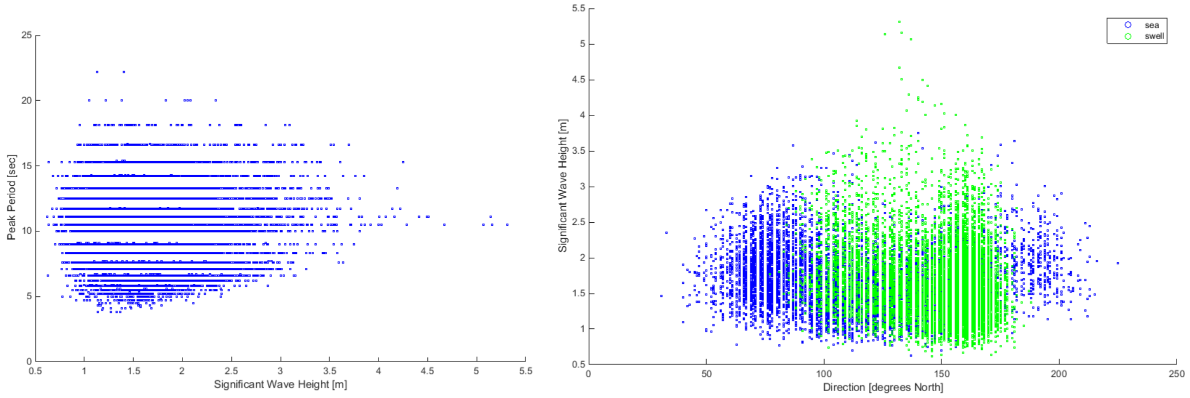


Figure 2-4 Correlation Hs - Tp (left) **and Dir - Hs** (right)

2.1.5 Coastal conditions

2.1.5.1 Classification coast

South Africa, part of the African Plate, is tectonically stable and is surrounded by diverging boundaries. The east coast of South Africa is classified as an afro-trailing edge coast. The continental shelf is offshore bounded by the Agulhas current. In the Durban Bight the shelf is approximately 40kilometers wide, while north and south of the Durban Bight the shelf varies between four and ten kilometer (Flemming, 1978). The coast of Durban has an energetic wave climate and can be classified as a wave dominated coast following Galloway (1975). River mouths are often blocked by the sediment banks and most of them breach through the sand bank during high discharges. The predominant south-southeast wave direction observed for the Durban coast yields a net northward longshore drift.

2.1.5.2 Sediment characteristics

The coast has an energetic wave climate. The associated sediment grain size is therefore relatively high. Sediment grain size measurements (d10, d50 and d90) from 2007 till 2012 are available for all location along the South Durban coast. Sediment samples are gathered and monitored every three months by CSIR. The sediment grain size is an important parameter in the calculation of longshore sediment transports. The larger the grain size the more energy is needed to transport the particle along the shore. In this study yearly averaged conditions are considered to obtain net yearly longshore sediment transports. In Table 2-2 the average grain size over the years is presented for three main subsection of the studied coastal system. On average a d50 of 620micrometers is found for the total coastal stretch, fluctuating in between 440 to 760micrometers.

Table 2-2 Sediment grain size

Location	Average sediment grain size (µm)
Bluff	660
South of DigOut Port	660
South of Amanzimtoti	540

Average grain sizes are obtained by averaging the three monthly measurements. The sediment samples are taken at certain moments in time and hence dependent on the conditions at that moment. For instance, during winter storms finer sediments will be taken by the currents and transported offshore leaving the larger grain sizes at the beach. Furthermore, the quality of the sample is also dependent on the location, where the sediment sample is taken. Adjacent to main coastal structures such as for example the rocky headlands, larger sediments could accumulate after a storm. This level of detail is not taken into account in this study and thus annual measurements per location are averaged for further use.

2.1.5.3 Longshore sediment transport

The net annual alongshore sediment transport in Durban is directed northwards, due to a predominantly southerly to south-easterly directed wave climate. An average net longshore sediment transport rate is found of 500,000m^3/year (Schoonees, 2000). This is obtained by an analysis of monitored data from dredging works and a hydrographical survey of the accumulated sediment in a sand trap at the Durban Port over a period of seven years (1986-1992). Since 1979 the port authority of the Durban Port operates a by-pass system with a dredge hopper to replenish the Durban Bight beach (Laubscher, Swart, Schoonees, Pfaff, & Davis, 1990). The dredged material is obtained from a sand trap south of the Durban Port, see Figure 2-5. The sand trap is located just south of the long breakwater at the Durban Port, which crosses through the surf zone. Since the Durban Port was built in 1857, erosion started at the lee side of the Port, where the recreational beach of the Durban Bight can be found. Since the eighties the replenishments provide a relatively stable coastline.

The data on which the net longshore sediment transport is based is particularly old. Assumed is that the coastal system has remained approximately the same and that this value is still applicable. It is furthermore based on data from the dredging operations, which are related to economic interests. According to experts of the CSIR, a net longshore sediment transport of 500,000m^3/year ± 20% is a correct approximation. In the modeling part this one of the target values which represents the main characteristics coastal system. In Appendix A.1.3 the method is explained how the Durban sand trap case is used to obtain the long-term net longshore transport rate. Further, the pros and cons of this approach are discussed and how these could affect this research.

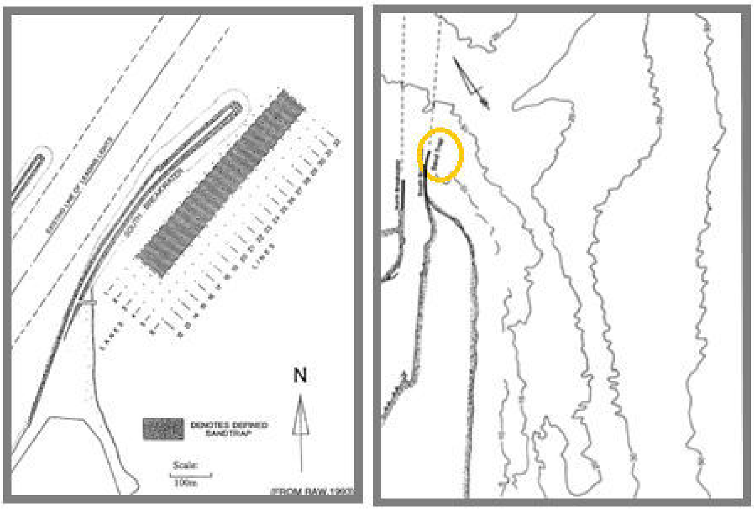


Figure 2-5 Sand trap Durban Port (Schoonees, 2000)

2.1.5.4 Sediment sources and sinks

The main sediment sources in the coastal system are rivers. At the coast of South Durban several rivers provide the coast its sediments. These sediments sources are necessary to counteract the losses in the system. In the following paragraph the sediments sources and sinks are discussed, which serve as input in the 1D shoreline model.

Rivers

The inland of KwaZulu Natal, the province of EThekwini Municipality, contains mountains, where many rivers originate. The largest rivers have their origin in the mountains of Lesotho, like the Umkomaas River. These rivers provide input of sediments into the coastal system. In a CSIR report from 2008 (Theron, de Lange, Nahman, & Hardwick, 2008) estimated sediment yields from rivers are determined. In Table 2-3 the sediment input is shown for the largest rivers of the studied area, see Figure 2-6 for their location. In Appendix A.1.4 more information is given about the determination of the river input. The largest river is the Umkomaas River, which has a sediment input of 140,000m^3/year (Theron et al., 2008) and is not dammed. Most of the other rivers are dammed. Lots of sediments are trapped upstream and this could be a major contributor to structural coastal erosion over the past years. Another contributor could be the mining industry. Mining activities have intensified over the past decades, extracting significant sediment volumes from rivers. South of the Bluff the Umlazi Canal flows into the sea, which is the second largest river of South Durban. The channel borders the project area of the DigOut Port in the North. The sediment input into the coastal system of the Umlazi Canal is determined to be 33,000m^3/year (Theron et al., 2008). However, extensive river mining decreases the sediment input of this canal into the coastal zone. The channel has a poor water quality, mainly due to waste disposals in the lower regions (CSIR, n.d.).

Table 2-3 Sediment budgets by rivers (Theron et al., 2008)

Sediment budgets by rivers [m3]				
River	**Sediment yield**	**10% Sand**	**# dams**	**incl. dams**
Umlazi	450000	45000	2	33000
Mbokodweni	50000	5000	0	5000
Manzimtoti	130000	13000	0	13000
Lovu	19000	19000	2	13000
Umgababa	110000	11000	1	8000
Umkomaas	1400000	140000	0	140000

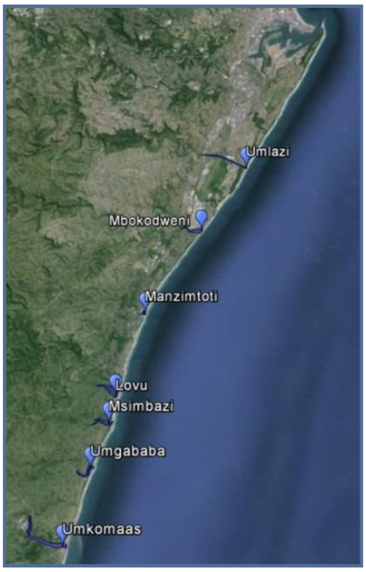


Figure 2-6 Rivers South Durban (Google Earth)

It can be clearly seen on aerial photographs that most of the rivers don't have a constant seasonal discharge. At the mouth of the river, banks are formed by the strong waves at the coast that prevent the river from flowing into the sea. During floods or high discharges the river breaches through the banks to discharge its water into the sea. This has also been observed during a site visit. River damming could be one of the reasons for clogging of the rivers, because high discharges are controlled by the dam. In this way rivers do not frequently breach anymore.

Other sources and sinks

For the research area no offshore canyon are found, where sediment are able to leave the coastal system. These are offshore discharges of sediment are called sinks. At the Durban port might sediment been loosed by offshore flows. When the sand trap is filled and dredging works are not operational, sediments will pass the breakwater tip and fill the entrance channel of the Durban Port. Dredged sediments out of this channel are not always returned into the system. There might also be a possibility that sediments are transported offshore by offshore return currents. These return currents are residual currents set by the interaction between the Agulhas current, mid-ocean currents and the fact of a protruding continental shelf around Durban (Lutjeharms & de Ruijter, 1996). The contribution of this mechanism to offshore transportation and sinks is not known and therefore not taken into account.

Aeolian transport is assumed a minor contribution. Most beaches are narrow and are therefore unlikely to contain transport rates equal to volumes of other sediment sources and sinks.

2.1.6 Water-level

2.1.6.1 Chart Datum

On the South African east coast Chart Datum is referred to the Lowest Astronomical Tide (LAT) as from 1 January 2003, which is the lowest level predicted to occur in a 19years cycle. For Durban the mean sea level is determined to be CD+0.913m.

2.1.6.2 Tides

Durban has a semi-diurnal tide and experiences a meso-tidal range regime (Bosboom & Stive, 2013). Highest Astronomical Tide of the 18.6years cycle is 2.302m above Mean Sea Level, according to Mather & Stretch (2012). For the year 2012 the tidal levels are presented in Table 2-4. The relative contribution of sediment transport due to a tidal current compared to the wave induced sediment transports is minor. Since the goal is long-term shoreline modeling, the influence of the daily and monthly changing water-levels and the interaction of it with the waves are averaged over the tidal period. For these reasons, tides are not taken into account in this research.

Table 2-4 Tidal levels (ProjectDurban et al., 2014)

Tidal level	Water level (m + CD)
LAT	0.00
MLWS	0.21
MLWN	0.87
MWL	1.11
MHWN	1.36
MHWS	2.01
HAT	2.30

2.1.7 Agulhas Current

In front of the South African East Coast the Agulhas Current flows from 27°S to 40°S (J.Gyory, L.M Beal, E.H.Ryan, A.J.Mariano, & B.Bischof 2004). It is one of the world's strongest ocean current with a mean velocity of 1.6 m/s throughout the year and in most of the months peaks of 2.5 m/s (M Tomczak & Stuart, 1994). The Agulhas Current is fed by the Mozambique current and the East Madagascar Current, which transports warm water towards the circumpolar current, as can be seen in Figure 2-7. Due to its large scale, the Agulhas Current has major impact on land and oceanic climate. The westerly wind patterns from the southwest lie opposite to the current resulting in large waves, which is very well known by seagoing vessels. For the Durban coast a few residual currents are found close to the shore. These residuals of the Agulhas Current seem to coincide with the topographical contour lines of the continental shelf. The residuals lie offshore of the wave-generated longshore currents and are assumed to have a minor contribution to the longshore transport. The residual currents will be explained in more detail in the next paragraph and in Appendix A.1.5.

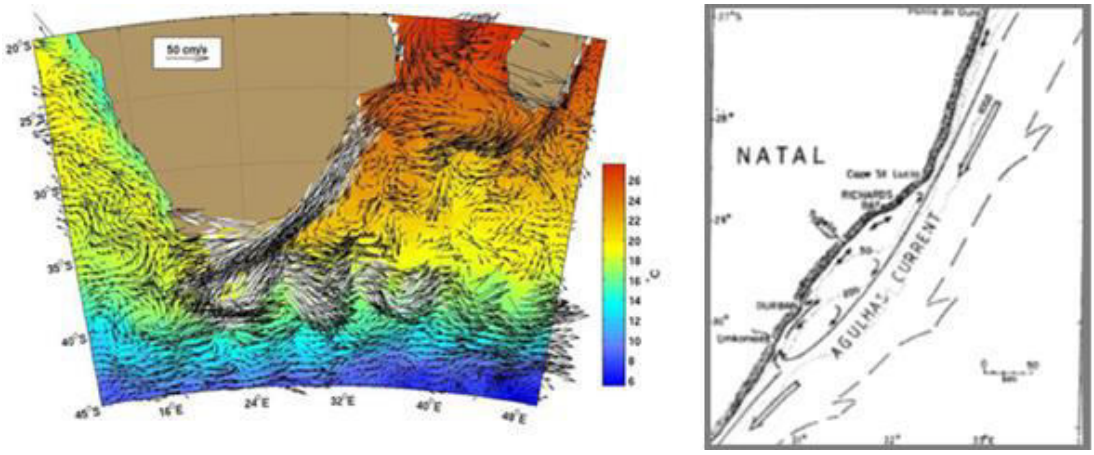


Figure 2-7 **Agulhas current** (J.Gyory et al. 2004) **and residual currents** (Lutjeharms & de Ruijter, 1996)

2.1.8 Bathymetric data

In the bathymetry can be seen that around the Durban Bluff the continental shelf is narrow compared to the area north of the Durban Port. From the Durban Port to Amanzimtoti the cross-shore slope of the hydrographical profiles remains the same in the nearshore and is particularly steep. South of Amanzimtoti a gentler slope is observed. Furthermore a bay-type area can be distinguished around Amanzimtoti. At this height a return current of the Agulhas Current rotates and flows in the opposite northerly direction. Whether this is related to the bathymetry cannot be established and no literature is found. However, the non-uniform bathymetry characterizes the area and has its effects on the waves. In the wave modeling part wave propagation is studied, which is highly related to the changes in bathymetry. The total bathymetry, including distinctive depth contour lines, is presented in Figure 2-8. North of the Durban Bight a broader continental shelf is observed. The continental shelf is in this study defined as the plateau which does not exceed 350meters water depth. In Appendix A.1.5 the continental shelf is described in more detail. The bathymetric data consists of yearly monitored bathymetry by CSIR and Global Gebco data. Information about the bathymetry data can be found in Appendix A.1.6.

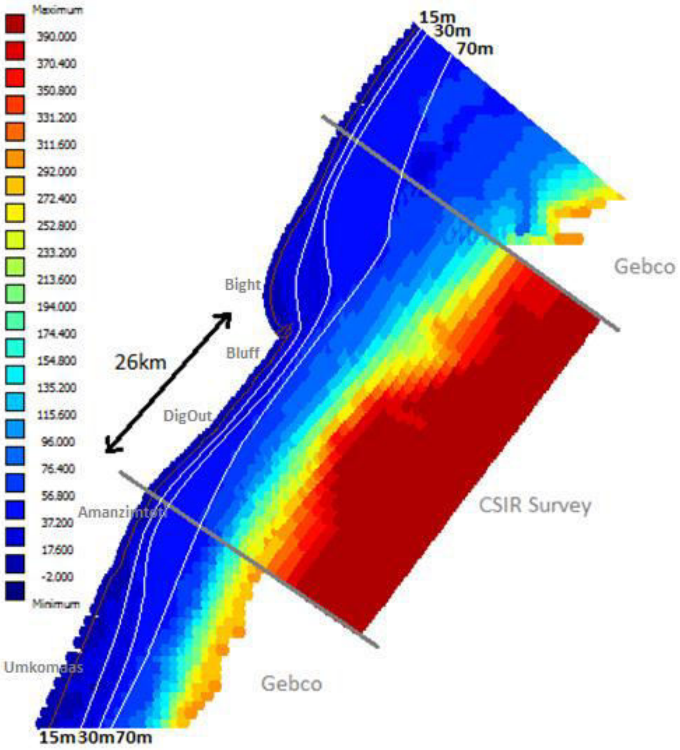


Figure 2-8 Bathymetry Indian Ocean around the EThekwini Municipality (CSIR & GEBCO)

2.1.9 Climate change

2.1.9.1 Wave climate

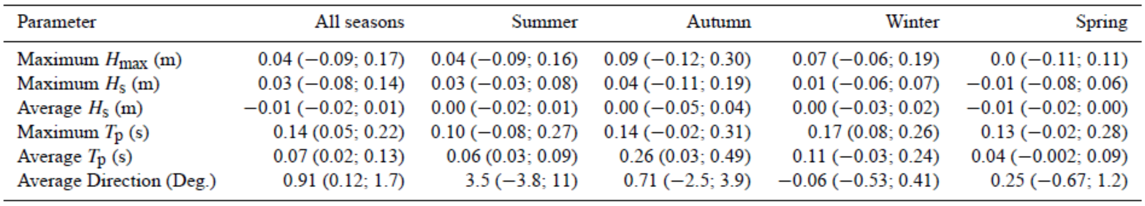
Waves are one of the drivers of coastal morphology. Changes in wave climates lead to changes in coastal dynamics. Especially, for a wave-dominated coast such as the east-coast of South Africa this is a topic of concern. However, long-term wave data from satellites or altimeters is not available yet and therefore it is hard to obtain trends in wave climate projections. Dynamic atmospheric models are currently in development, but still do not take all processes in the interaction between sea and atmosphere into account in predicting wave climates. Present literature has been reviewed to investigate trends in wave climate development on a regional and global basis. This provides a basis for the creation of scenarios, to study the effect of changing wave climates on the shoreline of the Durban coast.

In the current and latest IPCC AR4 climate change reports (IPCC, 2013) not much attention is paid to changing wave climates. Current models do not include all processes between atmosphere and sea, which are key to future predictions (M. a. Hemer, Wang, Weisssse, & Swail, 2012). The role waves play in these processes is emphasized in a paper by Cavaleri, Fox-Kemper, & Hemer (2012). All exchanges of momentum, energy, heat, mass and radiation fluxes are relevant in the projection of gravity wave-driven processes at the interface between air and sea. It is one of the recommendations of the COWCLIP conference (M. a. Hemer et al., 2012) to study wave climate projection with more advanced models, like the wind wave coupled climate system. This dynamic approach is based on the physical processes. A second method to analyze this phenomenon is based on a statistical approach reviewing satellite data to analyze trends. Unfortunately, accurate satellite or wave buoy datasets are not sufficiently long enough to make reliable projections. It has to be kept in mind that in most of the articles global models were used, which are not very accurate for a regional study.

Hemer, Fan, Mori, Semedo, & Wang (2013) present projected changes in wave climate from a multi model ensemble. They compared five independent studies, which project the global wave climate based on a dynamical (four) and a statistical basis (one). Dynamical wave climate models are process-based and take the interaction between atmosphere and sea into account. Statistical models relate atmospherically pressures and wave-wind characteristics to each other.

Regional research for South African East Coast, in particular the Durban area, on average trends in wave climate has been done by several researchers. In a study of Rossouw & Theron (2009) wave buoys around the South African Coast are investigated for possible longer term trends in South African wave climate. The average wave conditions appear to remain constant, only in the extreme conditions were some changes observed. The following trends in wave characteristics are observed by Corbella & Stretch (2012b) using combined wave data of several buoys from the province KwaZulu Natal, see Table 2-5. In all these studies not more than twenty years of wave data is reviewed.

Table 2-5 Annual rate of change of Durban's wave parameters (95% confidence intervals)



Parameter	All seasons	Summer	Autumn	Winter	Spring
Maximum H_{max} (m)	0.04 (−0.09; 0.17)	0.04 (−0.09; 0.16)	0.09 (−0.12; 0.30)	0.07 (−0.06; 0.19)	0.0 (−0.11; 0.11)
Maximum H_s (m)	0.03 (−0.08; 0.14)	0.03 (−0.03; 0.08)	0.04 (−0.11; 0.19)	0.01 (−0.06; 0.07)	−0.01 (−0.08; 0.06)
Average H_s (m)	−0.01 (−0.02; 0.01)	0.00 (−0.02; 0.01)	0.00 (−0.05; 0.04)	0.00 (−0.03; 0.02)	−0.01 (−0.02; 0.00)
Maximum T_p (s)	0.14 (0.05; 0.22)	0.10 (−0.08; 0.27)	0.14 (−0.02; 0.31)	0.17 (0.08; 0.26)	0.13 (−0.02; 0.28)
Average T_p (s)	0.07 (0.02; 0.13)	0.06 (0.03; 0.09)	0.26 (0.03; 0.49)	0.11 (−0.03; 0.24)	0.04 (−0.002; 0.09)
Average Direction (Deg.)	0.91 (0.12; 1.7)	3.5 (−3.8; 11)	0.71 (−2.5; 3.9)	−0.06 (−0.53; 0.41)	0.25 (−0.67; 1.2)

Wave Height

Regional research by investigating wave buoys (Rossouw & Theron, 2009) (Corbella & Stretch, 2012b) shows that the average significant wave height is not likely to increase significantly in time, see Table 2-5. By Hemer et al. (2013) in global models for the South African East Coast an increase in significant wave height in the austral winter is found. However, on a yearly basis not much change could be seen. In a study by Mori, Yasuda, Mase, Tom, & Oku (2010) average and extreme trends in significant wave height are investigated. For South Africa an increase of four percent for mean wave heights is obtained over approximately a hundred years (difference between the future climate (2075-2099), minus the present climate (1979-2003)), which is a relatively small trend considering the effect on the longshore sediment transport. They used the following method. By running the atmospheric Global Circulation Model (GCM), which also is used for the climate predictions of the AR4 IPCC, wind speeds are obtained for 10meters height. The model is forced by the sea surface temperature. SWAN is used to create wave heights out of the wind speeds.

Since accurate buoy data is limited and high resolution satellite data has not been obtained yet for more than a few decades, sufficient information to predict future changes on a statistical basis is lacking. However, ships are already navigating the oceans for centuries and have recorded wave heights. In an article by Gulev (2004) changes in ocean wave heights over the last century are analyzed from visual observations of ships. For the region off the South African Coast an increase of significant wave height of 0.32% per year was obtained. These observations are not very reliable and the increase seems to be relatively high. However, it gives an indication that wave heights are not expected to decrease.

Wave Period

In some studies investigated by Hemer et al. (2013) not only the significant wave height was determined, but the mean period was also projected. An annual increase of the absolute mean period of 0.08seconds in austral winter was found for parts of the western Indian Ocean close to South Africa. The projected changes are based on 1979-2009 satellite altimeter data and are projected for 2070-2100. The increase is related to the stronger Westerlies in the Southern Hemisphere. Waves generated in the Southern Ocean propagate throughout the world's oceans into the northern basins. The effects are an increase in swell components, which needs further attention to identify the changes in impacts in the coastal zone (Mark A. Hemer, Church, & Hunter, 2010). In Table 2-5 a trend in average peak period is presented of 0.11seconds/year for austral winter and seems to be statistically significant by Corbella & Stretch (2012b). More energetic waves from the south-southeast could lead to larger net longshore sediment transport towards the north. The effect on the shoreline will be studied in a scenario analysis.

Wave Direction

Following Hemer et al. (2010) the wave climate direction is likely to rotate clockwise in the in mid-latitudes of the Southern Hemisphere. For Durban this would mean that the average wave direction would shift towards the south, generating larger net longshore sediment transports. The clockwise shift coheres with the finding by Corbella & Stretch (2012b), see Table 2-5. The average annual wave direction shift towards the south as well. In a scenario analysis is checked whether this clockwise shift has a significant effect on the future state of the shoreline of Durban South.

Extreme wave conditions

If the number of storms increases, this could lead to a change in average longshore transports. Several literature describe an increase in the probability of exceedance of future storms, which leads to more frequently occurring extreme wave conditions. However, for an average year is found that the effect of this increase is minimal and therefore is neglected. This is explained in Appendix A.1.7.1. In this research therefore an increase in extreme conditions is not taken into account.

Cyclones

In the observed data from the wave buoy no swell waves were observed from the north east, which coincide with tropical cyclones from the Indian Ocean. This is not strange since only seven cyclones have impacted the coast between 1962 and 2005 (Corbella & Stretch, 2012a). They caused significant damage to the South African East Coast. By Malherbe, Engelbrecht & Landman (2013) the projected changes in tropical cyclone climatology under enhanced anthropogenic forcing are studied, which is in line with the AR4 IPCC. They concluded in projections for the latter part of the 21st century an indication of a decrease in the occurrence of tropical cyclones over the Southwest Indian Ocean adjacent to southern Africa, as well as a northward shift in the preferred landfall position of these systems over the southern African subcontinent. These trends are beneficial for the Durban area, because in that case less tropical cyclones will impact the coast.

2.1.9.2 Sea level Rise

Out of tidal data measured by Durban wave buoys a sea level rise of 2.7± 0.05 mm/year is found by Mather (2007). This is in coherence with global sea level rise according to the IPCC (IPCC, 2013). They have established several scenarios for sea level rise on the basis of different carbon reduction policies. Sea level rise will have an effect on the coast and causes structural erosion manifested by a landward translation of the shoreline. In this research is assumed that the Bruun theory (Bruun, 1962) can be applied for the Durban coast, which tells us that cross-shore hydrological profile of the coast remains the same under a changing sea level. An equilibrium profile is assumed, which translates in line with the waterline over the cross-shore. In this way, sea level rise could be to be considered and added to possible shoreline translations due to the studied interventions and climate changes. In Appendix A.1.7.2 more information can be found about global sea level rise and historical sea levels of the South African east coast.

2.2 Historical developments

The coast of South Durban is in this research defined as the coastal stretch from the Umkomazi (or Umkomaas) River in the south to the Durban Port in the North, which includes the project area of the Durban DigOut Port and the Durban Bluff. In this paragraph the historical development is described, which includes the analysis of the geology and historical beach profiles. Knowledge about the historical development of the coast teaches us how the coast is formed and what the current state of the coast is.

2.2.1 Geology and related coastal characteristics

2.2.1.1 Durban Bluff

The Durban Bluff is a geological dune front with a height of almost hundred meters. The dune stretches out over the total Bluff and is a stable formation that already exists for a thousand of years. The dune consists of Pleistocene Aeolian sands and Pleistocene Aeolianites which are rocks formed by compression of sandy dunes over thousands of years (Cawthra, Uken, & Ovechkina, 2012). For a cross-section of the central Bluff around Ocean View is referred to Figure 2-9.

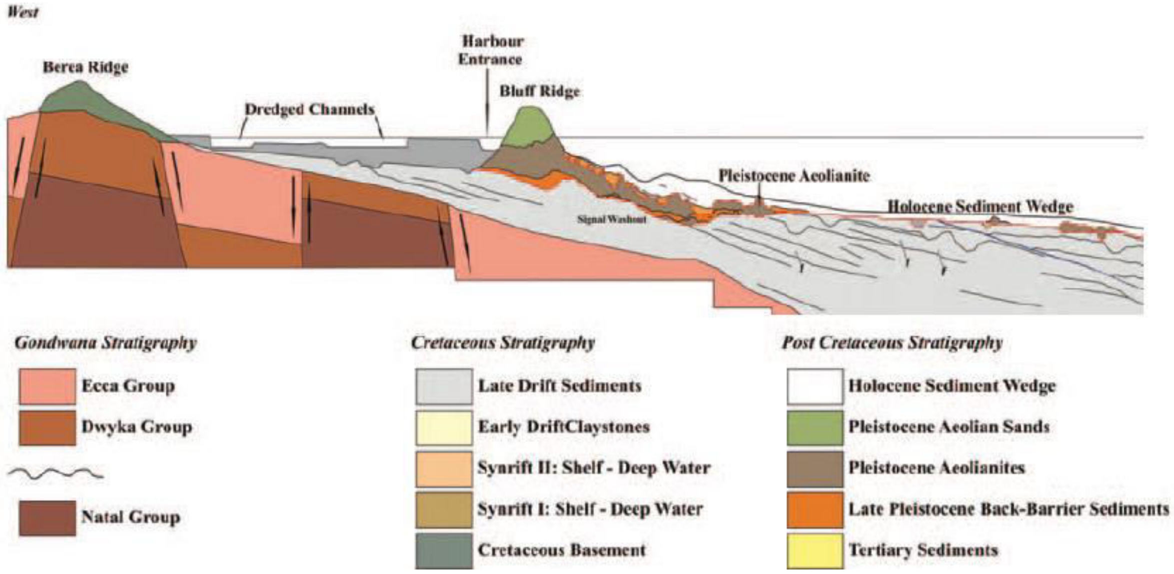


Figure 2-9 Geology Durban Bluff (Cawthra et al., 2012)

Along the Durban Bluff at some locations the Pleistocene Aeolianite rocks are exposed above the sea level, see Figure 2-10. They lie in the surf zone and for sediment transports this has to be taken into account, because not the full transport capacity will result in actual volumes of sediment transported. They also prevent the coast from eroding and thus fix the shoreline position. This has to be kept in mind for the evaluation part of this research. The rocks provide also space for recreation. Around some of the protruding rocks swimming pools are built, which extend into the surf zone. Around these features characteristic erosion/accretion patterns are observed.

Figure 2-10 Durban Bluff (photograph: Google Earth by Rhino and Hedgehog)

2.2.1.2 South Durban

In the area from the Umkomaas up to the DigOut Port the dune face is not as high as at the Bluff. It decreases in a southerly direction. At the projected entrance of the DigOut Port some major headlands characterize the surrounding dune face, which are shown in Figure 2-11. Between the headlands a little bay has formed, due to the morphological response of the bathymetry. The surf zone is minimally interrupted by the headlands, so sediments can easily flow past the rocks. Between the headlands a small estuary can be found, which is known for its mangroves. The mangroves are protected and can't be touched. Since an open connection with the ocean is lacking at the moment due to a significant shortage of discharge from the Isipingo River, the mangroves are not doing well. The waste water from the river is making it even worse. In this research it is assumed that the estuary will be fully implemented in the ecological design of the new DigOut Port (ProjectDurban et al., 2014) and not be affected by erosion/accretion responses around the new port.

Figure 2-11 Rocky headlands near Project location DigOut Port (GoogleEarth, 2015)

The area between the Durban DigOut Port and Amanzimtoti is characterized by a uniform sandy coastal stretch. In the area from the Umkomaas up to Amanzimtoti several rocky outcrops can be found around Kingsburgh, see Figure 2-12. These rocky outcrops are not longer than a hundred meters and protrude partially into the surf zone. It results in some characteristic erosion/accretion patterns around them. It yields a shore normal orientation opposite towards the main wave direction for this region, resulting in lower longshore transports. The rocks seem to pin the shoreline to a fixed position. Around these rocks heavy erosion hotspots can be found during major storms.

Figure 2-12 Rocky Outcrops Kingsburgh area (GoogleEarth, 2015)

2.2.2 Historical shoreline behavior

The history of the shoreline translations of the coast of South Durban is investigated by analyzing shoreline trends from three-monthly monitored beach profiles by the CSIR and reviewing aerial photographs from Google Earth. Trends in shoreline translation could teach us whether the current state of the coast is eroding or accreting. Furthermore, the 1D shoreline model has to reproduces the trends in the system as a validation and to obtain insight in its predictive skills to understand future shoreline behavior.

The +2m CD points of the beach profiles are evaluated, which are the most densely populated in the available data and are assumed to be a stable indication of the beach profile. In Google Earth the vegetation line is studied over a period of twelve years, which is used as an indicator for coastal erosion or accretion. For the total study about historical trends in the shoreline position and all assumptions, see Appendix A.2.1.

2.2.2.1 Durban Bluff

In the Durban area only the Durban Bluff has been monitored from 1989 to 2012. In this region wealthy residences are situated, which is probably the reason for a focus of measurements around this area. The data is useful to this study, because it is the only piece of information about shoreline behavior in the past. At a few neighboring locations on the Bluff, beach profiles are monitored since 1998. Along the total study area, from the Umkomaas River up to Cave Rock measurements are available from 2005-2009.

Table 2-6 Erosion/accretion central Bluff

Beacon	Erosion/Accretion [m/y]
B6	-1.14
B7	-1.01
B8	-1.21
B9	1.35
B10	-0.54

Figure 2-13 Locations beacons Bluff

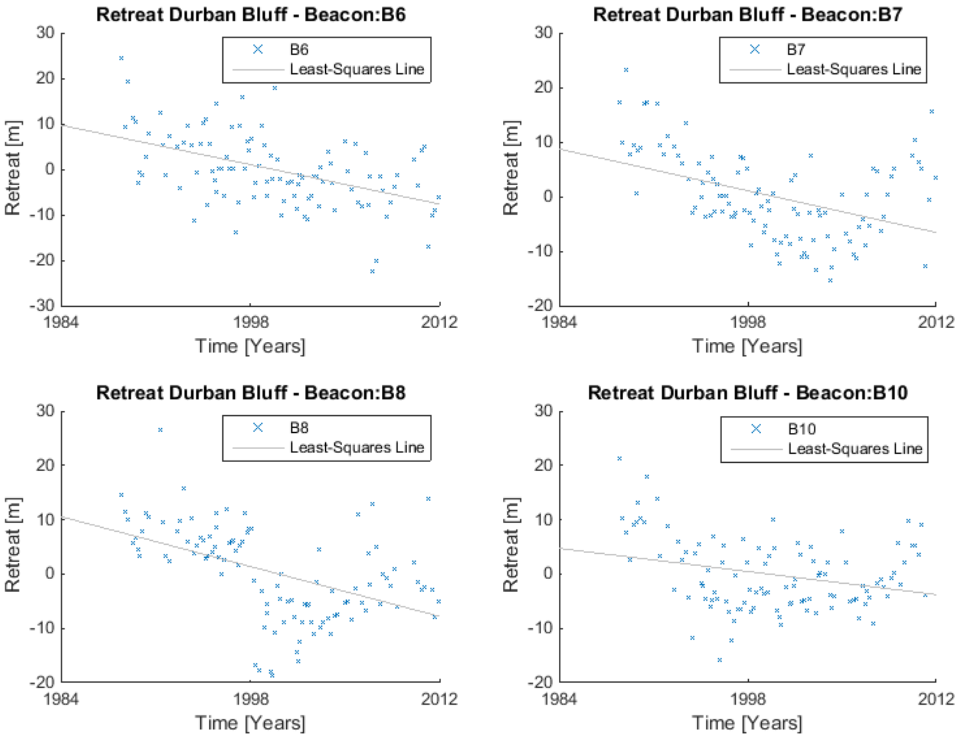


Figure 2-15 Beach profiles Bluff

For four of the five long measurement points or beacons, a retreat of approximately 1m/year was observed, see Figure 2-15. The blue measurement marks show the shoreline translation relative to the sample mean of the data set. The CSIR has investigated the shoreline retreat using beach profiles and an aerial study from the seventies. They also concluded a shoreline retreat of 1m/year for the Bluff (Theron et al., 2008).

In Google Earth the vegetation line shows a shoreline retreat of approximately twenty-five meters in the northern area around Cave Rock over the twelve year period, which results in an average retreat of 2m/year. For the southern part of the Bluff area no significant trend can be seen. This is in coherence with the observation by the monitoring measurements, where for Cave Rock a retreat of approximately 1m/year is observed and where south of the Bluff the shoreline seems to be stable.

2.2.2.2 South of Durban DigOut project area

Over the rest of the system only four years of beach profile measurements are available, which range from 2005 till 2009. In these measurements the shoreline south of Amanzimtoti is retreating. The area between the DigOut Port and Amanzimtoti is stable over the four year period, which can be confirmed by the Google Earth aerial photographs. For the southern part of the research area the Google Earth research shows a stable shoreline position. Only some changes can be seen between Kingsburgh and Umgababa, where several river mouths enter the ocean. Major floods over the years may be the reason for these fluctuations. Furthermore, erosion hotspots are observed around some large rocky headlands, during heavy sea storms. So, the position of this shoreline fluctuates due to these episodic events, for example beach profile SC26 see Figure 2-16.

Since the time to recover from a major storm, like the March2007 storm, lies in the time range of the measurements, carefulness is requested in using these measurements. The dataset gives insight in the variation of the shoreline over four years, wherein the model has to perform well. By studying the boxplot of the shoreline translation a visual indication is given of the variation in the shoreline behavior. For most locations over the four years a variation of ±15meters is accepted. Again the spread is relative to the sample mean of the data set. The SB1 to SB5 locations are located in the northern Bluff area. SC11 till SC13 lie in the DigOut Port area. SC16 to SC31 are equally spread over the distance between Amanzimtoti to the Umkomaas River.

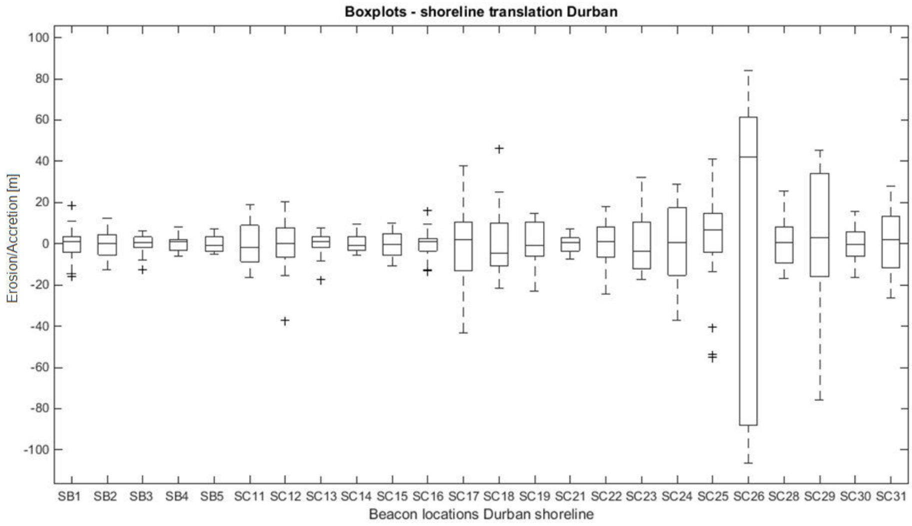


Figure 2-16 Boxplot shoreline variation 2005to2009

2.2.3 Conclusion current coastal state

The coast of South Durban is characterized in the north by a large coastal bluff, called the Durban Bluff. The Durban Bluff has a height of dozens of meters and consists of Pleistocene sediments and rocks. By an analysis of beach profiles over a period of twenty-three years and aerial photographs from Google Earth over a period of twelve years, is found that the northern and central Durban Bluff is eroding with 1m/year. In the south of the Durban Bluff the shoreline position seems to be stable. In the rest of the coastal system of South Durban long records of beach profile measurements are not available. Only a data set is available from 2005-2009. For the area between the DigOut Port and Amanzimtoti the shoreline is sandy and uniform. It remains a relatively stable position and doesn't vary more than ±5m over the four years. For the area south of Amanzimtoti the shoreline varies significantly more during the seasons. Most of the areas show a retreating trend over the four years of monitoring. From twelve years of aerial photographs in Google Earth could be seen that the shoreline from the Umkomaas River up to the DigOut Port has a stable position and doesn't significantly erode or accrete. Although not much quantitative information is available, experts and experienced coastal engineers have told that the Durban coasts hasn't changed much in the past, which coheres with the analyzed available data. In the total system rocky outcrops are found, which consist of lithified sediments. These rocks provide that the shoreline is fixed and ensure that the shoreline will not uniformly erode on a larger scale. Local erosion around these outcrops is common due to storms. The 1D shoreline is a uniform coastline model and therefore not directly able to cope with these rocky outcrops within dunes. This has to be kept into mind for evaluation of the shoreline behavior in the future. One of the main targets of the 1D shoreline model is to reflect the past and current shoreline behavior. The observed trends should be reproduced by the model. The 2005 to 2009 data beach profile data is the only available resources reflecting quantitative measurements over the years of shoreline behavior, which is interesting information for model validation purposes.

2.3 Social economic functions

The social economic functions of the South Durban coast are studied to map and identify valuable areas or so called key locations, in the coastal zone of the research area. The main focus lies on the area around the Durban DigOut Port. As we have seen at the Durban Port in the past, significant erosion is likely to occur around such an intervention. Future shoreline behavior around the Durban DigOut Port will be studied using a 1D shoreline model. With the identification of key location possible consequences due to predicted shoreline retreat can be qualitatively assessed and recommendations can be made. Social economic functions are defined as all businesses or properties which add value to the coastal zone, like industries, recreational areas, residences, etc. Actors with interest or authority are identified related to these valuable areas. At the end a preliminary design of the Durban DigOut Port is presented, which is used for this research.

2.3.1 Stakeholder analysis

In the stakeholder analysis, groups, firms and governmental agencies are identified who have a stake or interest in the DigOut Port project. The stakeholders or actors might experience negative or positive effects of the project. The attitude of the actors towards the project and their power to influence it is important knowledge for the project initiators, because this could lead to delays and extra costs. In this analysis the main actors are identified, scaled by their attitude and power and mapped by their geographical location in the project area. To make the outcome of the scenario analysis useful for policy decisions, it is important to relate the possible consequences to the main actors in the project area. By identifying and prioritizing the main actors, interest fields are created with different criteria for each actor.

Table 2-7 Stakeholder Analysis

Stakeholder	Area of Interest	Attitude	Power	Interest
Transnet	Port Operator	++	++	++
EkwMun[3]. - environment	Sustainable coastal system	+/-	++	++
EkwMun. – general	Economic development	+	++	++
Sapref Refinery	Economic development	+	+/-	+
Residences Bluff	Property / Safety	+/-	+/-	+
SDCEA[4] - NGO	Environmental damage	-	+/-	++
Business companies	Economic development	+	-	+
Residences Isipingo/Athlone	Property / Safety	+/-	-	+
Durban public	Regional development	+/-	-	+/-

In Figure 2-17 the key locations are shown of all identified stakeholders. The new port is marked in a light green color. In the area of the port the Sapref Refinery is located. South of the port within the breakwaters an area is marked red, which is the estuary with the protected mangroves. The yellow areas are the residential areas, where in front of Brighton Beach and Ocean View some recreational places are located. On top of the map the existing Durban Port can be seen. For more information about every stakeholder and specific key location is referred to Appendix A.3.

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[3] EThekwini Municipality

[4] South Durban Community Environmental Alliance

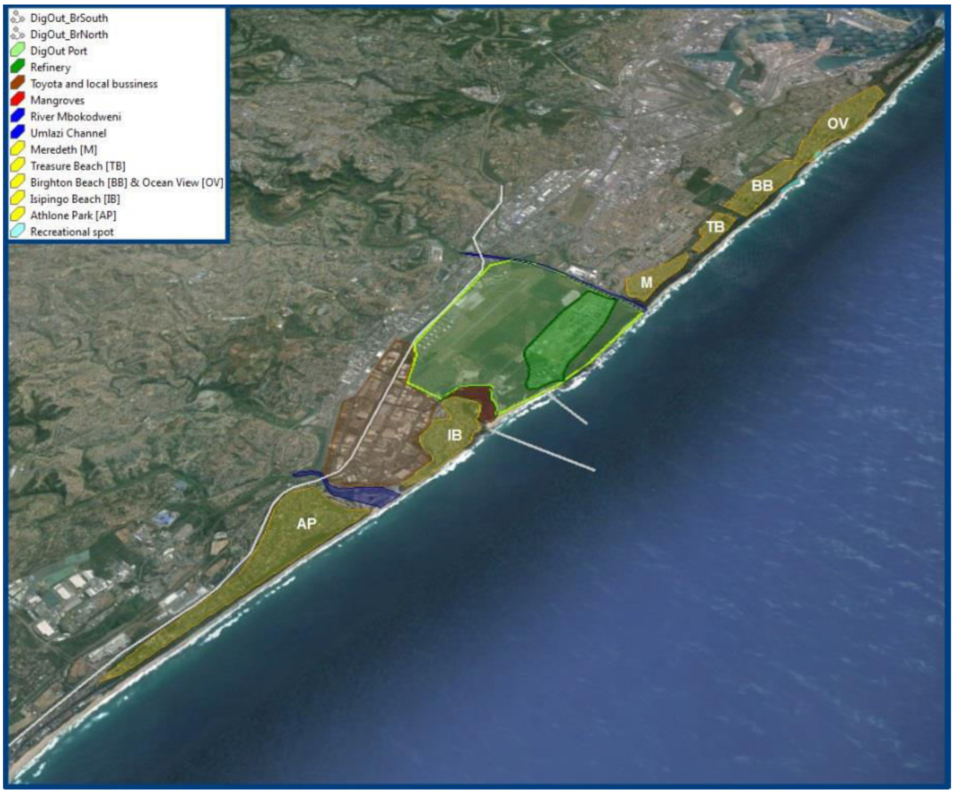

Figure 2-17 Durban DigOut area

2.3.2 Durban DigOut Port

The new Durban DigOut Port will be built to comply with the growing demand of throughput for container, liquid bulk and vehicles in the future. The current Durban Port is not able to cope with the projected growths and to compete with other ports of Africa on the world market, especially in the transportation of containers, a second port is required. A first impression is shown in Figure 2-18. The port should be ready by 2025, but it is already likely to be delayed (Harris, 2015). In this research is assumed that the port will be operational in 2025.

Figure 2-18 Artistic Impression of Durban DigOut Port (Mather, 2013)

The final design of the DigOut Port is not officially presented yet. In this study a preliminary designs of the port is used, made by the TU Delft MSc project team 'Project Durban' (ProjectDurban et al., 2014), to evaluate the consequences of these designs for the shoreline. The nautical dimensions of the port layout will be incorporated in this study, which means basically the location of the entrance channel and the length of the breakwaters.

In the report two different designs are suggested. The first design is based on conservative guidelines of PIANC to design the entrance channel, not considering any cost-related factors. The conservative manner of designing leads to a long entrance channel which need to be sheltered from the predominantly south-south-eastern swell waves by a southern breakwater of approximately 1850meters long. A northern breakwater, which protects the port mainly from sea waves from the north-east, is designed to be 1085meters long. The long breakwaters also make sure that large waves will not enter the port basin, diminishing the downtime of the port for handling the cargo. However, due to the rapidly increasing depth in the nearshore, the breakwaters become very costly. A second design takes the advice of more experienced port engineers into consideration, mainly to decrease the costs for the breakwater construction. Major changes are a decrease in the maximum entrance speed and tying up of the tugboats outside the breakwaters, yielding a decrease of the entrance channel length. These changes lead to a southern breakwater design of 1210meters and northern breakwater of 477meters. The downtime of the port will increase, because more severe waves will enter the port. It is concluded by the MSc Project Durban team that a short configuration of the breakwaters is preferred.

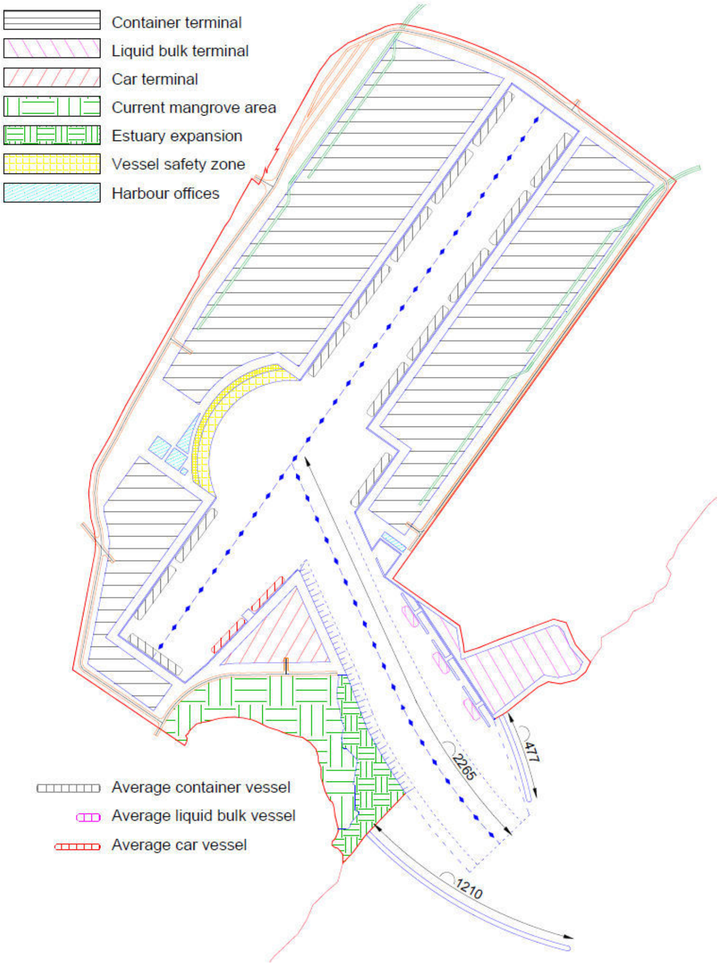

Figure 2-19 Lay out Durban DigOut Port – Short breakwaters (ProjectDurban et al., 2014)

3. Wave and shoreline modeling

In this chapter the model methodology is elaborated for the waves, sediment transports and the setup of the 1D shoreline model for the Durban coast. The 1D shoreline model will be used for evaluation of future shoreline behavior in the next chapter. After this chapter, the coastal system is analyzed in depth and a 1D shoreline model is obtained, which reflects the current coastline sufficiently compared to the set targets. Confidence is generated in the models ability to reflect coastal behavior in future situations.

3.1 Introduction

In this study large scale and long-term coastal processes are studied. The Durban coast is in the order of approximately 45kilometers long and predictions are made 40years from the present. On a high energy coasts, like the Durban coast, long-term shoreline changes (years to decades) are predominantly due to human-induced longshore effects. Short term processes (days) like the cross-shore movements of sediments due to storms or seasonality have little effect on the longer term shoreline position. Only if sediments will be structurally lost by cross-shore processes, effects are observable. However, for the Durban coast these 'natural sinks' are not found. A down-scaling modeling approach will be used to model the shoreline behavior, where an equilibrium concept is forced based on a sediment balance and an equilibrium cross-shore profile. The used model is the Unibest-CL+ software (Deltares, 2011), which consist of a longshore transport module (Unibest-LT) for calculating the longshore transports distributed over the cross-shore and a coastline module (Unibest-CL) which is based on the single line theory. A process-based computer model to compute morphological responses, like Delft3d, is considered to be too computational extensive for a large scale study like this.

Firstly, the wave modeling part will be elaborated on. A representative annual wave climate is obtained by a reduction of available wave data. Nearshore wave conditions are obtained by modeling the waves in SWAN (SWAN, 2014). A 2D curvilinear model is setup, to compute the propagation of offshore waves from a boundary into the nearshore, accounting for refraction, shoaling and other physical processes. Nearshore wave conditions are necessary to calculate the longshore sediment transport, which is done in the Unibest-LT module. These longshore transports apply as input for the 1D shoreline model in the Unibest-CL module, which is the main model to get answers on the research questions by doing an extensive scenario analysis. In the Figure 3-1 an overview is given about input, output and the main modeling processes.

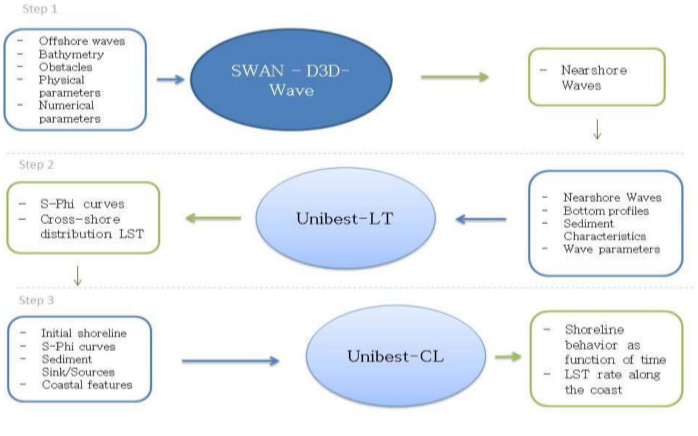

Figure 3-1 Overview modeling

3.2 Wave Modeling

3.2.1 Introduction

A wave model is made to get nearshore wave conditions of a representative annual wave climate to calculate the sediment transports along the coastline. The SWAN software is used to model waves propagating from a deep water boundary to the nearshore.

The set-up of a shoreline model to predict changes of the shoreline in time is highly related to the wave climate. For the Durban coast the waves are the dominant forces that drive the hydrodynamics in the nearshore, creating currents and stirring up sediment. Sediment transport formulas relate currents and sediment characteristics to obtain the amount of sediment moving along the coast. Important variables in these formulas are the significant wave height (Hs), the peak period (Tp) and the angle of incidence of the wave (phi) at the moment of wave breaking in the nearshore. It is therefore important to get accurate predictions of the waves entering the breaker zone.

Two wave sources are considered: the numerical model WaveWatch3 and the Waverider Buoy. The WaveWatch3 data is considered to be not applicable for this project area, due to the fact that not all waves are incorporated in the source, see Appendix A.1.1. Hence, the Waverider Buoy data is used for wave modeling with available wave data from September 2007 till November 2013. The wave buoy is located around 30meters water depth, which means that low frequency swell waves are influenced by the ocean floor and need to be extrapolated towards deep water to apply as an accurate boundary condition in the model. The length of the studied coastline is in the order of tens of kilometers. Over this area waves are affected by non-uniform bathymetric changes, oceanic currents and other coastal features closer to the coast. This implies that waves are not uniformly distributed along the coastal stretch, because the wave conditions are changed by refraction, diffraction and shoaling as they propagate into shallower water. These phenomena are calculated in the wave model for a representative wave climate, which reflects an average wave climate for the Durban coast.

First, the SWAN model will be shortly explained and model settings are discussed after that. The model is built on several grids, which contain depth files. Choices made in the creation of these grids are a point of discussion. Furthermore all input values are treated, which means parameters, coefficients and processes. Validation of the model is shown and output for the next modeling phase is explained. Finally, characteristics of wave propagation in front of the South Durban coast are explained to understand the formation of the local nearshore wave climates to calculate longshore sediment transports.

3.2.2 The SWAN model

A SWAN model (SWAN, 2014), which is built in the Delft3D-Wave software (Deltares, 2014), is set up to see how waves enter the coast and to yield nearshore wave conditions just outside the breaker zone, which apply as input for the shoreline model. It is a third-generation wave model, where the spectrum is free to develop without any shape imposed a priori. The model is based on the spectral action balance equation, which accounts for wave-current interactions. The SWAN module is freely available, open-source and based on the theories explained in the book Waves in Oceanic and Coastal Waters of L.H. Holthuijsen (Holthuijsen, 2009). The Delft3D-wave interface software is used to run the model. For all processes incorporated in the model is referred to the SWAN Website or Delft3D-Wave manual.

3.2.3 Wave climate conditions

The SWAN model is used to obtain average annual local wave climates in the nearshore along the coast of South Durban. In the model an offshore wave climate is uniformly placed at the offshore boundaries of the computational grid, which serves as input for the computation of the nearshore climates. The offshore wave climate has to represent the average annual wave climate in deep water and is obtained from the data recorded by the Waverider Buoy. A reduced wave climate gains computational efficiency.

An average annual wave climate is obtained after an analysis of the available wave record from the Waverider buoy. The aim is that with the chosen wave climate the known net longshore sediment transports can be approximated. In this study is chosen to bind the recorded wave data (2007-2013) to get a reduced wave climate with almost 300 wave conditions for an average year. Assumed is that the six years of data are representative for the current wave climate of Durban. This is emphasized by a comparison with the average wave conditions of 18years of combined wave records for the KwaZulu Natal coast by Corbella & Stretch (2012a). The choice of 7 bins for the significant wave height, 7 bins for the wave period and 20 bins for the wave direction, has resulted in a climate of 288 wave conditions, see Figure 3-2. In Appendix B.1.1 the full analysis is given to obtain the representative wave climate. In Appendix B.1.2 the method is given how the wave record from the buoy at 30meters water depth is extrapolated towards deep water.

The choice for the bins arises from the wave analysis. As we have seen waves are likely to occur over the full frequency spectrum. In other words, swell and wind waves are both frequently occurring and contribute both to the longshore sediment transport. The wave period and wave height are minimally correlated. Swell waves occur for all wave heights, just like the wind waves. The contribution of the wave period and significant wave height to the net longshore sediment transport differs per sediment transport formula, but do not differentiate much. Based on these reasons, the choice is made to use an equal number of seven bins for both wave characteristics. Waves approach the coast from all directions. The wave direction is a sensitive factor in the sediment transport formulas and therefore is chosen to use a larger amount of bins for the wave direction, namely twenty bins. The bins are equally distributed, not accounting for more concentrated bins at higher interest areas. Since the bins are averaged, errors are introduced, however these are considered to be small due to a relatively large reduced wave climate, see Appendix B.1.1.

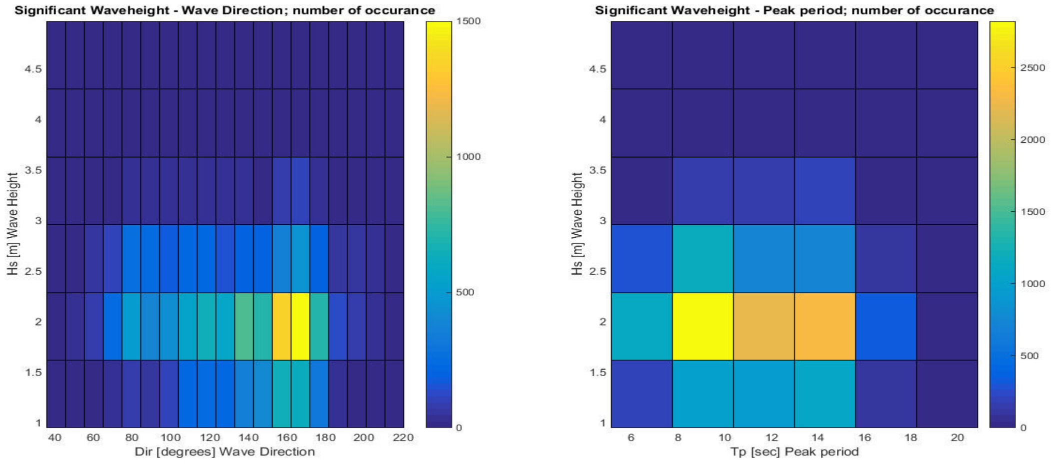

Figure 3-2 Reduced wave climates: 'Probability of occurrence'

3.2.4 Model settings

In the Delft3D-Wave model no coupling is made with the Delft3D-Flow software, which means that additional currents due to tides or other oceanic currents are not incorporated. Also wind is excluded in this analysis, because the wave buoy data is used and all wind induced waves are already included in the recorded information of the waves. The buoy lies at approximately 1.5kilometers offshore and waves are determined not to increase significantly due to this fetch. Three computational grids are created in Delft3D-RGFGRID, which are 2D curvilinear grids, see Figure 3-3. The more the grid is related to processes in the nearshore, the higher the resolution of the grid and the more alignment with the shoreline. This is obviously related to influence of the relevant processes in the nearshore, such as refraction, shoaling and diffraction. The three grids are nested in each other, so that outcomes from a larger grid will be placed at the boundary of a smaller grid. At the outer boundary the representative wave climate is placed, where wave conditions are presented in a parametric way and uniformly distributed over the boundary-lines. These boundary-lines are located in the south, south-east and north of the model and are the borders with the ocean. The western boundary is land. In the Delft3D-QUICKIN module for every grid a depth file is created by triangular interpolation, which contains a reflection of the bathymetry at every grid point. A difference in resolution of the bathy-sources leads to irregularities in the depth-file after interpolation. Therefore some minor changes are made by adapting depth samples, which is explained in detail in the Appendix B.1.3.2. The depth-files are of importance due to the relevance of the depth in major processes like refraction and shoaling. The third generation wave model takes the following non-linear processes into account: depth-induced breaking, non-linear triad interactions and bottom friction. Depth-induced breaking is of importance in the nearshore. The non-linear process of triad interactions is taken into account, because waves in shallow water are modeled. For bottom friction (Madsen, Poon, & Graber, 1988) has been used with a coefficient of 0.05meters, based on research of the CSIR for the South African East Coast. Diffraction is not approximated in the model. For white capping (Komen & Hasselmann, 1984) is used. The model is formulated in Cartesian co-ordinates. All parameters, including the numerical parameters can be seen in

Table 3-1. For more information on computational grids, the wave parameters and the actual values and consideration behind it, is referred to the Appendix B.1.3.

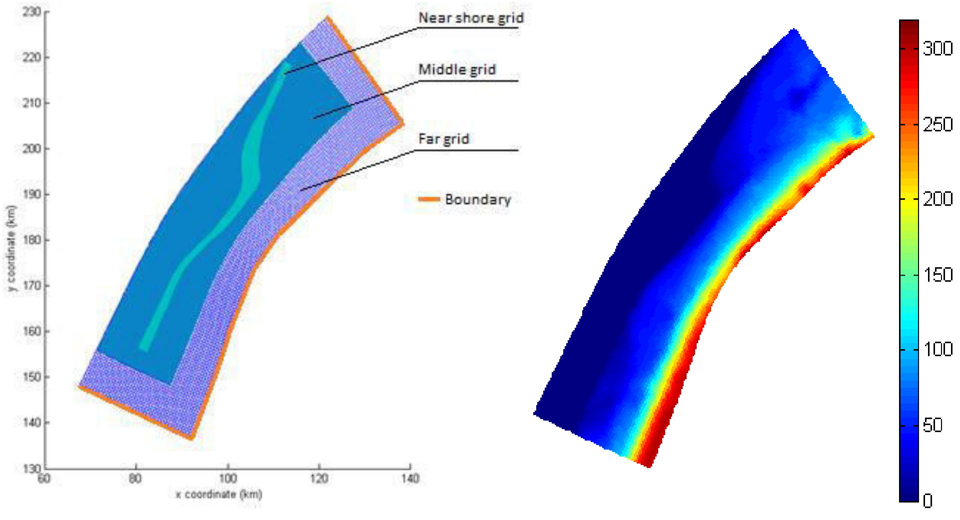

Figure 3-3 Computational grid, including boundaries and depth file for largest computational grid

Table 3-1 Wave model settings

					Spectral resolution				
		Grid specifications			Directional space	Frequency space			
	Filename	**M**	**N**	**Bathymetry**	**Directions bins**	**Lowest frequency**	**Highest frequency**	**Frequency bins**	**Nested**
Computational grid	Far2107.grd	145	45	far2107.dep	36	0.03	1	36	none
	Mid2107.grd	707	179	Mid2107.dep	36	0.03	1	36	Far2107.grd
	nearFINE2107.grd	73	860	Fine2107.dep	36	0.03	1	36	Mid2107.grd
	Orientation relative to grid	**Conditions**	**Spectra**	**Spectral space**	**ms**	**Wind parameters**	**Water level H0**		
Boundaries	North / South / SouthEast	Uniform	Parametric	Cosine power	4	zero	zero		
	Filename	**Type**	**Reflection**	**Height [m]**	**Alpha [-]**	**Beta [-]**	**Segments [#]**		
Obstacles	Breakwater South	Dam	No	6	2.6	0.15	3		
	Breakwater North	Dam	No	6	2.6	0.15	3		
Physical parameters									
Constants	**Gravity**	9.81 m/s^2							
	Water density	1025 kg/m^3							
	North w.r.t. x-axis	90deg							
	Minimum depth	0.05m							
	Convention	Nautical							
	Forces	Radiation stress							
	Wave set-up	None							
Wind	**Speed**	0 [m/s]							
	Direction	0 [deg]							
		Alpha	**Gamma**						
Processes	**Depth-induced breaking** (B&J model)	1	0.73						
		Alpha	**Beta**						
	Non-Linear triad interactions (LTA)	0.1	2.2						
		Type	**Coefficient**						
	Bottom friction	Madsen et al.	0.05m						
	Diffraction	Not taken into account							
Various	**Whitecapping**	Komen et al.							
	Wave propagation in spectral space	Refraction & Frequenty shift							
Numerical parameters									
Spectral space	**Directional space (CDD)**	0.5							
	Frequency space (CSS)	0.5							
		Hs-Tm01							
Accuracy criteria	**Relative change**	0.02							
	Percentage of wet grid points	98%							
		Hs	**Tm01**						
	Relative change w.r.t mean value	0.02	0.02						
	Maximum number of iteration	15							
Additional parameters	None								

3.2.5 Model performance

The performance of the model is checked by reviewing the grid dependency, orthogonality and expected output. Since the model has nested grids, the transition between these grids must not introduce any side effects, for instance affecting the propagation of the waves. In Figure 3-4 the transition in water depth is shown for the nearshore grid (nearFINE2107.grd) and the middle grid (middle2107.grd). The edge of the nearshore grid is located on the 30meters depth contour line. The depth-file of the finer grid is more specific than the depth-file of the coarser grid. Due to a steep slope of the hydrographical profile, averages in depth over a larger surface (larger grid cells) will introduce errors. In Figure 3-4 can be seen that the transition between the different depth-files goes fluently, not introducing any unexpected errors. For the middle and larger grid the grid dependency is assumed to be correct, since these are a multiplication of each other.

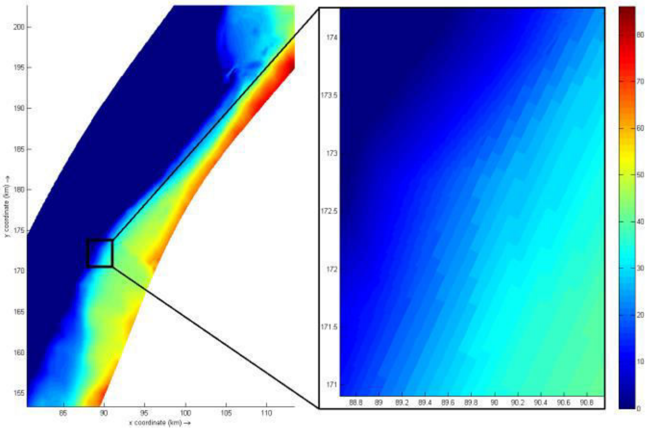

Figure 3-4 Depth-files of nested computational grids (nearFINE2107.grd and middle2107.grd)

At five specific points over the total research area grid output of computational grids is generated for different wave conditions. These are compared to check and quantify the dependency of the near and middle grid for wave height and wave direction. This is done for points not too close to the shore, because there non-linearity is playing a major role. As already said, the transition of grids can play a role. If grids are not orthogonally connected errors can be introduced. To show that the model functions well and that the use of different grids does not lead to unexplainable physical outcomes such as jumps in wave heights, scatter plots are made of output at the same locations, but from different grids, see Figure 3-5. In Appendix B.1.4 this is elaborated for the other computational grids.

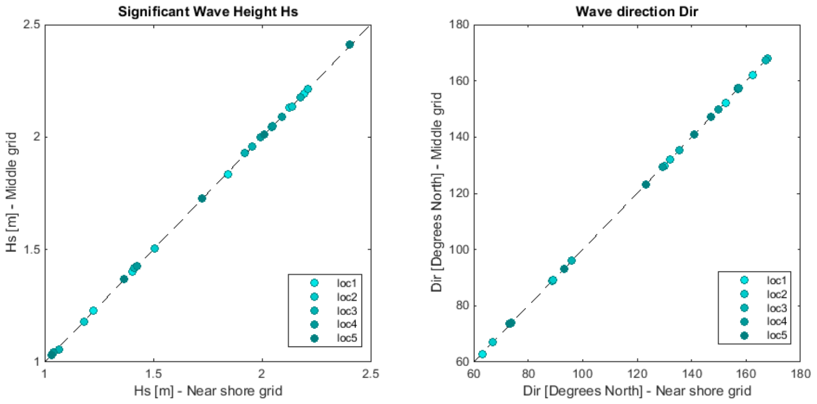

Figure 3-5 Grid dependency Near2107.grd and Middle2107.grd

The orthogonality of the computational grids has been obtained by aligning the splines with the shoreline. In this way a curvilinear grid is created that is orthogonal to the shore line with grid lines parallel to the depth contour lines. Thereby, the orthogonal-function in the Delft3D-QUICKIN software is used, which aligns the gridlines with the depth-file. For more details about the model performance refer to the Appendix B.1.4.

3.2.6 Results wave modeling

The wave model computes the wave conditions for all grid points on the computational grid. In this paragraph the propagation of the three main wave conditions is studied, which are the primary and secondary wave conditions of the wave climate. These are set on the boundary of the large computational grid. The significant wave height is shown in Figure 3-6 and Figure 3-7. The mean wave direction is given by the arrow and the color of the arrow shows the wave height. In Table 3-2 the wave conditions are given.

Table 3-2 Wave Conditions

Hs [m]	Tp [sec]	Dir [°N]	Figure
3.78	13	209	Figure 3-6
1.83	10	158	Figure 3-7
2.31	5	65	Figure 3-7

Large swell is entering the modeling area from the south. In the south swell refracts towards the shore over a large area as a result of the gentle slope of the shelf. The wave height and wave direction decreases due to refraction. Refraction provides the energy of the waves to spread out over a larger area resulting in a decline in wave height. Around Amanzimtoti a small bay-type area can be found. North of this point the swell waves from the south propagate straight towards the coast and are less sensitive for refraction. This leads to higher waves and a larger impact. Over the total area the southern swell approaches the shore under an angle generating large sediment transport rates, which will be discussed in the next chapter.

The third wave condition is a significant wind-wave from the north-east, shown in Figure 3-7 on the right. North of the Durban Port the waves will refract into shallower water, following the depth contour lines. The shelf has a gentle slope in this area, not like the steep slope around the Durban Bluff just south of the Durban Port. This results in a more fluent pattern of refracting wave and a decline in wave height. In the area of South Durban waves from the east-northeast the wind-waves approach the coast under small angle. Because they are less dependent on the bathymetry in deeper water, the local wave conditions for these waves do not change significantly along the South Durban coast.

In the Durban Bight itself (north of the Durban Port), the bathymetry is not uniform due to the entrance channel to the Durban port, the Durban mound and the Mgeni river. The Durban Bight consists of shoals and channels, where waves are concentrated or diverged. This can be seen by the color bulbs in this area, which indicate locations where wave heights converge. Again the blue area indicates the shadow zone of the port. Also the shadow zone can be observed due to the breakwaters of the Durban Port.

The uniform wave conditions at the southern boundary behave differently if they are set at different depths. To diminish the boundary effects, the computational grids have been broadened compared to the actual research area.

In the Unibest CL+ model, for different locations along the shore the nearshore waves are obtained. The locations are determined and implemented in Unibest, but the information is obtained from the output files of the Delft3D-Wave model. In the next paragraph this is explained in more detail.

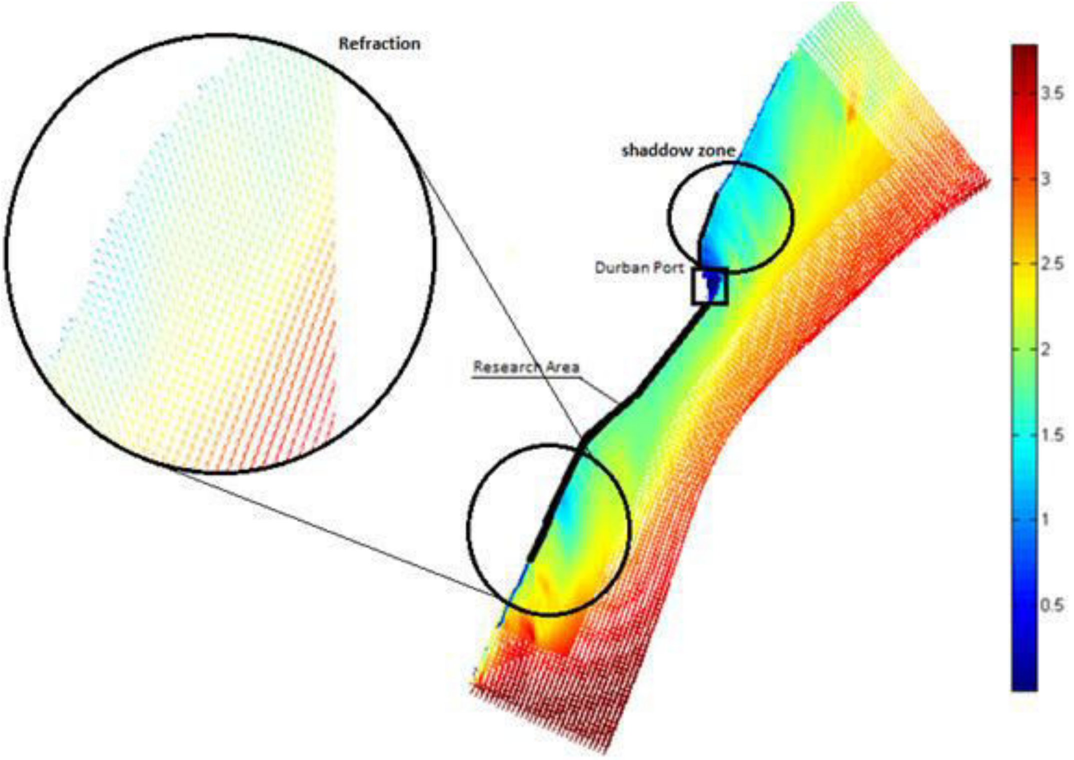

Figure 3-6 Swell wave from the south

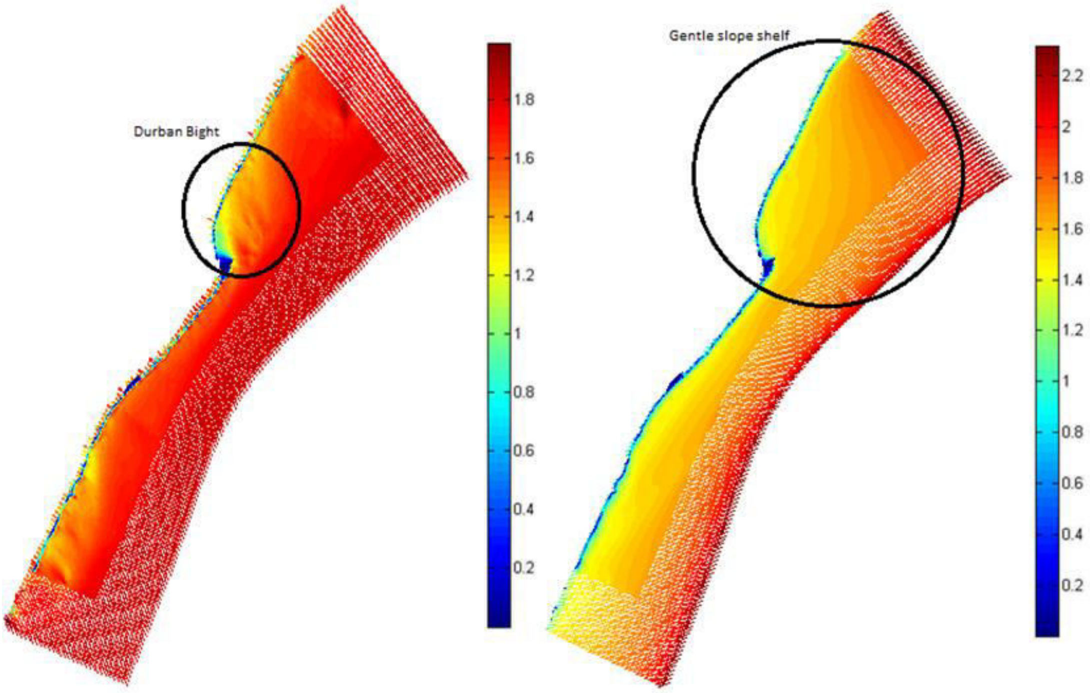

Figure 3-7 Significant wave height [m] (color) and wave direction (arrow)

3.3 Shoreline model

3.3.1 Introduction

In this study long-term shoreline behavior is researched for a large scale area, the South Durban coast. Three assumptions form the basis for modeling of longer timescale averaged shoreline changes (Bosboom & Stive, 2013). The lower shoreface (larger depths) responds slowly to wave actions. It shows negligible activity over the profile compared to the upper shoreface consisting of the first dune, the beach and the surf zone. Therefore is assumed that the morphological active zone extends from the first dune or cliff to the closure depth, not far behind the surf zone. In this active zone shorter timescale cross-shore processes remain at a dynamic equilibrium when averaged over time and longshore space. It means that profile variability in response to instantaneous, episodic and seasonal forcing is averaged over time. The amount of sediments in the active zone remains unchanged for zero longshore transport gradients, implying no cross-shore structural losses. Therefore a dynamic equilibrium profile is assumed along the coast, which is the average cross-shore profile over a year, see Figure 3-8. In the long run, shoreline translations are mainly caused by alterations in longshore sediment processes, which are mostly human induced. A sediment balance can be setup over a coastal stretch, see Figure 3-9, to determine long-term shoreline translations assuming an equilibrium profile for a coast. This approach is called the single line theory and was first described by Pelnard-Considere (1956). Hence, a cross-shore shoreline translation over a bordered coastal stretch is a change in beach volume. This is initiated by a difference in out- and inflowing sediments at the borders and could be counteracted by external sediment sources as for example by a river input or a structural offshore sink. Structural erosion is a result of a structural change in the environmental conditions, such as a decrease in the input of sediments by rivers. In order to predict shoreline translations, it is thus necessary to understand the longshore sediment transports and sediment budgets along the coast of South Durban, because gradients in these longshore sediment transports will lead to a reaction of the shoreline.

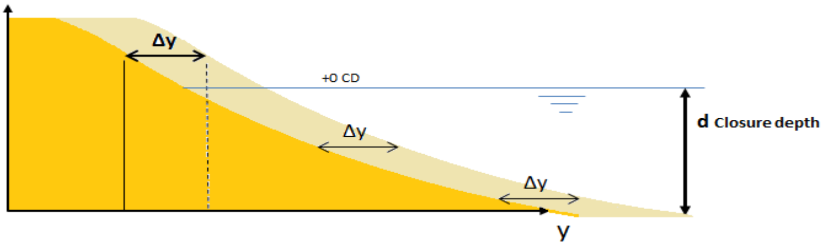

Figure 3-8 Equilibrium profile

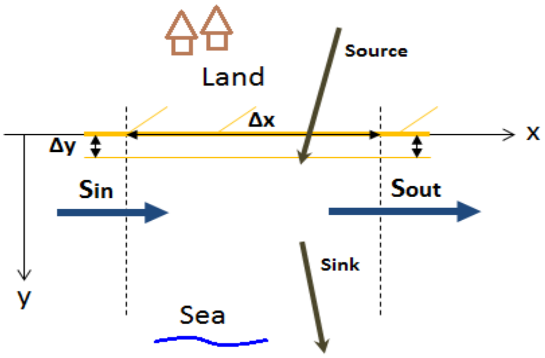

Figure 3-9 Sediment balance

The single line theory is the basis of 1D shoreline model, built with the Unibest-CL+ software (Deltares, 2011), which is used to assess future shoreline behavior for the South Durban coast. In Appendix B.2.1 the theory is more elaborated on.

The Unibest-CL+ software (Deltares, 2011) consist of a coastline module (Unibest-CL) and a longshore transport module (Unibest-LT). In the Unibest-LT model the annual longshore sediment transports are calculated at specific locations, distributed over a constant cross-shore profile. The sediment transports are driven by a longshore current that is forced by the wave hydrodynamics, a tidal current or other currents in the nearshore. For the Durban coast waves are dominant. Tidal currents are neglected, because these are small relative to the currents forced by the waves. In the Unibest-LT model a wave-current interaction model is used to calculate the long- and cross-shore currents induced by the incoming waves, which are obtained with the SWAN model. In the wave-current interaction model, the model for wave energy dissipation due to wave breaking under random wave (Battjes & Janssen, 1978) is included. A sediment transport formula is used to relate the wave hydrodynamics to actual transportation of sediments. The net and gross volumes of sediments transported along the coast are computed. An analysis is carried out to find the best performing sediment transport formula for the coast of South Durban.

The net longshore transport rates are stored in S-Phi curves, which give information about the annual net sediment transport volumes (S) and the angle of incidence of the waves (Phi). The net sediment transports are given in dry sediment particle volumes. The angle of incidence is the angle of the incoming waves relative to the coastline orientation. Since the wave climate is constant for a certain cross-shore profile at a certain location, the angle ‘Phi’ can be considered as the coastline orientation. In the S-Phi or transport curve the equilibrium coastline is shown for normal incident waves, where the longshore transport is zero. In Unibest-CL the sediment transports are calculated in time over the total shoreline based on an initial coastline (orientation), the S-Phi curves gained in the Unibest-LT model for different locations and other sediment sources or sinks. At the borders of the 1D shoreline boundary conditions have to be defined. Changes in longshore sediment transport in time result in a shoreline translation, as explained in the beginning of this paragraph. This methodology is used to determine future shoreline behavior.

The model has to reflect certain target values obtained in the analysis of the coastal system, see Chapter 2. Target values are defined as characteristics of the coastal system, which characterize the actual and historical situation at the South Durban coast. If these target values can be met, the shoreline model is said to be validated and confidence is gained to do future predictions with the model.

At the end of this chapter model observations are analyzed per subsection to understand the sediment transports and sediment budgets of the South Durban coast. Further, the gross and net sediment transports over the total area are studied, which is important to understand the erosion/accretion patterns around the new DigOut Port.

3.3.2 Model setup

3.3.2.1 Input

Sediment characteristics

Sediment grain sizes obtained by three monthly measurements by CSIR from 2007 until 2012 are used for the calculation of longshore sediment transports and the creation of equilibrium profiles using the method by Dean (Dean, 1987). This covers approximately the same period as the used wave record. In the chapter Coastal Environment the averaged median grain sizes are shown for three locations along the South Durban coast. In Appendix B.2.2.1 the six years averaged, d10, d50 and d90 are shown, which are used in the modeling.

Cross-shore Profile

An equilibrium cross-shore beach profile is assumed. Annual beach profile variations remain in an envelope, which is stable over time. This can be explained by storms which erode the coast. Sand is cross-shore transported in offshore direction, where a sandy bar is created. During calmer periods the bar migrates towards the coast and the initial profile is again approached. A similar process is recognized for seasonal changes during the year. The equilibrium profile does not vary in time and could be determined by the average characteristics of the coast. After (Bruun, 1954), (Dean, 1987) determined a method to obtain the equilibrium profile based on the fall velocity, which is related to the sediment grain size, d50 ,and the relative density of the sediment in water. The end of the equilibrium profile is the closure depth. The closure depth corresponds to the surf zone width for extreme conditions exceeded twelve hours per year (Hallermeier, 1977). Offshore of this point, topographical activity due to wave hydrodynamics is assumed to be negligible, considering the time and spatial processes within this research. For the Durban coast bathymetry in the breaker zone is not available to determine the equilibrium profile. Cross-shore profiles are therefore created by interpolation of coarser offshore bathymetric data at locations where beach profiles are measured by CSIR. The averaged beach profiles over a year, measured till 0m+CD, are connected to the hydrographical profiles obtained by interpolation. In this way a hydrographical profile is obtained. The total method is explained in Appendix B.2.2.2. Dean profiles (Dean, 1987) are obtained using the sediment characteristics at the monitored location along the beach. Dean profiles are based on the reasoning that for certain grain sizes nature strives towards uniform energy dissipation across the surf zone. By comparing both profiles, it is decided that the cross-shore profiles are applicable for modeling. See Figure 3-10 for a created profile at northern part of the Durban Bluff compared to the Dean profile.

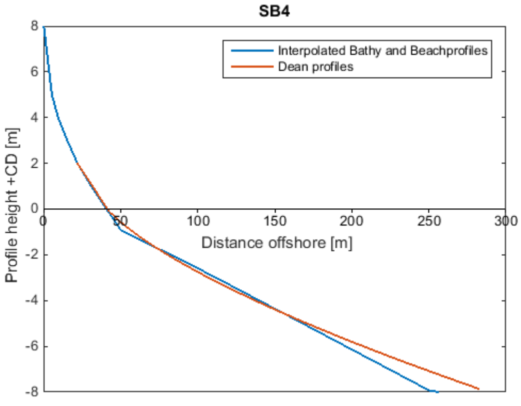

Figure 3-10 Beach profile North Durban Bluff

Wave information

In the Chapter 3.2 is explained how waves are modeled to obtain a representative annual wave climate for the nearshore. For each wave condition of the wave climate the longshore sediment transport is calculated, distributed over the cross-shore profile. By summation of all conditions the annual net longshore sediment transport is computed for a certain location.

The wave information computed in SWAN is coupled to the Unibest software to extract the annual nearshore wave climates at specific location along the South Durban coast. The nearshore wave climate consists of 288 wave conditions, which represent an average annual climate. In Appendix B.1.1 an analysis presents the used reduction method to get the annual representative nearshore wave climate. The reduced climate is approved by comparison of the calculated sediment transports of the reduced climate to a full annual climate, see Appendix B.2.2.3. For most of the locations the wave climates are taken at a depth of 8m+CD, which is the depth just outside the zone where the highest waves start to break and induce sediment transports. The obtained wave climate will be set at the offshore boundary of the cross-shore profile to determine the wave hydrodynamics in the surf zone. The depth at the boundary of the cross-shore profile and the depth where waves are taken from have to match. Otherwise, waves could be shoaled or refracted twice in both models, yielding an increase or decrease of the actual wave height and angle of incidence, which is unwanted. The wave hydrodynamics over the cross-shore profile are calculated over a single ray, where uniform bottom contours are assumed. It provides that 2D spatial irregularities in the bathymetry, such as circular shoals, are not taken into account in the surf zone. For irregular depth contours in shallower water is chosen to decrease the depth of the bottom profile to 5m+CD. This is done for the rocky headlands and bay type beach at the location of the Durban DigOut Port.

Wave parameters

Wave parameter input consists of coefficients for the hydrodynamic formulas. The surf zone dynamics are calculated by a random wave propagation and decay model by Battjes & Janssen (1978), calibrated and verified by Battjes & Stive (1984). The model requests parameters for wave breaking, bottom friction and bottom roughness, see Table 3-3 for the input parameters. In the model wave dissipation due to wave breaking is computed for random waves, which makes integration of the energy balance over the surf zone possible. Using the momentum balance longshore currents are computed. In Appendix B.2.2.4 the wave-current interaction model is explained, including the background of used parameters.

Table 3-3 Wave parameters

Wave parameters	
Coefficient for wave breaking (gamma) [-]	0.8
Coefficient for wave breaking (alpha) [-]	1.0
Coefficient for bottom friction (fw) [-]	0.01
The value of bottom roughness (kb) [-]	0.05

Transport formula

In order to calculate longshore sediment transports along the South Durban coast a sediment transport formula is used. Longshore sediment transport is mainly driven by longshore currents generated due to the cross-shore gradients in the shear component of the radiation stress in longshore direction. This is driven by incident breaking waves under an angle. The longshore current carries sediments, which are stirred by the orbital motion of waves and the turbulence of the wave breaking. The formulas relate these main processes using different parameters. Outcome is a certain volume of dry sediments that is transported along the coast. For this analysis three bulk longshore transport formulas are evaluated to assess their applicability for the South Durban coast, see Appendix B.2.2.5. The sediment transport formula by Kamphuis (2000) is determined to be best applicable, because it approximates the found net longshore sediment transport (Schoonees, 2000) at the northern part of the Bluff within the 20% uncertainty range. The Kamphuis formula includes the effects of grain sizes, beach slope and wave steepness, through wave period. For the Durban coast, which has steep beach slopes and a significant swell climate, these parameters are relevant. This transport formula, see Equation 3-1, is used in the rest of this research.

Equation 3-1 Kamphuis transport formula (Kamphuis, 2000)

$$Q = 2.27\, {H_{sb}}^{2} {T_p}^{1.5} {m_b}^{0.75} {d_{50}}^{-0.25} sin^{0.6}(2\theta_b)$$

Q : $Dry\ bulk\ transport\ volume\ \left[\frac{m^3}{y}\right]$

H_{sb} : $Significant\ wave\ height\ at\ breaker\ depth\ [m]$

T_p : $Peak\ period[sec]$

d_{50} : $median\ sediment\ grain\ size[\mu m]$

θ_b : $angle\ of\ incidence\ at\ breaker\ depth\ [degrees]$

m_b : $beach\ slope\ at\ the\ breaker\ points\ [-]$

Initial shoreline

The vegetation line of the coast of South Durban, obtained in Google Earth on 13-08-2003, is used as initial shoreline in the model. This is the oldest available shoreline position covering the total research area. Measurements of beach profiles are available from 2005. This makes the shoreline of august 2003 interesting to use, because trends from the model could be compared to the available data from 2005 till 2009. The beach profile measurements itself are not densely populated along the total coast, which makes them unfavorable as input. The moment of the aerial photograph is in winter, where wave conditions are largest and beaches could be locally eroded due to storms. However, at this moment wave data is not available to understand whether the coast was suffering from erosion due to an episodic event at the moment of the photograph. Following Corbella & Stretch (2012a) the wave climate in the winter of 2003 was moderate compared to 18years of data. For the above reasons the vegetation line is considered to be acceptable to be used as initial shoreline for modeling of the South Durban coast. It is assumed that the vegetation line lies at approximately the same height along the total coast. It is thus assumed that the vegetation line will shift uniformly over the cross-shore.

Advantages of using the vegetation line are the clear visibility on aerial photographs and the fact that the line is relatively stable over time, because it takes time for the vegetation to settle. If the vegetation line is structurally retreated over time, one can assume that the coast is eroding. In the model the vegetation line is set as the 2m+CD line. Most of the beach profiles, monitored over the total coastal system, contain a long set of the +2m CD levels, which makes this line interesting to model. Beach profiles are assumed to be constant over time, which means that a translation of the vegetation line is inextricable linked to a translation of the 2m+CD contour line.

Sources and Sinks

Sediment budgets by rivers are positively contributing to the sediment balance in the total system. In Chapter 2.1.5.4 is in an analysis of the largest rivers explained what the contribution in the South Durban coast is. It was found that most of the rivers are dammed. Mining activities are also of major concern nowadays. The sources implemented in the model are sandy deposits, which are based on a report of the CSIR (Theron et al., 2008). The sandy deposits, consisting of bed load material, are assumed to be 10% of the total sediment yield, which is adopted from the CSIR report. Losses by dams, all built before the year 2000, are included. Sediment losses by mining activities in the future are studied in the scenario analysis. In Table 3-4 below the contributions of rivers can be found, which are modeled as sediment sources in the shoreline model.

Table 3-4 Sediment input by rivers

River	Sediment input [m3/year]
Mgababa River	8,000
Illovo South River	15,000
Amanzimtoti River	13,000
Mbokodweni River	5,000
uMlazi Canal	33,000

3.3.2.2 Calibration

Along the South Durban coast, confined in the north by the Durban Port and in the south by the Umkomaas River, the coastal conditions differ locally. For the setup of the model specific locations are selected to calculate longshore sediment transport. The locations are selected based on differences in local wave climates, coastal conditions and existing coastal features, such as rocky headlands. In that way the characteristic conditions along the coast are modeled. At the Durban Port the found net longshore sediment transport needs to be approximated by the model. Longshore sediment transports for all other locations along the coast are unknown, because no further information on sediment transports is available. However, it is known that the longshore drift is directed towards the north, see paragraph 2.1.5. By analysis of the historical shoreline development was found that in the long run the shoreline seems to have a stable position in the south and erodes with approximately 1m/year in the north. Rivers contribute to a positive amount of sediments in the system. Fact is that these annual river inputs are only a small portion of the known northward net longshore sediment transport rate of 500.000m^3/year. Large longshore sediment transports gradients along the total system are not expected, providing a relatively stable shoreline.

These characteristic developments of the coastal system are the basis of the qualitative calibration of the shoreline model using. In the next paragraphs per modeling element will be explained what the physical background is of the implemented elements and how they perform after calibration in the model. Elements are the local longshore sediment transports, boundary conditions, coastal features, such as rocky headlands, sinks and sources.

Global longshore sediment transports

Waves undergo a transformation when they propagate in shallower water. They shoal and refract at natural shoals or islands in front of the coast or other non-uniformities in the bathymetry. Changes in wave conditions lead to differences in longshore sediment transports. At these locations longshore sediment transports are calculated to reflect the present conditions. For uniformly distributed depth contours, offshore waves will undergo the same transformation. For a uniform coastal stretch with approximately the same conditions, less longshore sediment transports are calculated. In Figure 3-11 different areas considering the difference in bathymetry are indicated, which lead to differences in wave conditions in the nearshore. Also around coastal features, such as rocky headlands and breakwaters, local changes in wave conditions are recognized, which results in different longshore sediment transports.

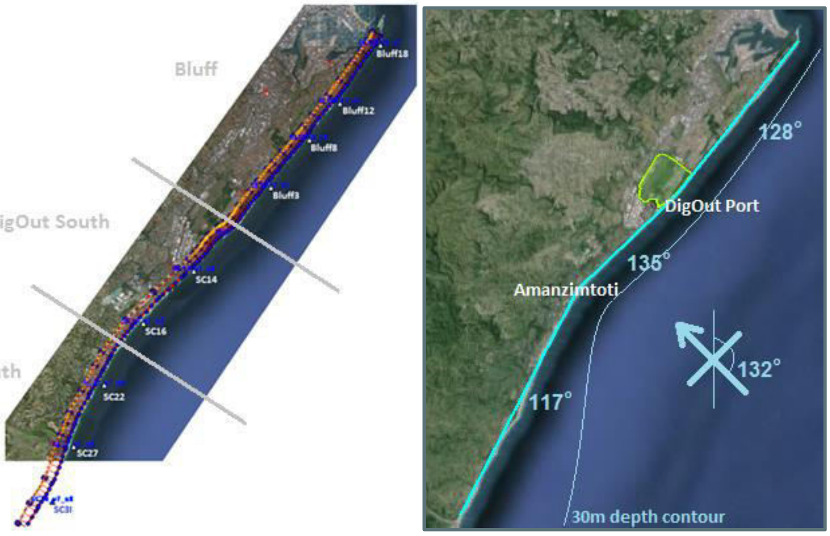

Figure 3-11 Overview location for sediment transport analysis

In the model sediment transports are depicted densely over the South Durban coast. The locations are taken equally spread out over the coast with a higher concentration at the interest area around the Durban DigOut Port to determine future responses.

Transport rays

The longshore sediment transport distributed over a cross-shore profile is calculated for pre-determined locations along the coastline. The longshore sediment transports are calculated with the Unibest LT model. Input values for the global transports are nearshore wave conditions, sediment characteristics, bottom profiles and initial coastal angles. The longshore sediment transports are calculated for specific location along the coasts. The output contains the S-Phi curve, which for different coastal angle the amount of transport gives. Refer to Appendix B.2.3.1 for information on the S-Phi curve. In the 1D shoreline model the transport rays are implemented and checked whether transports behave as expected.

For the longshore sediment transport ray at the Durban Port is checked whether the 500,000m^3/year is approached. The shoreline is not significantly varying in time and net longshore transport is directed northwards over the total area, as is observed in the analysis of the coastal environment in Chapter 2. Therefore the transport rays along the coast are assumed to stay within a certain range from this northward directed longshore transport. A qualitative check is done, where is looked at the direction of the longshore sediment transports and the magnitudes over the system. In the end the transports are implemented in the shoreline model, where is checked whether the coast is behaving as expected.

Boundaries

The shoreline model needs input at the two boundaries: in the south at the Umkomaas River and in the north at the Durban Port. The southern boundary lies relatively far from the Durban DigOut Port. In the bathymetry and wave modeling study is shown that in the south waves are likely to refract, opposite to the north, where profiles are relatively steep due to the narrow continental shelf. By incorporating this area in the shoreline model, knowledge is obtained about the longshore sediment transports in this area, which have never been studied. It is one of the goals of this research to understand the sediment transports and budgets of the coastal system south of Durban. The Umkomaas River is the largest river in the south where a known amount of sediment is annually discharged into the coastal system. Small rocky headlands are found around the river mouth, which establishes the stable position of the shore in that particular area found in twelve years of aerial photographs of Google Earth. The boundary condition in the south at the Umkomaas River has been calibrated to give a net constant input of sediments into the system of 420,000m^3/year. The longshore sediment transport rate, calculated in Unibest LT over a cross-shore ray, close to the river mouth was found to be approximately 300,000m^3/year ± 50%. With this knowledge and the fact that the river inputs 140,000m^3/year into the system, the initial input was set to be 440,000m^3/year. This seemed to give an accumulation of sand, which is not in line with the observation over the last decade. Therefore the boundary has been lowered to a value of 420,000m^3/year, which yielded a stable shoreline in time.

The northern boundary is located just south of the southern breakwater of the Durban Port. At the boundary the shoreline is fixed, because of a revetment and rocks in the upper shoreface. The northward longshore sediment transport fills the sand trap, just north of the boundary, which is periodically dredged to provide the Durban Bight its sediment input. The fixed shoreline is modeled as a fixed position in the model. It means that downstream calculated net sediment transports are governing the amount of sand that is flowing out of the system. The net longshore sediment transport at this point was determined to be 500,000m^3/year (Schoonees, 2000), which is checked in the model. The model gives a sediment transport of 700,000m^3/year, which is an overestimation of the expected outflow and does not lie within the 20% acceptable range. Although this seems to be inaccurate and not very promising, the model is used for further analysis, because of the following reasons. The Unibest model is based on uniform conditions, but in reality this is not fully true. The coast consists of rocky outcrops in the upper shoreface, which could mean that in reality the potential longshore transport capacity is not fully approached. Furthermore, the variation by using empirical longshore sediment transport formulas is large and a factor 1.4 larger than the existing net longshore sediment transport is usually accepted.

Rocky headlands

Along the coast of South Durban at some locations lithified rocks characterize the coast. They are a component of the Bluff and protrude by approximately twenty meters into the surf zone. One of the locations is the Durban DigOut Port. In the preliminary designs the port entrance will be situated in between two larger rocky outcrops. Furthermore, in the region south of Amanzimtoti these rocky outcrops protrude further into the surf zone approximately 50 to 100meters, and characteristic erosion/accretion patterns are observed around them. Physically the headlands pin the shoreline in position.

At the Durban DigOut area the rock formations are excluded from the model. The rocks protrude over a little distance into the surf zone and will therefore not capture any sediment. In reality sediments will pass the headlands, as if it's a straight uniform coast. This is also observed in aerial photographs, where no significant retreat is seen on the lee side of the protruding headlands. However, in the model unexpected local erosion patterns are observed as soon a revetment or groyne is implemented into the model. A uniform coastal stretch with constant longshore sediment transports should lead to a constant shoreline position over time, which is reflected in the model. An exclusion of the headlands in the model provides the shoreline to translate freely in cross-shore direction. For later research should be kept in mind that results are more extreme than in reality, because of the absence of rocks who will fix the coast. In an ideal situation the local wave phenomena around the rocky headlands are taken into account providing the local transport rates. However, the available data does not contain the level of detail requested for modeling these phenomena. On the other hand are such detailed modeling purposes not in line with the large scale shoreline modeling. These phenomena consist of a smaller spatial scale, which is not in the scope of this research.

The rocky outcrops in the area south of Amanzimtoti protrude significantly into the surf zone. Clear erosion/accretion patterns are found around them and therefore these are modeled in the 1D shoreline model as groynes. In fact the numbers of rocky outcrops form a groyne field, where the shore normal is oriented toward the dominant wave direction, leading to lower sediment transports. By measuring the length in Google Earth, the length of the groynes is obtained. The groynes are set relative to the shoreline and do not have any local ray files, because the scale of the hydrodynamics around the groynes is small in respect to the rest of the system. Only the major headlands are modeled. In the Table 3-5 the dimensions and blocking percentages can be found, which is calibrated on a stable shoreline position relative to the initial coast.

Table 3-5 Groyne dimensions

Location	Dimensions Unibest [m]	Blocking percentage [%]	Latitude	Longitude
Ocean View	15	100	29°55'59.43"S	31° 0'48.69"E
Amanzimtoti	90	50	30° 5'47.49"S	30°51'45.43"E
Doonside	80	50	30° 4'42.50"S	30°52'24.35"E
Kingsburgh	80	50	30° 3'51.02"S	30°52'54.78"E
Winklespruit	70	70	30° 3'5.51"S	30°53'28.41"E

3.3.3 Model performance

3.3.3.1 Targets

By an analysis of the coastal environment through literature and data analysis, information is obtained about the coastal system. The information consists of the identification of coastal characteristics, such as rocky headlands, historical shoreline behavior and information about longshore sediment transport. It represents the current characteristics of the system, which have to be reproduced by the shoreline model. The model is said to perform well, if it can reflect these characteristics, which are called targets. The model performance forms the basis to yield qualitative predictions of the future within a certain uncertainty range.

The main targets which the model is required to reflect are summarized below:

I. The stability of the total coastal system over the past 40years (Theron et al., 2008)
II. The EThekwini coast average shortfall in sediments of 300,000m^3/year ± 50%, compared to 'Natural' rates (Theron et al., 2008)
III. For the Durban Bluff a NET sediment transport rate of 500,000m^3/year ± 20% (Schoonees, 2000)
IV. A shoreline retreat of approximately 1m/year found for the central Bluff out of yearly monitored beach profile measurements
V. Shoreline behavior in Unibest-CL+ model and beach profile measurements from CSIR have to agree over a period from 2005 to 2009

In the figures on the x-axis the distance is shown from the southern boundary 'The Umkomaas River' (zero) up to the northern boundary 'The Durban Port'. In the figures two dashed lines are shown to provide the reader the ability to orientate. The lines coincide with Amanzimtoti at 13.5kilometers and the Durban DigOut Port at 13kilometers from the south. A positive shoreline translation shows an accreting shore, a negative translation shows erosion.

3.3.3.2 General performance

In Figure 3-12 is shown the net longshore sediment transport along the South Durban coast over a period of 50years. A clear pattern is observed with in the south lower net longshore sediment transports than in the north. It results in a gradient in the system, see Figure 3-15. After ten years the net longshore sediment transports are relatively stationary in the model, resulting in a stationary profile of the shoreline behavior, including structural erosion trends. At that moment the model has fully adapted to the implemented wave and transport climates and sediment sources, which has to be kept in mind in the evaluation phase of this research. The stationary net sediment transports result in a relatively stable position of the shoreline over the total system, which is in line with observation from the past. Target I is therefore said to be met. The shoreline stability will be highlighted per subsection in the next paragraphs.

The southern part of the Bluff has a constant net longshore sediment transport. In the northern part of the Bluff a small gradient is observed leading to coastal erosion. North of the central bluff a steady coastline retreat of approximately 1m/year is computed. It corresponds with observations found by analyzing twenty-three years of beach profile data at this location. Target IV is therefore said to be met. A shoreline retreat of approximately 1m/y for the area between Amanzimtoti and the DigOut Port is not observed in the twelve year Google Earth data. This should be kept in mind and will be discussed later. South of Amanzimtoti a relatively constant net longshore sediment transport is observed leading to a constant shoreline position.

The total EThekwini coastline has a shortfall in sediments of 300,000m^3/year ± 50% compared to 'Natural' rates, see target II. This is however a rough estimate, which is mainly based on less sediment input in the system due to mining of sediments in rivers and the damming of rivers which blocks sediments. The research area consists of approximately two-third part of the considered EThekwini coast. In Figure 3-12 is found that the system has a deficit of approximately 280,000m^3/year. This is based on the sediment balance of the total system: sediments flowing out of the system (700,000m^3/year) minus the sediments coming in from the south (420,000m^3/year) give a shortfall of approximately 280,000m^3/year. The model agrees with the order of sediment scarcity in the coastal system and therefore target II is met.

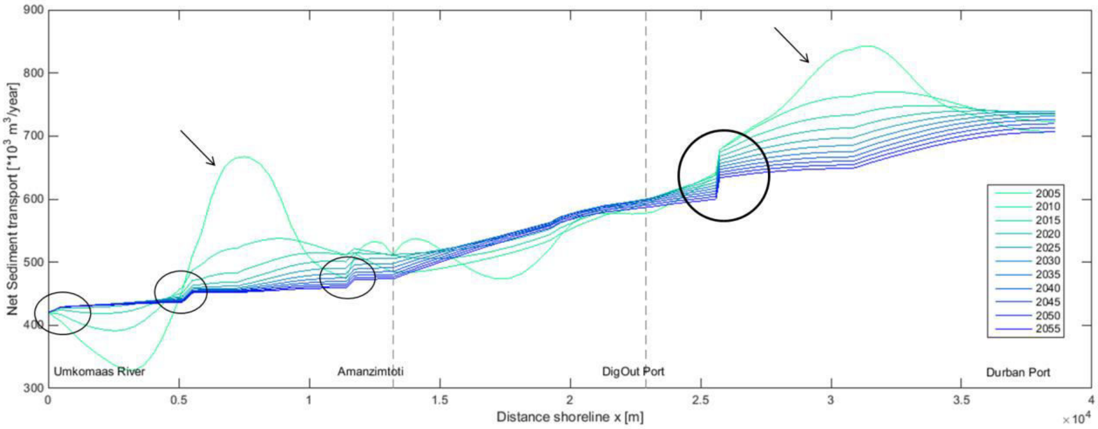

Figure 3-12 Net Longshore Sediment Transport 2005-2055

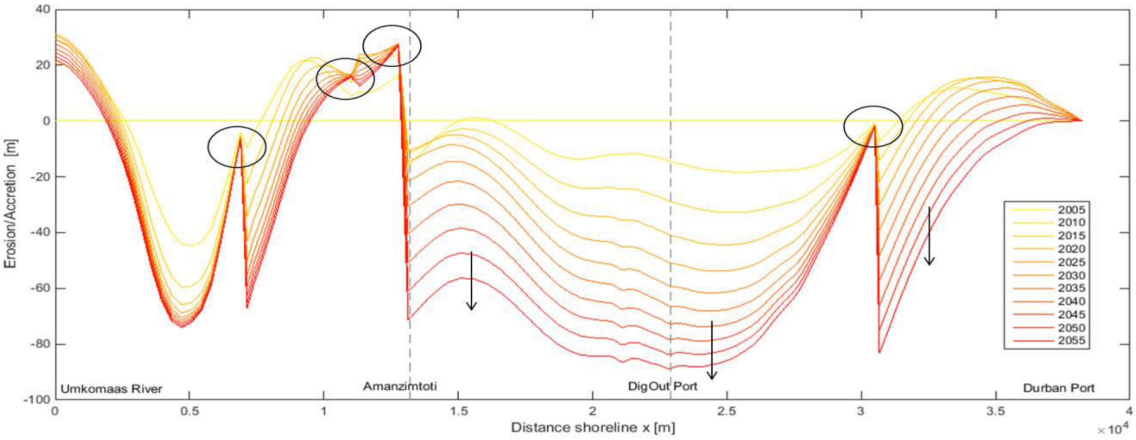

Figure 3-13 Computed erosion/accretion 2005-2055

For the Durban Bluff a net sediment transport rate of 500,000m^3/year was found in literature. The model approximates a net sediment transport of around 700,000m^3/year at the Durban Port. This is an overestimation. However, in the model is assumed that the potential transport capacity is the full capacity, which is not correct given the many rocky features in the nearshore. It is therefore reasonable that the transports in the model are higher than those in the paper, which makes target III acceptable.

In Figure 3-12 the circles are highlighting the input of sediment sources by rivers, which show an offset in the graph. This is an input of sediment into the system by a river, which therefore increases the amount of sediment carried by the littoral drift. The circle on the right shows for example a 33,000m^3/year input by the Umlazi Canal.

In Figure 3-13 the circles show the effect of groynes in the model, which are rocky outcrops in reality. The rocks protrude into the surf zone and block the sediments. Only the largest rocky outcrops are modeled. The circles in the figure show a fixed shoreline position at the groyne tip. It shows the characteristic shoreline adaptation around a groyne. The circle at the Durban Bluff shows the effect of a rocky outcrop where a swimming pool is built inside it. Initially the groyne is filled with sediments on the up drift side and erosion occurs on the down drift side. The shoreline approaches on both sides an angle normal to the incoming waves, which results in a decline of transports. Structural erosion in the system provides that these patterns are expanding, as can be seen in Figure 3-13. In the model the groyne remains in position and the coastline around it will transform. However, this is not the case in reality. At a certain moment the rocky outcrop with pool will be taken over by the sea, because sediment will start flowing behind the rocky outcrop. One should keep in mind that extreme erosion around the groyne does not reflect reality.

3.3.3.3 Initial disturbances

For the model an initial two years are taken into account to get rid of initial disturbances. It basically means that the model runs from 2003 to 2005 and starts outputting from 2005. These disturbances are related to physical differences between the model and reality. At the Durban DigOut Port the rocky headlands are not modeled as is explained in the previous paragraph. The initial shoreline will adapt to a straight uniform coast immediately. Other initial disturbances can be found in the south near Winklespruit, where a vegetation line fixes the coast, because it holds the sediments, see the left black arrow in Figure 3-12. However, the profiles in the model consist of purely sand and resisting vegetation is not present. The model approaches a slightly different shoreline orientation, because of the sediment transports in that particular region. In the north also such an initial trend in the longshore sediment transport graph is shown, see the right black arrow in Figure 3-12. In reality some non-uniform features such as rocks are present in the upper shoreface, which have their effect on the shoreline position. In the Unibest model the shoreline is uniform and therefore the bend in the shoreline is filled. The model is not able to deal with these detailed morphodynamics, because the available data has not the required level of detail. The explained parts of the coast are therefore averaged and this leads to initial disturbances, compared to the actual shoreline position. It takes some time before the shoreline has reacted on the presence of these structures in the model.

3.3.3.4 Validation

In this paragraph the model is validated. Available data consists of beach profiles measurements from the CSIR over the period January2005 to April2009. Every three months the beach profiles are measured. In order to obtain a trend in the available four year, the average beach profile position of 2008 is subtracted by the average beach profile of 2005. This is compared to the behavior of the shoreline in the Unibest model for the years 2005-2008, see Figure 3-14. The black line shows the shoreline position in 2008 minus the shoreline position in 2005. In this way the trend is obtained over a period of four years, which matches with the period of the available beach profile record.

The model agrees relatively well with the beach profile observations. In the north and central part of the South Durban coast the shoreline is stable over the plotted period, which is reflected by the shoreline model. South of Amanzimtoti the modeled shoreline does not match with the observations to a large degree. However, some trends are still clearly visible and reflected by the model, like the erosive trend at 5000m from the south.

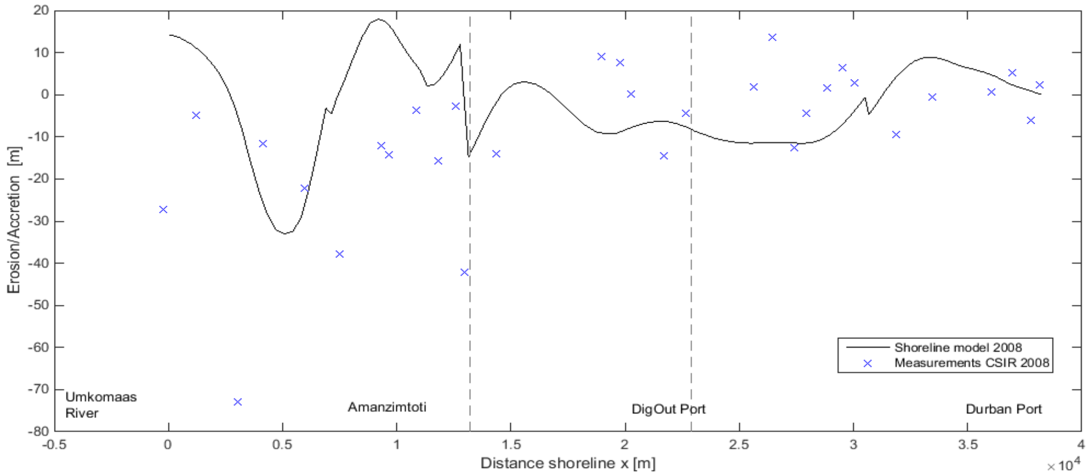

Figure 3-14 Modeled erosion/accretion for the year 2008 over the period 2005-2008

3.3.3.5 Discussion and Conclusion

In the previous paragraphs the input, model setup and performance of the model is elaborated on. In this final paragraph the setup and performance of the shoreline model is discussed and conclusions are drawn with respect to the next phase of this research. In the validation paragraph is shown that the model reflects the trends obtained from four year beach profile measurements. In particular the area between Amanzimtoti and the Durban Port agrees upon a high degree with the measured beach profiles, which is important, because this is the main area of interest of this research. However, the available data is short and relatively young, which provides less time for the model to adapt to physical differences between nature and model. Thereby, the four years of beach profile data is a very small period to obtain average erosion/accretion trends from to validate a model with which is built to predict 40years of shoreline behavior.

In the southern part of the studied area, the measurements vary significantly. This is related to short term cross-shore changes, as for example the recovery of the March2007 storm. The available four years almost touches the boundaries between long and short term processes. These processes are not incorporated in the model. Further, the validation is done over a period where the model does not seem to have approached the stationary situation considering the long-term modeling results, shown in Figure 3-12. However, variations are the result of the initial disturbances and these are diminished by subtracting the first two years.

Over the total area from Amanzimtoti up to the Durban Bluff the model shows a gradual erosive coast of approximately 1m/year. The area of the Durban DigOut Port is located within this coastal stretch, which is in reality not likely to erode because the shore is fixed by rocky headlands. In the model setup is chosen to leave the rocky headlands out of the model and model this coastal stretch as a uniform sandy coast. The model is not able to deal with the coastal dynamics around these headlands, because cross-shore processes play a role. Further, the necessary level of detail of the bathymetry is not available to model the wave hydrodynamics around these headlands. Since no large erosion phenomena are observed in the vicinity of the headlands, the net longshore transports are assumed to remain equal, not accounting for significant gradients. The model approaches the coast thus as a uniform coast, which is in this case acceptable given the validation results. However, by doing this some reservation is needed by evaluating coastal responses in the future. The shoreline model will give extreme predictions in case of coastal retreat around rocky features, because the shore is not fixed anymore.

A few differences are explained between the model and reality, which should be kept in mind during the evaluation phase of future shoreline behavior. Lithified rocks are found as submerged rocks, rocky islands in the upper shoreface and at dune foods. In reality the longshore transports could be less than predicted in the model, because less sediment is available due to these rocks. Only the largest features are modeled in the shoreline model as gryones, based on their observed impact on the shore. Significant coastal retreat leads to failure of the rock formation, because sand will eventually bypass behind the rocks. The rocks are taken over by the sea. The model cannot reflect these processes during significant coastal retreat. Further, rocky headlands could provide the coast to adapt to its equilibrium position, which stabilizes longshore transports. In case of sediment shortage through a gradient in the longshore transport the problem is transferred further downstream, which leads to extra coastal erosion.

3.3.4 Application for South Durban

3.3.4.1 Durban Bluff

In Figure 3-15 the shoreline behavior of the Durban Bluff is shown from 2005 to 2055 under the current conditions. The model shows a continuous line which is eroding over the total area. At Ocean View a discontinuous disturbance can be seen, where a protruding pool is modeled as a groyne. The shore is pinned at that location. The erosion/accretion pattern is stretched out over a long distance.

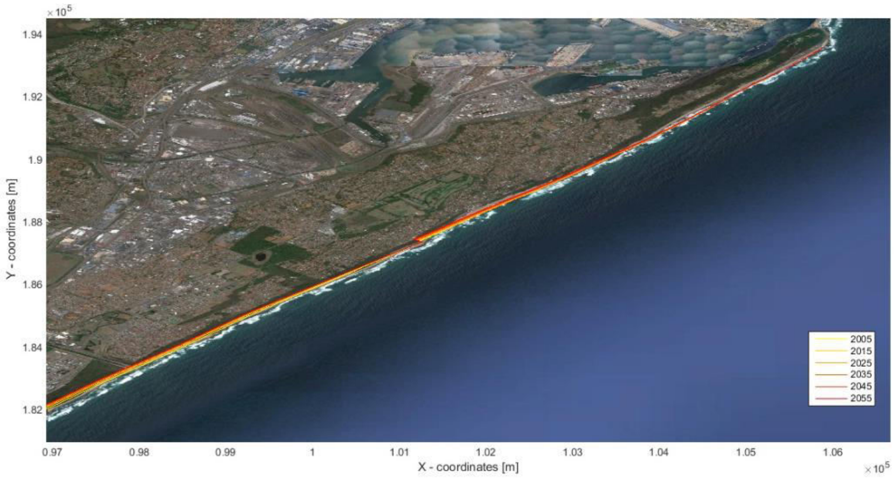

Figure 3-15 Modeled shoreline behavior Durban Bluff

At the Durban Bluff large potential longshore sediment transports are found. However the coast is close to its equilibrium position, which provides relatively low transports compared to the potential. In the transport curve, see Figure 3-16, a maximum potential transport of almost 3,000,000m^3/year is observed for both studied location at the Bluff. However, at the current coastline net sediment transport of around 500,000m^3/year is observed.

The fact that the orientation of the coast lies close to the equilibrium orientation, could result in a significant increase when the coastline orientation changes. It provides a rapid adaptation to local disturbances, because the shore will erode very fast in case of a local change in the shoreline. The equilibrium angle of the Bluff18 location, just south of the Durban Port, is 127degrees north. South of the

Bluff at location Bluff3, the equilibrium position is 132degrees north, which is almost in line with the average wave direction.

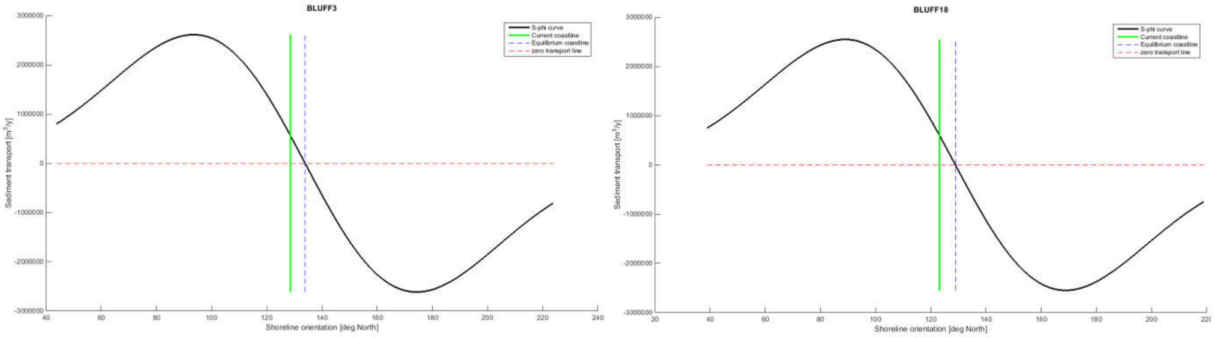

Figure 3-16 S-Phi curves Durban Bluff - BLUFF3 (left) and BLUFF18 (right)

3.3.4.2 Amanzimtoti – Durban DigOut Port

South of the project area of the Durban DigOut Port the equilibrium coast lies around 135 to 140degrees north, see Figure 3-17, which is again closely approximated by the current coastal orientation. At location SC14, just south of the projected DigOut Port the coast has a steep slope, just like at the Bluff. Waves from the dominant south-southeastern direction are still not very sensitive to refraction processes. However, this is different for location SC16, where waves from the south refract over a larger area, shown in Chapter 3.2. SC16 lies in a bay-type area, which results in lower potential transport. Further, the coast approximates the equilibrium angle closer than at location SC14. The potential transport capacities for SC16 are therefore lower than for SC14, resulting in a gradient in longshore sediment transports. This leads to coastal erosion over the particular area, which is shown in the previous paragraph.

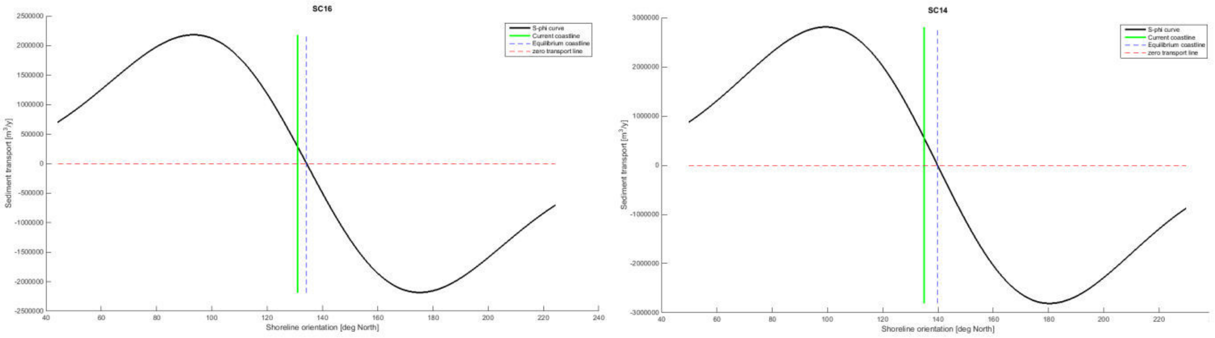

Figure 3-17 S-Phi curves DigOut South - SC16 (left) and SC14 (right)

3.3.4.3 Amanzimtoti South

In the south, from the Umkomaas up to Amanzimtoti the net longshore sediment transports are relatively constant along the shore, providing a constant shoreline position in time. In this area the rocky headlands can be found, which function like a groyne system. Minor erosion can be observed in the south, where the coastline is pinned by the rocks. Sediments are captured behind these natural structures and the shoreline approaches an orientation in line with the observed wave climate. In Figure 3-18 the modeled shoreline behavior is shown over a period of 50years between the Lovu River and Amanzimtoti. It can be seen that the coast is relatively stable and that no significant coastal retreat over this area is observed.

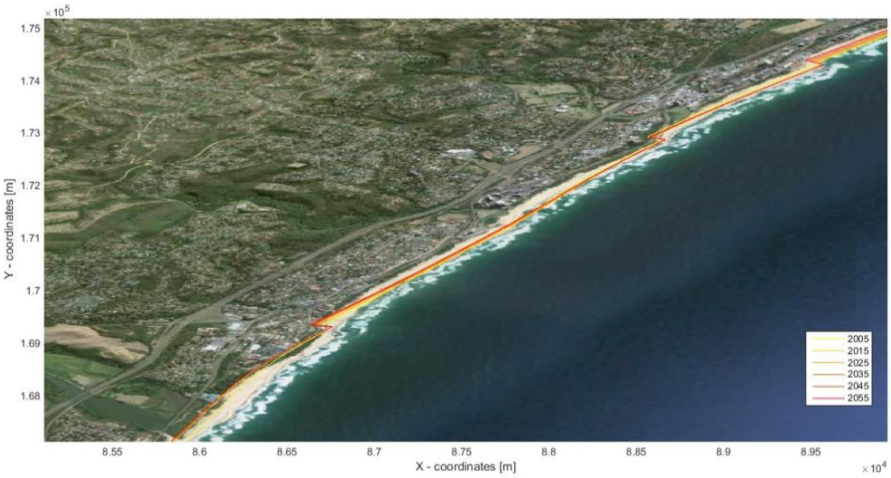

Figure 3-18 Modeled shoreline behavior in the south near Kingsburgh

Figure 3-19 shows that south of Amanzimtoti the magnitude of the potential transports is significantly less. The maximum transport for the location SC22 is 1,500,000m^3/year, which is almost half of the maximum transport possible at the Bluff. Waves from the dominant south-eastern direction are refracted due to the gentle slope of the bathymetry. This results in a decline in wave height and a smaller angle of incidence which subsequently results in a less potential transport. The average equilibrium shoreline in this area is determined to be approximately 125degrees north.

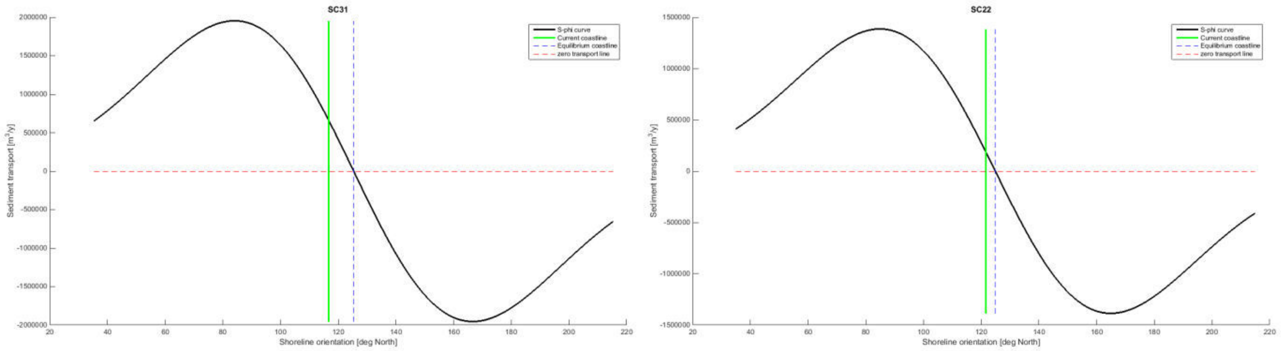

Figure 3-19 S-Phi curves Amanzimtoti South - SC30 (left) and SC22 (right)

3.3.4.4 Gross and Net sediment transports

In this analysis the longshore sediment transports are determined for the initial shoreline. Gross longshore sediment transports determine the erosion/accretion patterns around a shore-normal structure, like the breakwaters of a port. In the shadow zones the secondary waves play a major role. Further, the accretion of a port entrance is dependent on the total gross sediment transports. In Figure 3-20 the gross and net sediment transport are drawn over the project area.

Gross southward longshore transport is relatively stable and continuous, which is mainly induced by wind-waves. These waves approach the shore from the east-northeast under an angle and are relatively insensitive to changes in the bathymetry at larger depths. The waves will enter the surf zone along the South Durban area at approximately the same angles. Gross northward sediment transport is related to the significant swell waves during winter. An increase in northward transports can be seen from location SC22 to SC14, which can be attributed to the small bay-type area around Amanzimtoti. At this location the shoreline orientation turns in northern direction in a more obliquely position relative to the east-northeast main direction of the waves. Larger swell waves from the south are sensitive to bathymetric changes around twenty to thirty meters depth. South of Amanzimtoti swell waves refract due to a gentle slope of the shelf yielding that wave energy is spread over a larger area. This results in lower northward gross sediment transport. As the slope increases towards the north, the waves have a larger impact on the coast, resulting in higher northward gross sediment transports around the Durban Bluff.

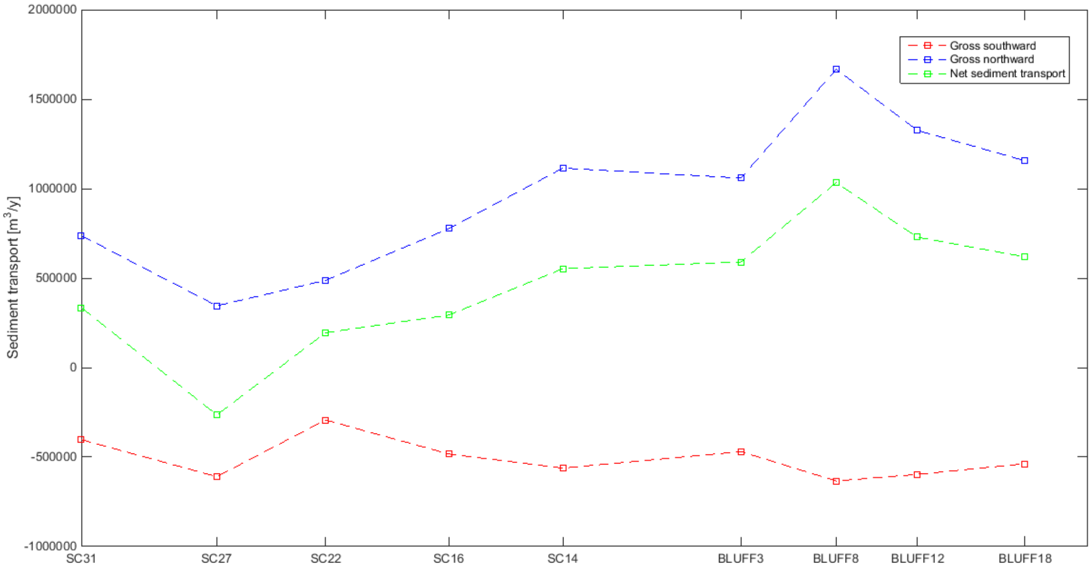

Figure 3-20 Sediment transports over research area Durban South

4. The impact of the Durban DigOut Port

In this chapter future shoreline behavior is predicted and evaluated as a result of the Durban DigOut Port. First, the impact of the Durban DigOut Port without mitigating measures is discussed. Second, alternative mitigation measures are introduced and evaluated on their effectiveness in retaining a sustainable shoreline for South Durban.

4.1 Introduction

The design of the Durban DigOut Port is still in a preliminary stage and construction work hasn't started yet. The port is expected to be operational in 2025 following the latest news. Therefore this date is used for the modeling. The design of the DigOut Port is based on a study of the MSc Project team, described in the Chapter 2.3.2. They have investigated the expansion of the DigOut Port and made recommendation to the Port Authority for a preliminary design (ProjectDurban et al., 2014). Like in the report, in this research is also assumed that the port entrance is fixed. Points of interest of this study are the adaptation of the angle of the shoreline after implementation of the breakwaters, the potential erosion/accretion phenomena around the port, the maximum retreat and the natural bypass potential of sediments. At the up drift side, rivers could be clogged, which could provide problems upstream of the river. At the end of this chapter mitigation measures are introduced to protect the shoreline from potential erosion. The effectiveness is studied of these mitigating measures to remain a stable shoreline in the future.

A study is done to understand how the shoreline is expected to behave near both breakwaters. This is all explained in the Appendix C.1.1. Waves enter the coast under an angle and are reflected against the breakwater. This results in a sheltered zone on opposite side of the breakwaters, where a locally different wave climate can be found. The local wave climates also accounts for diffraction around the breakwater tip. By using the diffraction rule of Kamphuis (Kamphuis, 1992), the wave climates are obtained in the shadow zone of the breakwaters, which are used for the modeling. Local erosion/accretion phenomena are studied because of the secondary waves.

Table 4-1 Overview of evaluated measures Durban DigOut Port

Durban DigOut Port
Durban DigOut Port + Bypass
Durban DigOut Port + Local groyne field
Durban DigOut Port + Bypass and Local groyne field
Durban DigOut Port + other alternatives

4.2 Durban DigOut Port without mitigation measures

For the Durban DigOut Port two breakwater designs are studied. Due to the northern net longshore transport a significant retreat on the lee side of the northern breakwater is expected. The 'Long breakwater' design concept from the Project Durban group (ProjectDurban et al., 2014) is modeled as a southern breakwater of 1885meters long and a northern breakwater with a length of 1085meters. The second design of the breakwaters is the 'short breakwaters' option. The dimensions of the short breakwaters are 1200meters for the southern breakwater and 450meters for the northern breakwater. In Figure 4-1 the erosion/accretion pattern is shown in time for short breakwater designs and the final situation for the long breakwater design. The figure is plotted minus the 'Do nothing' scenario, which means that the direct effect of the intervention is studied without any side effects in time.

The erosion/accretion pattern for both breakwaters designs is equal. They both protrude into the ocean far behind the surf zone. Thirty years after construction in 2055, the coast is still accreting at the up drift side, which means that sediments are not bypassing the breakwater tip. Sediments continue to be deposited at the up drift side of the breakwaters. It yields on-going erosion at the down drift side, because of a stop of sediment input and the on-going demand of the longshore current to take sediment with it. In further research the shorter breakwater designs are used.

The construction of the DigOut Port without any mitigating measures, results in large erosion at the lee side of breakwaters of approximately 500meters after 30years. It basically means that total geological dunes will be eroded, which exposes the refinery to the open ocean. However, in the 1D shoreline model it is assumed that the shoreline is uniform and consists of sand, which is not fully true. Rock formations north of the port will pin the shoreline and prevent on-going erosion processes. Therefore the erosion at the lee side is an extreme calculation of a potential future situation.

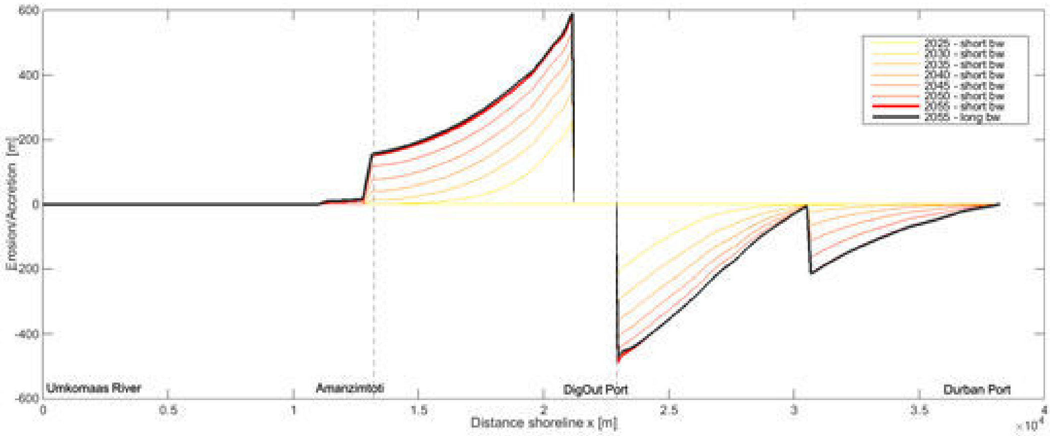

Figure 4-1 Computed erosion/Accretion pattern in time for breakwaters at the DigOut Port

Another protrusion can be seen further downstream at the central Bluff, where a pool (modeled with a little groyne) protrudes into the surf zone and has pinned the shoreline. Erosion effects due to the DigOut Port will continue past the groyne, which covers the total area of the Bluff. At Amanzimtoti the erosion on the lee side of a small groyne is filled due to the accretion, which explains the abrupt ending of the accretion pattern.

In Figure 4-2 an overview is given of the computed erosion/accretion around the DigOut Port, including the current erosion of system. Near the southern breakwater the shoreline gets an angle of 138degrees, which is in line with the dominant direction of the primary waves. Since the process is still on-going, the final angle equal to the average wave direction of the total climate has not been approached yet. Thus, in the end the full breakwater will be accreted and sediments will start to bypass the groyne tip. In the Appendix C.2 a simple calculation shows that the total amount of incoming sand by the net longshore transport is equal to the volume of the accreted coast five years after construction of the breakwater. This shows that the model is approximating the patterns around the breakwaters as expected.

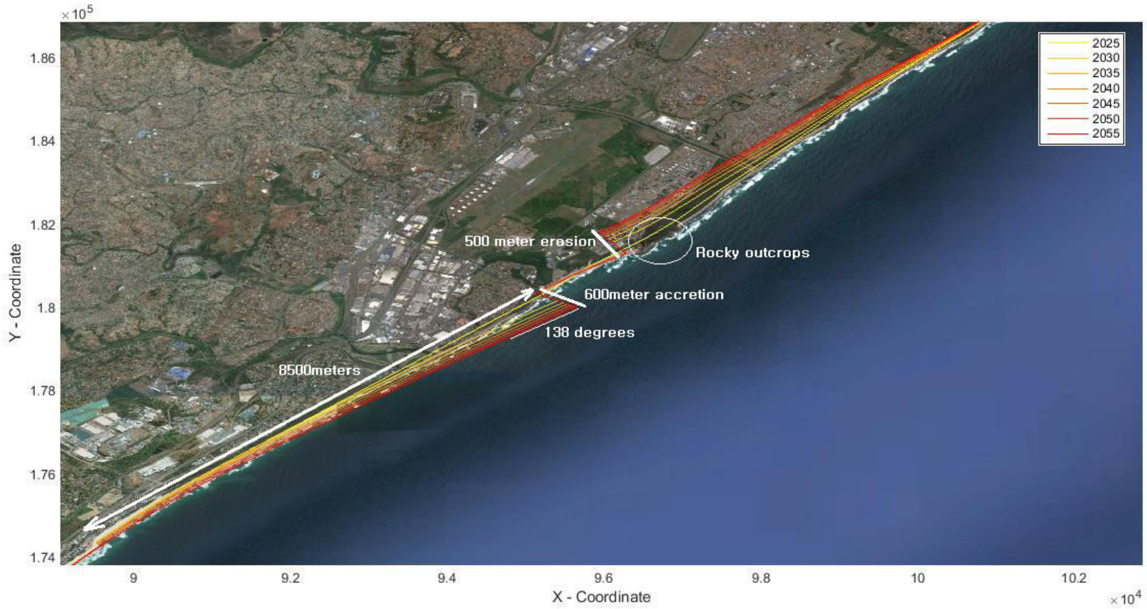

Figure 4-2 Overview of modeled shoreline behavior Durban DigOut Port - Short breakwater design

In the current situation the Durban DigOut Port has severe negative effects on the adjacent shoreline. As can be seen in Figure 4-2 a shoreline retreat of 500meters is to be expected at the lee side of the port, where a refinery can be found. Erosion will continue further downstream and have a major impact on the Durban Bluff, where inhabited areas can be found. At the up drift side, the Mbokodweni River will be clogged by the accumulated sediment, which could lead to potential flooding of the upstream area of the river. In further research alternatives are investigated to mitigate the effects around the port. For more information about the processes around the breakwaters refer to the Appendix C.1.1.

4.3 Durban DigOut Port with mitigation measures

In this section several alternatives are presented to mitigate the effects of the Durban DigOut Port investigated in the previous paragraph. Erosion on the lee side of is one of the major problems. In the alternatives the short breakwater design is used. In these alternatives no environmental variables are taken into account.

4.3.1 Artificial bypass system

An artificial bypass system is implemented to provide sediments to the down drift side of the port. A single deposition point and many deposition points are investigated. The bypass system could for example consists of a dredger who dredges the sediments on the up drift side of the breakwater at a predetermined sand trap and will deposit them at the down drift side on a single point or via a pumping system with several discharge points, like at the Durban Port.

Figure 4-3 shows the sediment transports around the DigOut Port for the ‘Do Nothing’ scenario in the year 2025. Near the Durban Port the transports are in the order of 600,000m^3/year, see the green line. A calibration has been carried out to check whether this amount is enough to prevent the shoreline eroding. The bypass system extracts 550,000m^3/year on the up drift side (southern breakwater) and supplies the down drift side with the same amount. A larger extraction of sediments results in erosion at the up drift side of the breakwaters, because too much sand is taken from the system compared to the incoming sediments from the south. In Figure 4-4 again the situation of the intervention minus the ‘Do Nothing’ situation is shown.

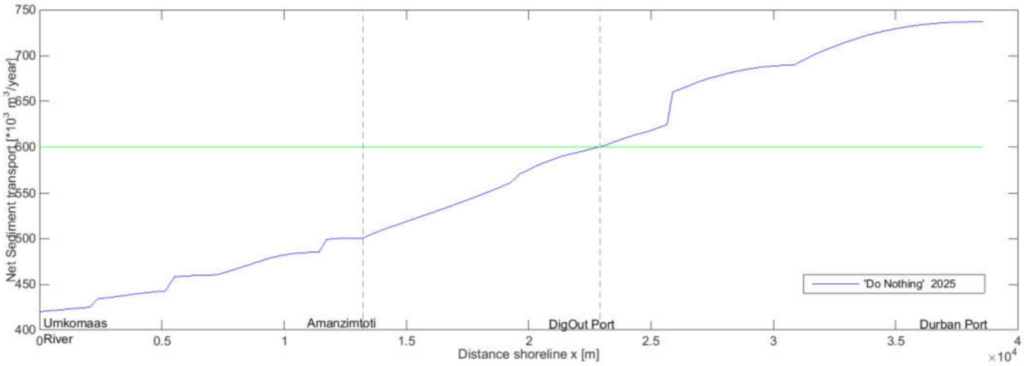

Figure 4-3 Sediment transport in the year 2025 (DigOut Port Operational)

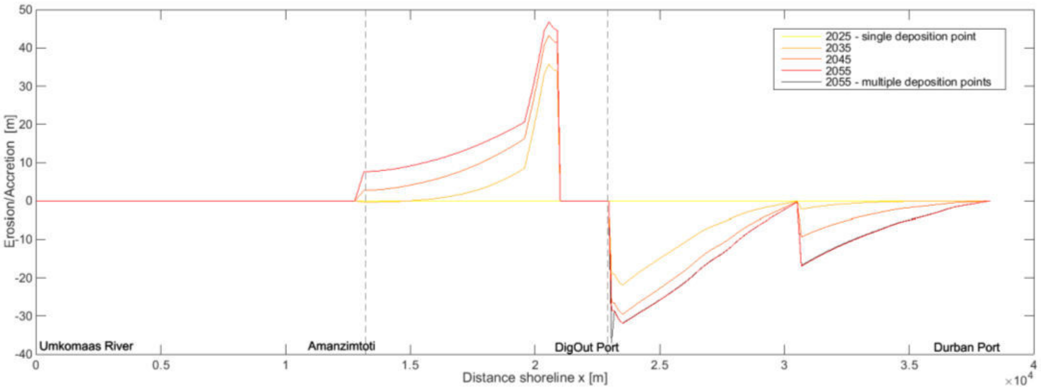

Figure 4-4 Computed erosion/accretion at the DigOut Port with artificial bypass systems

In Figure 4-4 can be seen that the retreat around the Durban Bluff has significantly decreased compared to the situation without a bypass system. For the year 2055 still a maximum retreat of approximately 30meters is determined based on the modeling results and less than 20meters at the Bluff. The erosion and accretion patterns stabilize after approximately twenty years. The erosion is caused by a decrease in sediments entering the system as naturally would occur, plus a steeper gradient which is created due to the port. The two different bypass systems, which use one outlet and multiple outlets over a distance of 1250meters, are not significantly different. In Figure 4-4 the erosion/accretion pattern is shown for both systems in the year 2055 and no differences can be seen. The sediment outtake is not located directly next to the breakwater at the up drift side of the breakwaters. As a result the angle of the shoreline close to the breakwaters is not aligned with the average direction of the wave climate.

4.3.2 Local groyne field

A local groyne field is constructed between the northern breakwater and the Umlazi Canal to make sure that the shoreline will not retreat at the Durban DigOut Port location, where hazardous goods are stored. The groynes have a length of 60meters from the +2CD line into the sea, which is determined by considering an erosion rate of 55,000m^3/year over the local groyne field. A blockage of 10 percent of the net longshore transport provides the shoreline enough sediment to stabilize. The spacing between the different groynes is determined to be approximately 200meters. In the Appendix C.3 the determination of the groyne length is elaborated on. Additional to the groyne field, the rocky outcrops are included just north of the DigOut Port, see Figure 2-11. They are modeled like a revetment.

In Figure 4-5 the effect of the revetment and the groyne field are shown. The shoreline is pinned at the down drift side of the breakwaters. However, erosion increases further downstream of the longshore drift towards the Durban Bluff. At the most southern point of the Bluff a shoreline retreat of approximately 400meters can be observed. In 2055 the shoreline position seems to stabilize between the local groyne field and the little groyne at the Durban Bluff. The shoreline has adapted and the shore normal is orientated in line with the dominant wave direction. Sediment transports become zero and erosion continues further downstream until an equilibrium orientation is found there as well. This shows the effect of erosion shifting further downstream in time.

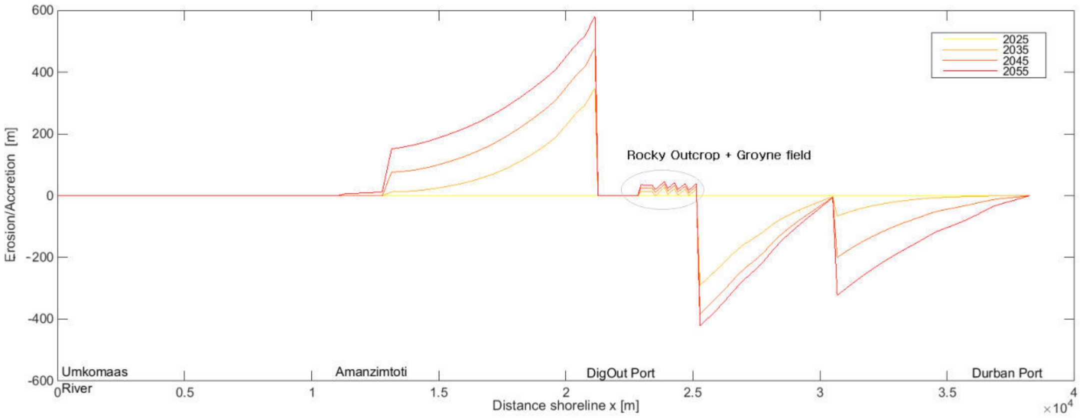

Figure 4-5 Computed erosion/accretion at the DigOut Port with groyne field

Although the groynes prevent the valuable DigOut area from erosion, the groynes are not sustainable: they only prevent the shoreline to erode in the area where they are situated. Downstream of the groyne field the erosion continuous and gets even worse. This is explained with in Figure 4-6. The net sediment transport is given for the situation with groynes and the situation without groynes. For both situation sediments are totally blocked by the breakwaters. No sediments are flowing into the system northward of the breakwaters, which leads to a large gradient in the longshore transport over the Durban Bluff. In the situation without groynes sediment transports are set into motion directly downstream of the breakwater, shown by the dark blue line, which leads to coastal erosion directly downstream of the breakwaters. However, in case of a groyne field sediments are trapped by the groynes, where the shore approaches the equilibrium position. Past these groynes the longshore current increases again. It results a stronger gradient in longshore transports, which subsequently generates more erosion.

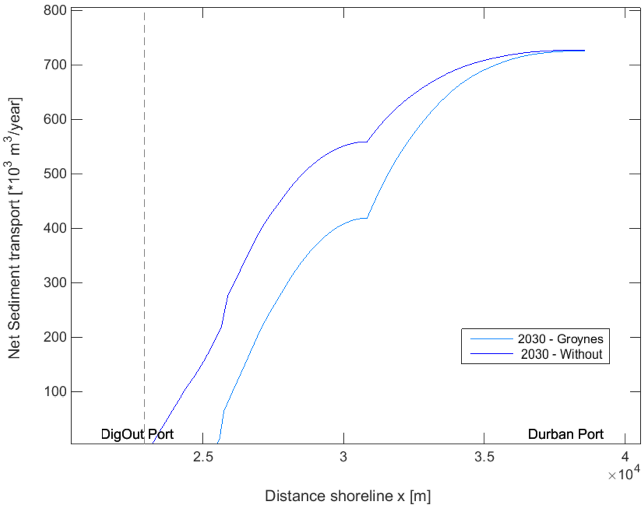

Figure 4-6 Net sediment transport

4.3.3 Groyne field and bypass

The groyne field is an alternative to protect the area of Durban DigOut Port from significant coastal retreat. However, it leads to additional erosion at the Durban Bluff. An additional alternative has been set up combining the local groyne field and the bypass system. Erosion at the Durban Bluff could be counteracted by an artificial bypass system. Sand is again dredged from the up drift side of the breakwaters and replenished at the down drift side. In Table 4-2 the volumes are shown. Again no environmental variables are incorporated.

Table 4-2 Dredge and annual dumping volumes

Year	Dumped	Dredged
2025-2030	550,000m^3/year	0
2030-2055	550,000m^3/year	-550,000m^3/year

In the first five years from 2015 sand is replenished at the dumping side using sand from excavation works at the DigOut Port. This is done to overcome initial erosion patterns due to the implementation of the breakwaters as we have seen in the previous alternative. Replenishments follow every year at the same location, just downstream of breakwater. The groyne field is designed in such a way that the groynes capture only the amount of sediments necessary to stop the coast from eroding. Therefore the dredged sediments can be replenished next to the breakwater without using a large pumping system to transport it to the down drift side of the local groyne field. During the dredging works not more than the yearly incoming sand can be dredge, otherwise the coast will erode. Therefore the dredging volume will not exceed a volume of 550,000m^3/year.

In Figure 4-7 the erosion/accretion graph is shown with the locations of the anthropogenic interventions. All shoreline translations can be directly attributed to the mentioned interventions. Again the groyne field shows a stable coast, which prevents the DigOut Port from eroding. A maximum coastal retreat of approximately 60meters is observed in 2045, which remains constant in the following years. At the central Bluff erosion initially continues in time until an equilibrium situation is approached. Breakwaters and groynes are built at the same time, which is obviously not the case. To protect the DigOut area at the down drift side from initial erosion after constructions of the breakwaters, the groyne field is constructed first. However, this will lead to additional erosion downstream since the coast is structurally eroding over the area of the groyne field, as is explained in the previous paragraph. A possibility is to do a nourishment at the Durban Bluff to mitigate these initial erosion problems.

South of the DigOut Port the coast is accreting after construction of the breakwaters in 2025. As dredging starts in 2030 the coastline retreats nearby the dredging pit. However, from Amanzimtoti, where the shoreline has accreted due to the initial positive disturbance, to the DigOut Port the shoreline approaches a stable position. An area is created which is advantageous for recreational purposes.

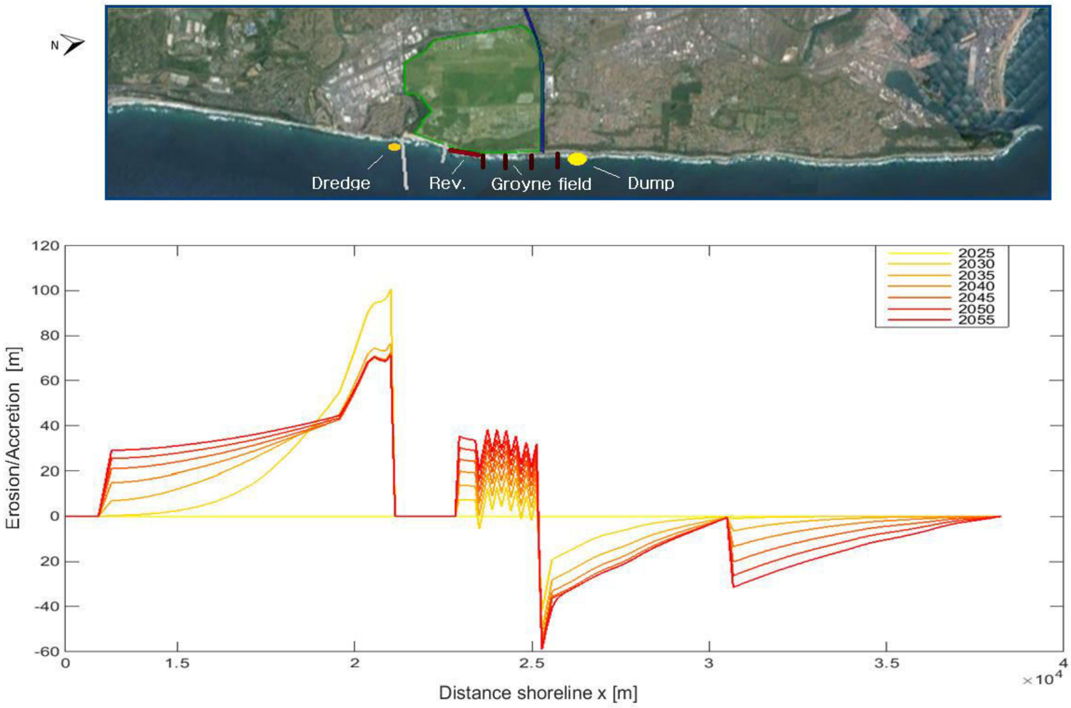

Figure 4-7 Computed erosion/accretion at DigOut Port with local groyne field and artificial bypass system

4.3.4 Other alternatives

Other more extreme alternatives are created as well, to check whether these contain effective measures to counteract the erosion due to the DigOut Port. The alternatives are presented in Appendix C.4. Examples are nourishments, a large groyne field covering the total Durban Bluff and others. These are not presented, because they are assumed to be not feasible.

5. The impact of changing environmental conditions

5.1 Introduction

A change in the environmental variables of the coastal environment has its effect on the coastal dynamics. In this study future sediment budgets and longshore sediment transports are researched, which are the drivers behind long-term coastal morphology of the South Durban coast. Changing environmental variables, such as the wave climate or river inputs are closely related to these sediment budgets and transports. In the Chapter 2.1.9 was explained that climate change could lead to a change in different wave components. In this chapter the effects of each changing wave component on the coast is evaluated using the obtained 1D shoreline model. Further, an expected increase in river mining is evaluated, which leads to less sediment input into the coastal system and could lead to a significant shoreline retreat. Changes in the average wave climate and river inputs are evaluated by the setup of scenarios. Based on the studied literature ranges are created to investigate the sensitivity of each changing variable on the coast. A first order study is carried out, where the outcomes of the different variables are added together, to understand the spatial spreading of the impacts on the shoreline. In this way vulnerable locations are identified, which is valuable information for policy decisions in protecting the coast from eroding.

Table 5-1 Overview evaluated environmental changes

Wave heights
Wave peak Period
Wave direction
River Mining

5.2 Changing wave climate

5.2.1 Wave height

For the South African east coast in the western part of the Indian Ocean no trend in the average significant wave height is observed according to Corbella & Stretch (2012b), Rossouw & Theron (2009), and Hemer et al. (2013). Furthermore, the observed increased trend in extreme wave heights can be neglected considering an average wave climate, see Appendix A.1.3.1. For the significant wave height no trend is found for the Durban coast and is therefore not evaluated.

5.2.2 Wave peak period

Trends are found in wave periods. Swell waves from the south-southeast during winter time are likely to increase due to climate change. A rate of change of 0.11seconds per year in peak period was found for the Durban area by Corbella & Stretch (2012b) by analyzing 18years of combined wave buoy and altimeter data. A trend in the mean period of 0.08seconds per year can be found in austral winters for the South African coast in a paper by Hemer et al. (2013), who compared five different global climate studies.

A growth in wave period from the south south-east direction provides more energetic waves from this direction. Waves with larger periods start to refract in deeper water, because these waves tend to feel the bottom earlier at larger depths. Considering the shallower ocean depth in the southern part of the studied area (south of Amanzimtoti), the increased southern swell waves are likely to refract further off the coast in the south. They refract over a larger distance, yielding a smaller angle of incidence and lower wave heights near the shore. In the more northern area around the DigOut Port and around the Bluff, the shelf is steeper and thus waves are less sensitive to refraction. These variations in wave height, period and direction over the total system could lead to additional differences in longshore sediment transports. The proportionalities of the wave characteristics are investigated due to refraction and the relation of them in the Kamphuis transport formula to get insight to their contribution to longshore sediment transports.

Scenarios are setup on the basis of the studied literature to study the effect of an increased wave period from the south-southeast. One of the scenarios will include a trend of 0.1seconds per year increase in peak period for austral winter, which means larger swell conditions for the winter. The 0.1seconds per year is used as a neutral growth. Uncertainty ranges of 50%, yielding a growth of 0.05seconds per year and 0.15seconds per year are made to investigate the variability in impact.

Table 5-2 Swell scenario

Scenario	Growth Peak Period [sec/year]	Growth 2055 [sec]
‘Zero’	0	0
‘Minimum’	0.025	1
‘Mean-Hemer’	0.10	4
‘Maximum’	0.15	6

In the wave climate from November 2007 till November 2013 wave periods from the first of June till the 31st of August, between 140 and 170degrees north are increased with a linear growth of 0.1 sec/year. For a period of 40years, this means a total increase of 4seconds. For the modeling one specific climate will be used and so the growth over 40years is linearly averaged by 2seconds over the total period. In Figure 5-1 the cumulative distribution is shown of the peak period for the total dataset and the ‘Mean-Hemer’ scenario.

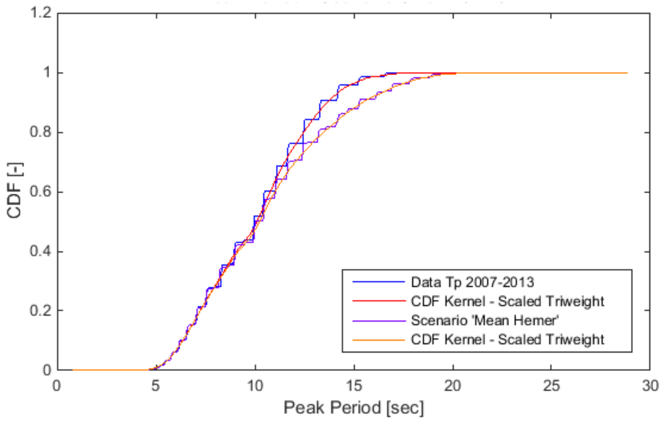

Figure 5-1 ‘Hemer – mean’ and ‘Do Nothing’ scenario

5.2.2.1 Results

By reviewing the S-Phi curves at characteristic locations along the coast the changes in transports are studied. The locations of the profiles are shown in Figure 5-6 by the red arrows. The SC22 profile has a shore-normal of 122degrees north, a gentle slope and is situated at Kingsburgh, a few kilometers south of Amanzimtoti, see Figure 5-2. In Figure 5-3 the S-Phi curve is shown for profile SC14. It has a shore-normal of 135degrees north, a steep hydrographical profile and is located just south of the DigOut Port. The Bluff18 profile, located at the end of the Bluff near the Durban Port, has a shore-normal of 125degrees north, a steep slope, see Figure 5-4.

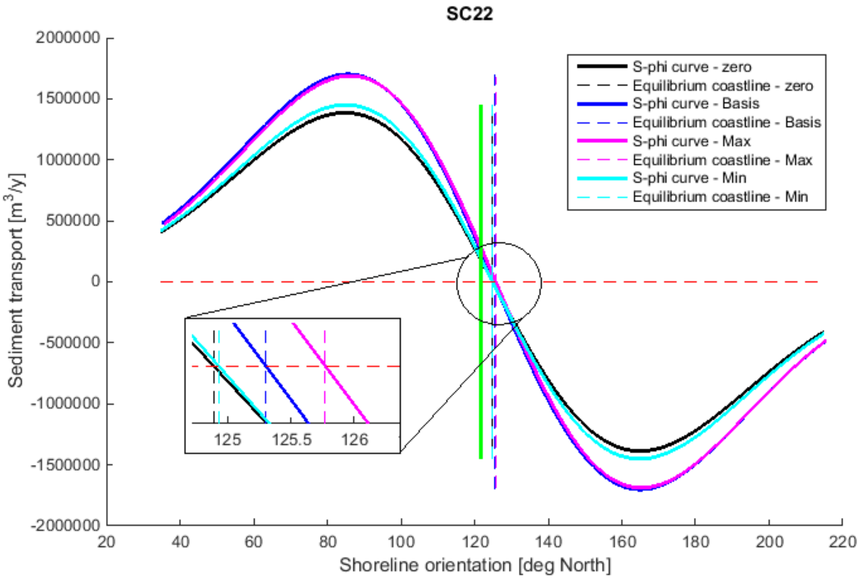

Figure 5-2 S-Phi Curve for location SC22

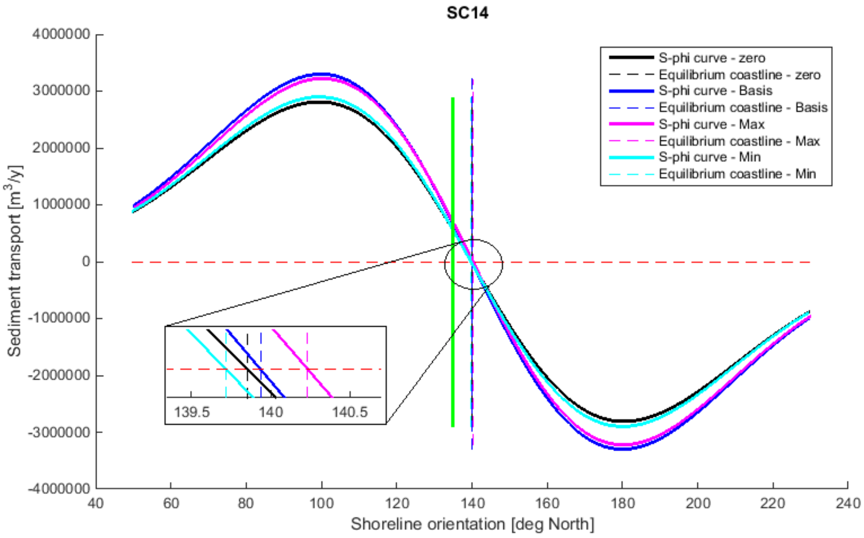

Figure 5-3 S-Phi Curve for location SC14

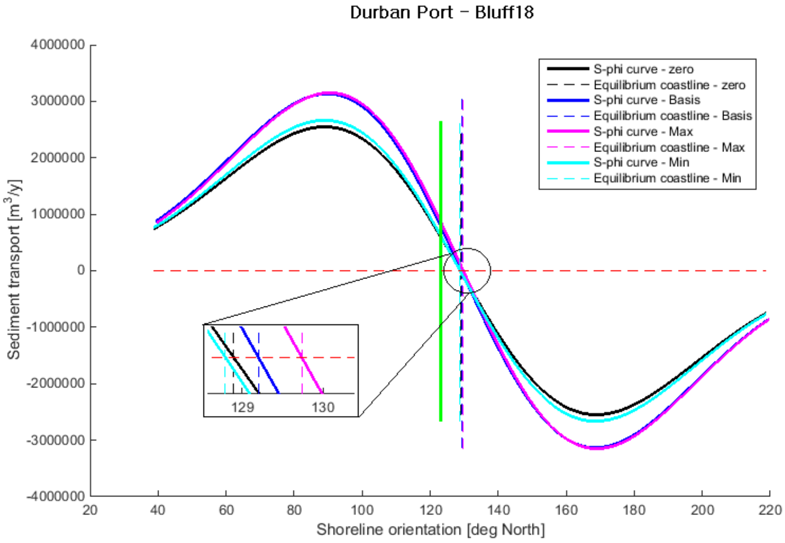

Figure 5-4 S-Phi Curve for location Bluff18

In all S-Phi curves clearly the magnitude of potential longshore transport is increased due to an increased wave period from the south, which can be observed by the dark blue and magenta line. It provides higher potential longshore sediment transports along the Durban coast. Also all equilibrium coastlines will be shifted a little bit towards the south, which varies for the three profiles between half a degree for profile SC14 to one degree for the Bluff18 and SC22 profile. The current coastline orientation lies close to the equilibrium coastline and the potential transport capacity is large. A change in the coastline orientation leads to a significant increase in transports, because we are in the steep part of the S-Phi curve. The latter two profiles have in common that the waves approach the coast with a larger angle of incidence, which is related to the steep foreshore where waves do not refract as much as in the south.

The changes in transports over the total system and in time are studied with a relative transport factor, see Figure 5-5. The relative factor is the net sediment transport for the scenario divided by the 'Do Noting' situation. The net sediment transport graphs differ in magnitude, but show a similar form for each swell scenario. A relative factor emphasizes the minor differences along the coast. A significant gradient is observed between Amanzimtoti and the DigOut Port as a result of the initial change from the actual wave climate to the swell wave climate in the model. This leads to a significant effect on the shoreline. In the erosion/accretion graph, see Figure 5-6, is shown how the shoreline adapts to the gradient. In the 'maximum'-scenario the largest disturbance is observed, resulting in the largest translations of the coast.

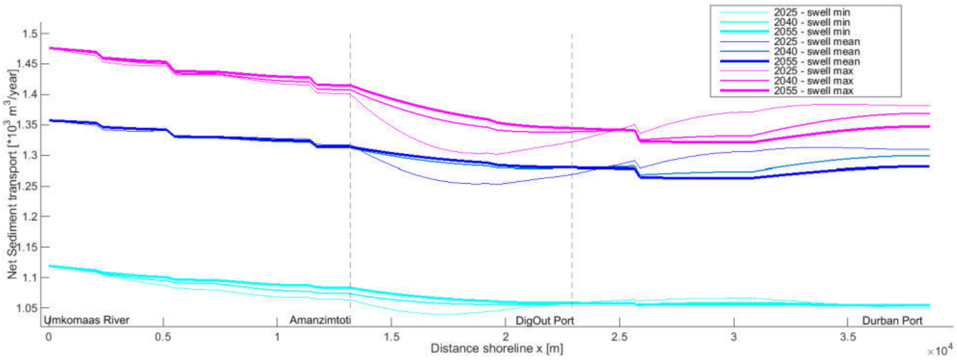

Figure 5-5 Relative transport factor: 'Swell scenario' divided by reference situation 'Do Nothing'

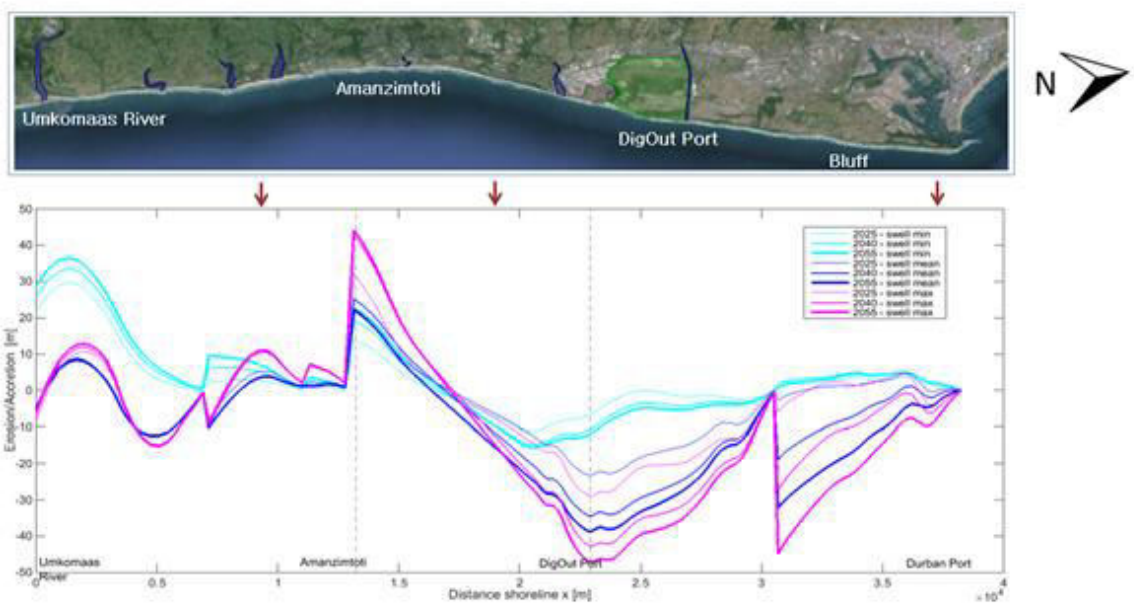

Figure 5-6 Computed erosion/accretion in 2055 - Swell scenario

From the modeling can be learned that waves with an increased peak period during the austral winter generate larger sediment transport rates over the total system. These waves are approaching from the south-southeast, which results in a little shift in the equilibrium coastline as is found in the S-Phi curve. The effect is that the shoreline will adapt to this change. For the southern area not much erosion can be found in time for all three scenarios. However in the northern area around the Bluff the shoreline erosion is ongoing. This structural erosion is calculated to be approximately 1m/year for the 'Mean-Hemer' scenario at the northern Bluff.

The change in wave climate will lead to changes in the area south of the studied area as well. Longshore transports are expected to increase, such that the boundary condition in the south has been set on 570,000m^3/year after calibration. This leads to an increase of the longshore transport that is entering the system from the south by 100,000m^3/year. The growth in swell in winter season leads to extra coastal erosion. The net longshore transport gradient between south and north is increased, which makes the system in this scenario more vulnerable in the future.

5.2.3 Wave direction

By Hemer et al. (2010) was found that wave climates are likely to rotate clockwise in the Southern Hemisphere, leading to a more southern wave direction relative to the Durban coast. Corbella & Stretch (2012b) found a clockwise mean annual rate of change of 0.91degrees, which is assumed to be very extreme. Scenarios are established to identify areas vulnerable for changes in wave direction due to future climate changes. Two scenarios are investigated. For 40years a clockwise change of 5degrees is assumed for the first scenario. A clockwise change of 10degrees southward is investigated in a second scenario. These ranges are built on the basis of a study in press by Theron and Rautenbach, which have investigated directional changes in wave climate and coastal responses for the Durban Bight. The scenarios are studied compared to the 'Do Nothing' scenario, see Table 5-3 for an overview.

Table 5-3 Wave direction scenarios

Scenario	Clockwise rotation per 40 years
‘Do Nothing’	0 degrees
‘Minimum’	5 degrees
‘Maximum’	10 degrees

Since the average direction is shifted more towards the south, the northward longshore transport is expected to increase. This will lead to changes in the area south of the studied area as well. Therefore the boundary condition of inflowing sediments is increased with 70,000m^3/year for the 5degrees shift and with 130,000m^3/year for the 10degrees shift. This is done by calibration. The longshore transport at the boundary may not give additional gradients compared to the reference situation, because the shore at the boundary is particularly uniform. This does not stimulate extra gradients due to the scenario. The shoreline retreat at the boundary should be thus be minimized.

Figure 5-7 shows the net longshore transport in the system for the two scenarios in time. As a reference the end situation of the ‘Do Nothing’- scenario is included. As expected the net longshore transports have increased, because the southward shift of the wave climate stimulates the northward directed transport. In the ’10degrees’- scenario an extra gradient in net longshore transport is observed for the area between Amanzimtoti and the DigOut Port compared to the reference situation, yielding coastal erosion, which is shown in Figure 5-8.

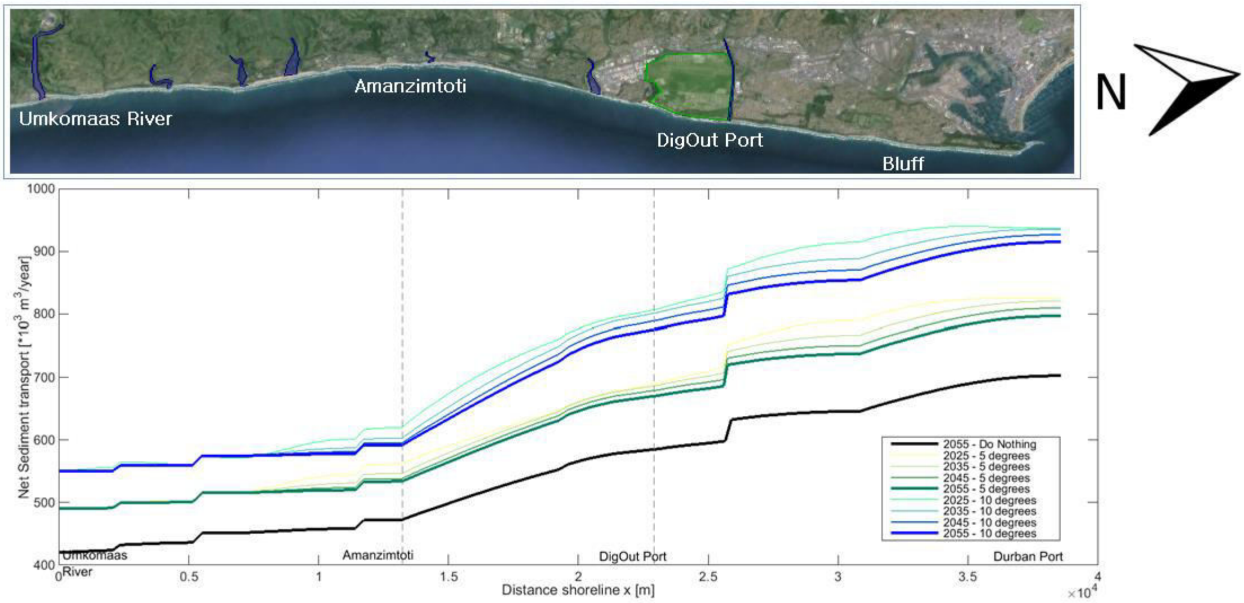

Figure 5-7 Net sediment transport – Wave direction scenarios

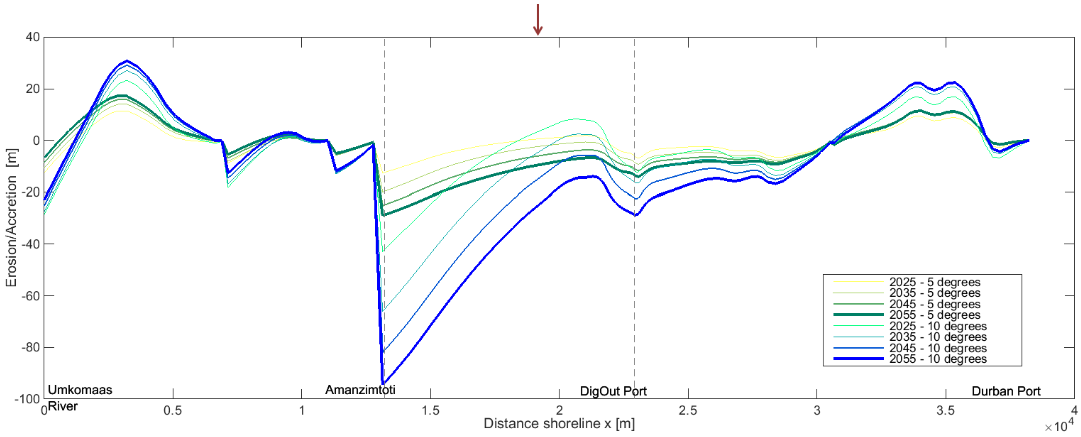

Figure 5-8 Computed erosion/accretion - Wave direction scenarios

For beacon point SC14, south of the DigOut Port, the S-Phi curve is given. The location is shown in Figure 5-8 by the red arrow. The S-Phi curve shows that a new equilibrium coastline orientation is approached with the new climate, which is obviously rotated in a clockwise direction just like the wave climate. The rotation is 2degrees and provides an initial increase in sediment transports of 25,000m^3/year. If such a shift in the S-Phi curve will happen equally along the coastal system, no extra gradients are initiated in longshore sediment transports. However, this is not the case for the South Durban coast, where an additional gradient is observed over between Amanzimtoti and the Durban Bluff compared to the ‘Do nothing’ situation. The gradient increases significantly for a more extreme scenario.

A reason for the extra longshore transport gradient for a larger average clockwise shift in the wave climate can be found in the fact that refraction of waves becomes more important in the southern area and has not so much influence on the waves in the north. Waves from the south are sensitive to refraction due to shallower waters in the south. At the Durban Bluff water depths increase rapidly allowing less chance for the waves to refract. The more the waves will come from the south the larger this difference will be. Sediment transports in the north are therefore larger than in the south, which results in a gradient in longshore sediment transport over both areas for the ’10degrees’-scenario. It leads to significant coastal erosion in the area between Amanzimtoti and the DigOut Port.

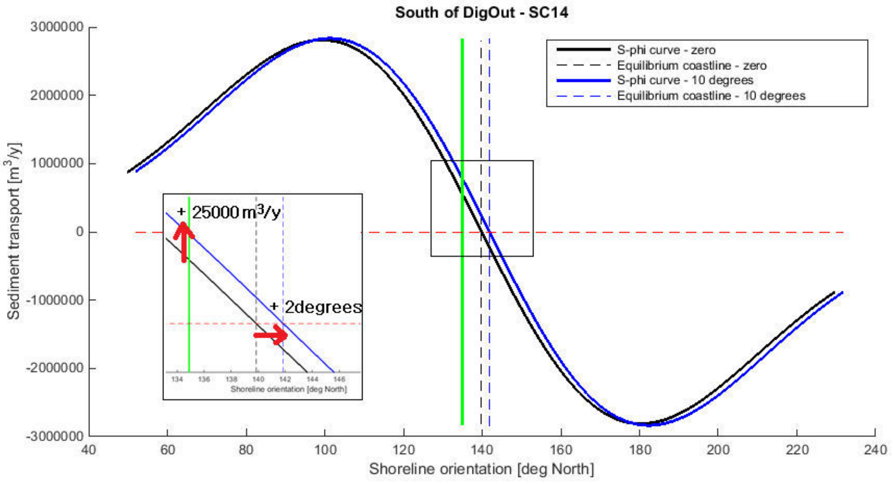

Figure 5-9 S-Phi curve - South of DigOut Port

5.3 River mining activities

In this scenario the impact of river mining is studied. In a CSIR report (Theron et al., 2008), sediment budgets from rivers are estimated for the EThekwini area. Research by CSIR done in 2003 by surveying mining operators and research by the EThekwini Municipality and others have resulted in an aerial overview of locations where dredging activities have taken place. Information is obtained about the magnitudes of the mining activities by the presentation of estimated volumes of sediments that have been dredged out of the rivers legally. Mining activities are likely to increase since the Durban area is developing economically, resulting in more building activities, which demand sand as construction material. Illegal mining activities are not included in the studies and mining activities further than 25kilometers upstream are not considered as well. The input of sediments budgets to the coastal zone by rivers is thus likely to decrease. To understand the impact of these future mining activities on the coastal system three scenarios are created. The scenarios are included after 2005.

Table 5-4 Mining scenarios

River	Source	Mining 'Basis'	-25%[5]	-50%[3]
Umlazi	33000	0	0	0
Mbokodweni	5000	0	0	0
Manzimtoti	13000	13000	3250	6500
Lovu	13000	0	0	0
Umgababa	8000	8000	2000	4000
Umkomaas	140000	140000	35000	70000

The basic-scenario is a constant input by the river per year, which is based on estimations from the report, shown in the Table 5-4. In a few rivers, such as the Umlazi River, Mbokodweni River and Lovu River, the mining activities are so extensive that all natural deposits are mined. The two other scenarios assume that mining activities will increase in the near future, due to the economic growth in the area. The’-25% scenario’ assumes a decrease in deposits of 25% over 50years. The ‘-50% scenario’ assumes a 50% decrease per year over a period of 50years. In Appendix D.1 the setup of the scenario is explained.

Results

In the area of South Durban several rivers open into the Indian Ocean depositing sediments into the coastal zone. In the past many dams have been constructed upstream yielding a blockage of sediments, which has led to a sediment deficit in the coastal area. Nowadays mining activities are a main cause of concern. Extraction of sediments is likely to increase in the future probably resulting in less sediment deposits into the coastal zone. In the scenario analysis the setup of the scenarios is discussed. The results are analyzed by reviewing locations of significant coastal retreat. Figure 5-10 shows the situation in 2055 for all three scenarios.

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[5] Trend in [m^3] per 50years

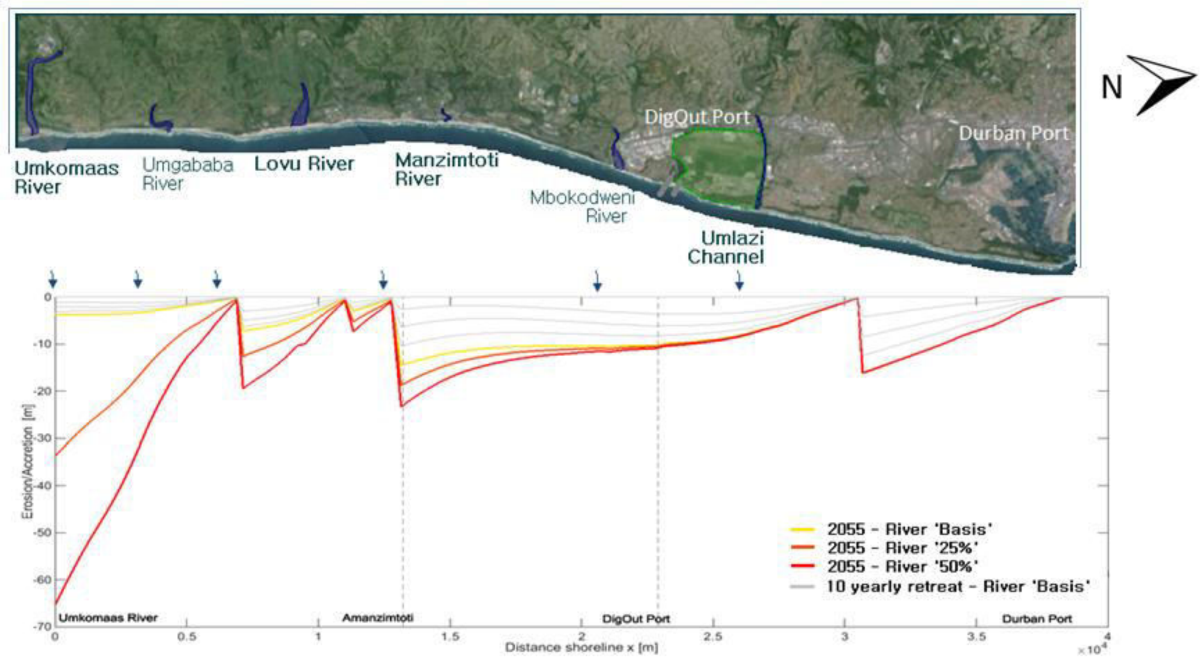

Figure 5-10 Computed erosion/accretion for River mining scenario

In the 'basis' scenario a few rivers don't input sediments to the system anymore. These rivers are the Lovu River, the Umlazi Canal and the Mbokodweni River, with the latter two rivers closest to the city. The net longshore transport is northward; hence a change in river input is felt by the system northward of the river. This is explained for the situation north of the Umlazi Canal. The area in the Bluff is continuously eroding with one meter per year. However, the input of sediments by the Umlazi Canal and Mbokodweni River is stopped by extensive river mining. This leads to less sediment input to the system, while the longshore current demands an equal amount of sediments to be transported. A response to the change is that the system takes the sediments from the coast, which results in a retreat of the shoreline. As long as the river input is stopped, the shoreline will erode and therefore one can speak of structural coastal erosion. It is shown by the gray line with ongoing erosion in the 'Basis' scenario. The 'Basis' scenario yields an additional average coastal retreat of 0.2m/year on top of the current erosion.

Especially, mining of the large Umkomaas River will have significant effects. As can be seen the erosion will not equally impact the total system, but it is highly related to the area where the sediments are extracted from the system, hence near the rivers itself. As erosion continues, larger parts of the system are feeling the sediment scarcity and the erosion gradually creeps in the main direction of the longshore current.

5.4 Future climate scenarios

In the previous chapter the results are shown of each individual scenario. The effect of each scenario on the shoreline is explained and the underlying processes are clarified. In this chapter scenarios are combined to study the most vulnerable location along the coast due to the changing environmental variables. This is done for a most likely future, a less likely future and an extreme future. In this way a qualitative assessment is done to provide knowledge about the possible states of the South Durban coastline. A future is modeled for 50years from 2005 until 2055.

A first order assessment is done, which assumes that outcomes of each individual scenario could be linearly added. Taking into account the non-linear relations between the different environmental variables lies outside the scope of this study. For example, larger wave periods and a clockwise direction of the wave climate could lead to non-linear differences in wave propagation, which could result in unexpected increases in longshore transports. In Table 5-5 an overview is given of the different future scenarios. Figure 5-11, Figure 5-12 and Figure 5-13 show the erosion/accretion graphs of respectively, the 'Most likely' future, 'Likely' future and 'Extreme' future in 2055.

Table 5-5 Future Climate Scenarios

		Future Scenarios		
Environmental Variables		**Most likely future**	**Likely future**	**Extreme future**
Wave Direction	0%	x		
	5%		x	
	10%			x
Wave Peak Period	0.025 sec/y	x		
	0.10 sec/y		x	
	0.15 sec/y			x
River input	Basis	x		
	Basis - 25%		x	
	Basis - 50%			x

In the south the shoreline remains its stable position under all different scenarios. A changing wave climate leads to increased longshore transports. However, no additional gradient is found along the coast from the Umkomaas River up to Amanzimtoti, which leads to a stable shoreline in time. A decrease in sediment input by rivers is directly observable downstream of the main rivers in this area and leads to structural coastal erosion.

For every scenario the gradient in longshore transport is enhanced in the area between Amanzimtoti and the Durban Port due to changing environmental conditions, which leads to additional coastal retreat. A rotation in the wave climate provides additional coastal retreat between Amanzimtoti up to the Durban Bluff. An increased peak period results in erosion over the Durban Bluff. A decreased river input provides constant erosion over the total area. In the 'Most likely' scenario coastal retreat is relatively small compared to coastal retreat under the current conditions. Current erosion rates, as observed in the Chapter 3.3.3.2, will be doubled under the 'Likely' scenario. The area from Amanzimtoti towards the Durban Port is especially vulnerable, which can be attributed to two factors. The first is a significant decrease in river input, mainly due to the Umlazi Canal. Secondly, the total Bluff protrudes into the ocean and is therefore sensitive to variations in the wave climate. In Figure 5-14 the modeled shoreline in 2055 of the 'Likely' scenario is shown in a top view. In Appendix D.2 more observations are described.

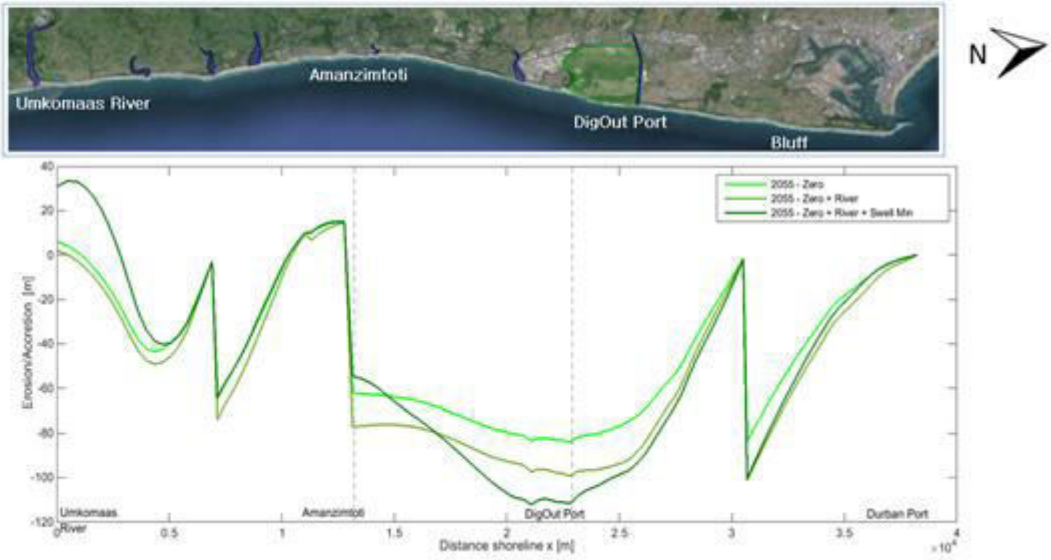

Figure 5-11 Most likely future

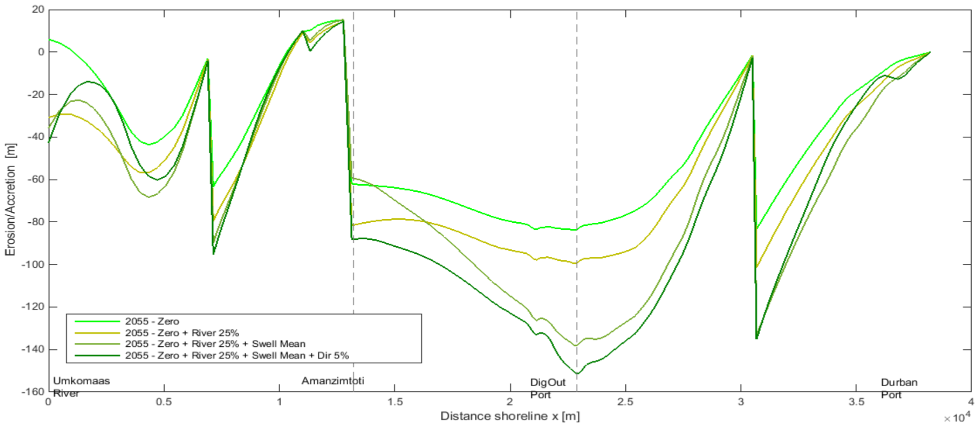

Figure 5-12 Likely future

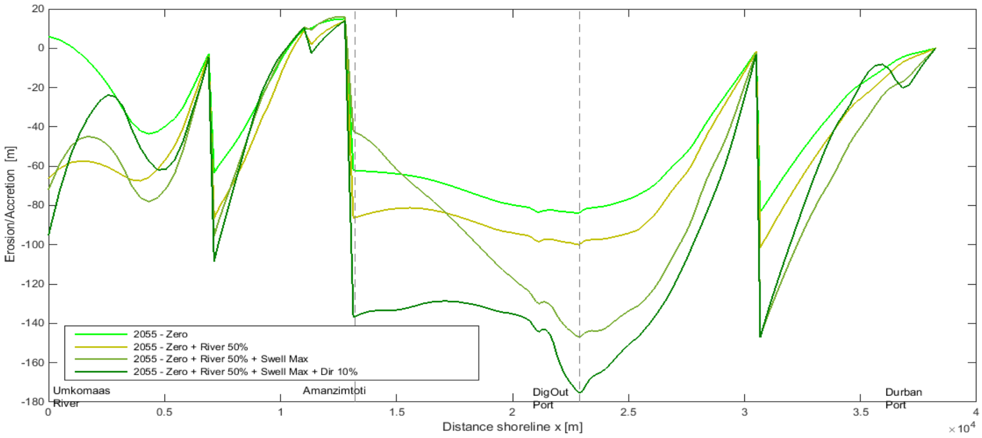

Figure 5-13 Extreme future

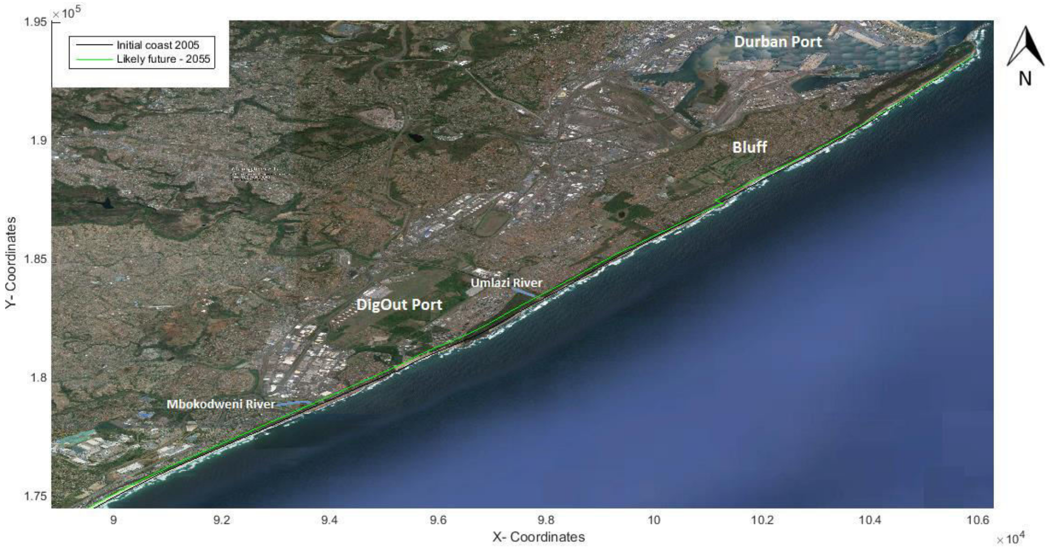

Figure 5-14 Modeled shoreline position in 2055 of 'Likely future'

6. Impact on the Durban Bluff

Key locations are identified in the field and stakeholder analysis to map high value areas. The key locations are representatives of a larger area and are picked based on their critical dune width. Figure 6-1 shows the key locations on the down drift side of the Durban DigOut Port. In this paragraph we zoom in to review the local effects on the down drift side of the Durban DigOut Port, which is the focus because of the significant erosion that is likely to occur after construction of the DigOut Port. Since erosion on the lee side will cover a large part of the southern area, every residence at the Bluff is included in the study. At the Durban DigOut project area a refinery with storage tanks of the hazardous fluid LNG is located, which is included as key location. Further downstream at the Durban Bluff several residences are located close to the beach. These are marked in yellow. For every area the most critical location for analysis is depicted. The most critical location can be described as the location where the protection by the dune is smallest. In Google Earth the vegetation line up to the habitation line is measured, which will be used as critical dune width. The shoreline retreat is studied over 40years. For every ten years from the present the shoreline retreat is shown. One should remember that the model is based on a uniform coast, which provides extreme predictions. Some rocky features are excluded, which could provide the coast from eroding and could shift erosion further downstream.

Using the modeling results per location the different future situations are reviewed, see Table 6-1. The future situations are based on the modeling results and are discussed in the previous chapters. It is a first order assessment of the potential consequences of a retreating shoreline, where the effects of the Durban DigOut Port and changing environmental conditions are assessed.

Table 6-1 Future situations

Do Nothing
Durban DigOut Port
DigOut Port + Likely future
DigOut Port + Bypass + Likely future
DigOut Port + Bypass + LocalGroyneField + Likely future

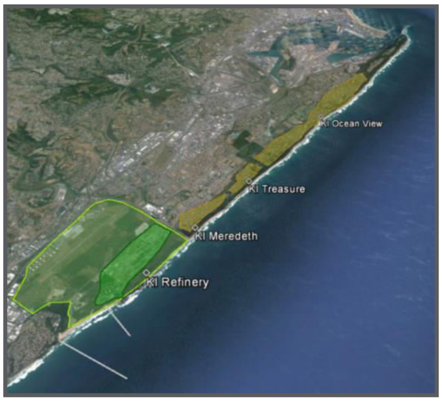

Figure 6-1 Key locations – Durban Bluff

Refinery

The Sapref Refinery is located on the proposed Durban DigOut Port site. It is protected by the large Durban Bluff and not exposed to any risk of coastal erosion or flooding. The refinery is located in the area where largest retreat is expected to occur assuming a uniform coast, which means that the refinery is vulnerable for coastal erosion, see Figure 6-2. The critical dune width is determined to be 320meters. Without any mitigation measured, this could have large consequences, because of the hazardous goods stored at the refinery. Mitigation measures as for instance an artificial bypass system will reduce the risk of breaching through the Durban Bluff significantly. Furthermore, a local groyne field is proposed, which protects the refinery in case a bypass system is lacking.

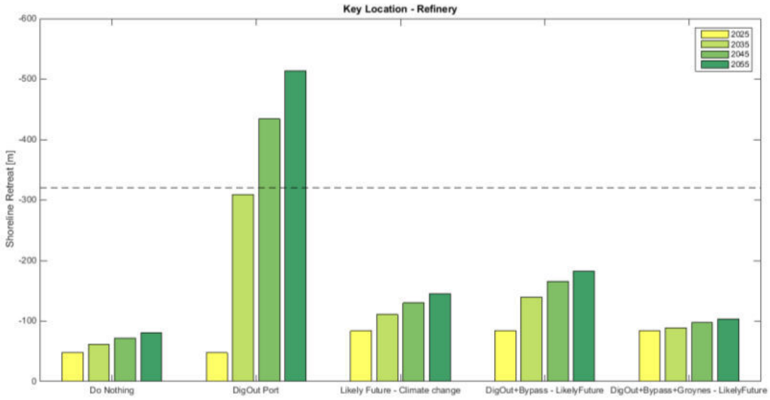

Figure 6-2 Modeled shoreline retreat – Refinery

Meredeth

Meredeth is a residential area, located just south of the Umlazi Canal and is part of the Durban Bluff area. Houses can be found on top of the Durban Bluff overlooking the Indian Ocean. In Figure 6-3 the impact of shoreline retreat based on the different future situation is shown. The critical dune width at Meredeth is approximately 120meters. Under the current conditions the key location will not be harmed by coastal retreat in the upcoming 40years. However, under the effects of climate change and a reducing sediment input by rivers a critical situation could arise before 2055. The residential area should be aware of possible coastal retreat affecting the living circumstances of the inhabitants. Erosion on the lee side of the Durban DigOut Port is felt at Meredeth and therefore a mitigation measure is recommended, such as the bypass system.

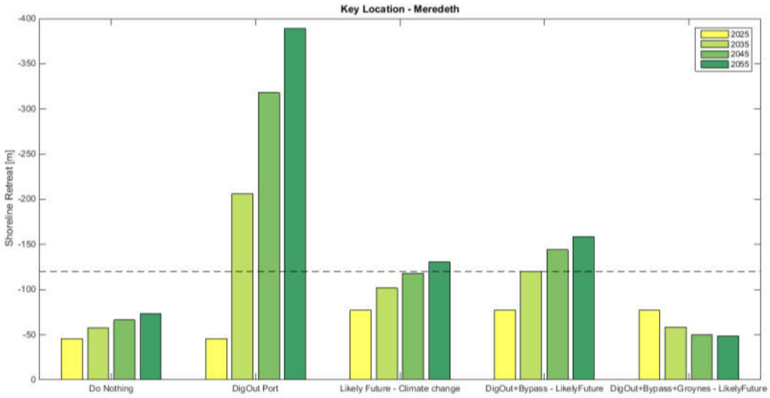

Figure 6-3 Modeled shoreline retreat – Meredeth

Treasure Beach

At the residential are Treasure Beach the critical shoreline retreat is approximately 110meters. For most situations the critical line will not be crossed, see Figure 6-4. Also in this area houses can be found on the top of the Bluff. Compared to the Meredeth, Treasure Beach is located more to the north. Coastal retreat because of the DigOut Port decreases and also the effect of a changing wave climate decreases. Also at this location the consequences of a new Durban DigOut Port without mitigation measure can be felt. Implementing and properly maintenance of an artificial bypass system is thus highly recommended.

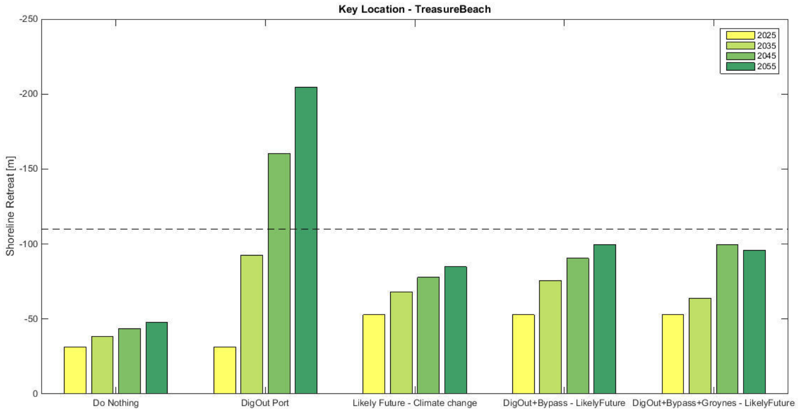

Figure 6-4 Modeled shoreline retreat - Treasure Beach

Ocean View

At Ocean View a coastal stretch can be found which is narrow compared to the rest of the Durban Bluff. In the area several recreational pools are located in the surf zone, surrounded by rocks. At the critical key location at Ocean View the dune width is approximately 40meters wide. Even in the current situation the coast at Ocean View is vulnerable for shoreline retreat. In this area the coast is eroding with approximately 1m/year, which leads to critical shoreline retreat, as shown in Figure 6-5. Obviously, interventions like the Durban DigOut Port and the studied alterations in the environmental conditions will lead to even more coastal erosion. This location shows that one should be aware of current state of the coast and the potential consequences of alterations in the future.

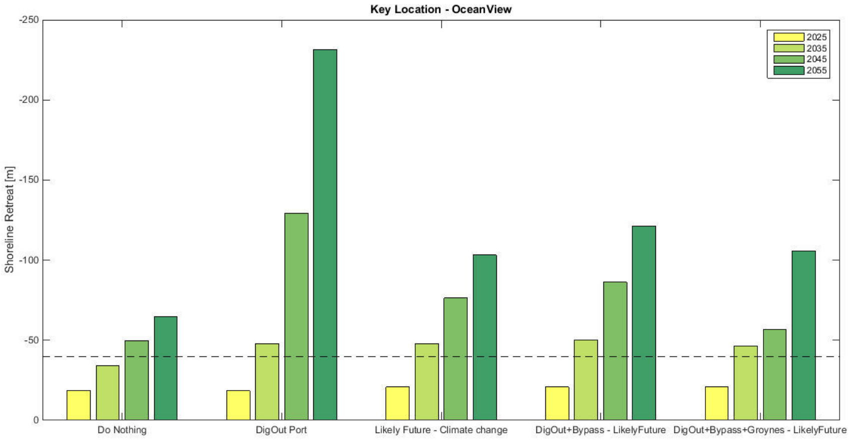

Figure 6-5 Modeled shoreline retreat - Ocean View

7. Conclusions & Recommendations

The conclusions paragraph provides the answers to the research questions and determines whether the goal of this research is achieved. Additional insights are included at the end. In the recommendations alternatives are addressed for a sustainable coast. Recommendations for future research work are included.

7.1 Conclusions

The main goal of the research is to understand the sediment transports and budgets around South Durban both now and in the future. The goal is fulfilled by answering each of the research questions in turn.

A. Understanding the current coastal system of South Durban

A.1. Are currently any trends in the translation of the shoreline identifiable and what could be the cause of these trends? What is the current state of the coast, accreting or eroding?

The coast of South Durban is characterized by a large coastal bluff in the north. The total coastal stretch consists of sandy beaches containing several rocky outcrops at different locations. The northern and central part of the Durban Bluff is found to be eroding by approximately 1m/year, based on ten to twenty years of beach profile measurements from the CSIR and twelve years of aerial photographs from Google Earth. Based on the available aerial photographs, the southern part of the South Durban coast seems to be stable, as is established by experts from the CSIR. Erosion in the coastal system can be attributed to a decline in input of sediment by rivers, as found by (Theron et al., 2008). Structural erosion around the Bluff is most likely related to less sediment input from the Umlazi Canal.

A.2. What is the interaction between the waves and the bathymetry of the continental shelf of South Durban; how do waves propagate towards the coast and what is the relation with the longshore sediment transport rates along the coast?

South Durban is characterized by a narrow continental shelf. Analysis of the bathymetry shows a steep profile in the north and a more gentle profile in the south where the shelf is wider. Waves are predominantly entering the Durban coast from the south-southeast and yielding a northward sediment transport of 500,000m^3/year (Schoonees, 2000). Large swell from the southeast is characteristic for the system during the winter. Wind waves are entering from all direction and are therefore contributing to an equal extent to the longshore sediment transports. Modeling simulations have established the relevance of the bathymetric variation for refraction. The high energy waves from the south are refracted in the southern area, which causes the waves to decline in wave height and minimizes the angle of incidence with the coast. In the north refraction plays a minor role due to the steep slope, yielding large impact by these high energy waves. It leads to a gradient in net longshore sediment transport along the coast, because the net longshore sediment transports in the south are lower than in the north.

A.3. What are anthropogenic natural features along the coast of Durban? Do they have a significant influence on the sediment balance or trigger sediment gradients? Are they quantifiable?

Along the South Durban coast rivers and rocky headlands can be found. River discharge into in the Indian Ocean and provide sediments to the coastal zone. Most of the rivers are dammed, which leads to a blockage of sediments and to less high river discharges. The high discharge is needed to breach through the sand banks at the beaches, which are created by the high energetic waves. Further, river mining is a problem, as it diminishes the sediment supply to the coastal zone. River mining activities are likely to increase in the future. These developments lead to structural coastal erosion.

Rocky headlands are lithified sediments. They anchor the coast in a stable position. In the south several rocky headlands are found, which pin the coast in position and function as groynes. This results in a relatively constant longshore sediment transport in this area.

A.4. *What are the boundaries of the system and what characterizes them as a boundary?*

The boundaries of the studied system implemented in the shoreline model are in the south the Umkomaas River and in the north the Durban Port. The southern boundary lies relatively far from the area of interest of this study; the Durban DigOut Port. In the bathymetry and wave modeling study is shown that in the south waves are likely to refract, in contrast to the north, where the coastal shelf is relatively steep. By incorporating this area in the shoreline model, knowledge can be gained about potential longshore sediment transports differences along the coast. The goal of this research is to understand the sediment transports and budgets of the coastal system of South Durban. The Umkomaas River is the largest river in the south, where a known amount of sediment is annually discharged into the coastal system. It is assumed to remain in position due to some rocky headlands close to the river mouth. The northern boundary is located just south of the southern breakwater of the Durban Port. At the boundary the shoreline is fixed, because of a revetment and rocks in the upper shoreface. The northward longshore sediment transport fills the sand trap, just north of the boundary, which is periodically dredged to provide the Durban Bight with sediment. The fixed shoreline is modeled as a fixed position in the model. It means that downstream calculated net sediment transports are governing the amount of sand that is flowing out of the system.

A.5. *How are net and gross longshore sediment transports distributed along the South Durban coast?*

Gross longshore sediment transport in a southward direction fluctuates between 400,000m^3/year in the south and 600,000m^3/year in the north. It is thus relatively continuous along the coast. This is related to the wave climate. Waves from the east-northeast are higher frequency wind-waves. They are obliquely approaching the shore and are less sensitive to changes in the bathymetry at larger depths. The waves approach the surf zone along the total coast at approximately the same angles, providing the continuous southward gross longshore sediment transport. Larger swell waves with wave periods of 14 to 18seconds from the south are sensitive to bathymetric changes at around twenty to thirty meters depth. South of Amanzimtoti swell waves refract due to a gentle slope of the shelf and the wave energy is spread over a larger area providing a lower wave height and decreasing the angle of incidence of the waves. Lower northward gross sediment transport of approximately 700,000m^3/year are found in the south. As the slope of the bottom topography increases towards the north, the waves have a larger impact on the coast, resulting in higher northward gross sediment transports around the Durban Bluff of approximately 1,250,000m^3/year. The ratio between south and north gross transports thus increases towards the north. This also increases the potential erosion/accretion shoreline responses around a port with extensive breakwaters. The net longshore sediment transport is approximately 300,000m^3/year and 650,000m^3/year, respectively in the south and in north.

B. *Evaluation of shoreline responses to the Durban DigOut Port*

B.1. What is the direct effect of the protruding breakwaters of the DigOut Port on the adjacent shoreline? What is the effect of different breakwaters lengths?

The intervention of the Durban DigOut Port will lead to erosion of more than 500meters on the lee side of the breakwaters over 30years. After these 30years sediment will not naturally bypass the breakwater tip and therefore the erosion is likely to increase. However, a cautionary note is appropriate, because the coast is in reality not uniform. Although the model predicts erosion of the Bluff, this is not realistic. The Bluff consists of lithified rocks which pin the coast in position and prevent it eroding. The erosion/accretion patterns extend over a large area of more than 8000meters. The steep bottom topography demands a lot of sand to accrete the shore. Adjacent to the breakwaters the coast will approach the equilibrium orientation, where net longshore transports are zero. However, the fact that the angle of the equilibrium profile with the current positions is small, leads to a very long extent of the erosion/accretions patterns. This is found by studying the S-Phi curves.

B.2. How will appropriate mitigation measures function to diminish possible negative effects on the shoreline?

Mitigation measures to counteract the unwanted erosion at the lee side of the port entrance of the DigOut Port are studied with the shoreline model. One of the alternatives is a bypass system similar to the artificial bypass at the Durban Port. A volume of 550,000m^3/year per year is computed to be necessary and should be replenished on the lee side of the breakwater. In this case the 500meters erosion is diminished to 30meters over 30years, which seems to be an appropriate alternative. In case a bypass system is not working or not set in operation the coast is computed to erode approximately 200meters in the first 5years on the lee side of the breakwaters. An alternative is researched, where the hazardous storage at a refinery is protected by a local groyne field. The local groyne field could be built together with the bypass system and is design to block 10% of the bypassed 550,000m^3/year, which is the needed sediment to provide a stable coast.

B.3. How are longshore sediment transports adapting to a new situation with the DigOut Port and mitigation measures, considering for example the sand trap near the Durban Port, which is crucial for a stable shoreline of the Durban Bight?

The Durban DigOut Port will block all the sediments. Longshore sediment transports on the lee side at the breakwaters will decrease, because the coast adapts to the equilibrium orientation after erosion. However, at the Durban Port, which is located 15kilometers downstream of the DigOut Port, after 30years still sediments will flow into the sand trap. These originate from the eroding coast. One should keep in mind that the computed longshore sediment transport and erosion due to the DigOut Port are extreme predictions. It is very likely that the shore is not able to erode as far as is modeled. This would result in a situation where equilibrium profiles are approached between the different headlands resulting in less net longshore sediment transport than computed. Therefore, available sand for the sand trap at the Durban Port could be reduced without an artificial bypass at the DigOut Port.

B.4. How critical is the shoreline response of the DigOut Port with and without mitigation measures with respect to the Durban Bluff?

Additional sediments need to be replenished on the lee side of the DigOut Port, otherwise all of the key location identified at the Bluff will suffer from significant erosion with large consequences, given the shoreline translation obtained in the model. A bypass system will prevent these key locations from significant erosion. Under the current conditions the key location at Ocean View is a problematic situation. The construction of the DigOut Port with a bypass system, will only increase problems.

C. Evaluation of shoreline responses to environmental variables, like climate change and river mining

C.1. How does climate change influence the current wave climate; can any trend be identified?

Changes in the wave climate for the east coast of South Africa are studied in literature. No trend in the average wave height is found, based on atmospherical models (Hemer et al., 2013) (Mori et al., 2010) and wave buoy records (Rossouw & Theron, 2009) (Corbella & Stretch, 2012b). For the wave period an increase is found in the austral winter (Mark. A. Hemer et al., 2013) (Corbella & Stretch, 2012b). The increase in swell components is related to the stronger Westerlies in the Southern Hemisphere. Swell waves generated in the Southern Ocean propagate throughout the world's oceans into the northern basins, which also affects the east coast of South Africa. Following Hemer et al. (2010) the wave climate direction is likely to rotate clockwise in the in mid-latitudes of the Southern Hemisphere. The clockwise shift coheres with the findings from different wave records by Corbella & Stretch (2012b).

C.2. What is the effect of a changing wave climate on the longshore sediment transports at the South Durban coast?

For Durban a clockwise rotation of the average wave climate would mean that the average wave direction would shift towards the south, generating larger net longshore sediment transports. It also enhances the already existing gradient in longshore transport between Amanzimtoti and the DigOut Port, which results in coastal erosion. Through an increased wave period for waves from the southeast during winter, the potential longshore sediment transports increase, as is seen in a study of the S-Phi curves. The irregular bathymetry along the coast causes swell waves in the south to refract earlier in contrast to northern part of the coast where the bottom topography is steep. Variation in wave characteristics over the system due to a changing climate lead to gradients in the sediment transport curves, which provide additional coastal erosion. Especially, the area between Amanzimtoti and the Durban Bluff is vulnerable to erosion, because this is the transition area from a gentler bottom slope to a steeper one in the north.

A change in wave direction results in a horizontal shift of the S-Phi curve, because a different equilibrium angle is approached. For an increased peak period during winter the magnitude of the potential longshore sediment transport is increased. In combination these effects will lead to a significant increase in longshore sediment transports, which cannot be linearly added as is done in this first order assessment. The effect will also differ along the coast, which could lead to additional gradients in the longshore sediment transports.

C.3. What is the prognosis on sediment inputs by rivers and what is the effect of a decreasing sediment budgets by rivers on the South Durban shoreline?

A decrease in river input leads to coastal erosion. The increasing demand for sediment due to a gradient in the longshore sediment transports along the coast could be balanced by the input of river sediments. However, in the current system the river input is only a minor part of the magnitude of the longshore sediment transport. The total contribution of rivers in the current situation is estimated to be 67,500m^3/year, where the shortfall of sediments over the system is modeled to be 280,000m^3/year. Therefore the coastal system is eroding. Most of the rivers are dammed, which leads to a blockage of sediments and less high discharges. The fact that river mining is still an urgent problem, could lead to an increase in coastal erosion in the future. For the Durban Bluff the provision of sediments by the Umlazi Canal is important, but this is estimated to decrease to zero in the future due to river mining.

C.4. *What are the most vulnerable locations along the coast considering these climate change scenarios?*

The area between Amanzimtoti and the Durban Bluff is found to be the area most vulnerable to changes in the wave climate considering the modeling results. For the Durban Bluff is found that critical situations could occur due shoreline retreat at Meredeth and at Ocean View. One should remember that these predictions are extreme predictions, because the model assumes a uniform coast and not all rocky headlands are included. These rocks should prevent the coast from eroding.

7.2 Recommendations

7.2.1 Recommendations to Local Government and Project Initiators

In this thesis report the sediment transports and budgets along the South Durban coast are researched, which provides understanding of the coastal system. The modeling results show a gradient in the longshore sediment transports between Amanzimtoti and the Durban Bluff, which leads to shoreline retreat, because sediment input by rivers is lacking. By doing research on the coastal system of South Durban knowledge is obtained, from which recommendations are outlined to stimulate coastal policies and optimize plans. These recommendations concern knowledge gaps, risks and possible alternatives.

7.2.1.1 Gather data for modeling purposes and to understand long-term coastal processes

The little available data for the South Durban coast limits the opportunity to do accurate research in the area. Trends are obtained from beach profile measurements, which are only available for a concentrated area at the Durban Bluff. To understand whether the coastal system is changing, it is recommended to do regular beach profile measurements along the total South Durban coast. Further, for calibration and validation of the models, beach profiles measurements and bathymetry is required. Only four years of beach profile measurements are available to validate the 1D shoreline model with. This is too little considering the aim of the project; predicting shoreline behavior for the coming 40years. For the area south of Amanzimtoti low resolution bathymetric data are used, while this bay-type area is crucial in understanding the differences in wave propagation in the nearshore. It is recommended to gather bathymetric data, which can be implemented in the model. Regular measuring of the bathymetry could also be an option to obtain trends in shoreline behavior.

7.2.1.2 Identification and regulation of sedimentary rivers

One of the reasons for shoreline retreat is the lack of sediments discharged by the rivers into the coastal zone. The provision of sediments is crucial for a sustainable coast. River dams block sediments upstream, but also provide less extensive river discharges. These are necessary to breach through the by the waves clogged river mouths. River mining diminishes the available sediment for the coastal zone. In the modeling it is shown that if sediment sources by rivers are likely to decrease, the shoreline will structurally erode. In Theron et al. (2008) river mining activities are estimated and quantified. It is recommended to identify and map the current size of the river mining activities and regulate the activities to prevent further erosion of the South Durban shoreline.

7.2.1.3 Bypass Durban DigOut Port

The construction of two substantial breakwaters at the Durban DigOut Port entrance is expected to lead to significant shoreline retreat. Without any mitigation measure, sediments are not able to flow in a natural path around the breakwater tips, resulting in a total blockage of sediments at the up drift side of the DigOut Port. At the down drift side this will lead to significant coastal erosion. Therefore in the port designs an artificial by-pass system is recommended, which should fulfill is capacity of 550,000m^3/year. The large potential longshore sediment transports due to the energetic waves will lead to a direct response of the shoreline. If such a bypass system is not implemented or not maintained carefully, the Durban Bluff is in danger, which could lead to unforeseen and unmanageable situations.

7.2.1.4 Climate change

In the future, changing wave conditions could lead to a strengthening of the currently observed gradient along the South Durban coast. A stronger gradient in longshore transports will lead to additional coastal erosion. This indicates the vulnerability of the area between Amanzimtoti up to the Durban Bluff for changes in the wave climate. It will not lead to direct exceedance of critical shoreline retreat at key location in the upcoming twenty years. Regular monitoring of the position of the shoreline is necessary to observe the current trends.

Shoreline retreat due to sea level rise lies not in the scope of this research. This research therefore does not cover all processes leading to shoreline retreat. Coastal erosion due to sea level rise could be taken into account by means of applying the Bruun rule (Bruun, 1962). It is recommended to use this research as one of the elements which contribute to shoreline retreat to determine setback lines. Shoreline retreat due to climate change should be included in policy decisions, as in the future the coast becomes less flexible to adapt from storms. This increases the risks of living along the coast.

7.2.1.5 Alternative for sustainable coast Durban Bluff

In order to prevent the Durban Bluff from erosion alternatives are investigated with the obtained 1D shoreline model. One of alternatives is to use nourishments to strengthen the coastline of the Durban Bluff. A 5 yearly nourishment of 1,650,000m^3/year is found to be sufficient. However, the high energy wave climate provides large longshore sediment transports, which is the most important driving force for the nourishment diffusion (Stam, 2014).

7.2.2 Recommended further research areas

7.2.2.1 Residual flows of the Agulhas Current

The Agulhas Current is the dominant ocean current in front of the East African Coast. In front of the Durban coast eddies can be found, where residual currents of the Agulhas turn around. The location of these residuals is unknown. The influence of these currents with the nearshore hydrodynamics and their indirect relation to sediment transports is unknown. However, they seem to align with the bathymetry of the shelf between Amanzimtoti and the DigOut Port, and thus have an indirect influence on the formation of the Durban coastline. If the breakwaters of the Durban DigOut Port interfere with these currents should be investigated. Further research is recommended on these residual flows to understand their relation with the nearshore dynamics.

7.2.2.2 Erosive character Durban Bluff

The Durban Bluff consists of aeolianite sediments and lithified rocks. These characteristics are important to understand the erosive character of the Durban Bluff. In the shoreline model a uniform sandy beach was assumed. However, if the Bluff is composed of rocks, the erosive trend could have a different outcome than predicted. Understanding the composition of the Bluff is valuable information to assess whether the Durban Bluff has the potential to erode or whether it can withstand structural erosion trends, due to the existence of rocky headlands, which fix the coast. The latter results in a downstream shift of the erosion trend due to existence of a longshore gradient.

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List of Abbreviations

1D	One-dimensional
2D	Two-dimensional
ADCP	Acoustic Doppler Current Profiler – hydro-acoustic current meter
AR4	Fourth Assessment Report of the Intergovernmental Panel on Climate Change
AR5	Fifth Assessment Report of the Intergovernmental Panel on Climate Change
B.V.	Besloten Vennootschap (Private Company)
BLUFF3	Location of wave ray in 1D shoreline model
BLUFF18	Location of wave ray in 1D shoreline model
CD	Chart Datum
CDF	Cumulative Distribution Function
CERC	Coastal Engineering Research Center
CSIR	Council for Scientific Industrial Research
d	Depth
d50	Median sediment size
Deg.	Degrees
.dep	depth file
Dir	Wave direction
Et al.	et alii (and others)
EIA	Environmental Impact Assessment
GCM	Global Circulation Model
GDAS	Global Data Assimilation Scheme
GIS	Geographic Information System
.grd	Grid file
Hs	Significant wave height
IPCC	Intergovernmental Panel on Climate Change
L	Wave length
LST	Longshore Sediment Transport
LAT	Lowest Astronomical Tide
Lat.	Latitude
Long.	Longitude
LTA	Non-linear triad interactions
m	meters
mm	millimetres
md-vwac	ASCII file with offshore wave conditions
MSL	Mean Sea Level
NCEP	National Centers of Environmental Prediction
NGO	Non-governmental organisation
NOAA	National Oceanic and Atmospheric Administration
PDF	Probability Density Function
Phi	Angle of incidence of an incoming wave
PRASA	Passenger Rail Agency of South Africa
RCP	Representative Concentration pathways
s	seconds
S	Net annual sediment transport volumes
SA	South Africa
SC14	Beacon point & Location of wave ray in 1D shoreline model
SC16	Beacon point & Location of wave ray in 1D shoreline model

SC22	Beacon point & Location of wave ray in 1D shoreline model
SC30	Beacon point & Location of wave ray in 1D shoreline model
SDCEA	Sout Durban Community Environmental Alliance
SLR	Sea Level Rise
SWAN	Simulating Waves Nearshore – third-generation wave model
TNPA	Transnet Port Authority
Tp	Wave peak period
TU Delft	Delft University of Technology
Unibest-CL	Unibest Coastline model
Unibest-LT	Unibest Longshore Transport model
WW3	WaveWatch III
y	year

Appendix

A. Coastal environment

A.1 Waves

A.1.1 Wave sources

Two data sources are available: a wave record of six years of the Waverider buoy en of sixteen years obtained from a numerical model, NOAA WaveWatch lll, called NCEP wave data. The wave data will be analyzed and used as boundary conditions in a wave model to get the nearshore wave conditions. These are used for the sediment transport calculations over the surf zone. Since the Waverider buoy actually measures the wave conditions, this is the most reliable source. However, the buoy is located in relatively shallow water, which means low frequency waves are likely to be transformed before they are recorded. On the other hand, waves recorded at the wave buoy contain information how waves are refracted by large ocean currents, such as the Agulhas current and its residual currents.

The NCEP data for the Indian Ocean is based on global wind field measurements, where waves are calculated from in a numerical model. This is interesting for this study, because these waves could be directly implemented on the deep water boundary of the model. Furthermore the dataset is more extensive, which makes it interesting for long-term wave analysis. Firstly, both data sources are analyzed. Thereafter the NCEP data is compared to the wave buoy to validate the usefulness of the data source. By a final evaluation about the applicability of each wave source a decision is made, which wave source will be used.

A.1.1.1 Waverider Buoy

The Waverider buoy with station code DB08 is located at 29.88latitude and 31.07067longitude, approximately 1.2 km out of the coast at 30meters depth. A dataset of six years is used covering the period of 01-11-2007 to 01-11-2013. In the Figure A-1 the total record can be seen.

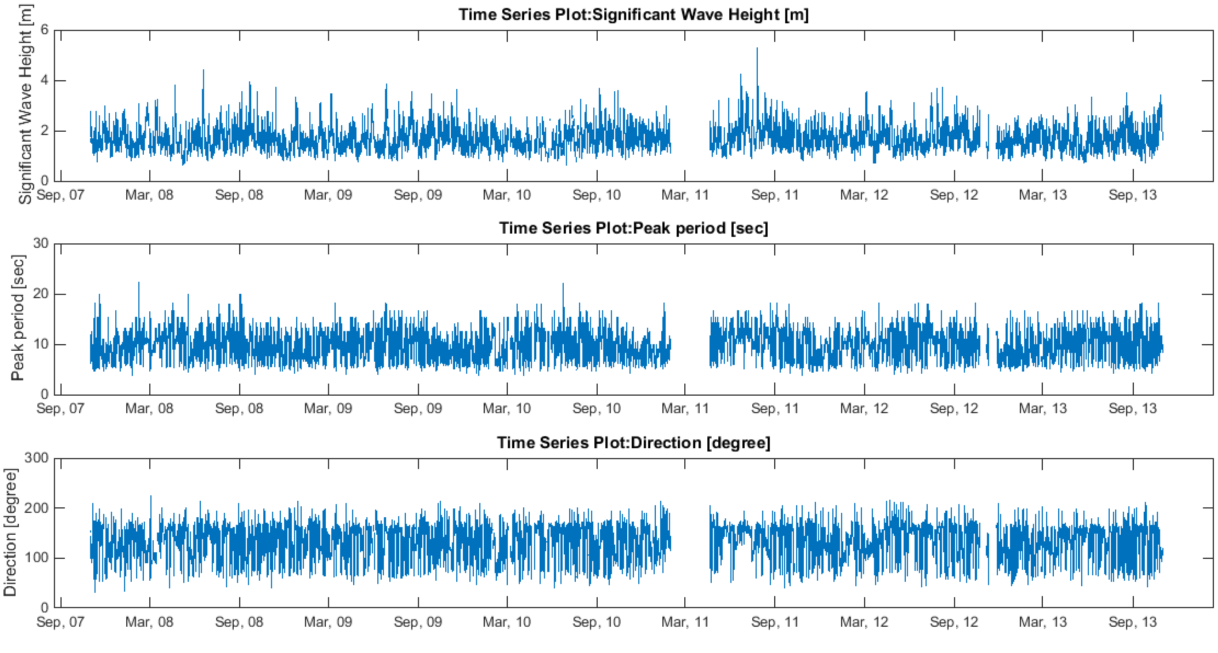


Figure A-1 time series Wave conditions record Waverider Buoy

The Waverider buoy is a buoy of the company Datawell B.V. (Datawell.nl, n.d.). The company is known for its buoys, which are used all over the world. The used Waverider buoy records every three hours the significant wave height Hs, Peak period Tp, direction, maximum wave height and the spreading-factor. Only the parametric wave conditions are used in the analysis and later in the modeling part.

A simple calculation demonstrates that low frequency waves already feel the bottom at this depth, which means that they are recorded in intermediate water. Swell waves are likely to be transformed before they are observed by the wave buoy. Therefore it is necessary to extrapolate waves back to deep water to use them as uniform boundary condition for the total research area. This is all explained in Appendix B.1.2. A dataset of linear waves in deep water will be implemented as a boundary at a computational grid.

Wave analysis: Correlation wave characteristics

By analyzing the correlations between the different wave characteristics information is gained about the characteristics of the wave climate. In Figure A-2 (left) the wave direction is plotted against the peak period. Two bulbs of waves (circles) with a lower peak period are observed entering from north-easterly and south-westerly directions. This corresponds with the cold fronts propagating almost parallel to the coast, given the average shore normal of approximately 130degrees.

In the figure on the right can be seen that the significant wave height of these sea-waves vary between one and three meters. The local wind waves are entering the coast with an oblique angle. For waves having a period larger than approximately nine seconds (defined as swell waves), it is observed that they are pre-dominantly entering from the east to south-southeast (100 to 170degrees north). Swell waves with wave height varying from one to five meters are monitored. The densest area for swell waves is observed from 165degrees north with an average significant wave height of 1.5meters.

From these figures a better understanding is gained about the waves and the background of them. However, the waves vary too much to get a linear regression plot, which could be useful to obtain the correlations between the different wave characteristics. Therefore it is difficult to quantify the correlations between the wave characteristics, which would have been beneficial for the next step: reducing the wave climate to a representative wave climate.

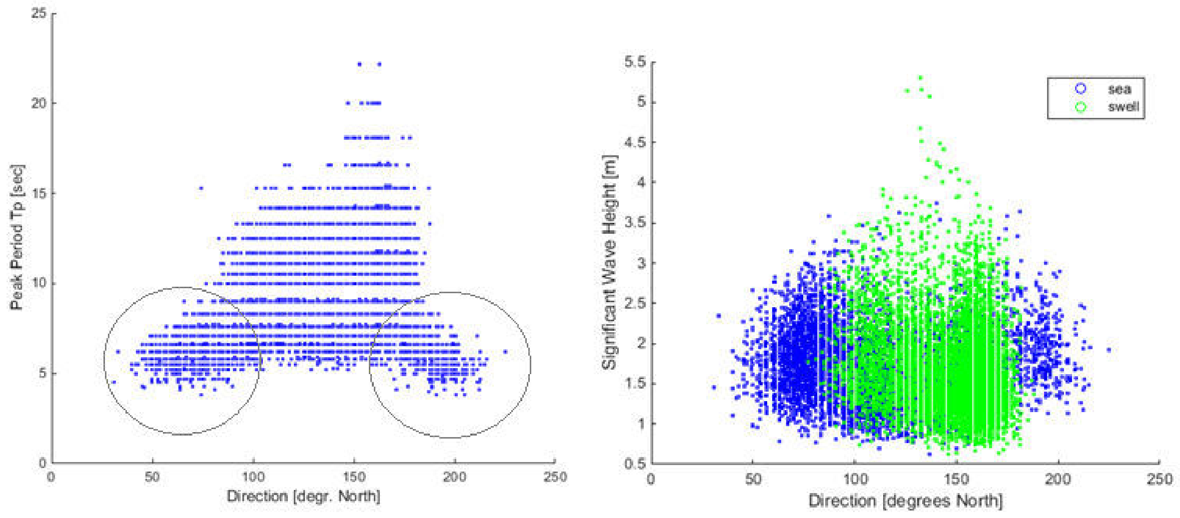


Figure A-2 Correlation Wave direction and peak period

A.1.1.2 NOAA WavewatchIII

From the Wavewatch III model sixteen years of wave data is available for this analysis. Three output points are considered, see Figure A-3. The Environmental Modeling Center at the National Centers for Environmental Prediction in College Park, Maryland is responsible for the development of improved numerical marine forecasting and analysis systems within the NOAA National Weather Service (NOAA, n.d.). They run a third generation wave model four times a day, which starts with 9-, 6- and 3-hour hind casts and produces forecasts of every 3 hours. Main input consists of wind and ocean current velocities. For all processes in the model is referred to the WaveWatchIII manual (NOAA, 2002). The output of the wave data is called NCEP data.

NCEP Point	Depth
31130	*±300m*
31131	*>500m*
31418	*>500m*

Figure A-3 NCEP points and Waverider buoy in the Indian Ocean

Model input are wind fields from the operational Global Data Assimilation Scheme (GDAS) and the aviation cycle of the Medium Range Forecast model, main ocean currents and hydrographical ocean profiles. The wind system is now called the Global Forecast System or GFS. The wind fields are converted to 10m height assuming neutral stability. The wind fields are available at 3h intervals using analysis and 3h forecast part of the wave model run. Coverage and resolution of the NWW3, type Global, model are 77S by 77N and 1.25 x 1.00 (approximately 120km x 110km offshore of Durban coast).

Disadvantage is that the model does not encounter all ocean currents, which means that the Agulhas current and its residuals is not taken into account. If the NCEP data corresponds with measured data at intermediate depth from the WaveRider Buoy, the data could be used at the outer boundary of the SWAN model to get nearshore waves for the shoreline modeling. Furthermore, structural changes in wave conditions due to climate change could be implemented on the offshore boundary of a larger computational grid to see what could happen in the future and to provide more detailed simulations. The long data set is valuable to obtain long-term trends in wave climates.

A.1.1.3 Validation NCEP data

Validation of the NCEP data is necessary to make use of the data. Validation will be done by comparing the NCEP data with the WaveRider Buoy data at the 30meters water depth contour using a validated SWAN model. However, on forehand is known that there are some discrepancies regarding the modeling approach. Firstly, the Agulhas Current will not be taken into account as a current. The SWAN model is used without the flow-modes of for example Delft3d-Flow. A lack of data about the Agulhas current and difficulties in the implementation of the current into the model are reasons for excluding the Agulhas current in the qualitative analysis. Furthermore, the current is variable over time and according to experts of the CSIR up to now there has not been any model that gives a good approximation of it.

Model setup

In the overview below can be seen the basic approach in the SWAN model, built with the Delft3D-wave software. At the large 'offshore' grid, NCEP wave data is in a parametric way uniformly placed at the boundary. On the offshore grid wind fields are implemented rom the NCEP wind data for the same time intervals. These offshore wind conditions are significantly different than the nearshore wind conditions. On the inner grid, which is closer to the shore, wind data from a local wind station is used, located at the port entrance of the Durban Port. In this way a difference is made in the weather systems between offshore conditions at the Indian Ocean and nearshore conditions, such as the cold fronts, which propagate more shore parallel.

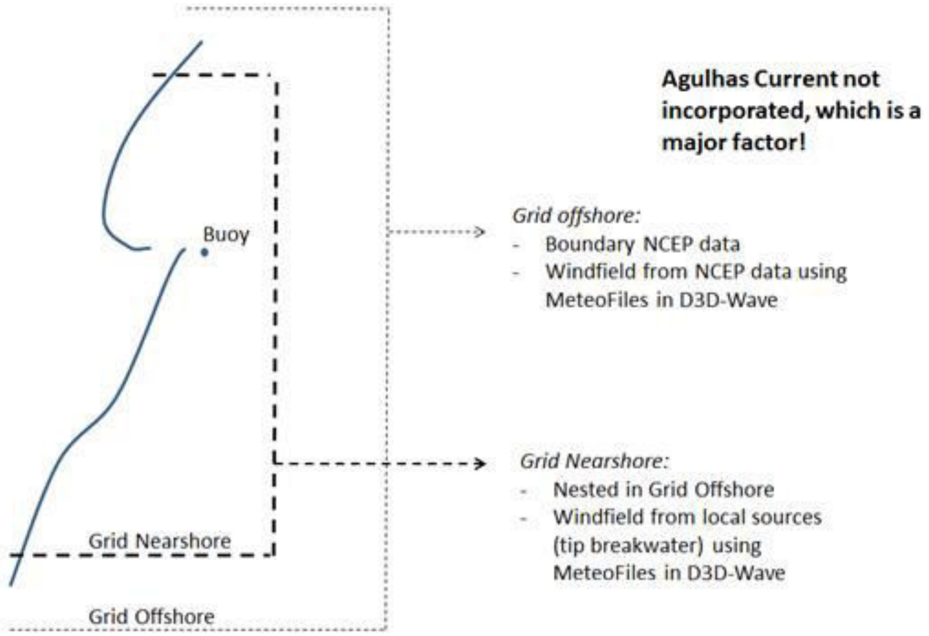


Figure A-4 Overview modeling approach

Results

For three NCEP points is checked whether they show significant correlation with the wave buoy. The point 31131 is located, closest to the shore. The other two points are located further offshore. The point 31131 shows the highest correlation and is therefore presented in this report. At the location of the wave buoy, data is obtained from the model to compare the NCEP data (point 31131) with the data from the buoy. This is done for all recorded data in the year 2009, because this year can be seen as a moderate year with a few storms, which is for validation purposes useful because of the variety in conditions. The year 2009 is furthermore densely populated in both wave sources without any large periods with errors. In Figure A-5, Figure A-6 and Figure A-7 the time-series and probability density functions are shown. The time is given in the amount of measurements. To be clear: a measurement covers three hours, which means eight measurements a day and 2920 per year.

First the time series of the waves are reviewed. For the significant wave height can be seen that the sequences of the records coincide. It means that no additional shift is necessary between the offshore NCEP wave record and the wave buoy record. The histogram shows that both probability density functions overlay each other. The buoy gives on a minor scale larger wave heights opposite to the modeled NCEP data.

For the wave direction can be seen that at some stages the wave buoy is approximated quite accurate. The graph doesn’t show the complete year, but is zoomed in to show the similarities and differences. At 1310 and 1358 the NCEP data shows waves from the northeast, however at the buoy wave from the southeast are recorded. This seems to be a frequently observed phenomenon. In the histogram the probability of occurrence of the wave condition is shown. Waves from the east-northeast are observed more frequently compared to the NCEP data. As a result fewer waves from the south are observed.

In the peak period a significant difference can be seen. Recorded swell by the wave buoy is significantly less observed in the NCEP data. The wave buoy is assumed to record these waves accurately, so the problem lies probably in the NCEP data or the modeling. In the modeling periods are not changed significantly: periods are relatively stable and will not change at all. Hence, swell waves cannot be created in the model. It leads to the conclusion that the input by the NCEP data is probably not correct.

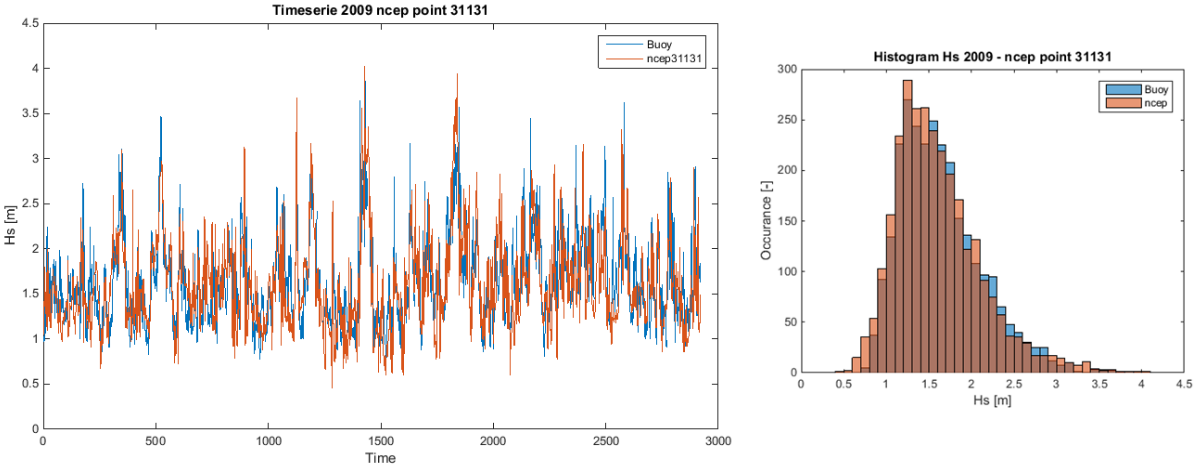


Figure A-5 Significant wave height - time series (left) and histogram (right)

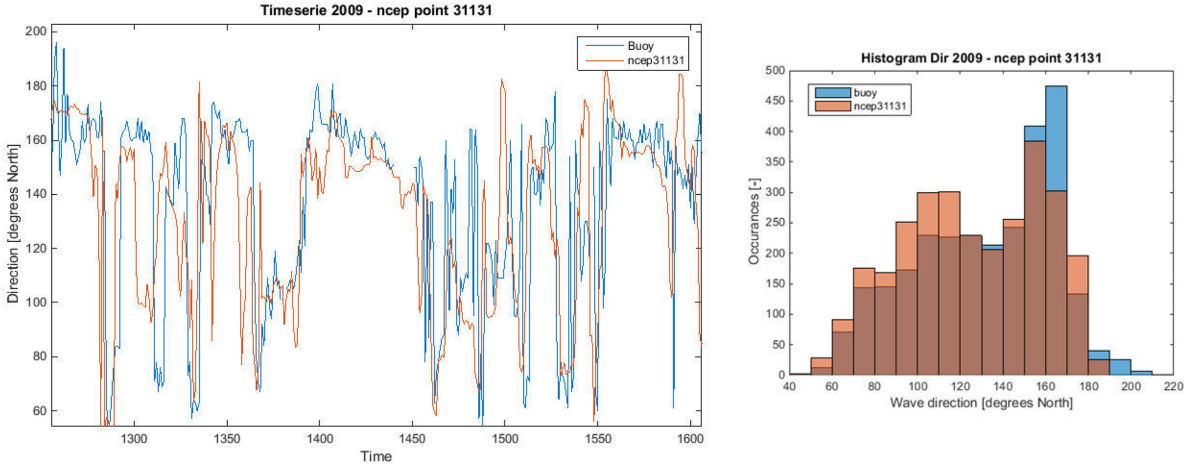


Figure A-6 Wave direction - time series (left) and histogram (right)

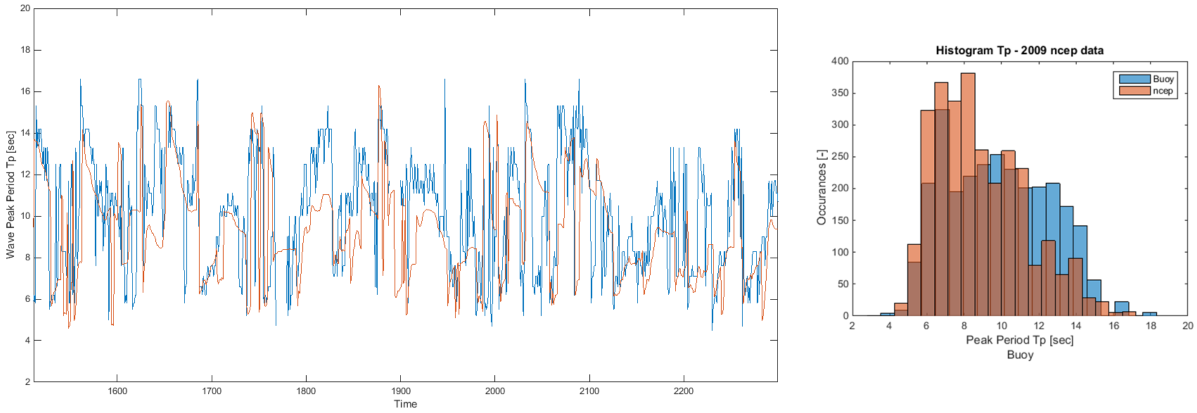


Figure A-7 Wave period - time series (left) and histogram (right)

Correlations

To get a better inside in the correlations between the different wave sources, scatterplots are made. In the figures below the correlations are given for the three different wave characteristics. For the wave height and wave direction swell *(green marks)* and sea waves *(blue marks)* are separated to show the differences in sea and swell. A qualitatively analysis is done, not considering root-mean-square errors to show the correlation quantitatively, which is sufficient to fulfill the purpose of this analysis: providing information for the decision to choose a wave source for further analysis of the shoreline behavior. As can be seen, the wave height is approximated reasonable well. The marks show the correlation of wave heights within a certain envelop close to the one-to-one line. The one-to one line shows hundred percent correlations. For the wave direction can be seen that swell waves from the southeast recorded by the buoy are reflected as waves from northeast in the modeled NCEP data. Furthermore, the spreading around the one-to-one line is large as well. However, still some correlation can be seen around the one-to-one line, but this will not be within a large confidence zone. The correlation in peak period between the two sources is very weak. Large wave periods recorded by the wave buoy are reflected in the model as significantly lower wave periods.

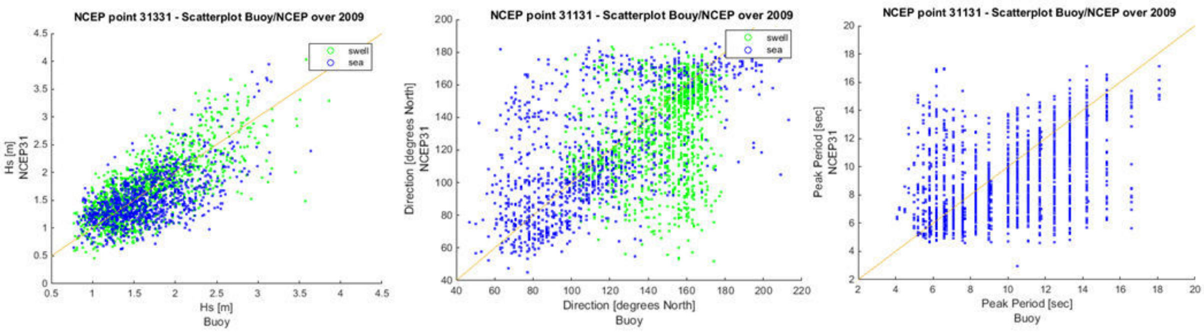


Figure A-8 correlations Wave characteristics

Conclusion

In the wave source analysis the applicability of the NCEP data is researched for the Durban coast. This is done with the setup of a SWAN wave model. In the model the representative year 2009 is used, which has been set at the outermost boundary of the model in deep water. The NCEP data point 31131 is located very close to the boundary, but contains output which is recorded over a surface of approximately 100km by 100km. In the SWAN or Delft3D-wave model the wave propagation is computed. At the location of the wave buoy, the modeled NCEP data is retrieved from the model. By comparing this output with the actual measured waves from the Waverider buoy at the same point, the model and the reliability of the NCEP data could be validated. The advantages are a more extensive data set by the NCEP data and broader reliability for wave modeling with two data sources. Furthermore, waves recorded in shallower water do not need to be extrapolated towards deeper water.

After analysis of both sources is concluded that the Waverider buoy data and the NCEP data are insufficiently correlated, especially in wave period are significant differences found. The NCEP data is therefore not applicable for being used in the shoreline modeling. The Waverider buoy data measures accurately the water surface. The recorded waves at the buoy contain information about wind generated waves over the continental shelf and refraction phenomena because of the Agulhas current, because the buoy lies relatively close to the shore.

Especially, observed swell waves from the southeast are not correctly reflected by the wave model using the NCEP Data. This could be attributed to the poor representation of swell waves in the NCEP data. Poor wind input for the WaveWatchIII model around the area where the swell comes from (south-southeast) could be a reason for this.

A.1.2 Extreme wave climate

For an accurate investigation in the extreme wave events a more extensive wave data record is necessary. In the six year data from the Waverider buoy only a few storms can be observed, see Figure A-9, which is inaccurate to extrapolate extreme events from. This analysis is therefore indicative and compared with an analysis by Corbella & Stretch (2012), which have analyzed 18years of wave data from three combined data records from a buoy at Richardsbay and a buoy and altimeter at Durban.

According to the authors storms at the Durban coast are considered to be events with a significant wave height larger than 3.5meters, indicated by the red line. From three hourly wave data a histogram is made with bins of half a meter to get the probability of occurrence of the wave heights. With the threshold value of 3.5meters, the extreme wave events are investigated by fitting a double logarithmic (Gumbel distribution) trend line with a MSE of 0.076.

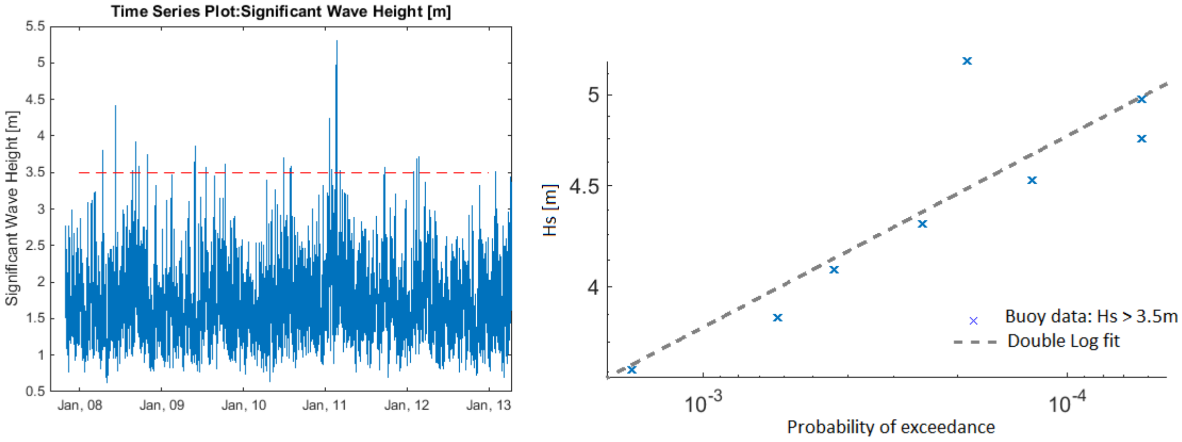


Figure A-9 Probability of Exceedance - Significant wave height

It gives an indication of the probability of occurrence of storm events for the Durban coast. Corbella & Stretch (2012) found for the Durban coast a higher probability of exceedance by analyzing 18years of data by different wave sources. In Figure A-10 the percentages of exceedance are shown for the different seasons, with the dark red triangles representing winter and the red squares implying summer observations. The lines are also fitted on a double logarithmic scale. Comparing own research with the paper, the data from the Waverider buoy matches the red squares, implying the summer data.

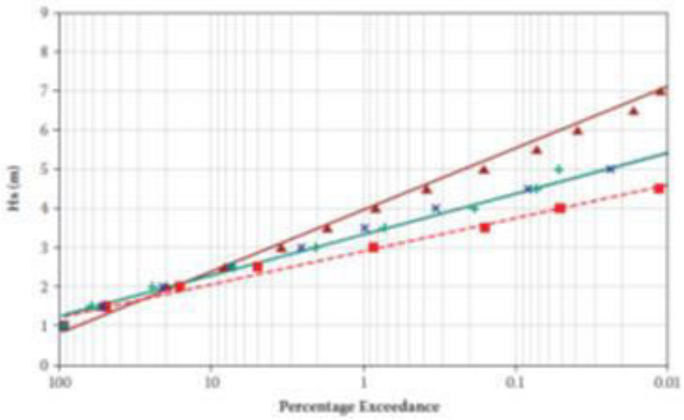


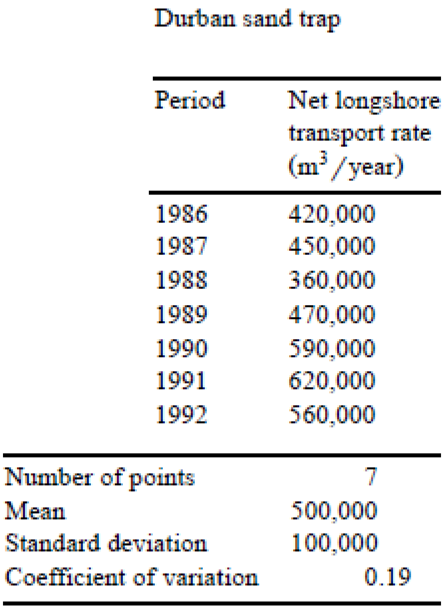
Figure A-10 Percentage of exceedance for seasons

A.1.3 Net Longshore sediment transport from Durban Sand Trap

The net longshore sediment transport along the Durban coast has been a topic of research in the past. The net longshore sediment transport can be obtained by extensive measurements in the surfzone, which are time-consuming, costly and still not very accurate. It is also possible to get an estimate out of the accumulation of sediments at the up drift side of a groyne in a certain time, which gives a good indication of what could be expected. At the Durban coast a sand trap is located at the up drift side of the Durban Port. Schooneesch has investigated six years of survey and annual dredging volumes to obtain the net longshore sediment transport within a certain variation. The goal of Schoonees (2000) was to obtain a robust estimation of the long-term net longshore sediment transport and to recommend methods to obtain the long-term mean net longshore transport rate in a cost-effective way. In this paragraph the method is explained how the Durban sand trap case is used and how the long-term net longshore transport rate is obtained. Further, the pros and cons of this approach are discussed and how these affect this research.

The sand trap shown in Chapter 2.1.5.3 was surveyed by a hydrographical survey roughly every two weeks in a period from 1986 to 1992. Volumetric differences were computed from the surveys, taking into account dredging rates from the sand trap. In this way the net longshore transport rate for every year is obtained. This research was done by Raw in 1993, established in an internal report of Portnet, which is not available for this research. In Table A-1 the dredging volumes are shown, where a mean volume of 500,000m^3/year is found from.

Table A-1 Dredging record Durban sand trap (Schoonees, 2000)



Durban sand trap

Period	Net longshore transport rate (m^3/year)
1986	420,000
1987	450,000
1988	360,000
1989	470,000
1990	590,000
1991	620,000
1992	560,000
Number of points	7
Mean	500,000
Standard deviation	100,000
Coefficient of variation	0.19

By acquiring the volumetric differences between the different surveys, assumptions are made. Therefore is discussed, what the pros and cons of the sand trap are and in which ranges the obtained net longshore sediment transport should be interpreted, because this could lead to less variation and different values compared to potential net longshore transport capacity.

Cross-shore losses or gains are assumed to be zero, which yields that losses in longshore transports are attributed to the sand trap and not to other sinks, like offshore losses. This could indicate larger longshore transports than computed, because the surveyed differences do not include the losses. The sand trap lies in a sheltered zone for waves from the north, which provides less southward transport. Thereby, the northern part of the sand trap lies in deeper water at the end of the breakwater, where waves do not break and longshore sediment transports are not likely to occur. Other drivers of sediment transports besides wave-generated are not considered. It means that only sand is captured from northward transport. Since sediments are not able to leave the sand trap, due to the depth and steep slopes of the sand trap. If this would be gross northward sediment transport, the computed net longshore current is higher than the actual net longshore transport. However, in case of a southward transport no sediment will be available due to the sand trap, which leads to coastal erosion. This in turn needs to be filled by the gross northward transport, providing a net input for the sand trap. The shore near to the sand trap is hardened by a revetment and by rocks in the upper shoreface. The coast is thus not vulnerable for coastal erosion at that point. Further, the sand trap does not cover the total potential area where longshore sediment transport is likely to occur. It yields less sediments in the sand trap from the northward gross transports. However, significant build-up of sediment on the beaches is not observed and regular maintenance works to dredge the entrance channel of the Durban Port from by-passed sediments is not required. The reason for the latter argument is the depth of the sand trap; only if the sand trap is fully filled, sand naturally bypasses the sand trap, which is not likely to occur.

The above arguments show the uncertainties around the computed net longshore sediment transports. With the advice of experts of the CSIR, it is chosen to use a 20% uncertainty range for the computed net longshore sediment transport value of 500,000m^3/year.

A.1.4 Rivers

In a CSIR report from 2008 (Theron, de Lange, Nahman, & Hardwick, 2008) sediment input by rivers are estimated for rivers along the coast of EThekwini Municipality. Many rivers have been subjected by mining activities in a legal or illegal way. Thereby, many rivers are dammed. This extraction and blockage of sediments results in less sediments available for the coast of Durban. In this subparagraph a summary is given of these estimations to get insight about the sediment budgets, which could be used as input for the scenario analysis to investigate future problems along the Durban coast.

A.1.4.1 Sediment yield

In the report first the sediment yield for the rivers is determined by analyzing the river catchments. This is done by modeling the sediment availability in the catchment which can be discharged downstream towards the coast. It includes rainfall-runoff analysis, setup of ‘soil-erosion’ factors from soil properties, the topography of the catchments and management practices, such as surface covering. The model results are verified by a study about sediment yields of the three largest rivers including the Umlazi River and the Umkomaas River. Sediment yields are gained by surveys of accumulation of sediments behind dams. The sand loads or bed loads are considered to be 10% of the sediment discharge by the river. These provide the coastal zone its sediments. Others are suspended finer sediments and mostly transported further offshore.

A.1.4.2 Dams

Most of the rivers are dammed. The locations of the dams are related to the amount of sand that is deposited into the coastal areas. Dams located downstream in the catchment will take approximately hundred percent of the sediments. A reduction of one-third in sand yield to the EThekwini coast can be appointed to the dams. Sand captured by the dams, called the trapping efficiency, is calculated for different sediment textures by a ratio of the total dam volume and the mean annual runoff. Most of the rivers are already dammed since the early eighties and therefore not much change in sediment budgets by river damming is expected to be seen in the future. Only the Umkomaas River is not dammed, which has the potential to be dammed, but due to the importance of the river for the catchments runoff; it is very unlikely to happen.

A.1.4.3 Mining activities

Mining activities are studied by aerial research by EThekwini Municipality in 2007 and by a survey of the CSIR in 2003 for rivers in the coastal belt. These numbers are based on known volumes by operators and estimated volumes per activity found by the aerial study. Some rivers are clearly exhausted, meaning that almost all natural deposits are mined.

There are some discrepancies in the numbers. Since 2003 the area of EThekwini Municipality has developed significantly and large areas have been urbanized. Building activities and sand demands have increased, which could mean that in 2015 these figures have been changed dramatically. Furthermore, during the studies upstream mining activities are not taken into account and the number of illegal mining operations is not known. This asks for new research. In the scenario analysis sediment budgets by rivers are studied by assuming that mining activities have increased with some uncertainty ranges.

A.1.5 Continental shelf

The continental shelf of southeast Africa is studied to obtain knowledge about large scale morphology of the shelf and to understand the transformation of waves due to the bathymetry. The continental shelf is investigated by Flemming (1978) through a side-scan sonar survey. At Cape St. Lucia, north of Richard Bay, the shelf width is less than 4 km, which is very narrow (Flemming, 1978). Around Durban the shelf width is significantly larger and was found to be 40 km wide north of the Durban Port. This area is called the Tugela cone area, due to the outflowing river Tugela. South of Durban, from the Umkomaas River up to Port St. Johns, the shelf is very narrow again, on average 10 km wide. Narrow shelf widths are associated with clear shelf breaks with steep slopes down to the deep ocean. For the central Durban area the shelf break is poorly defined.

Between the Umkomaas River and Dolphin coast, the nearshore dynamics are sheltered from direct influence of the Agulhas current, but are subjected by a return flow of it (Flemming, 1980). Flemming found northwards facing dune fields from the Umkomaas River on to the Tugale cone area, which indicates a northward flow. The return flow is analysed by Lutjeharms & de Ruijter (1996). Possible mid-ocean eddies are responsible for the return flow, which may fluctuates as a result of dynamical changes at the outer shelf. The fact that the Durban area has such a widening of the continental shelf compared with its neighbours makes the Durban shelf part unique on the east coast of Africa. For this research, it is important to determine how close those dynamical changes in currents have an effect on the nearshore bathymetry or hydrodynamics, because these currents could indirectly have an effect on the stability of the shoreline. As can be seen in Figure A-11, south of the Durban Port a flow is directed northward and north of the port a current is directed southward. The influence of these currents on the longshore sediment transports not known, but the currents seem to flow offshore of the surf zone. During storms the surf zone is extended to deeper waters. Whether during storms sediments are carried by such a current is not known. Further, at locations with extensive shore normal structures, these return currents might interact with the hydrodynamics around the structure. Whether the current could capture volumes of sand and transport them further offshore is not known. This could result in a sink of sediments. However, the effect and interaction of these currents with the nearshore morphology demands more attention and should be investigated.

Furthermore, Flemming (1980) pointed out that the Agulhas current affects the continental shelf by its meandering. This is not further analysed, but could lead to bulbs and troughs in the bathymetry affecting wave propagation.

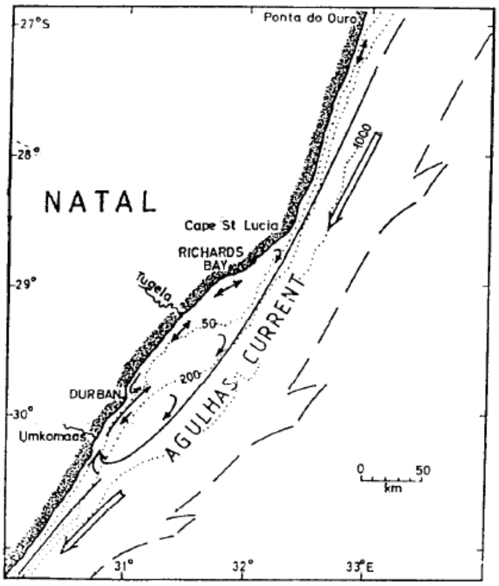


Figure A-11 Residual currents of the Agulhas current (Lutjeharms & de Ruijter, 1996)

A.1.6 Bathymetry

The bathymetric data consists of yearly monitored bathymetry by CSIR and Global Gebco data. A hydrological survey by the CSIR is done every year. The bathymetry, transformed to mean sea level (MSL), is used for the wave modeling and the creation of hydrographical profiles in the nearshore. The bathymetry from CSIR covers the area between Amanzimtoti the Durban DigOut Port, which is only part of the interest area. South of Amanzimtoti the bathymetry is extended by the Gebco global ocean hydrographical data. The Gebco08 data is measured relative to mean sea level. For the CSIR bathymetry, which is obtained by marine sonar survey, the resolution varies per region and per water depth. For the Durban Bluff area nearshore resolution of approximately 100m cross-shore to 650m parallel to the shore can be found. The offshore resolution is approximately 500m by 1350m. The Gebco data has a coarse standard resolution of 1000m by 1000m. For the wave modeling these depths are interpolated, which introduces errors. This is relevant information for wave modeling part and may not introduce non-physical phenomena.

A.1.7 Climate Change

A.1.7.1 Extreme wave conditions

Rossouw & Theron (2009) identified a change in the storminess. Peaks of individual storms during the austral winter showed an increase in wave heights. However, the increasing trend of 0.5m over the past 14years for the winter period was assumed unlikely to be a true reflection of the actual longer-term change. Mori, Yasuda, Mase, Tom, & Oku (2010) found also an increase in significant wave height in the future (2075-2099) for extreme events using the atmospheric GCM model. In the southern Indian Ocean a maximum difference of one meter can be found for significant wave heights during wave events with a probability of exceedance of 10^{-5}, see Figure A-12 (left). Since this is the most promising paper for a change in storminess for the South African coast, the effect is included in this study.

In Figure A-12 the projected increase in extreme significant wave heights is shown according to Mori et al. and extreme waves observed by six years of data from the Waverider Buoy. Assuming that the trends in the Indian Ocean are fully correlated to the waves in the nearshore of the Durban, it can be checked what the effect of Mori would be for the Durban coast. For the six years of data waves with a significant wave height above a threshold value of 2.5meters are considered. The fitted double logarithmic trend line, which is related to the Gumbel distribution, shows the extreme wave climate for Durban. Obviously, six years of data is insufficient to make projections for extreme wave events with a return period of more than once in a thousand years.

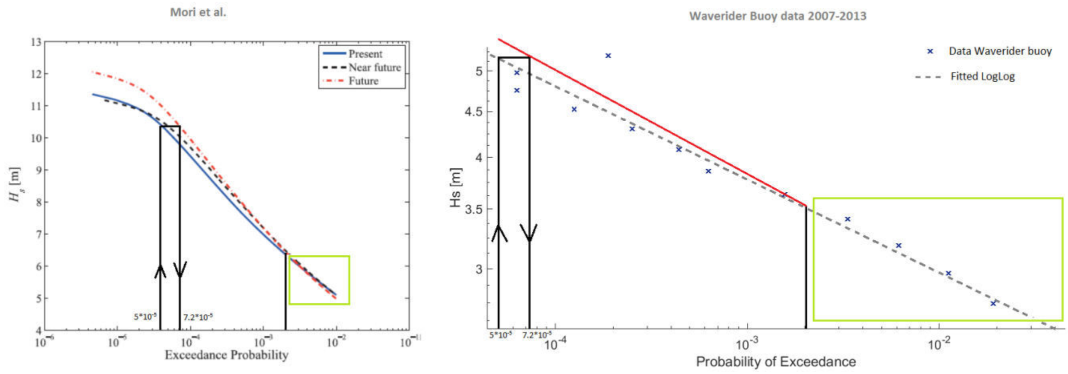


Figure A-12 Trend in Hs for southern Indian Ocean (Mori et al., 2010) **and extreme wave heights Durban**

However, in for this research it is used to indicate that the changes projected by Mori are irrelevant for this study. The growth in extreme events is so rare, that it is only a very minor contribution to an average annual wave climate. The paper by Mori could be worthwhile to study in cases where a single extreme wave height could be important, as for example in the design of a breakwater. In this study the increase in extreme wave heights is considered to be too little and will be neglected.

Extreme wave heights during storm conditions are mainly regionally generated. They can therefore be correlated to extreme wind speeds. For wind speeds larger data sets of information are available, which could yield more reliable results. In Young, Zieger, & Babanin (2011) statistical significant trends in wind speed and wave height are investigated based on 23years of satellite data from radar altimeters. Young has found no significant trend in mean wave height for the African region. For the mean Hs and for the 90% extremes no significant increase can be seen. However, for extreme wave heights a growing trend is observed. For South Africa an increase of approximately 7.5% can be seen for the 99 percentile extremes. Again, these extreme wave heights are in an average annual year too little to contribute to a trend in sediment transports.

A.1.7.2 Sea level rise

Globally

In 2013 the Intergovernmental Panel on Climate Change (IPCC) presented an assessment of the physical science basis of climate change, as part of the Fifth Assessment Report (AR5). It contains information of the current state of knowledge on global climate change. Relevant for this research are the wave projections and sea level rise (SLR) scenarios, which are reconsidered after the Fourth Assessment Report (AR4) in 2007 and yet presented with higher confidence projections. SLR is not considered in the main report, but is included in this Appendix to provide background information for future research.

The IPCC states that the two main factors of global sea level rise are the expansion of ocean water and the increased transfer of water from land to the ocean as a result of glacier melting. Other factors are the Greenland and Antarctic ice sheets and other water storage sources from land. In Figure A-13 is shown the projected sea level rise up to the year 2100. The uncertainty level of the various scenarios lies in between 5 – 95 %. The solid line is the average per scenario. For the exact values of all scenarios and their uncertainties, see Table A-2.

The scenarios in the AR5 are based on ambiguous levels of climate policy; the more one invests in tempering CO2 emissions, the lesser radiative forcing will be observed in the atmosphere. The scenarios are called representative concentration pathways (RCP) and show different radiative forcing values; RCP2.6 (2.6 W/m^2) for highest ambiguous level, RCP8.5 (8.5 W/m^2) for the lowest ambiguous level. Those radiative forcing values are via various models related to oceanic expansion and other factors that generate sea level rise. In the outcomes of the IPCC is not dealt with potential marine ice sheet instability in Antarctica, where large ice sheet are positioned against sloping bedrocks. Melting and breaking of these ice sheets could lead to significant higher projections, but at the moment real evidence on this topic is lacking.

Table A-2 Global mean SLR for the mid- and late 21st century relative to reference period of 1986-2005(IPCC, 2013)

	Scenario	Mean	*Likely* range[d]	Mean	*Likely* range[d]
Global Mean Sea Level Rise (m)[b]	RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

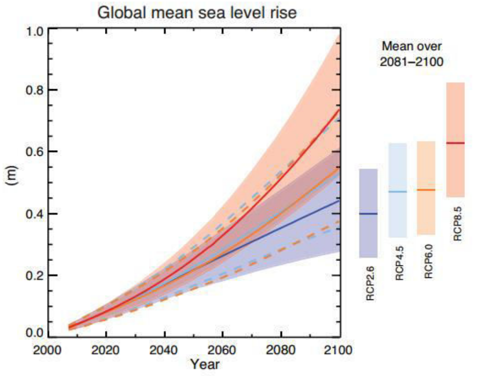


Figure A-13 Global Mean Sea level Rise (IPCC, 2013)

Locally

Ramsay & Cooper (2002) have studied the Durban area to discover the late Quaternary sea-level changes in South Africa. They set up a sea-level curve for the past 200,000years, based on available sea-level indicators from the South African coast and shelf, see Figure A-14. Various indicators were used, such as carbonate contents or hidden organisms in beach rock. Others are woody debris in contemporary wetlands behind the coastal barriers, which showed erosion holes from historical floodings. Furthermore a Uranium-series date was obtained from an aeolianite core of a high coastal dune sequence at Isipingo south of Durban sands (Reunion ridge). The curve shows a strong transgression of the coastline in the late Holocene. The research is in line with earlier findings from (Fairbanks, 1989), who studied the historical properties of coral reefs in Barbados. The curves of Barbados and South Africa are almost equal, apart from sea level peaks. The curve shows several peaks above present mean sea level of ±4m in stages 5e (111,000 – 130,000 B.P.) and 5c (93,000 – 103,000 B.P) with a fall till -44m in between, that correspond with the last interglacial. The Caribbean data shows no peaks larger than present MSL during the last interglacial and during the late Holocene. Reasons for this could be steric expansion or isostatic deformations.

As can be seen from Figure A-14, after the rapid transgression the sea level seems to stabilise. From previous literature by Ramsay & Cooper a rather oscillatory trend in the last 6500years B.P. is found. A range of approximately 6meters is observed and a highest sea level of 3.5 + MSL in 3880years B.P.

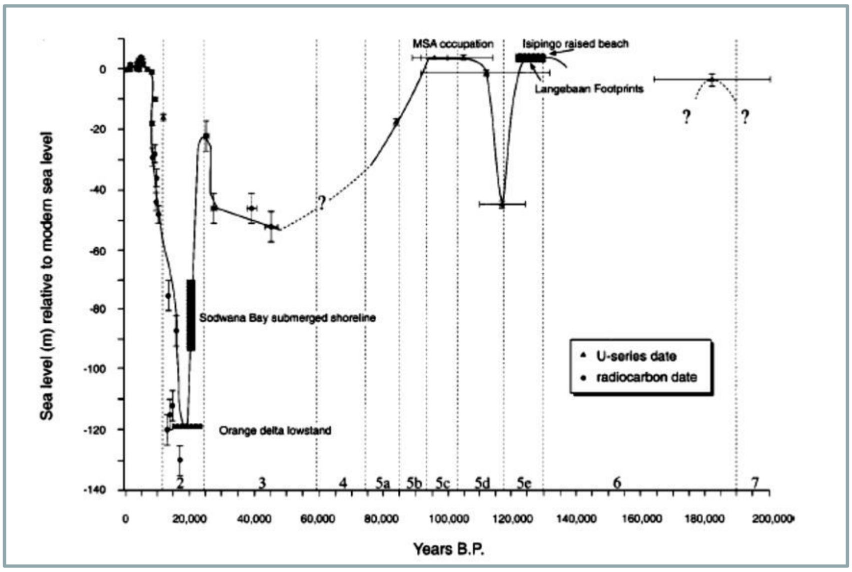


Figure A-14 Sea-level curve for past 200,000 year (Ramsay & Cooper, 2002)

Current research done by Mather (2007) gives linear trends of monthly and yearly mean sea level rise of respectively, 2.7± 0.05 mm/year and 2.4 ± 0.29mm/year. Mather analysed a tidal record of South African Navy's tide gauge located near the entrance of the harbour in Durban, which includes water surface elevation from 1970 to 2003. The values cohere with global SLR values, see the record of 1985-2005 in Table A-2. Following Mather, Durban is one of the relatively few sites in the world that can be used directly to assess global sea-level change, because of Africa's stable cratonic base. It makes the land mass around Durban tectonically stable. Therefore the data should have an equivalent trend with the worldwide observed trends, which is confirmed by Mather.

Conclusion

Tidal gauge measurements do not go any further than the seventies, which results in a lot of uncertainty in predictions of future sea level rise. Just like the IPCC does, it is best to work with scenarios to cover uncertainty ranges. As a result of Mather's research, the chosen scenarios of the IPCC can be used for the case of Durban provided that they are converged with the sea level rise found by Mather. As Cooper and Ramsay observed; during high stands of sea level, it is reasonable to state that for local sea level rise isostatic features or local steric expansion can make a significantly different.

A.2 Historical developments

A.2.1 Historical shoreline behavior EThekwini South Coast

By mapping the shoreline behavior of the Durban coast south of the Durban Port in the past, knowledge is obtained about the stability of the coast over time. It provides understanding of the current coastal system, but also insight in the variation of the shoreline in the past. The shoreline is studied by monitored beach profiles of the CSIR and by reviewing aerial photographs in Google Earth. Aerial photographs are available from 13-08-2003 to 15-05-2015 on several dates.

A.2.1.1 Google Earth Research

By a review of the Durban shoreline in Google Earth, information is obtained about the translation of the shoreline in time. The vegetation line is chosen to check fluctuations of the shoreline in tine. Regarding different heights of the dunes in the studied areas, the vegetation line is not consistent in height. However, it is a clearly identifiable mark and therefore easy to use as reference line. An indication of structural erosion and accretion patterns could be observed, because vegetation needs time to settle on places where the environmental conditions are suitable. This is at a calm place, where waves will not frequently destroy the vegetation. The aerial photographs in Google Earth show a certain moment in time, which could be dependent on seasonal effects. Chosen is to use available photographs taken around the same date during the year, to diminish seasonal effects. In all figures an overview is given with two different lines. The Orange line represents the shoreline on 13-08-2003, the Green line represents the shoreline at 03102015. Both dates are around the end of the winter, beginning autumn.

Bluff

For the Durban Bluff shoreline retreat of approximately 25meters is observed over the twelve year period in the Northern area around Cave Rock, which results in an average retreat of 2m/year. This has been measured in the Google Earth. For the Southern part of the Bluff area no significant trend can be seen, see the area around Treasure Beach in Figure A-15.

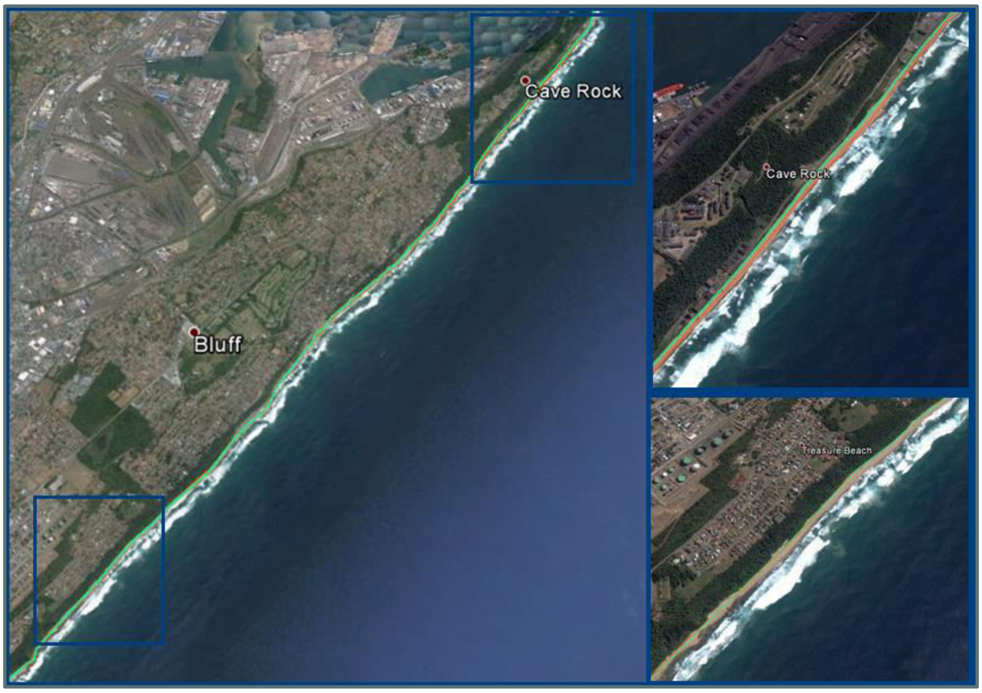


Figure A-15 Bluff

DigOutPort-Amazimtoti

The project area for the Durban DigOut Port seems to have a stable shoreline, which is plausible due to the many rock headlands in the area. Just south of the Umlazi Canal (north of the projected harbour entrance) the shoreline seems to decay a little bit, but this is considered to be negligible. South of the DigOut Port area up to Amanzimtoti no trend can be seen over the past twelve years from the present, see Figure A-16.

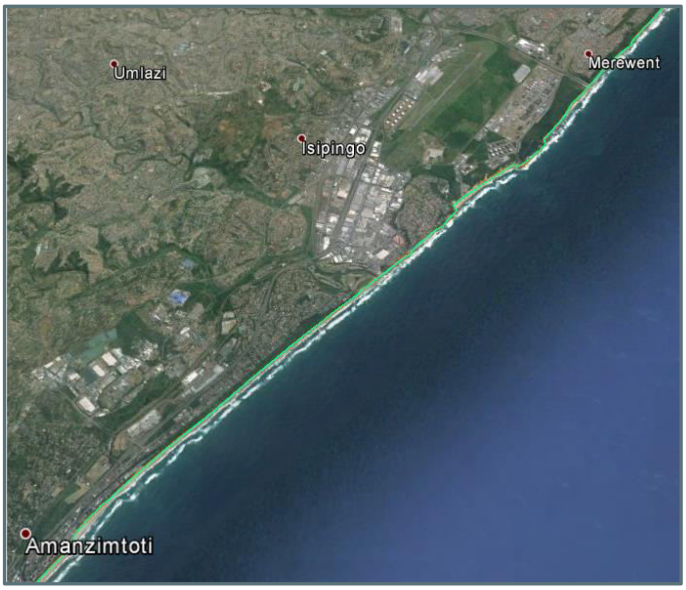


Figure A-16 Amanzimtoti - DigOut

Amanzimtoti – Umkomaas River

In the Southern part of the studied area the shoreline is stable as well. Only some changes can be seen between Kingsburgh and Umgababa, where several rivers mouth into the ocean. Some of them are not dammed, which results in major floods over the years. Furthermore, erosion hotspots are observed around some large rocky headlands, during heavy sea storms. So, the position of this shoreline fluctuates seasonally due to these episodic events, but the shoreline is stable as well as can be seen over the twelve year period.

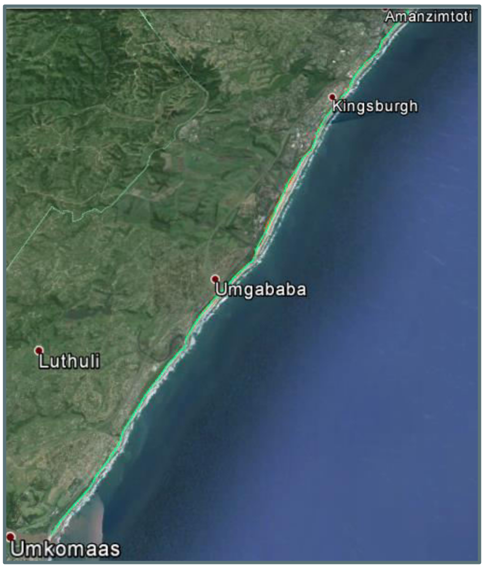


Figure A-17 Umkomaas - Amanzimtoti

A.2.1.2 Beach profile monitoring

In the Durban area only the Durban Bluff has been monitored since 1989. In this region wealthy residences are situated, with some recreational swimming pools at the bottom of the bluff close to the ocean. The villas on top of the bluff have a beautiful view over the ocean. Only the Durban Bluff was a topic of concern during the past decades, probably due to its high economic value. The data is useful to this study, because it the only resourceful piece of information about shoreline behavior in the past. At some neighboring locations, beach profiles are monitored since 1998. Along the total study area, from the Umkomaas River up to Cave Rock four measurements per year are available from 2005 to 2009. The Durban shoreline south of the Durban Port hasn’t been a major topic of investigation in the past, which is the reason why not so much data is available.

Total Durban Coast

Over the total Durban coast beach profiles are measured since 2005. The beach profiles from 2005 till 2009 are available. A period of only 4years, including a significant storm year in 2007 is not a very reliable representation of possible structural trends. However, the profiles can be compared with the Google Earth research to see if any trend over the same period is recognizable.

Table A-3 Erosion/accretion Beach Profiles

Beacon	Erosion Accretion [m/y]
‘SB1’	-1.34
‘SB2’	-1.42
‘SB3’	-0.06
‘SB4’	-1.32
‘SB5’	0.03
'SC11'	-3.23
'SC12'	-0.08
'SC13'	0.64
'SC14'	1.41
'SC16'	-2.44
'SC17'	-9.26
'SC18'	-2.58
'SC19'	-3.49
'SC21'	-0.42
'SC22'	-4.53
'SC23'	-6.82
'SC24'	-10.86
'SC25'	-13.8
'SC26'	7.37
'SC28'	-4.92
'SC29'	-18.97
'SC30'	-1.18

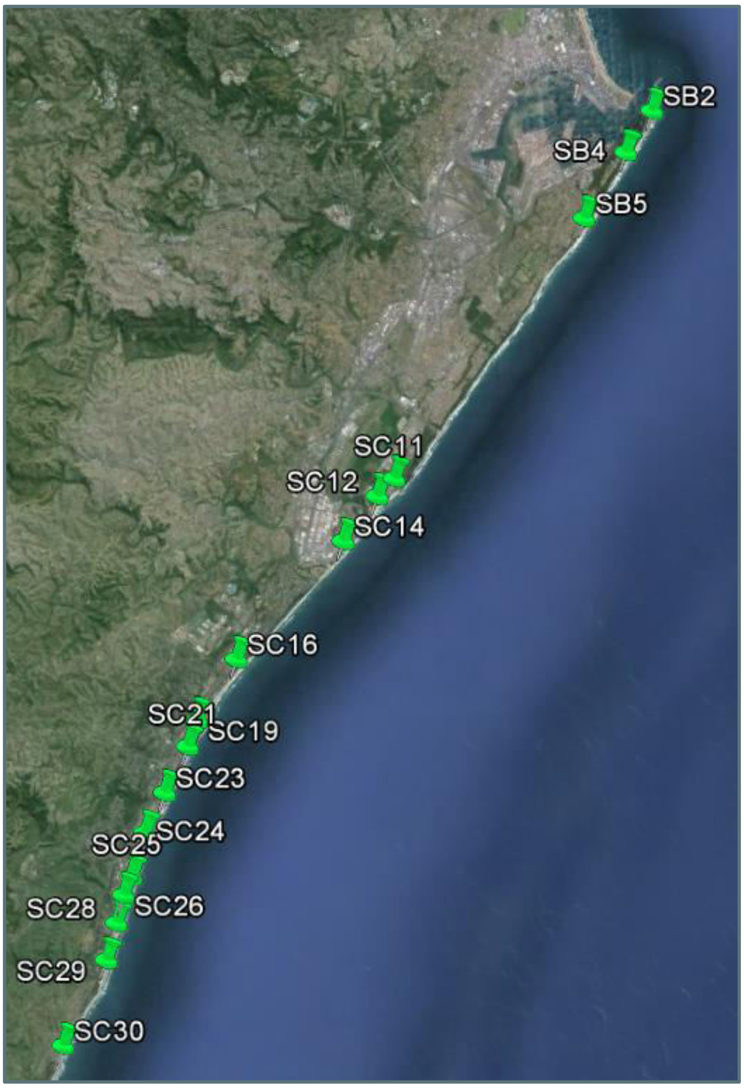


Figure A-18 Overview beacon points South Durban

Bluff North

For Cave Rock, represented by the beacon points SB2, SB4 and SB5, most of the beacons show an erosive trend, which is in line with the findings in Google Earth.

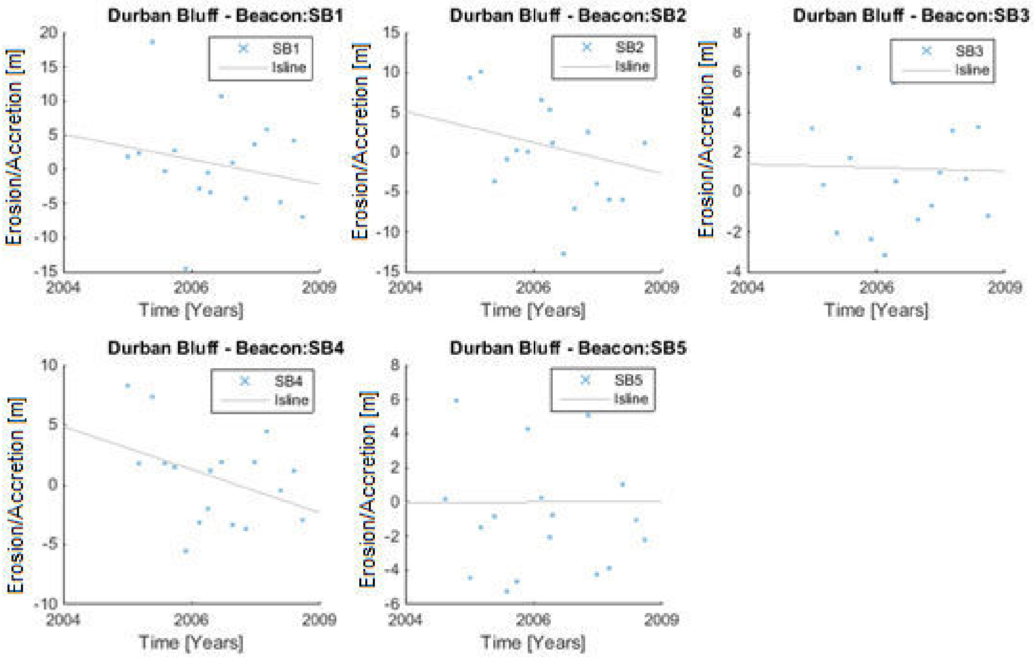


Figure A-19 Erosion/Accretion Cave Rock

South of DigOut Port – Amanzimtoti

The area in between Amanzimtoti and the DigOut Port shows a rather stable situation, where in the northern part an accreting trend can be seen an in the southern part an erosive trend, see beacon SC16.

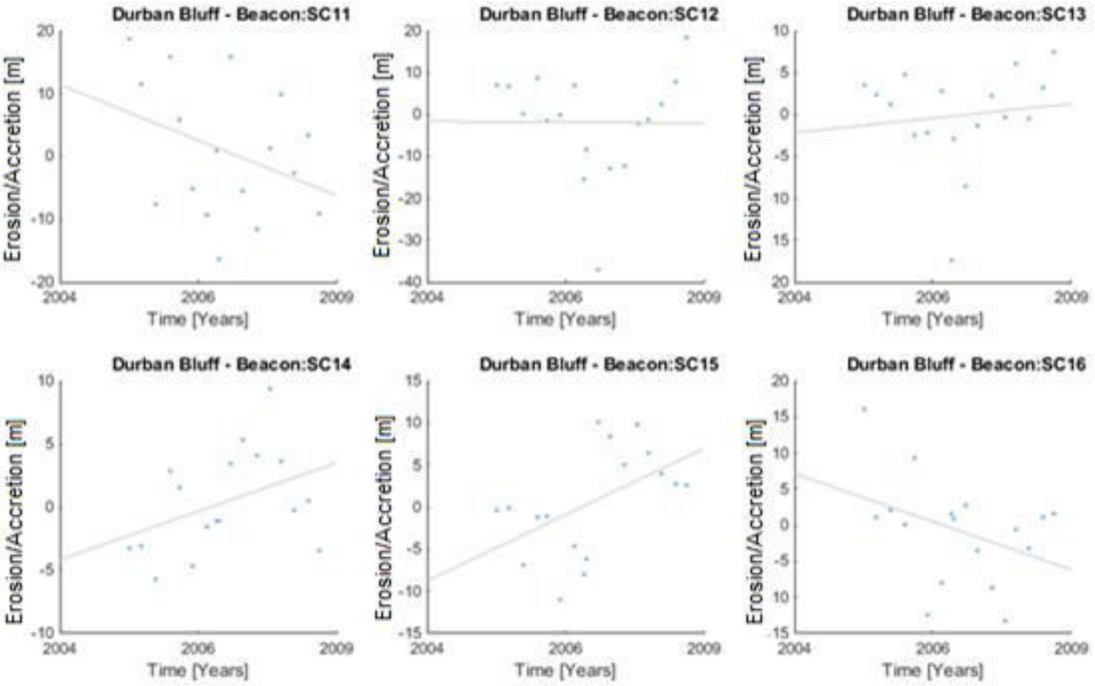


Figure A-20 Erosion/Accretion DigOut - Amanzimtoiti

Amanzimtoti - Umkomaas River

In this section the shoreline translations are relatively large. This could be attributed to storms. The existence of rocky headlands makes the region vulnerable for these storms, because wave energy is converged at these spots, yielding erosion hotspots. The beacon points alongside them are obviously influenced by these seasonal changes. For example beacon point 26 shows within a year already a change of almost two hundred meters for the +2CD line.

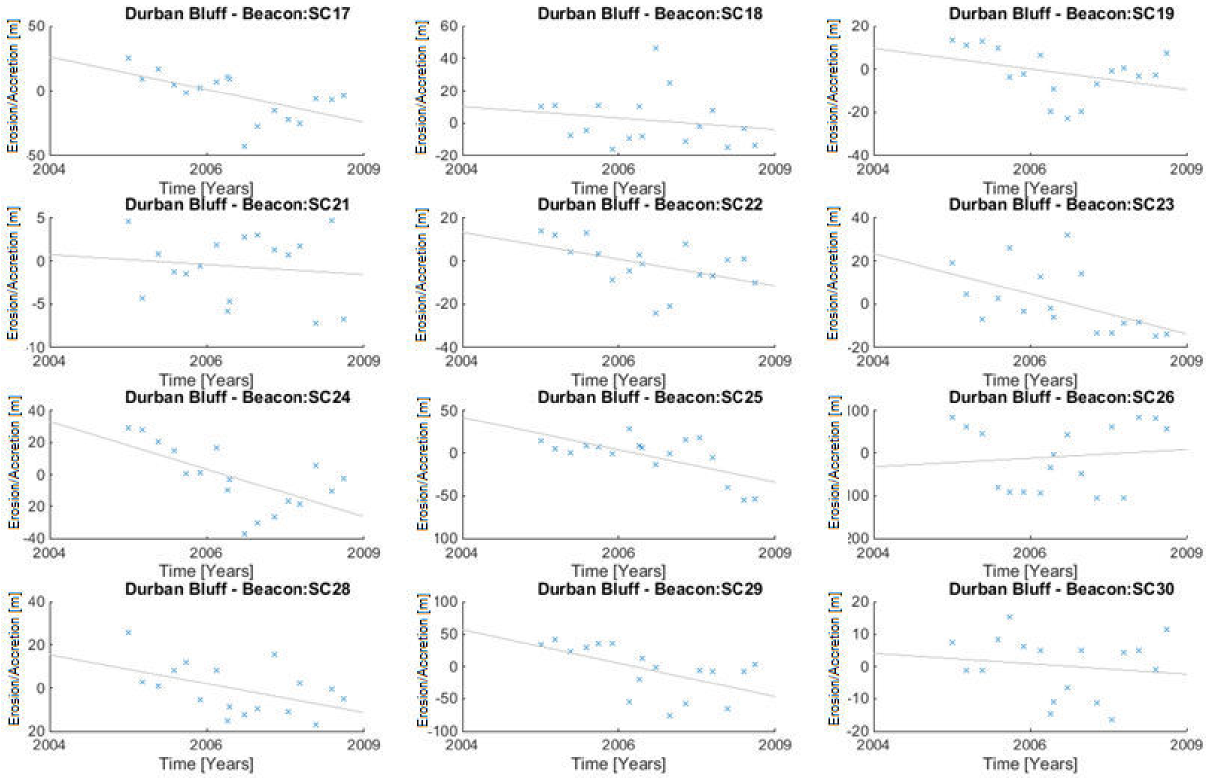


Figure A-21 Erosion/Accretion Amanzimtoti – Umkomaas River

A.3 Stakeholders

In the table below the identified actors are given in an overview. Their attitude towards the project, either supportive or resistant, their power for the project for better or worse and their level of interest in its success or failure are criteria to assess them. Their interest in and the relation with the project is further outlined in the subparagraphs below the graph.

A.3.1 Transnet National Port Authority

The Transnet National Port Authority is one of the project initiators and will be the owner of the new port. As a port operator they will maintain all port's businesses. This includes transport to the hinterland, because they also control main South Africa's main infrastructure, such as the railway system. The new DigOut Port is expected to enhance their growth. Transnet is also in charge of the dredging activities around the port. The entrance channel has to be dredged to prevent it from sedimentation to leave the entrance channel open and the port operational. They will be in charge of an eventual bypass system, which has to make sure that the port doesn't suffer from erosion.

A.3.2 EThekwini municipality

General

The EThekwini Municipality is one of the major stakeholders in the development of the new DigOut Port. They are together with Transnet project initiator. The new container terminals at the DigOut Port create jobs and are beneficial for local businesses. It stimulates economic growth in the region of eThekwini. In general the Municipality is involved in the project due to the financial and economic benefits. However, the municipality also has to deal with side effects of the port, which are research in this analysis.

Environment

The environment around the Port has some high valuable species, like the preserved mangrove field. Furthermore, some rare bird species are found in the project area. From an environmental perspective, the municipality has to take care of these valuable areas. Another part of the municipality is the drainage of the cities excess of water during intensive rain events. The Umlazi River Canal, located at the northern edge of the DigOut Port drains part of the city. The Mbokodweni River flows into the ocean just south of the DigOut Port. Both rivers have a major function in the water system inland of the port and care should be taken they remain their functions in the future.

A.3.3 Residential areas Bluff

At the top of the Bluff some wealthy residential areas can be found. From south to north they are called Meredeth, Treasure Beach, Brighton Beach and Ocean View. They are located at on top of the Durban Bluff. However, if shoreline retreats some of the residence might suffer from this. In the Meredeth area the main road near to the sea is located approximately 150meters from the +2CD shoreline, just like in Treasure Beach. In Brighton beach, residences lie almost at the beach in front of the vegetation line, see Figure A-22. Also some recreational swimming pools can be found, almost lies in the ocean. This is also the case in Ocean view. The residential areas lie in the vicinity of the project area, where Meredeth lies closest by an approximately 2.5kilometers measured from the northern breakwater. People living in these residences have significant interest in any shoreline retreat in the future. Seen their wealthy standards, they could have potential high positions in major companies or governmental entities, which makes them influential. On the other hand, they could also have a minor stake in the new DigOut Port due to the economic opportunities the new port will give directly as an employee or as an investor, or because it will improve the quality of life in the province itself.

Figure A-22 Recreational Pool Bluff

A.3.4 South Durban Community Environmental Alliance (SDCEA)

The SDCEA is an environmental organization in South Durban, which stretches out from the Durban Port up to Umkomaas River. It is a vocal and vigilant grouping in terms of lobbying, reporting and researching industrial incidents and accidents in this area. It contributes to the struggle against Environmental Racism for Environmental Justice and Environmental Health. The SDCEA was once organizer of protest marches against the Durban DigOut Port.

A.3.5 Passenger Rail Agency of South Africa (PRASA)

The PRASA is a South African state owned enterprise, which is responsible for most of the passenger services. Together with Transnet, they are responsible for the maintenance and operators of the rail tracks. The railway in the South of Durban close to the ocean, see field analysis, is called the Metrorail, which provides commuters services in urban areas. The railway in the south between Amanzimtoti and the Umkomaas River is located very close to the ocean. Due to risky situation, the problems in the past and PRASA's responsibility in this case, PRASA is incorporated as actor in this stakeholder analysis.

A.3.6 Local farmers

At the location of the Durban DigOut Port currently farmers have their land to do their business. The farmers have to leave the land and will lose their business. They have a large interest in preserving their land, however minor influence in the total project, because they will probably simply be bought out and have to leave the area.

A.3.7 Business companies

Business companies lie close to the project area, have very much interest in the new DigOut Port since they can profit from the benefits the port them will give. Two major companies are the Sapref Refinery and Toyota. For Toyota it is obvious, that a large container terminal in front of their industry will enhance them to grow. They have a positive attitude towards the project, with enormous positive interest. This holds for many companies, which can benefit of the better connection to the worlds market via the container terminal. However, their power will be not so large, since it will, as far as known, will not directly invest in an own terminal.

A.3.7.1 Sapref Refinery

The Sapref Refinery has some mixed interests. On the one hand, a large developing industry with large shipping vessels is directly related to Sapref's market with some positive stakes. On the other hand, the Refinery could be disturbed in their regular business by the construction works in the port. Also because a major pipeline lies underground, underneath the new breakwaters, towards an offshore intake point.

Even more important, the hazardous liquids stored at the refinery lie at a minimal distance of approximately 350meters from the ocean. The refinery and the ocean are separated by the Bluff, which has a height of dozens of meters. The channel of the Umlazi river is an opening though the Bluff, which might be vulnerable for erosion.

Figure A-23 Sapref Refinery

A.3.8 NGO's

The Non-Governmental Organizations South Durban Community Environmental Alliance and EarthLife Africa have already registered objection towards the plans of the Durban DigOut Port proposed in the EIA (Harris, 2015). Key interests of them are preserved plants and bird species, which have their natural habitat in the project area. Some preserved mangrove plants are situated south of the harbor. However, this will not be a topic of concern in this analysis, because the mangroves will lie in between the breakwaters, which means they will not be harmed by any shoreline translation. Furthermore, they are concerned about the noise and pollution, which the new port will generate.

A.4 Project area

In the main report the area around the Durban DigOut Port is explained. In Figure A-24 the key location south of the Durban DigOut Port are shown. In future research these locations can be studied, as for example the railway between in the south. This has at some locations already a critical distance to the current shoreline position, which has resulted in problems in the past.

Figure A-24 Durban South

B. Waves and shoreline modeling

B.1 Wave modeling

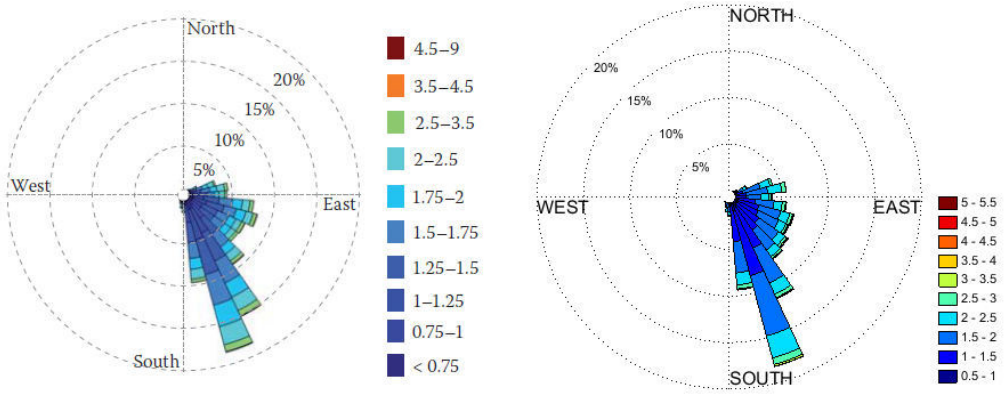
B.1.1 Representative wave climate

The six year dataset of November 2007 to November 2013, from the Waverider buoy is used to get a representative annual average climate. The dataset of six years is compared to an article by Corbella & Stretch (2012), see Table B-1 and Figure B-1, which present the wave climate of KwaZulu Natal coast based on combined datasets of two different Waverider buoys for the Durban coast: an ADCP measuring instrument and a Waverider buoy for the coast of Richardsbay, north of Durban. The wave sources used in the article have operated in different periods and at different depths. The average wave climate presented in the article and the own available dataset are compared and considered to be similar. The use of the six year of data is therefore correct for creating a representative yearly average.

The six years Waverider buoy dataset contains measurements for every three hours. Every wave condition is characterized by the significant wave height, Hs, Peak period, Tp, and wave direction, Dir. The total data set consists of 17537 conditions. By shrinking the total amount of condition to a set of 200-300 representative conditions for a year, the level of accuracy is reduced. However, efficiency in computational effort, which is wanted, is gained. The reduced climate is made by binning the wave characteristics. For every set of bins, which represents a single wave condition, the probability of occurrence is determined. The probability of occurrence is used to normalize the total set to a representative year.

Table B-1 Table comparison average wave characteristics

Data	Average Hs	Average Tp	Average Dir
2007-2013 Waverider buoy	1.67	10	132.6
1992-2010 Combined data (Corbella & Stretch, 2012)	1.65	10	130



1992 - 2010 combined data

2007 - 2013 Waverider Buoy

Figure B-1 Wave roses for 18 years data and 6 years data Waverider buoy

From the 2007-2013 data histograms are plotted to get information about the probability of occurrence of each wave characteristic. Assumed is that the six years of data are representative for the current wave climate of Durban. No long-term trends in the wave climate are considered, which lie on top of these six years. The correlation of each wave characteristic is investigated by scatter plots and analyzed in the Appendix A.1.1. By analyzing the probability of occurrence and the dependency amongst the wave characteristics, a basis is laid for the reduction of the climate, which has to be reflected as accurate as possible. The wave height is bounded by a bin of 0.665meters, the wave period by a bin width of 2.63seconds and the wave direction with a bin of 9.7degrees. The reduced climate is validated based on the net sediment transport found with data based on the sand trap by Schoonees (2000), see Appendix B.2.2.3.

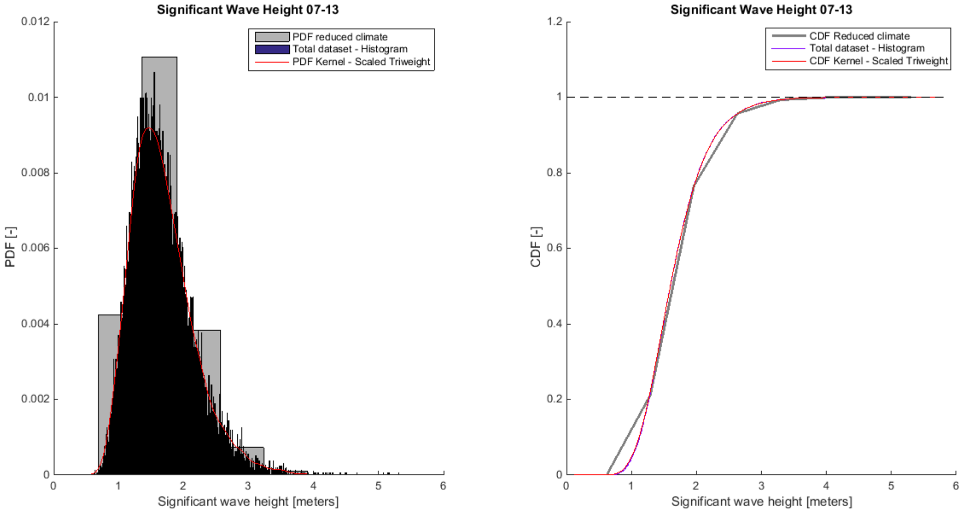


Figure B-2 Wave Direction PDF CDF

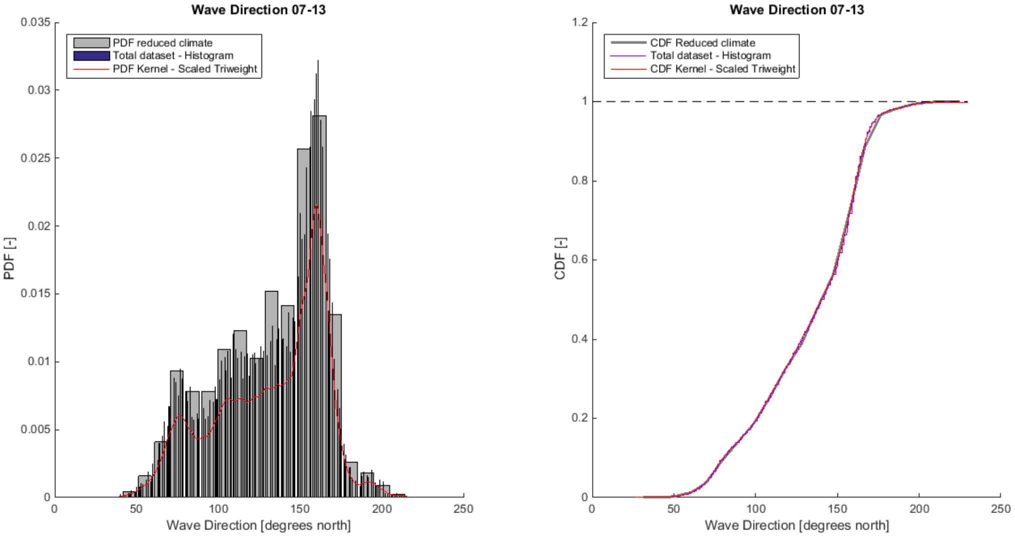


Figure B-3 Wave direction PDF CDF

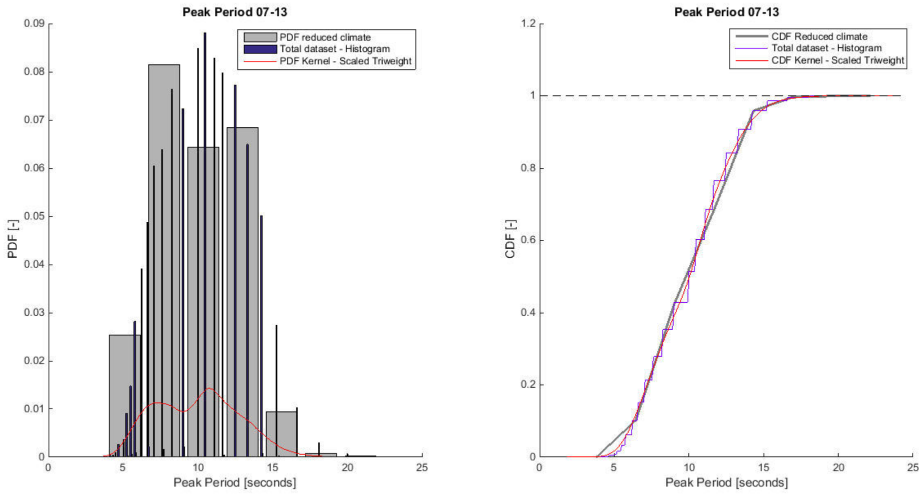


Figure B-4 Peak Period PDF CDF

In the Figure B-2, Figure B-3 and Figure B-4 the PDF and CDF functions are presented of the 07-13 dataset, including the reduced wave climate. The distribution function of the significant wave height approximates the Rayleigh distribution. This is commonly observed for offshore waves (Holthuijsen, 2009). Since, the Waverider buoy lies in arbitrary waters the distribution function already approximates the Weibull distribution, which is common for waves observed in shallower waters. The reduced climate with bins of 0.665m width approximates the full climate not totally accurate at the steeper gradients of the CDF. It means that the reduced climates takes a little more lower wave heights into account and a little less higher wave heights. The distribution function of the wave direction shows that waves approach the shore predominantly from the southeast and is accurately approximated by the reduced climate due to the higher resolution of bins. In the PDF function of the peak period a clear difference can be seen in swell and sea waves: two small peaks. Since the wave buoy concentrates measurements of the wave period to fixed values, the distribution function shows isolated bars.

The distribution functions are obtained by the Kernel density estimation, using a Scaled Triweight Kernel 'K' (Dekking, Kraaikamp, Lopuhaa, & Meester, 2005). For step size 'h' an effectively used formula, is used as a first approximation, $h = 1.06\ sn^{-1.5}$, with 's' as the standard deviation of the dataset and 'n' the number of samples. The formula is smoothened by using a larger 'h', which can be seen in for example the Peak Period graph. For the significant wave height and the wave direction smooth PDF and CDF function are found, which can be used to drawn from the distribution to get a representative climate.

One needs to keep in mind that these values are 3-hourly averages from the wave buoy, which means that in these three hours of course some variations occur. Another uncertainty is the way of measuring by the instruments at the buoy. For the peak period it can be seen that the device outputs only a few values, which diminishes the accuracy level. This is assumed to be a shortcoming of the device. It is also shown in the PDF/CDF function. However, for this study an average wave climate is required, which means that the above mentioned shortcomings can be neglected.

B.1.2 Extrapolating the buoy record to deep water

The Waverider buoy is located at approximately 30meters depth, which is close to the coast. Waves are deformed before they are recorded mainly due to refraction. This is shown by a calculation for the average wave conditions. The average peak period is approximately 10 seconds. Assuming that the recorded waves are deep water waves with a mean peak period of 7 seconds yields a ratio of approximately 0.5 for the depth over the wave length (d/L). If those values are used according to the arbitrary wave formula, see equations below (Holthuijsen, 2009), a wave length of 76.5meters gives a ratio d/L equal to 0.39.

Equation B-1 Linear wave dispersion

$$L = \frac{gT^2}{2\pi}\tanh(kd)$$

$$k = \frac{2\pi}{L}$$

Since waves are in deep water for the ratio d/L > ½ most of the waves already feel the bottom and therefore is said that the wave buoy is located in arbitrary water. Waves are already loosing energy or distributing energy along the wave crest. This gives a distorted picture of the waves measured at the buoy at 30meters depth. For wave modeling the wave boundary lies in deep water at the edge of the continental shelf. In that way waves can propagate over the continental shelf into shallower water and all relevant processes affecting the waves are taken into account. Local wave climates are obtained in the near shore, which vary along the coastal stretch of 45kilometers. The waves from the wave buoy are therefore extrapolated towards deeper waters by a ‘backwards’ calculation of wave propagation, accounting for refraction and shoaling. In the script below the equations are given for this backward calculation. A depth of 30meters is assumed, from where the waves are recorded. The orientation of the contour lines is 128degrees. By assuming linear depth contours in the nearshore the orientation of the contour line is aligned with the shoreline orientation. In this way the wave direction in degrees north is translated into the incoming wave angle ‘theta’, see Figure B-5.

All energy of the waves will be contained. A harmonic wave retains its period in a situation with no current and fixed seabed topography. Hence the deep water wave length, velocity and group velocity can be calculated. With Fenton (1988) (Holthuijsen, 2009) the wave number ‘k’ in intermediate depth can now be calculated, which is needed to calculate the wave group velocity in intermediate water. Shoaling is the process in which the wave group velocity will decrease if a wave arrives in shallower water under the above described circumstances. The energy will be retained and therefore the wave height will increase. At the moment a harmonic wave enters shallower water under an angle, over the wave ray a gradient in wave velocity can be found, because the wave velocity becomes dependent on the water depth. This results in a rotation of the wave towards the coast. Using factors for shoaling and refraction, the waves are calculated backwards, until the moment they don’t change anymore.

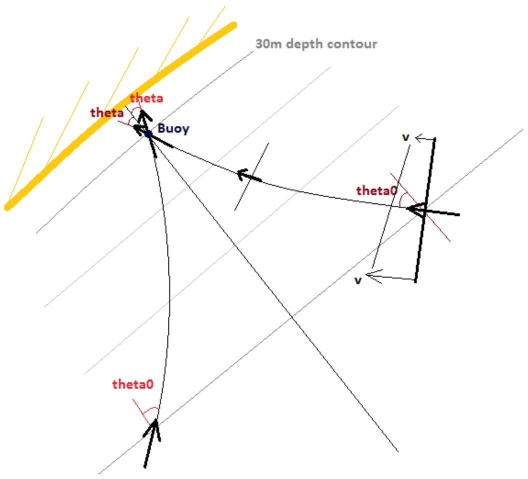
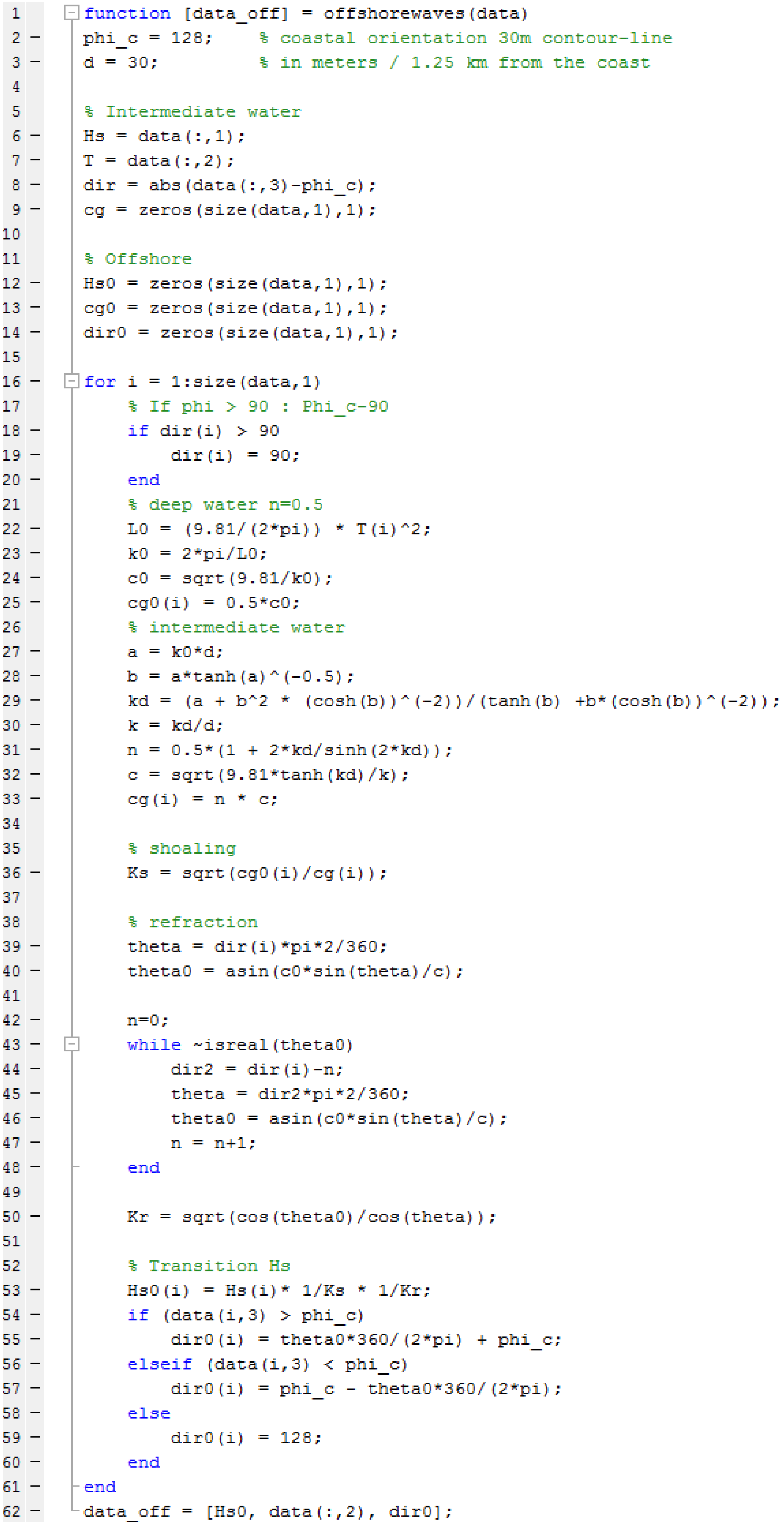


Figure B-5 Wave refraction



```
function [data_off] = offshorewaves(data)
phi_c = 128;    % coastal orientation 30m contour-line
d = 30;         % in meters / 1.25 km from the coast

% Intermediate water
Hs = data(:,1);
T = data(:,2);
dir = abs(data(:,3)-phi_c);
cg = zeros(size(data,1),1);

% Offshore
Hs0 = zeros(size(data,1),1);
cg0 = zeros(size(data,1),1);
dir0 = zeros(size(data,1),1);

for i = 1:size(data,1)
    % If phi > 90 : Phi_c-90
    if dir(i) > 90
        dir(i) = 90;
    end
    % deep water n=0.5
    L0 = (9.81/(2*pi)) * T(i)^2;
    k0 = 2*pi/L0;
    c0 = sqrt(9.81/k0);
    cg0(i) = 0.5*c0;
    % intermediate water
    a = k0*d;
    b = a*tanh(a)^(-0.5);
    kd = (a + b^2 * (cosh(b))^(-2))/(tanh(b) +b*(cosh(b))^(-2));
    k = kd/d;
    n = 0.5*(1 + 2*kd/sinh(2*kd));
    c = sqrt(9.81*tanh(kd)/k);
    cg(i) = n * c;

    % shoaling
    Ks = sqrt(cg0(i)/cg(i));

    % refraction
    theta = dir(i)*pi*2/360;
    theta0 = asin(c0*sin(theta)/c);

    n=0;
    while ~isreal(theta0)
        dir2 = dir(i)-n;
        theta = dir2*pi*2/360;
        theta0 = asin(c0*sin(theta)/c);
        n = n+1;
    end

    Kr = sqrt(cos(theta0)/cos(theta));

    % Transition Hs
    Hs0(i) = Hs(i)* 1/Ks * 1/Kr;
    if (data(i,3) > phi_c)
        dir0(i) = theta0*360/(2*pi) + phi_c;
    elseif (data(i,3) < phi_c)
        dir0(i) = phi_c - theta0*360/(2*pi);
    else
        dir0(i) = 128;
    end
end
data_off = [Hs0, data(:,2), dir0];
```

B.1.3 Modeling settings

B.1.3.1 Computational grids

Three computational grids are made in the Delft3D-RGFGRID software. The curvilinear grids are aligned with the coast. The grid resolution is coarse for deep water wave modeling and becomes finer for the nearshore, which is related to the relevancy of the nearshore processes.

The largest grid covers all smaller grids and is called 'Far2107.grd'. A coarse resolution is used in deep water, where waves do not significantly change. The main reason is to save computational time. One could simply say: the more grid points, the longer the computational time. In the Delft3D-RGFGRID software splines are created as boundary of the computational grid. The largest grid is bounded by the terrestrial plateau in the west and in the east by the edge of the continental shelf at approximately 120meters depth. On both boundaries in the north and south the computational grid is extended by approximately 20kilometers relative to the studied area. This is done to diminish unexpected physical effects at areas close to the boundaries. The waves measured by the wave buoy are recorded on the continental shelf. As can be seen in the bathymetry, behind the edge of the continental shelf the water depth will increase significantly. By setting the boundary at the edge of the shelf, the transition and the any physical change of waves from very deep water to water at approximately 120meters depth is neglected. The shelf can be clearly seen in Google Earth, which can be confirmed by the measured bathymetry. The largest grid has a resolution of approximately 600meters by 600meters.

The middle grid, called 'Mid2107.grd', is a transition grid nested in the largest computational grid. The middle grid provides a fluid transition between the coarse large grid and the fine nearshore grid. It is a refinement of the large grid. The largest grid is six times refined. The grid has a resolution of approximately 100meters by 100meters. The middle grid is located in intermediate water depths. Due to the refinement, relevant processes such as refraction are already calculated in greater detail. Furthermore, depth files between the bathymetry are better connected to each other. A middle grid is not only created to cover the inaccurate transformation of the large grid to the fine nearshore grid. It is also an optimization of the computational time.

The largest en middle grids are created a few kilometers larger than the model area. This is done to make sure that waves have some 'space' to refract and reform. Implementation of waves directly on the boundary of studied area will be incorrect. At the northeastern and southern boundaries deep water waves are uniformly implemented over totally different depth contours, which results obviously in strong reformation of the waves. This will happen outside the studied area near the boundaries of the computational grids.

In the nearshore a fine grid is created, called 'nearFINE2107.grd', which is aligned with the coast. The splines are drawn in line with the 30meters depth contour and in line with the land boundary. This is done to align the grid lines with the coast. The nearshore computational grid has a resolution of approximately 80m shore parallel by 20m cross shore, south of the Durban Port. North of the Durban Port the resolution is approximately 60m shore parallel by 50m cross shore. The reason for the difference in resolution can be found in the fact that north of the Durban port water depths are shallower than south of the Durban Port, which lies closer the continental shelf. The nearshore grid is nested in the middle grid. This means that the calculated wave conditions at the grid points of the middle grid apply as boundary conditions for the closest point next to the nearshore grid.

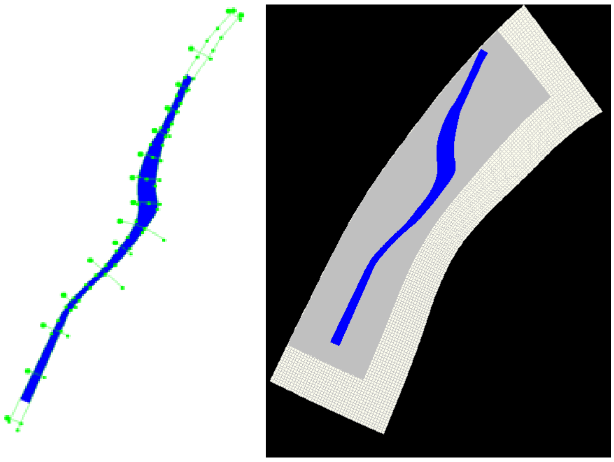


Figure B-6 Splines and nearFINE2107.grd (left) and all computational grids (right)

B.1.3.2 Bathymetry

In the Delft3D-QUICKIN software a depth file is created for the different computational grids. The depth points are based on CSIR hydrographical data and Gebco data. The bathymetry is implemented in the model as depth samples. The depth file is created by triangular interpolation using the depth samples at the grid points of the computational grid. The transition between the different data sources around the area of Amanzimtoti goes with some errors. Firstly, in the nearshore an average depth of an area of thousand by thousand meters (Gebco data) will not represent the exact depth. Secondly, the transition of higher resolution data to coarser data will have its influence on the triangular interpolation of the bathymetry. The depth contours will be formed around the 'isolated' samples from the Gebco data. A resolution of thousands of meters will not accurately approximate bathymetry around coastal headland with a length scale of hundreds of meters. In order to get a better approximation of the depth contours in shallower water, new depth samples have been created at the land boundary line. The land boundary represents the approximately +2CD line, which is implemented in the model. After interpolation the depth contours are more fluently aligned with the shore as almost shore parallel contour lines. Thirdly, in the transition area of both bathymetry sources are checked on their uniformity, which means significant differences in samples are removed. These could behave like artificial shoals or canyons and are not likely to occur around this area. Changes are made where necessary and tried to be minimized as much as possible. In the wave analysis is checked whether these artificial alterations in the bathymetry result in unexpected physical changes in the wave propagation.

In the Figure B-7 the transition area of the depth samples can be seen. The two data sources are compared and checked on their equality. In the nearshore smaller discrepancies are of major importance. In the figure can be seen that the Gebco data in the south has a coarser resolution. Further, the samples on the land boundary line, representing a 2m+MSL line can be observed. In deeper water the depth samples show less coherence between the data sources. Here samples are removed and some artificial samples are implemented. No coral reefs are found on this line or in neighboring areas. Therefore is accepted that problems with the accuracy of the data do exist and could be performed better in future research, using better and more extensive data sources for the bathymetry.

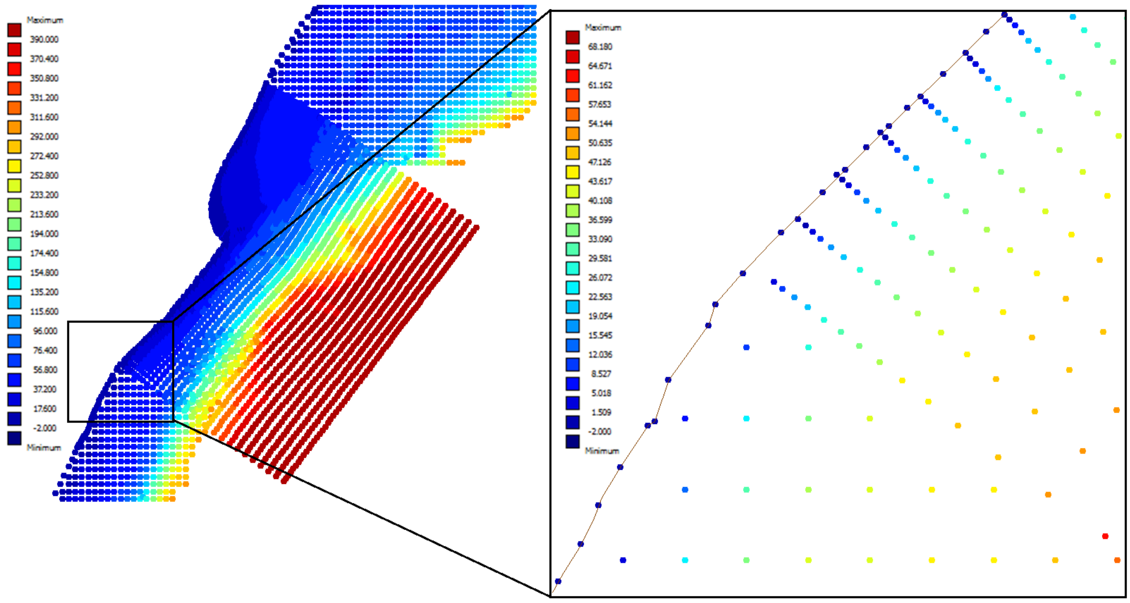


Figure B-7 Depth samples

In the Figure B-8 the depth files are shown from the nearshore computational grid and the middle grid. The depth files contain the bathymetry. In the figure the transition in water depth of the coarser middle grid to the finer nearshore grid is shown, which is fluently and not producing any additional physically unexpected errors.

The Courant Number is for the middle depth-file and larger depth-file always larger than 25. For the nearshore grid, at the locations where nearshore waves are needed the Courant Number is approximately 25 as well.

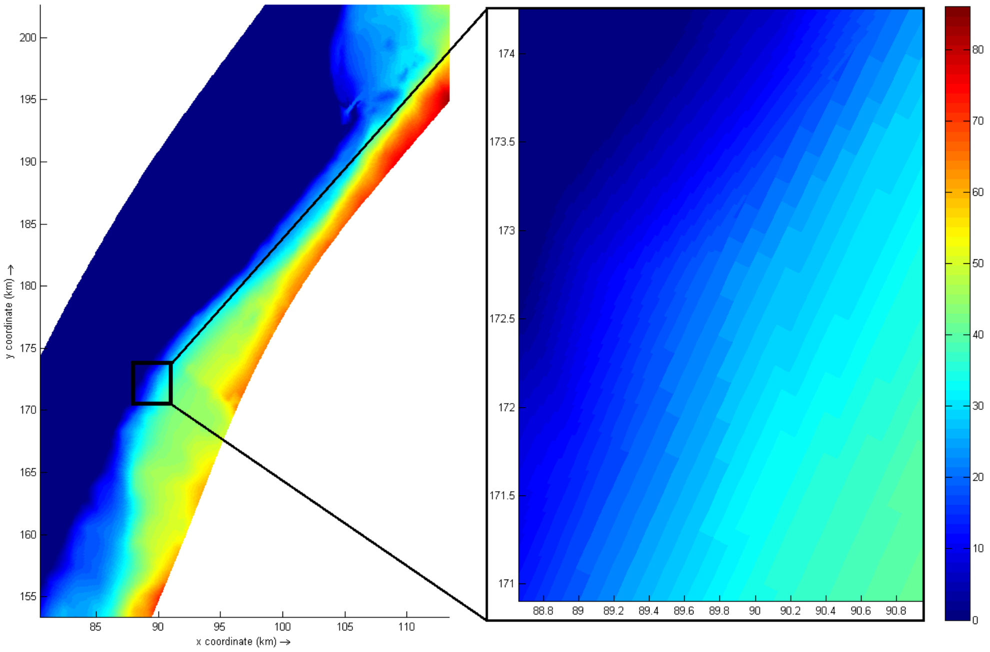


Figure B-8 Depth files Near2107.dep and Middle2107.dep

B.1.3.3 Boundaries

Unibest coupling

For the Unibest Shoreline model a representing wave climate is required. The wave climate is schematized into several wave conditions (Hs[m], Tp[s], Theta[N°]) and corresponding wind conditions (U10[m/s], Theta_wind[N°], which are all zero in this situation). Other parameters are the width energy distribution and the additional water level which is set to be zero. The spectral space factor, which determines the width of the directional energy distribution for idealized conditions, is chosen to be four for the cosine power model. For the Durban case this is arguable, because sometimes swell approaches from a different direction than the sea-waves. This is not further investigated, since every wave condition is considered separately in a parametric way. Sea waves created by local wind fields are already included in the recorded information of the wave buoy, which lies close to the shore. Wind velocity is therefore zero.

The total wave and wind climate is defined in a md-vwac file, which is added to the working directory of the wave model. The md-vwac file is coupled to the Delft3d-Wave model. In this way for all wave conditions defined in the md-vwac file, wave computations are carried out. In the Wave-GUI of the Delft3D-wave software, an equal amount of time points must be prescribed matching the amount of wave conditions in the md-vwac file.

Deep water wave conditions

The wave record information is transformed into a representative wave climate and will be set as boundary. The reduced wave climate is extrapolated into deep water, which is applicable for the deep water boundary. The deep water waves are assumed to be consistent over the total boundary. It leads to a better approximation of the local nearshore waves, which leads to a better performance of the sediment transport model.

The WaveRider buoy contains local wind-waves, generated by local winds. Most of the wind waves come from shore-parallel directions, due to the propagation line of the depressions and cut-off lows. These high frequency waves are without any transformation placed at the boundary of the model. Another possibility is to use local wind fields to re-create these wind waves. However, a correlation has to be obtained between wind and waves. For this case study it is not straightforward to get the correlation between the local winds and wind waves for reduced climates, due to the dependency of the different weather systems.

B.1.3.4 Obstacles

Obstacles are implemented in the wave model. These obstacles block waves from propagating into the Durban Bight. The obstacles do not reflect waves and therefore the obstacles do not have any influence on the nearshore waves for the Bluff shoreline. In case the Durban Bight is modeled, the breakwaters provide a sheltered zone. Also diffraction has to be included. The transmission through the obstacle will be almost none. The height of the breakwater, found in Google Earth is approximately six meters, which makes the freeboard of the breakwater almost two times the highest wave observed at the breakwater. For transmission coefficient a dam type with a slope of 1:3/2 is assumed. The dam will not reflect any waves, which could be of importance for wave modeling around the breakwaters. Furthermore, our interest points to obtain local wave climates do not lie close to the breakwaters.

B.1.3.5 Physical parameters

Default values are taken into account for gravity and minimum depth. A water density of 1025 kg/m3 is used for the ocean water. The northern direction with respect to the x-axis is 90degrees. The convention of the waves is nautical implying a wave direction in degrees north.

The following non-linear processes are incorporated in the model: depth-induced breaking (B&J)-model, non-linear triad interactions (LTA) and bottom friction. For the depth-induced breaking, the bore-based Battjes and Jansen model is used. The values for alpha and gamma are default values. Alpha is a coefficient determining the dissipation rate and is assumed to be of order 1. Gamma is the breaker parameter, which is the ratio of the wave height (before breaking) over the depth. Since nearshore wave hydrodynamics are considered non-linear traid interaction is taken into account. For alpha and beta default values are used. Alpha is the proportionality value and beta controls the maximum frequency. For more information on these processes is referred to (SWAN, 2014). For bottom friction Madsen et al. is used with a coefficient of 0.05m is chosen, which is for the South-African East Coast applicable. For white capping Komen et al. is used, which introduces energy dissipations. Furthermore, refraction is incorporated for wave propagation in spectral space.

B.1.3.6 Numerical parameters

The accuracy criteria are set as precise as possible, but taking in mind the computational effort. The higher the accuracy the more computational time is needed. The numerical parameters are not changed. All default values are used, not introducing any additional numerical diffusion.

B.1.4 Model performance

In this paragraph the performance of the model is qualitatively checked. The grid dependency is checked by extracting model output at five different locations, see Figure B-9. By comparing the modeling output per grid, the functionality of the model and the dependency on the grid is shown.

In Figure B-10 and Figure B-11 scatterplots are shown to show the dependency of the two computational grids, based on the wave height and wave direction, because these are expected to change.

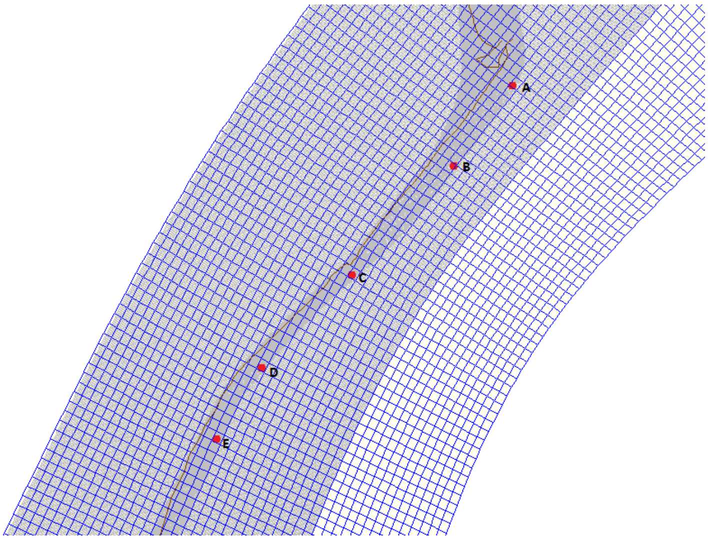


Figure B-9 Extraction points for grid dependency

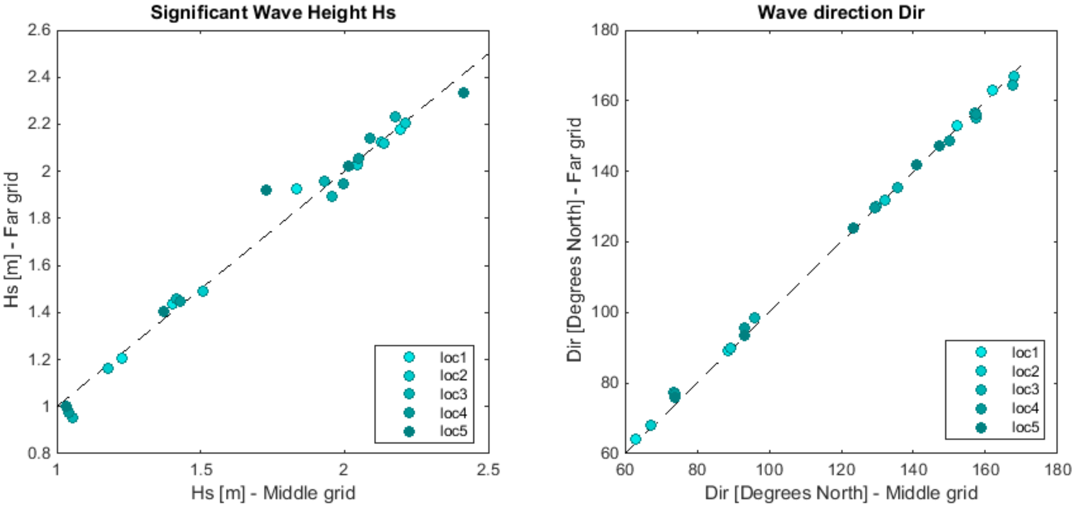


Figure B-10 Scatterplots grid dependency far grid and middle grid

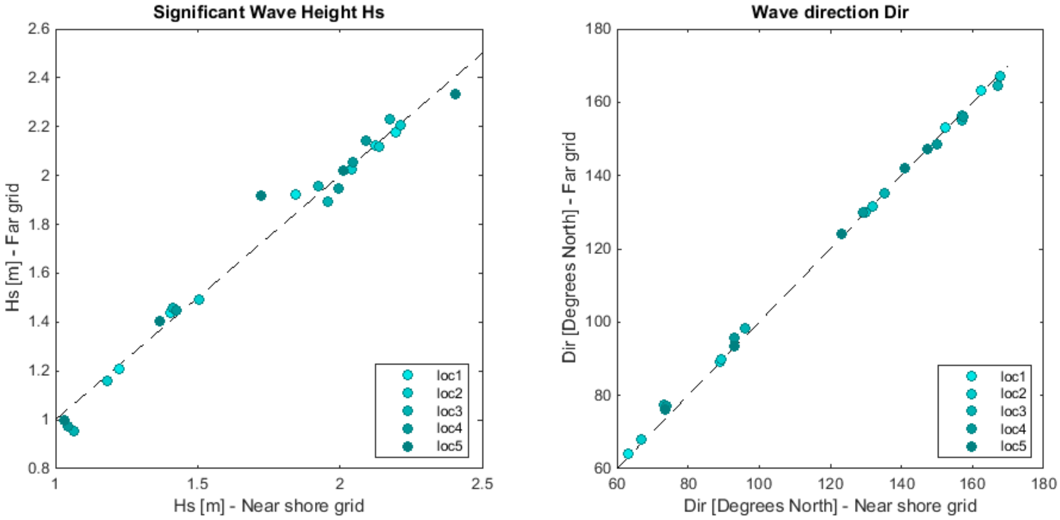


Figure B-11 Scatterplots grid dependency far grid and nearshore grid

B.2 Shoreline modeling

B.2.1 Single line theory

In this paragraph additional information on the single line theory is explained. The single line theory is the basis of the Unibest-CL+ model and is therefore an import theory. The first person who described the single line theory was R. Pelnard-Considere (1956).

An equilibrium profile of arbitrary shape is assumed, which doesn't change in time. The profile ends at the closure depth. Seaward of the closure depth, depth changes are considered to be irrelevant for shore dynamics. The depth is determined by governing wave conditions, which will have a direct effect on the profile up to this point. At this depth the profile is assumed to be horizontal, avoiding large quantities of sediment to be taken into account for a small seaward movement. Sediments are thus contained over the cross-shore profile and are only withdraw from the sediment balance due to longshore effects.

Consider a movement of the beach profile Δy over a predefined coastal stretch Δx in a certain time interval Δt. The total volume of the movement is called V. The difference of net volume of sediments entering and leaving the coastal stretch over Δt should be equal to volume of the displaced profile, following the sediment mass balance. Sediment sources or sinks are for simplicity neglected and considered to be zero. In the Equations B-2 these steps are given.

Equations B-2 Sediment balance

$$\int_{\Delta t} V\,dt = \int_{\Delta t} S_{in} - S_{out}\,dt$$

$$V = \Delta x\,\Delta y\,d$$

$$S_{in} = S_x$$

$$S_{out} = S_x + \frac{\partial S}{\partial x}$$

In Equations B-3 first the chain rule is applied. The relation between the angle of incidence 'phi' and the sediment transport 'S' is obtained, which is an important one, as we will see in the calculation of the S-Phi curves. These curves are calculated in the Unibest-LT model. The relation between 'phi' and 'x' is related to the shoreline translation, namely $\partial\varphi = -\partial y/\partial x$. By substitution of this equation, the parabolic partial differential equation is given for coastline position 'y'. This equation is solved in the Unibest-CL model.

Equations B-3 Parabolic partial differential equation for coastline position 'y'

$$\frac{\Delta y}{\Delta t} = -\frac{1}{d}\frac{\partial S}{\partial x} = -\frac{1}{d}\frac{\partial S}{\partial \varphi}\frac{\partial \varphi}{\partial x}$$

$$\frac{\Delta y}{\Delta t} = \frac{1}{d}\frac{\partial S}{\partial \varphi}\frac{\partial^2 y}{\partial x^2}$$

B.2.2 Input

B.2.2.1 Sediment characteristics

The sediment characteristics are used from a CSIR monitoring program. Every three months new samples are gathered. The d10, d50 and d90 obtained over a period of 2007 to 2012 are averaged. They are implemented in the transport formulas and used to obtain Dean's equilibrium Profiles.

Table B-2 Sediment grain sizes [mm]

Beacon	d10	d50	d90
SB4	0.355	0.591	0.967
SB5	0.403	0.615	0.978
BR8	0.452	0.758	1.176
BR11	0.494	0.745	1.583
BR13	0.304	0.603	1.110
SC12	0.367	0.652	1.236
SC14	0.431	0.848	1.380
SC16	0.300	0.611	1.178
SC19	0.304	0.522	0.867
SC22	0.317	0.609	1.068
SC24	0.259	0.443	0.939
SC28	0.269	0.486	0.849
SC30	0.312	0.608	1.137

B.2.2.2 Cross-shore profile

In this paragraph is explained how the cross-shore profiles are obtained. Since there are no cross-shore profiles for the Durban Bluff available, the profiles are tried to be created out of limited existing data. Available data consists of bathymetry and dry beach profiles. Levels are relative to Chart Datum (CD). The bathymetry consists of annually monitored bathymetry by CSIR and Global Gebco data. The bathymetry is relatively coarse, compared to the features along the coast, such as the headlands. These are not reflected at all. Furthermore, beach profiles are available, which cover the area of +8m CD to +1m CD. Beach profiles are regularly measured along the total coast. They are measured at Beacon points, which are not located uniformly along the coast. For most of the beach profiles +1m CD is the lowest vertical measuring level.

Using the shoreline orientation at the locations of the beach profiles, a line is drawn into deeper water over the measured beach profile. By interpolation from the existing bathymetry the depths at points on this line can be found. The shoreline angle is obtained at the location of the beacon points with the vegetation line. Due to the coarse measurement points of the bathymetry, a slight difference in the coastal angle could make a large error. Since the sediment characteristics are known for the beach profiles, a Dean profile is created too.

Equation B-4 Dean Profile

$$W_s = 1.6\sqrt{(2.65-1)*9.81*D} \quad Fall\ velocity$$

$$A = 0.5 * W_s{}^{0.44}$$

$$h = -A * x^{\frac{2}{3}}$$

$$D:\ d50\ sediment\ grainsize[\mu m]$$

$$x:\ distance\ offshore[m]$$

$$h:\ height\ profile\ [m]$$

The Dean rule is a general way of getting an equilibrium profile out of the characteristics of the coast, like the sediment grain size, and viscosity of the water, see Equation B-4. Uniform sandy beach conditions are assumed neglecting the existence of rocky outcrops. Bottom profiles are obtained at locations where an open and rather uniform coastline is observed in Google Earth.

In Figure B-12 four different equilibrium profiles are presented with their locations. The profiles at the Durban Bluff, SB4 and B13, are smoothly approximated following the equilibrium Dean profile. In the south the profiles are gentler and the Dean profile does not approximate the obtained profile accurately, see for instance profile SC24. However, for the first eight meters the profiles are comparable and therefore considered to be acceptable input for further modeling.

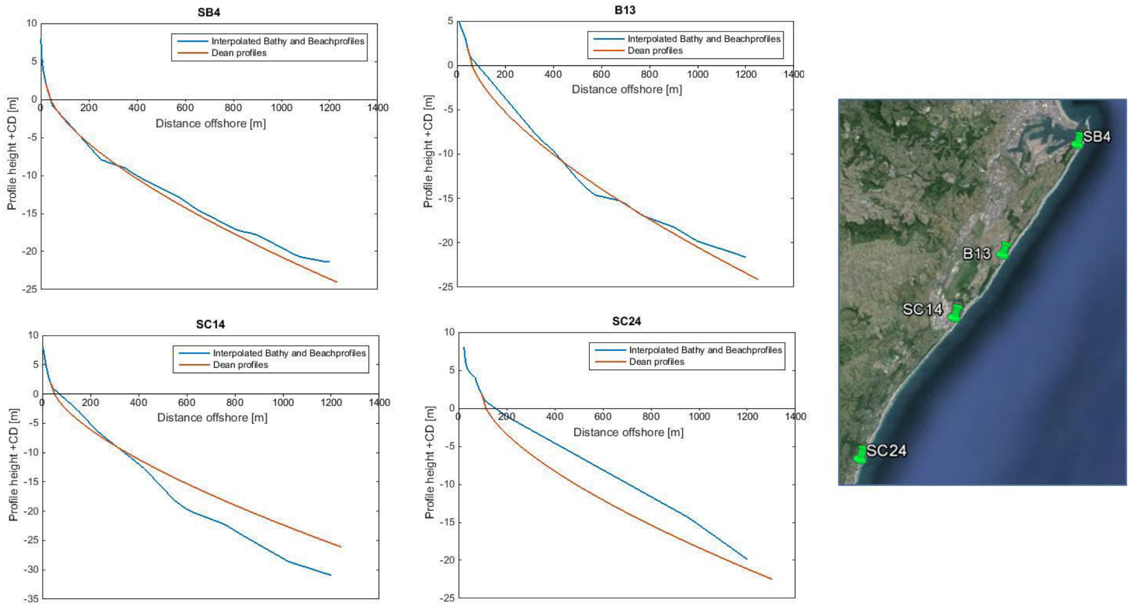


Figure B-12 Cross-shore profiles South Durban

B.2.2.3 Approval reduced representative wave climate

In the Paragraph 3.2.3 of the main report and in Appendix B.1.1 the method to get representative wave climates at different locations in the nearshore along the South Durban coast and the utility of it is explained. In this paragraph is checked whether this method is correct. A reduced wave climate has to give equal sediment transports compared to a total wave climate under the same conditions. To be sure that these transports match, sediment transport rates are calculated for three different positions along the coast with the total climate of 2008 and the reduced climate. The 'Kamphuis'-formula is used for the calculations.

The total 2008 climate is used for this analysis, because it matches the total data set. In Figure B-13 histograms are given, where a probability density function could be obtained from. They show that 2008 was an average year. The sediment transports obtained from the total year 2008 are compared with the sediment transports obtained with the reduction method of this total year.

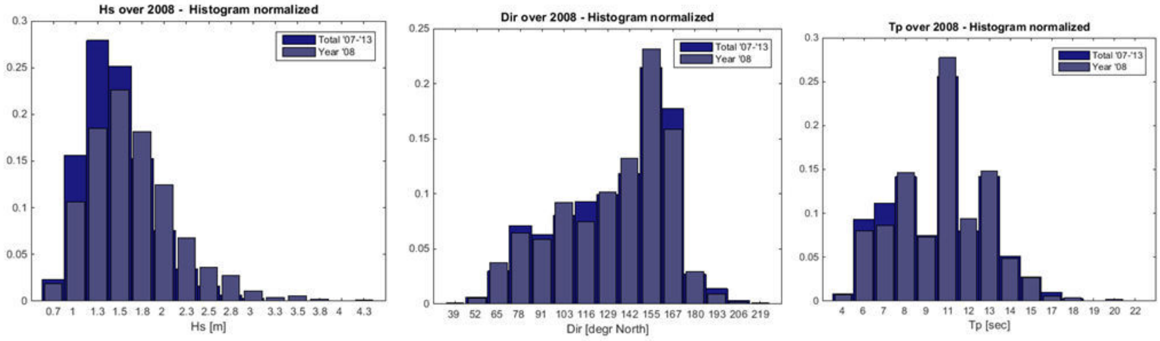


Figure B-13 histogram total dataset and 2008

The total year is compared to the reduced climate in terms of gross and net transports. For a point close to the sediment sand trap, where the 500,000m^3/year of Schoonees is based on, the sediment transport rates are calculated, see Figure B-15. The total climate and the reduced climate approximate the target value reasonably. However, the reduced climate has some smaller transports compared to the total climate. More reduced climates are analyzed by using different ratios between the wave characteristics. The presented representative climate showed the best results.

Figure B-14 Location sediment transports

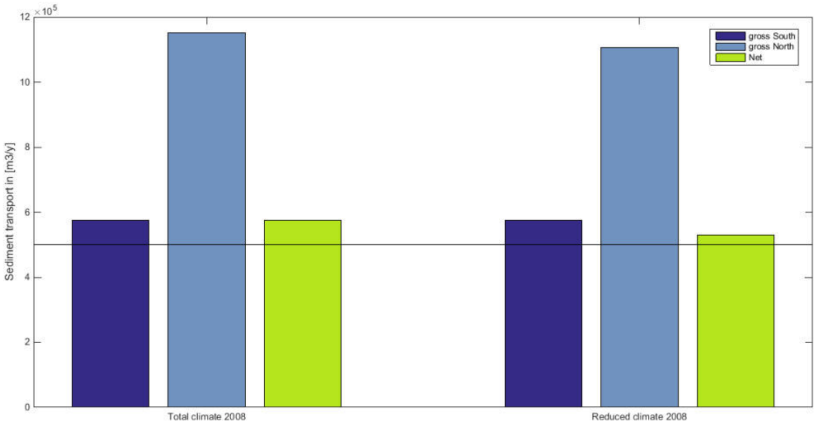


Figure B-15 Sediment transports 'Gross Southward / Gross Northward / Net'

Downsides

The simplicity of reducing a wave climate by binding the wave characteristics by a certain amount of bins with equal width has its downsides. One can understand that if larger bins are chosen, data is averaged over a larger area, which creates a less accurate climate. On the other hand, small bins lead to many conditions, which is not desirable as well due to computational efforts. The ratio between the different bins per wave characteristic could change the representative climate. As could be seen in the previous paragraph, there are some correlations between the wave characteristics. These are wanted to be reflected in the representative climate. Larger bin widths will diminish these correlations.

The use of the 2008 climate is not statistically supported. However, the analysis is done to check whether a total climate could be represented by a reduced climate. A little less northward longshore sediment transports is obtained, which is acceptable, but should be kept in mind in the rest of the research.

B.2.2.4 Hydrodynamics in the surf zone: model and accompanying coefficients

In this paragraph a short summary is given about the hydrodynamic models implemented in the Unibest LT module. In Unibest-LT the hydrodynamics in the surf zone are modeled by the random wave propagation and decay model (Battjes & Janssen, 1978), calibrated and verified based on an extensive set of data (Battjes & Stive, 1984). The model transforms the offshore wave data to the coast, based on the principles of the momentum balance and wave energy balance, incorporating processes as refraction, shoaling and energy dissipation by wave breaking and bottom friction. The longshore current distribution over the cross-shore profile is derived from the momentum balance, which is induced due to the cross-shore gradients in the shear component of the radiation stress in longshore direction.

To determine the dissipation component over the surf zone two aspects are distinguished. Namely, the rate of energy dissipation in periodic breaking waves and the probability of occurrence of breaking waves of given height in a random wave field. Energy dissipation in breaking waves is approximated based on a bore of the same height. The equation below shows the outcome of this approach.

$$D \sim \frac{1}{4} f \rho g {H_b}^2 \quad energy\ dissipation$$

In de equation ‘f’ is the frequency for the assumed periodic waves and ‘H_b’ is the wave height at wave breaking. ‘H_b’ is equated by the depth-limited height of periodic waves ‘H_m’ in water of local mean depth. This is based on the Miche-breaker index and where the wave breaking parameter gamma ‘γ’ comes from.

The local fraction of wave breaking ‘Q’ is generated by assuming a Rayleigh type of probability distribution function for all breaking and non-breaking random waves, cut-off by ‘H_m’. ‘Q’ can be written as function of $f(\frac{H_{rms}}{H_m})$. The total function and derivation is not shown and can be found in the paper of Battjes & Janssen itself. The described findings can be included in the bore-type energy dissipation function, see equation below.

Equation B-5 Energy dissipation - Wave breaking

$$\overline{D} = \frac{1}{4}\, \alpha\; Q\; f_p\; \rho g\; {H_m}^2 \quad energy\ dissipation$$

In the equation ‘α’ is the coefficient for wave breaking, which is of magnitude one and has to be reviewed for each specific case. Now a dissipation function is found, this is implemented as sink into the wave energy balance in its most reduced form (statistically steady, uniform along the coast and no other sources or sinks), see equation below.

Equation B-6 Energy balance

$$\frac{\partial P_x}{\partial x} + \overline{D} + D_f = 0$$

In the energy balance ‘P_x’ is the onshore energy flux, approximated as ‘Ec_g’, in which $E = \frac{1}{8}\rho g H_{rms}^2$ and c_g is the wave group velocity. In the energy balance also energy dissipation by bottom friction is taken into account. In the equation below the wave induced energy dissipation by bottom friction is shown.

Equation B-7 Energy dissipation - Bottom friction

$$D_f = \frac{1}{8}\rho f_w \pi^{-0.5} \left[\frac{\omega_r H_{rms}}{\sinh(kd)}\right]^3$$

In the equation ‘f_w’ is the bottom friction coefficient, where for a realistic value of 0.01 [-] is assumed.

The total energy balance is integrated over the surf zone, simultaneous with the momentum equation over the surf zone. A longshore shear stress in induced by obliquely incoming waves, which provides the longshore current.

Besides, the wave induced dissipation, also currents, such as tides can be implemented in the model. These are not used and therefore not discussed in detail in this research. In Soulsby et al. (1993) eight different wave-current interaction models are evaluated and parameterized for modeling. These can be implemented to obtain the stress term in the momentum equation, which consists of a current-only and wave –only stress term. In the manual of Unibest most of the background information on the wave-current interaction model can be found.

B.2.2.5 Transport Formula

In this analysis only wave generated-currents are included to compute longshore sediment transports. Bulk longshore transport formulas, which give the transport over the surf zone are investigated. Longshore sediment transport is thus driven by wave generated longshore currents due to obliquely incident wave breaking. The longshore current carries sediments, which are stirred by the orbital motion of waves and the turbulence of the wave breaking.

Three longshore sediment transport formulas are evaluated to check which formula is most applicable for the Durban Bluff. Target value is the net longshore sediment transport obtained by Schoonees (2000) through an evaluation of the dredged volumes of the sand trap at the Durban Port. Furthermore is checked whether gross and net sediment transports lie in a range of expected values. Expectations are created by the potential transports based on wave conditions from obtained nearshore wave information, the fact that the shoreline position remains relatively stable over a long period and discussions with experts from the CSIR.

Following an expert of CSIR, the Kamphuis formula shows reasonably well results for the Durban coast. The Kamphuis formula is shown in the main report. The CERC formula is the most widely applied formula and is for this reason included in the analyis, see Equation B-8. A paper by CSIR about the longshore transport analysis of the Durban Bight used the Bijker formula, see Equation B-9, for shoreline modeling, which seemed to give reasonable results for the Durban wave climate. Therefore this sediment transport formula is used as well.

Equation B-8 CERC formula

$$S = A\, H_{s0}\, 2\, C_{g0} \sin \emptyset_b\, cos\, \emptyset_0$$

$$\mathrm{A} : 0.02\ [-]$$

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

$$C_{g0} : group\ velocity\ waves\ at\ deep\ water\ \left[\frac{m}{s}\right]$$

$$\emptyset_b : wave\ angle\ at\ breaker\ depth\ [deg]$$

$$\emptyset_0 : wave\ angle\ at\ deep\ water\ [deg]$$

Equation B-9 Bijker formula

$$S = S_b + S_s$$

$$S_b : bed\ load\ sediment\ transport$$

$$S_s : suspended\ load\ sediment\ transport$$

$$S_b = bD_{50}\frac{v}{C}\sqrt{g}\,e^{\left[\frac{-.27\,\Delta D_{50}C^2}{\mu v^2\left\{1+\frac{1}{2}\xi\left(\frac{u_b}{v}\right)^2\right\}}\right]}$$

D_{50} =median (50%) grain diameter (m)

D_{90} =90% grain diameter (m)

Δ =relative density

r_c =bottom roughness ($\approx$0.5-1.0 times ripple height (m)

ρ_s =sediment's density

w =sediment's fall velocity (m/s)

u_b =orbital velocity near the bottom (m/s)

ω =wave frequency (rad/s)

From these parameters the following bottom parameters are derived:

C =Chezy coefficient = $18\log(\frac{12d}{r_c})$

C_{90} $=18\log(\frac{12d}{D_{90}})$

μ $=(\frac{C}{C_{90}})^{3/2}$

f_w $=e^{\left[-5.977+5.213(\frac{u_b}{\omega r_c})^{-0.194}\right]}$

ξ $=C\sqrt{\frac{f_w}{2g}}$

Results

Four locations along the South Durban coast with different coastal angles are considered. In Figure B-16 the gross and net longshore sediment transports (m^3/year) are shown calculated with three discussed transport formulas. All three formulas compute northward sediment transport for all three locations, which is as expected. Location A lies close to the Durban Port, where Schoonees (2000) determined the net longshore sediment transport to be 500,000m^3/y based on the monitored volumes of dredged sediments from a sand trap. From this analysis can be learned that the Kamphuis formula approximates the determined net longshore sediment transport within a 20 percent uncertainty range, which is what experts of the CSIR considered to be acceptable. The net longshore sediment transports over the different locations for the Kamphuis formula do not vary significantly, which is expected considering the relatively straight shoreline and moderate bathymetric changes. The CERC formula shows relatively similar results, except for location D, which is located in the southern part of the researched area. The Bijker formula gives a large variation in net longshore sediment transports over the total system, plus large gross transports. It does not approximate the target value of the net longshore sediment transport at location A well. Kamphuis approximates the target value the best. Add to that the experienced notes of some senior people from CSIR, the Kamphuis formula is chosen for further modeling.

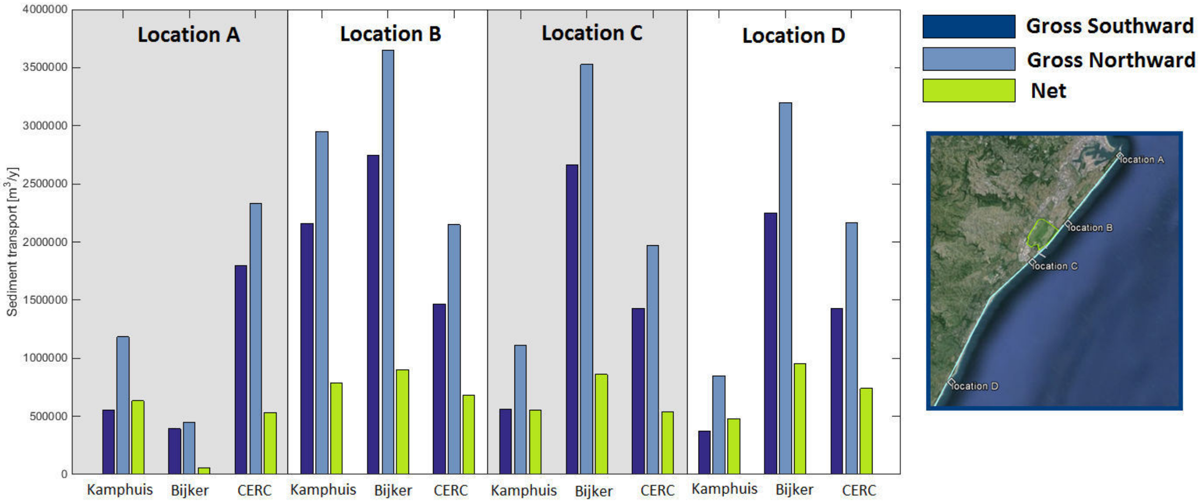


Figure B-16 Transport formula analysis

B.2.3 Output

B.2.3.1 S-Phi curve

The S-Phi curve or transport curve contains information about the net longshore sediment transport on a certain location along the coast. In the Kamphuis formula the net longshore sediment transport is proportional to the input variables consisting of the wave height, wave period, wave direction and sediment characteristics. The wave characteristics are based on a representative annual wave climate, which are constant in time, just like the sediment characteristics. The angle of incidence of the waves is not only dependent on the wave direction of the local wave climate, but also on the orientation of the coastline. Given a relatively constant wave climate along a stretch of coast, variations in the coastline orientation result in gradients in the longshore sediment transports. The relation between the net longshore sediment transports and angle of incidence is a central concept in shoreline modeling. In Bosboom & Stive (2013) this is explained as well and several examples can be found for applying the method of the transport curve on a beach with different coastal structures.

In Figure B-17 an example of the S-Phi curve is shown, with on the x-axis the coastline orientation 'Phi' and on the y-axis the net longshore sediment transport 'S'. In the 1D shoreline model (the Unibest-CL module) changes in the orientation of the coastline in time are researched under a representative annual offshore wave climate, therefore on the x-axis the coastline orientation is shown. In the situation below the equilibrium coastline orientation is found to be 140degrees north. Under these circumstances the net longshore sediment transport is zero; the wave direction is on average directed shore normal. The green line shows the actual coastline orientation of 135degrees north, yielding a net longshore sediment transport of approximately 500,000m^3/year. Under the constant wave climate for different coastline orientations the net longshore sediment transport is computed, which creates the S-Phi Curve. In Unibest LT this curve is approximated and saved in a file, which is used in the Unibest CL module, where the net longshore sediment transports by a change in the coastline orientation can be calculated. In Unibest LT the transport curve is approximated by the analytical function:

Equation B-10 Schematization S-Phi curve

$$Q_s^a = c_1 \theta_r e^{-(c_2 \theta_2)^2}$$
$$\theta_r = \theta - \theta_e \; is \; relative \; coastal \; angle$$
$$and \; \theta_e \; is \; the \; equilibrium \; angle$$

The coefficient ‘c_1’ and ‘c_2’ are determined by the method of the least squares. The parameters above are stored in the .RAY files, which are the main output of Unibest LT and serves as input in the Unibest CL module.

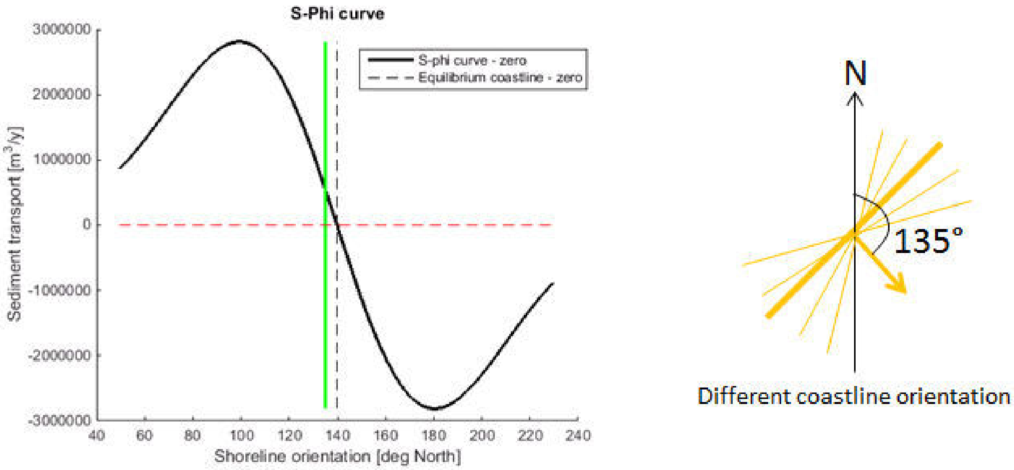


Figure B-17 S-Phi curve

C. Durban DigOut Port

C.1 Coastal change around shore-normal structure

In the scenario analysis interventions in the coastal zone are elaborated on. Two of these interventions are breakwater designs for the projected Durban DigOut Port. The effect of different breakwater lengths on the adjacent shoreline orientations is investigated. Points of interest are the angle of the shoreline after implementation of the breakwaters, the maximum retreat of shoreline due to erosion on the lee side of the breakwaters and the length of this erosion along the shore. In order to obtain information on these interest points, not only the breakwaters have to be implemented into the model, but also some additional local wave rays. Diffraction plays a role in the formation of the shore in the shadow zone of a breakwater. In this subsection is explained how these local wave rays are obtained and how they are implemented into the model.

Two designs of the breakwaters are used. One of the designs is based on the ‘Long’ design concept of the Project Durban group (ProjectDurban et al., 2014). They have proposed a southern breakwater of 1885meters long, stretching out into approximately 35meters deep water. In the group’s design, the breakwaters have a slight bend to make sure that the entrance is not aligned with the dominant wave direction from the South-East. The northern breakwater has a length of 1085meters and bends slightly to the south. The second design of the breakwaters is the ‘short breakwaters’ option. The advantage of shorter breakwaters lies in the costs, mainly because of the steep slope. However, more waves will propagate into the harbor, what could make berthing difficult in certain conditions. In this research is investigated whether the shorter breakwater have a different influence on the shoreline. The dimensions of the short breakwaters are 1200meters for the southern breakwater and 450meters for the northern breakwater.

C.1.1 Coastal change near breakwaters due to longshore transport

In both designs the Durban DigOut Port has got two breakwaters. South of the entrance channel a longer breakwater due to the larger swell wave from the south and in the north a shorter breakwater, protecting the harbor of wave from the northeast. These have to provide the vessels calmer waters by entering the port and preventing large displacements of the water surface at the berthing places. They also yield calmer waters at the opposite side of the breakwaters, resulting in sheltered zones where diffraction plays a role.

The prevailing wave direction is from the southeast resulting in a net northward longshore transport. The waves from the south are called primary waves. However, mainly during summer, sea waves from the northeast provide a gross southward longshore transport, as is investigated in the sediment transport paragraph. These are called secondary waves. After implementation of the breakwaters, the net northward longshore transport is blocked and at the up drift side (at the southern breakwater) an accumulation of sediments starts to build on the shore in a seaward direction. Until sediments will bypass the tip of the breakwater this buildup of sediments continues. On the other side, the initial cut off of the net sediment transport direction (no bypass is considered yet), results in zero sediment input from the south, while outside the shadow zone of the down drift longshore transport is demanding sediments. This results in erosion.

Besides the general erosion/accretion patterns around the groyne, some secondary effect will occur. For example, waves from the north are blocked at the up drift side of the southern breakwater, which enhances net longshore transport near the breakwater, because waves are only approaching from the south. A gradient in longshore transport initially results in some erosion at the updrift side. At the down drift side (at the northern breakwater) waves from the south are blocked, which also leads to local accretion next to the breakwater due to the gross southward longshore transport. These phenomena occur obviously on both sides. Diffraction plays a role as well, because waves from the south will diffract and lead to a different local wave climate. This climate will form the shoreline in the shadow zones of the breakwater.

Since in this study large breakwaters are implemented due to the energetic wave climate and because the gross northward transport is fed by waves predominantly from the south – southeast, diffraction will play a role in the eventual orientation of the coast.

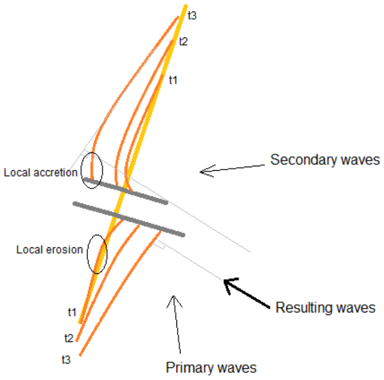


Figure C-1 Coastal changes around breakwater

C.1.2 Diffraction process

Diffraction is the process where the energy of incoming waves is distributed towards the shadow area behind, for example, a static structure. In this case they meet a maritime structure, which is a groyne perpendicular towards the coast, where they can't pass. Part of the wave crest will be reflected by the structure and part of the wave crest will propagate pass the tip of structure. Subsequently, wave energy will shift along the wave crest into the shadow zone behind the structure. The redistribution of wave energy yields a decline in wave height in the shadow zone, but also just outside this zone. Besides, the waves get a typical circular pattern in the shadow zone, resulting in a change in wave direction relative to the initial wave crest.

In this study diffraction is taken into account based on equations by Kamphuis (1992). In the book section Kamphuis determines diffraction coefficients by linear regression of irregular wave data (Goda, 1985), see Equation C-1. The coefficients are made for three zones: the shadow zone and two zones outside the shadow zone. These coefficients are used to calculate the effect of diffraction on the actual wave height without diffraction. For the change in wave direction a circle is assumed with its center on the wave ray (border of the shadow zone). In Figure C-2 the diffraction process can be seen for a situation to calculate the wave diffraction for location 'P' outside the breaker zone.

Equation C-1 Diffraction equation Kamphuis (Kamphuis, 1992)

$$\theta = \delta - \alpha_s$$

$$K_d = 0.69 + 0.008\,\theta \quad for \quad 0 \geq \theta > -90$$

$$K_d = 0.71 + 0.37\,sin\theta \quad for \quad 40 \geq \theta > 0$$

$$K_d = 0.83 + 0.17\,sin\theta \quad for \quad 90 \geq \theta > 40$$

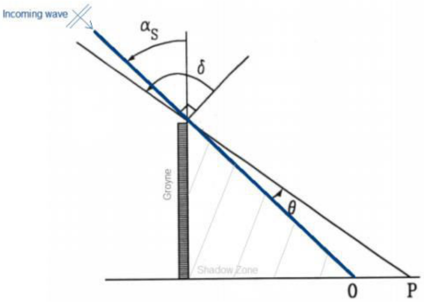


Figure C-2 Diffraction Kamphuis (Kamphuis, 1992)

C.1.3 Local wave rays – Unibest model

Local wave climates are obtained in the Unibest model distributed on key positions on both sides of the breakwaters at 5meters depth. In this way refraction phenomena are already taken into account. The distribution of the positions of the local waves can be seen in Figure C-3. Close to the breakwater the concentration of local wave ray is higher to emphasize the secondary phenomena. This method is not fully correct. The local waves obtained from 5meters depth are already refracted, which means that at the tip of the breakwater at 25meters depth a wave could have been exposed by diffraction. For the obtained local wave rays close to the structure, the diffraction process is leading and therefore the wave angle and height is not strongly dependent on the variation in wave direction due to refraction. However, further away from the breakwater a grayish area or transition area can be observed, where diffraction and refraction both play an equal role. Far away from the breakwater refraction plays a leading role.

In particular the gray area introduces some errors. For this research, it assumed that these are acceptable. In a perfect situation the diffraction and refraction phenomena, and the interaction between both, are included in a wave model. However, to save computational time, this has not been executed.

Figure C-3 Local wave ray locations 'Long breakwaters'

Diffraction is taken into account for each side of both breakwaters. Waves from the south will diffract at the southern breakwater tip; the northern breakwater lies already in the total shadow zone of these waves. For three local ray files, which lie closest to the northern breakwater in the shadow zone, diffraction mechanisms from the southern breakwater are included. It results in lower wave heights for waves from the south. The effect for other wave rays is minor. The local wave ray files are implemented as an 'offshore wave climate' and as explained in the above method, diffraction is taken into account by the Kamphuis coefficients. Basically, the wave climate is implemented in a basin with equal depth. The effect of diffraction is calculated and subtracted from the wave ray 'without breakwater'. This linear way of adding is not correct, because diffraction and refraction processes are correlated. However, nonlinear processes which will have a minor effect in this study are not taken into account.

C.2 Verification accumulation shoreline model at Durban DigOut Port

For ray SC14, just on the up drift side of the breakwater, a net yearly longshore transport of 500,000m^3/year can be found. Assuming no losses, yearly 500,000m^3 will be deposited on the up drift side of the breakwater. After five years this will be 2,500,000m^3. The beach profile of SC14, see Figure C-5, shows that 200meters seawards of the waterline a depth of approximately 6meters can be found. Figure C-4 is a clarification of the accretion, modelled with the shoreline model. It shows the accretion pattern after 5years.

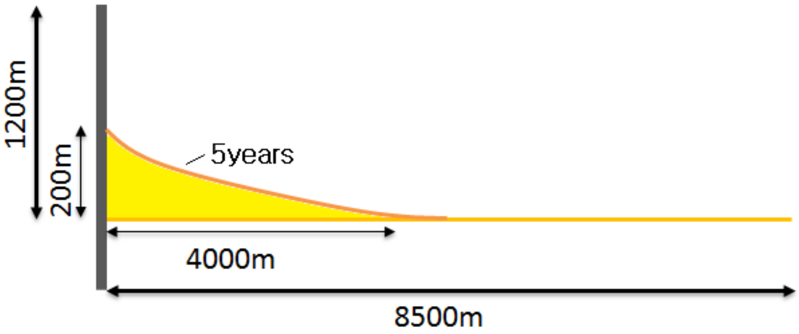


Figure C-4 Top view of accretion DigOut breakwater after 5years

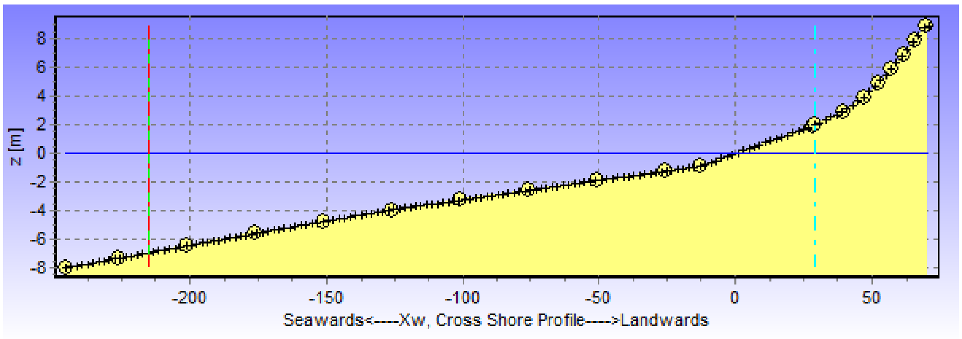


Figure C-5 Beach Profile SC14 beacon

A simple calculation shows that the accreted volume is of an equal amount as the incoming sediment volume, which verifies the model outcome:

Equation C-2 Accreted volume after 5 years

$$A = 200 * 4000 * 0.5 = \ 4.0 * \ 10^5 \ \ m^2$$
$$V = A * d = 4.0 * \ 10^5 * 6 = 2.4 * 10^5 \ m^3$$
$$IN = 500{,}000 \frac{m^3}{year} * 5 \ years = 2.5 \ * 10^5 \ m^3$$

C.3 Local groyne field at DigOut Port location

The groynes are used as an alternative to mitigate erosion effects on the lee side of the breakwaters. In this paragraph design of the groynes is elaborated on. The local groyne field is located between the northern breakwater and the Umlazi Canal and prevents the refinery from erosion. Over the groyne field coastal erosion occurs with a rate of 50,000m^3/y, as can be seen by the green lines in Figure C-6. To cover the 50,000m^3/y loss of sediment over the local groyne field, this amount of sediments has to be captured by the groynes to make sure that the incoming sediments equal the outgoing sediments. For the determination of the groyne length the Unibest LT model is used to gain information about the cross-shore distribution of the longshore transport. This is necessary to know what an effective length of the groyne would be. The groynes are assumed to be impermeable, which means that they will block 100 percent of the sediment over their length. Also the profile is taken into account, because the groyne is preferably situated over the inner surf zone between the shore and the trough of a seaward bar formation. However, as can be seen in Figure C-7, a bar is lacking in the profile. The 10% blockage percentage of the net longshore sediment transport is assumed to be sufficient to capture sediments to pin the shoreline without too much length of the breakwater. Therefore a length of 60meters is used.

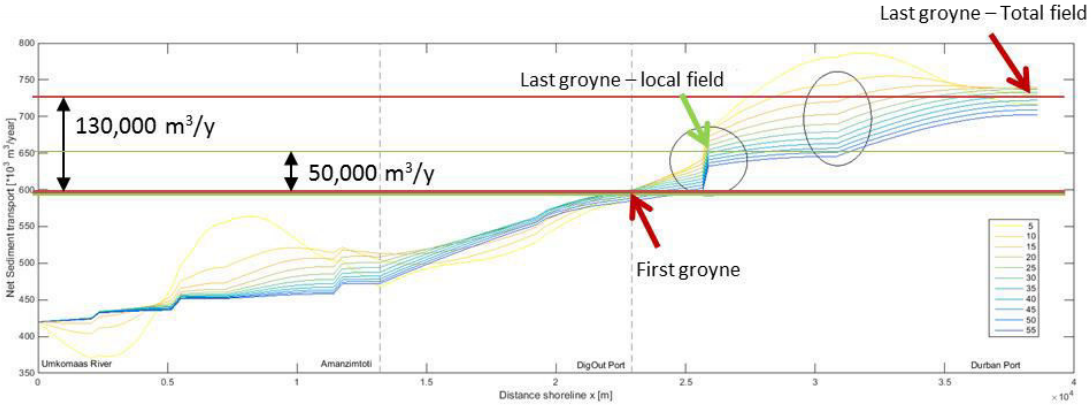


Figure C-6 Longshore sediment transport distribution

Following Van Rijn guidelines (Bosboom & Stive, 2013), a spacing between the groynes of 1.5 to 3 times the length of a groyne is preferred. Obviously, this is related to the dominant direction of the wave climate, since this angle will be approximated at the groyne tip. Hence, a spacing of roughly 3 times the groyne length is chosen, because this angle is particularly small and allows for a larger spacing. In the model the groynes have a spacing of approximately 200 to 300meters.

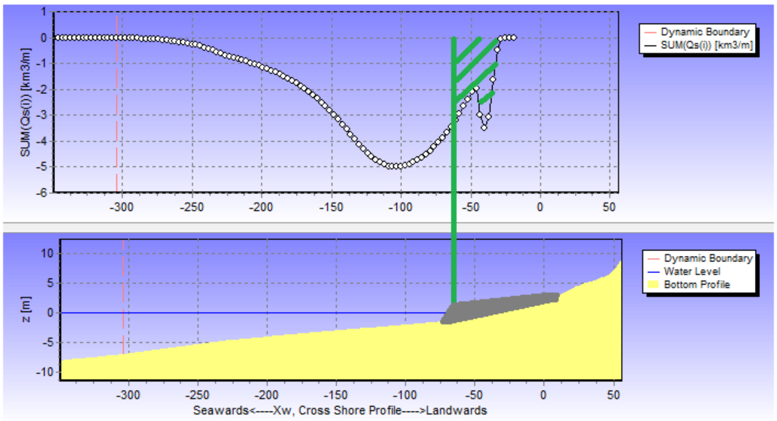


Figure C-7 Cross-shore distribution longshore transport at Bluff2 (Unibest LT)

C.4 Alternatives

For the Durban DigOut Port several alternatives are generated. Further some alternatives are created to counteract the erosion at the Durban Bluff. This paragraph explains the synthesis of different, more extreme alternatives.

C.4.1 Bluff Groynes

An alternative is to fill the Durban Bluff with groynes over a length of 15kilometers. The enormous groyne field provides a stable coast, where erosion is reduced to zero. However, when no artificial bypass will become operational longshore transports along the bluff will decrease to zero over time. For the Bluff this is not of a primary concern, because the beach will remain stable due to the groynes. It is a major problem for the Durban Bight. The Bight gets its sediments from a sand trap at the southern part of the Durban Port. Since no net longshore transport occurs along the Bluff and the trap will not be filled, sediments have to be come from somewhere else, otherwise the Bight will significantly erode, like has happened in the past.

An option is to use a bypass system with a capacity that is enough to provide the sand trap with sediments to feed the Durban Bight. The groyne field will be designed in such a way that enough sediment is captured by the groynes that the structural erosion or sediment scarcity in the system is covered and that enough sediments pass the groynes to provide sediment to the sand trap. However, this situation is not optimal, because the net sediment transports determined by the model are averages. A proper design should be robust, which demands some reservations to overcome unexpected low northward sediment transport rates during a year. This would lead to direct erosion of the Durban Bight.

By a preliminary assessment of the investment cost of a total groyne field and the accompanied artificial bypass system, the availability of material, and the risks of erosion at the Bight, it is decided not to elaborate on this alternative.

C.4.2 Nourishments

The Durban DigOut Port will be built at the former main airport of the province KwaZulu Natal. Lots of ground has to be excavated to create a port lay out. The exact geological properties of the soil are not known. Pleistocene Aeoliniate rock and Pleistocene Aeolian sand are likely to be dug out. In this alternative is assumed that enough sand will become available is used to protect the beach from erosion around the DigOut Port.

In the initial situation without any impacts of future climate changes the coastal Bluff system between the DigOut Port and Durban Port suffers from erosion with approximately 1m/y. This is also found in the analysis of net longshore sediment transports, where over a distance of 15kilometers a sediment deficit is found of approximately 130,000m^3/y. In order to provide a stable shoreline position an amount of 130,000m^3/y should be added to the system in the current situation. To provide a non-eroding coastline for 20years an amount of roughly 2,600,000m^3/y has to be replenished onto the coast, not taking into account any additional losses.

For the Durban DigOut Port a volume more than 50,000,000m^3/y will be excavated. The harbour moles will most likely be created from part of the available material. It assumed that also the sand necessary for the nourishment could be obtained from the excavated material. In this way in the 1D shoreline model is tested whether the large nourishment can protect the Durban Bluff coast from coastal erosion over a period of 20years. The nourishment is carried out in 2024, before the construction of the breakwaters. The artificial bypass system, as explained in the previous paragraph, will be operational after construction of the breakwaters in 2025. This has shown to be a good alternative to protect the shoreline from the erosion gap on the lee side of the port.

The location of the nourishment is determined by analysing the gross transport rates. Out of the Chapter 3.3.4 we know that ratio of gross transports at the Durban Bluff are expected to be 5:12, which means 500,000m^3/y of is transported southward and 1,200,000m^3/y northward. This ratio is used to determine the location of the nourishment, assuming that the deposited volume will be distributed along the shore with the same ratio. In Figure C-8 the net sediment transport figure can be found, which shows the change in transports over time.

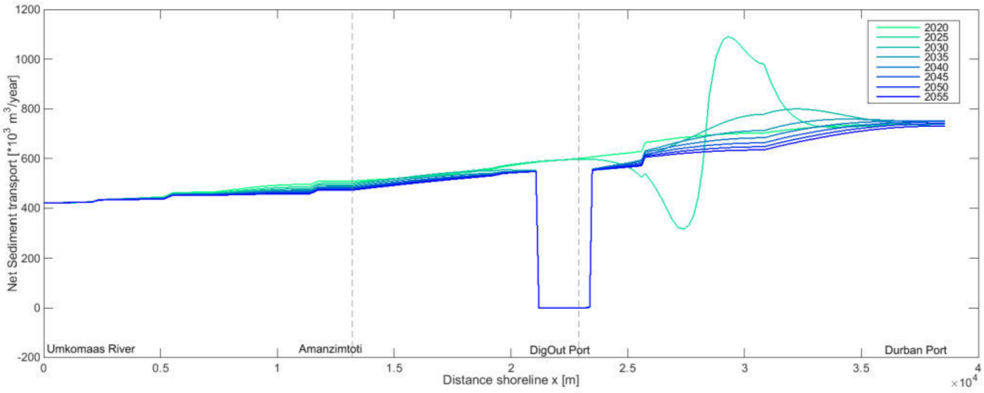


Figure C-8 Net longshore sediment transport DigOut with bypass and nourishment

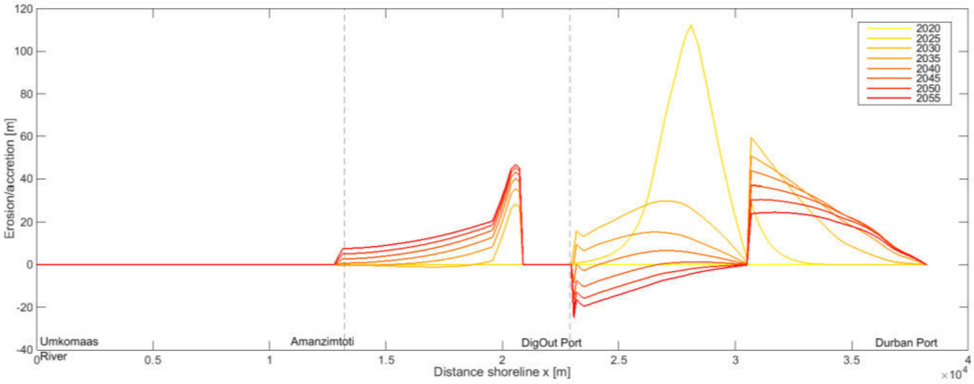


Figure C-9 Nourishment Durban Bluff

In Figure C-9 the erosion/accretion graph is shown. The nourishment provides the Bluff from eroding due to the structural erosion of 1m/y. After the year 2040 the coast starts to erode at the lee side of the port, which seems to stabilize at approximately -25meters from the initial position. In comparison to the bypass option without any additional nourishment the central Bluff doesn't suffer from erosion and for thirty years the Bluff seems to have a stable coast.

C.4.3 Bypass and 5 yearly nourishments

An alternative is created for the Durban Bluff to prevent the coast from erosion due to a 'likely' future. The alternative consist of a bypass system of 650,000m^3/year at the Durban DigOut Port and a 5yearly nourishment of 1,650,000m^3/year. This provides enough additional sediment to counteract the erosion trend of the Bluff. The nourishment is carried out at approximately 1:3 third of the coastal stretch of the Durban Bluff, which is related to the ratio of the gross longshore sediment transports. The exact location is shown in Figure C-10.

Figure C-10 Location nourishment

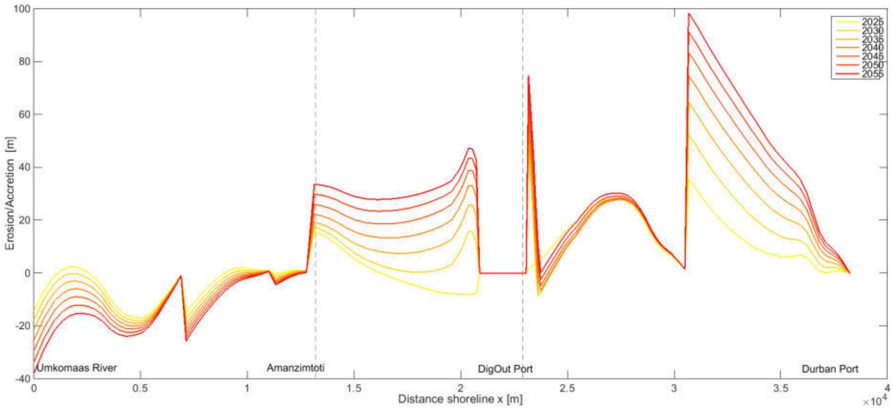


Figure C-11 Modeled erosion/accretion alternative

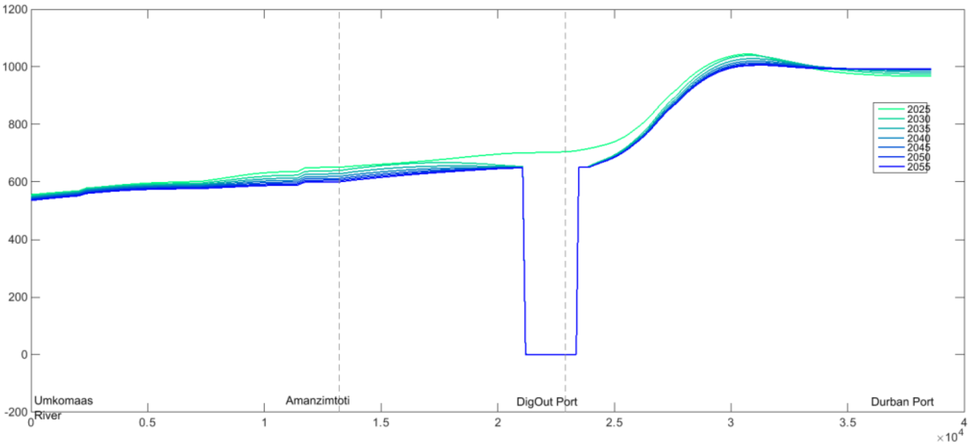


Figure C-12 Net longshore sediment transport alternative

D. Environmental variables

D.1 Set up Mining scenarios

In the ‘Basis’ scenario an initial stop of sediments is implemented in the source and sinks file. In the other two scenarios tab-files are implemented, which give a linear decrease per year indicating a gradual increase in mining activities. A linear growth is assumed. No extensive analysis has been done on relations between mining activities and the economic growth of the EThekwini Municipality, for example as a result of the Durban DigOut Port.

In the ‘25%’ and ‘50%’ scenarios in addition to the ‘basis’ scenario the Lovu River, Umlazi Canal and Mbokodweni River don’t input sediment to the system. In the ‘25%’ and ‘50%’ scenarios an extra extraction of sediments is assumed for the Umkomaas River, Manzimtoti River and Umgababa River. These are linearly decreasing in sediment input in time. In 50years the sediment input will be decreased by 25% and 50% compared to the initial situation in 2005.

For the latter two scenarios the boundary conditions are changed, because the input by the Umkomaas River is partly represented by the incoming sediments on the boundary of the system. Again a tab-file is implemented in the model to show a linear decrease of sediment input over time.

D.2 Observations scenarios environmental variables

In the ‘Most likely future’ the main part of the total erosion in 2055 originates from the current erosion in the system, because of a deficit of sediment input by rivers. This deficit is likely to increase in the future, where studies assume that the two most northern rivers at the South Durban coast, the Mbokodweni River and Umlazi River, don’t deposit any sediment anymore towards the coast. Modeling results show an extra 20meters coastal retreat for the total area from Amanzimtoti up to the Durban Port. A slightly increase in wave period during austral winter worsens the retreat at the DigOut Port with another 20meters coastal retreat by the year 2055. The Durban Bluff and the area around the Durban DigOut Port are identified as vulnerable areas. The Durban Bluff mainly due to a deficit in sediment input by the Umlazi River. The area around the DigOut Port mainly because of increased swell waves.

In the ‘Likely future’ sediment input decreases for rivers situated in the south. The effect is mainly observable at the area downstream of the river mouth. In the northern part of the system around the DigOut Port the effects of decreased sediment input are not felt anymore. The increased wave period has increased now with 0.1sec/year, which makes a large difference with the previous observation. The area from the Durban DigOut up to the Bluff suffers from extra erosion with a maximum of 50meters in 40years at the DigOut Port. The added shift in wave climate of 5degrees enforces shoreline retreat just north of Amanzimtoti up to the DigOut Port.

In the ‘Extreme future’ the effects observed in the ‘Likely future’ are enforced. Especially, the 10degrees clockwise shift of the wave climate yields strong coastal retreat north of Amanzimtoti. Extra coastal erosion due to larger swell components is also observed. For this future the total coastline from Amanzimtoti up to the northern part of the Bluff is vulnerable for coastal erosion. In the south erosion patterns are limited compared to the rest of the system for all different futures. A significant decrease in river input by the Umkomaas River will lead to large erosion on the lee side. The effect of less sediment input by the rivers is also observed further downstream. At Amanzimtoti the rocky outcrops pin the shoreline. The area between Amanzimtoti and the DigOut Port is vulnerable to changes in the wave climate. This area is a transition area from a gentler continental shelf towards a steep shelf at the Bluff. Differences in wave refraction over the system lead to changes in wave conditions and subsequently in transport gradients, as explained in the previous chapters.