Morphodynamics of the Ameland Bornrif

An analogue for the Sand Engine

Thesis

June 22, 2011

Deltares

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Fernanda Minikowski Achete

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Erasmus Mundus MSc Programme

Coastal and Marine Engineering and Management
CoMEM

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An analogue for the Sand Engine

TUDelft
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Summary
The thesis objective is to reproduce the Bornrif morphodynamics in order to better understand the possible development and impact of the Sand Engine Delfland. To reach the objective the first step was a data analysis from which a conceptual model was developed identifying the main features to be reproduced in the numerical model. The second step was a numerical simulation, performed with the Delft3D model, applying a 2DH schematization. The model was used to analyze the Ameland Bornrif processes and subsequently translate the findings for the impact/consequence of the Sand Engine.

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Preface

This report is the final requirement to finish the master program the Coastal and Marine Engineering and Management in the Civil Engineering department of the Delft University of Technology. It covers a study into the morphodynamics study of the Ameland Bornrif, in order to understand the Sand Engine behaviour and was carried out in Deltares.

The committee of this MSc thesis consisted of the following persons:

Prof.dr.ir. M.J.F. Stive	Delft University of Technology & CoMEM
Ir A.P. Luijendijk	Delft University of Technology & Deltares
Ir. P.K. Tonnon	Deltares
Ir. M.A de Schipper	TU Delft

Abstract

The objective of this work is the understanding of the development and possible impacts of the Sand Engine via a possible analogy with the Bornrif morphodynamics. The Sand Engine is the pilot project for a new nourishment technology (the mega nourishment), which consists of nourishing a huge amount of sand at once and let the nature spread it. For the pilot project Sand Engine Delfland 21 million meter^3 of sand are being placed. The evolution and impacts of such a project is widely unknow due to the unique character of the intervention. However, the Amelander Bornrif exhibits a similar shape to the one designed for the Sand Engine, so the understanding of a natural phenomenon may give knowhow to apply and monitor the Sand Engine project. The Bornrif analysis was based on a data analysis that resulted in a conceptual model, where the main features and process were defined. Another aspect derived from the data analysis was the comparison with a wave shape parameter, the breaking intensity, that describes the lagoon shape as well as the reaching of the hook. Applying the knowledge acquired from the data analysis a process based model, Delft3D, was used to numerically simulate the Bornrif.The experiments were divided in two groups: the short term, where the hindcast of 5 years of development was performed even as a sensitivity analysis. For the short-term it is concluded that the main forcings are the waves. The second group of simulations, covered the longterm hindcast, where the inclusion of cohesive sediment had a high impact on the overall Bornrif developement. The Bornrif development is reproduced only applying a wave climatology, not including individual storms. Therefore, some findings can be transferred from the Bornrif to the Sand Engine as the period of the hook evolution, taking approximately 5 years; the possibility of erosion of the mainland due to a channel formation; and the reduction of the morphological change after the hook merges with the mainland.

Acknowledgements

I am greatful to the Erasmus Mundus Program without the scholarship this master would not have been possible and for the wonderful professional and personal experience that provided me. A thanks for all the CoMEM staff who helps me during my staying in Delft, Trondheim and Barcelona.

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I would like to thanks my Deltares colleagues that listened me for hours specially Aleyda Ortega, Roland Vlijm, Arnold van Rooijen (hard to know where best fits you), Martin van der Wel, Martijn Muller and Timon Pekkeriet. And my friends, the ones who are with me since Brazil the ones that I made around the world even ending sharing a wonderful house (Claudia de Abreu).

Thanks for my family without the support during my whole life I could not be here today, Marlene, Carlos, Jana and the most recent one Marina, all my love.

And at last but surely not least to Bruno Primo, my everyday right arm, the one who knows all the process and share with me the best and the not best moments. Thanks for the patient and the love that you dedicate to me.

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1 Introduction

1.1 Research Background

The Netherlands has approximately 350km of sandy coastline. Taking into consideration that more than 50% of the total Netherlander area is below the mean sea level, the beach/dune system is extremely important as the main buffer area against flood risk. After the 1953 storm surge, the concern about coastal protection increased resulting in several political measurements. Among them continuous measurements of:

- the dune foot;
- the high- and low-water level line;
- the Delta works – several civil works along the Dutch coast
- the dynamic preservation of the coastline - safety measurement against flood, aiming the preservation of dunes and beaches.

In 1990, the Government and the Parliament implemented the Basal Coastline (BCL) policy where they define that the 1990 coastline position should be maintained. To follow this policy it is required that at least 90% of the Dutch land is situated landward of the BCL, demanding a pro-active approach regarding the chronic erosion problem. In order to archive the standards defined by BCL, a new concept was added in 2000 the dynamic preservation [Mulder 2000]. The aim is to keep the coastal foundation volume[1], preventing the shore to get steeper and so maintaining the BCL (Figure 1.1).

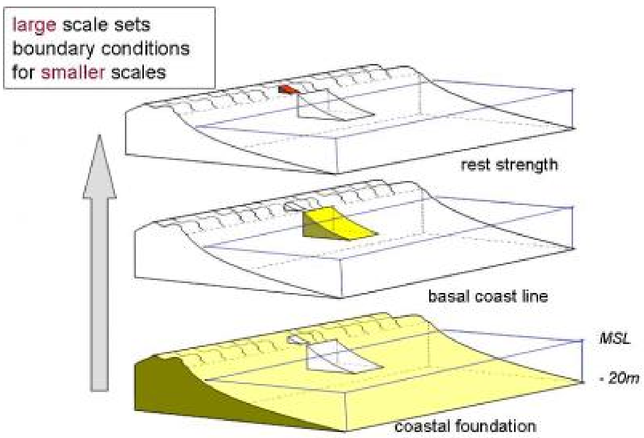

Figure 1.1 Three different scales in coastal management (source: Mulder et al., 2006)

1. *Volume between the first dune line till -20 NAP.*

Within this scenario, the Dutch research programme Building with Nature (BwN) aims to developed new basic knowledge, tools and Eco-dynamic alternatives for coastal, delta and estuarine areas. From this expertise, it will be possible to develop new bio-designs where human interventions are reinforced by natural processes. The present work is inserted in the theme 3 of the BwN program that focuses on the design, realization and evaluation of the Sand Engine for the Delfland coast and its contribution to the sustainable development of beaches and dunes.

1.2 Problem Description

The dutch coastal management policy to prevent erosion is based on sand nourishment that is carried out every 4-5 years. The mega-nourishment proposal arises as an alternative to the continuous beach nourishments. These projects consist in performing at once large-scale nourishment and then let nature, currents and wind, redistribute the sediment. In this context, the Sand Engine project was thought as a mega-nourishment pilot project that can be used as a test case for technical and political expertise development (Figure 1.2), however the morphological behaviour of this project is largely unknown and its predictability is uncertain due to a lack in validation data.

The South Holland province together with Ministry of Transport, Public Works, local municipality, Water Board NGO's and business, is carrying out such mega-nourishment in the stretch between Hook van Holland and Scheveningen (Figure 1.2). The nourishment started in March 2011 and the completion is foreseen in October 2011. It is a 21 million m^3 of sand project, which is expected to provide enough sand for beach completion for the next 50 years. This sand is going to create circa 35ha of new beaches and dunes leading to more room for recreation and nature; providing compensation of the natural area for Maasvlakte 2, the Rotterdam port expansion.

Figure 1.2: Sand Engine project sketch. Located between Hoek van Holland and Scheveningen, gives the idea of the project scale.

For this project, it was necessary to carry out an Environmental Impact Assessment (EIA). Among other studies, the EIA evaluated several feasible designs and the one chosen was the hook shaped alternative based on costs, safety, ecological and recreational aspects. This choice leads to a close comparison with the natural case in one of the Frisian Islands, Ameland. Ameland has an attached bar in its western edge, the Bornrif that around 1993 shows a hook shape similar to the Sand Engine Design. Furthermore, the eco-morphological evolution of the Bornrif shows large similarities with the numerical model predictions for the Sand Engine (Figure 1.3).

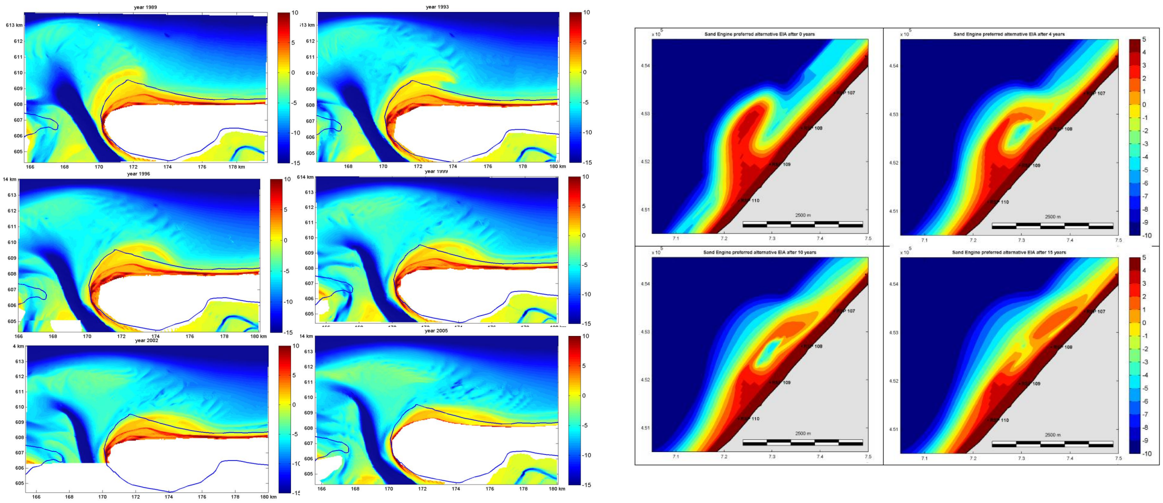

Figure 1.3: Morphological evolution. Left Bornrif Vaklondingen data from 1989 until 2002. In the right 20 years of the Sand Engine morphological simulation (source: Mulder and Tonnon, 2010).

1.3 Objective

There is extensive literature on Ameland, mainly accomplished by the Rijkswaterstaat, Deltares, Alkyon and TU Delft [Grimal 1998; Roelvink et al. 1999; Cleveringa et al. 2005; Cheung et al. 2007; Fockert 2008; van Rooij 2008]. These previous studies were mostly focuses on the entire estuary and/or the tidal inlet resulting in an incomplete model concerning the Bornrif evolution. In order to reproduce the evolution of the Bornrif in detail it is necessary to refine the numerical mesh, however it was not possible to refine the entire estuary system due to computational restrictions.

Considering the magnitude of the Sand Engine project and the possibility to become a new option for the coastal protection policy in the Netherlands, it is important to have a better understanding of the processes involved. As the Bornrif is a natural study case of what may occur along the South Holland coast a local, long-term model for the region can support decision making concern new projects and management of the permanent coastline..

The objective of this study is to numerically reproduce the Bornrif morphological evolution over a time scale of 10 to 20 years to identify relevant processes for- and gain insight in the behaviour and impact of the Sand Engine Delfland.

To achieve this objective, some smaller steps were defined as specific objectives, as follow:

- To define the main morphological evolution features of the Bornrif (literature review and data analysis)
- Investigate and model the observed conditions (conceptual and numerical model)
- Investigate cohesive sediment influence (numerical model, Delft3D)
- Link with the Sand Engine: compare the Bornrif behaviour with the sand engine

1.4 Reader Guide

The report is organized as follow:

- Literature review (processes, Bornrif), data analysis (Bornrif and estuary), conceptual model. In this chapter the main forcing of the Bornrif morphodynamics are discussed as well as a state of art of the Bornrif (chapter 2).
- Description of the model including the chosen parameters and process to simulate (chapter 3).
- Set up basic morphodynamics model in order to hindcast the short period dynamics (chapter 4).

- The sensitivity analysis is performed in order to define the most important parameters and formulation (chapter 5).
- In chapter 6, additional parameters are included to the basic simulation as result of the findings in chapter 5.
- The correlation and conclusions between the Bornrif and the sand engine are discussed in chapter 7.
- The general conclusion and recommendations are presented in chapter 8.

2 Bornrif Morphodynamics

The Bornrif is an attached bar at the northwestern edge of the Wadden Sea barrier island, Ameland (Figure 2.1). Ameland is located in the northern part of Netherlands and together with Terschelling it forms the Amelander inlet. The Bornrif is a dynamic feature influenced by the Ameland estuary dynamics, tides and wave driven currents; however, other aspects as wind, vegetation and bioturbation also play an important role in its development.

Figure 2.1 Location of Amelander inlet in relation to The Netherlands

Will be discussed in this chapter the characterization of the Ameland estuary (2.1); the morphodynamic processes (2.2); the theories used to explain the Bornrif evolution (2.3); the data analysis (2.4), human interference in the sediment transport (2.5) and the general conclusion as a conceptual model (2.6) and comparison with wave parameters (2.7).

2.1 Study area

The Dutch Wadden Sea is divided by watersheds in five smaller estuaries, amongst the Ameland estuary (Figure 2.2, estuary 4). Its inlet, the Borndiep, is located between Terschelling in the west and Ameland in the east; it is 4km long, with a maximum depth of 27 meters and maximum velocities approximately of 1m/s. According to Haynes [1980] classification, this is a mixed energy tide dominated estuary, considering the inlet is kept by the tidal currents. A summary of general characteristics of the estuary is in Table 2.1.

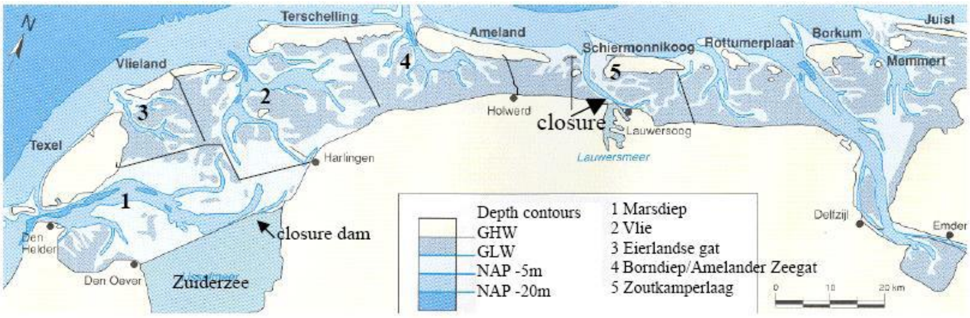

Figure 2.2 Overview tidal inlets Western Wadden Sea, the Amelander Estuary is the number 4 (source: Stive and Wang, 2003)

Table 2.1: Amelander Inlet description.

Amelander Inlet	
Basin Area (Ab)	269 km2
Ratio flats/basin (Af/Ab)	0.63
Length	30 km
Tidal Prism	475 M m3
Tidal range	2.15 m
Tidal Speed	15 m/s
Width tidal inlet	2,250 m
Mean depth inlet	14 m
Estimated sand influx	5.5-7.5 M tons/year

The Amelander basin influences the Bornrif in two different ways:

1. Acting as a controller for the sediment flux;
2. Increasing tidal current.

As sediment input controller two behaviours can be distinguished: it can be considered as a barrier for the wave induced alongshore drift or a source of sediment transported outside from the estuary by tidal asymmetry. These processes result in a non-homogeneous sediment input to the Bornrif [Stive et al. 2003].

The second point is related to the tidal current modification. The inlet (Borndiep) leads to a local stronger ebb/flood currents due to tidal energy convergence in this area, which can stir more sediment and so easier to be transported (Figure 2.3).

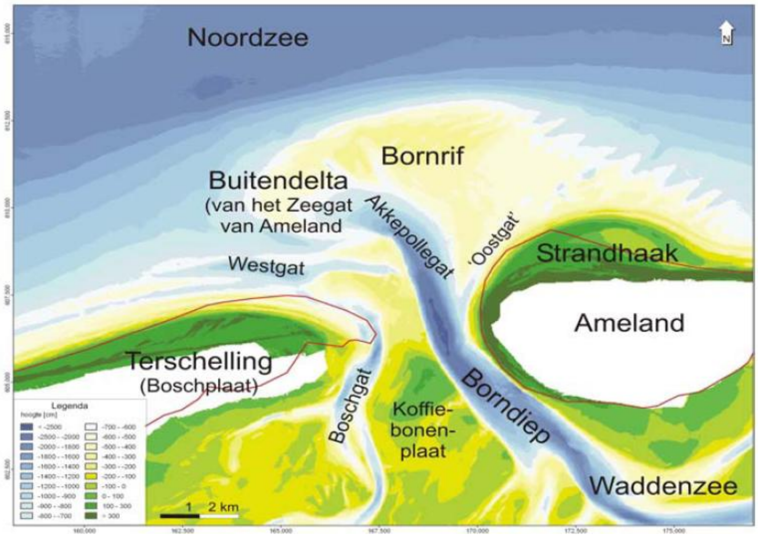

Figure 2.3: Amelander estuary and its main features (source: Cleveringa, 2005).

2.2 Morphodynamics Processes

This section presents the main forcing of the Bornrif morphodynamics. In section 2.2.1 the tides are presented and in 2.2.2 the waves, as discussed below the most important forcing. The sediment transport process is presented in 2.2.3.

2.2.1 Tides

The vertical movement of the rising and the falling of the sea level, which can be observed in almost every coastline stretch, is called tide. It is generated by gravitational attraction between celestial bodies, mostly the Moon and Sun. Considering the Equilibrium theory that states uniform depth ocean, no friction, no Coriolis force and no Earth axis declination, each point in the globe should experience two high- and two low- tides within a day, except the poles. However, several factors influence this motion among them the friction, presence of continents, non-uniformity of ocean depth and earth rotation leading to Coriolis force.

More specifically in the case of the North Sea, as it is a marginal sea, it is not big enough to develop its own tidal wave. The tide observed in the North Sea is generated in the Atlantic

Ocean and penetrates through two openings: one in the Southwest, “the Channel” and one in the Northwest, the most important one. Entering the North Sea the tidal wave energy is in part dissipated and in part reflected behaving as Kelvin waves (Figure 2.4) [Bosboom 2010].

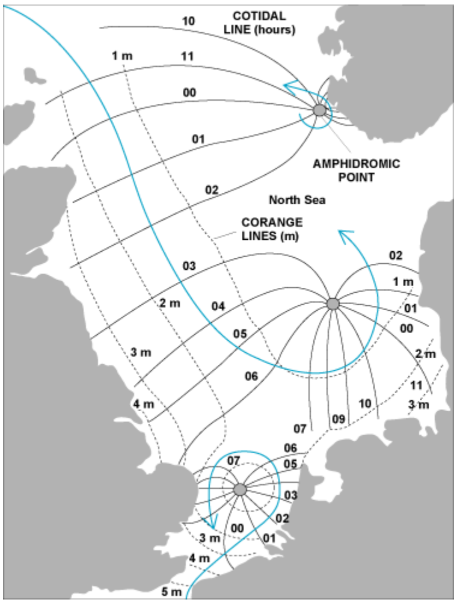

*Figure 2.4: North Sea amphidromic tidal system. Corange lines indicate equal tidal range. Cotidal lines show times of high water. Arrows show rotation directions of the tidal waves. (*Modified from R. W. Dalrymple, Tidal Depositional Systems, in R. G. Walker and N. P. James, eds., Facies Models Response to Sea Level Changes, pp. 195–218, Geological Association of Canada, 1992*)*

Kelvin wave is a forced standing wave that needs a closed boundary to propagate and rotates around a stationary point, called amphidromic point[2]. Kelvin wave comes from the equilibrium between inertia, Coriolis acceleration, pressure gradient and friction. As the North Sea is located in the Northern hemisphere, the movement is anticlockwise, once in this hemisphere the Coriolis force deflects the movement to the right.

Far from the coast, the cross-shore direction motion is governed by a geostrophic equilibrium while the alongshore can be considered the shallow water gravity waves approximation. Indeed, in coastal areas, the inertia is neglected and the friction becomes important again, due to shallower areas. In this scenario, the bed friction balances the water level that is 90 degrees out of phase in relation to the velocity [Bosboom 2010].

From the Ameland point of view, the tide propagates from west to east with amplitude of approximately 2m and 0.7m/s currents. The tidal wave enters in the Ameland estuary and

2. *Amphidromic point is a stationary point from which can be draw cotidal lines, which are rotating phase lines. As the amphidromic point is a zero amplitude point by moving away means higher tidal amplitudes, reaching the maximum on the coastline.*

loose energy due to bottom friction. During its entering it causes strong currents in the inlet that can reach 1m/s and its residual current is going to influence form the ebb tidal delta [van de Kreeke 1978].

2.2.2 Wind Waves

The friction of the wind in the water surface generates wind waves. When the wind starts blowing energy is transferred to the sea, forming ripples that can become waves depending on the wind duration, fetch width and water depth. After formation, the waves start to propagate, if there is fetch enough, the wave periods are going to split forming clean undulation groups; the swell. Otherwise, the waves reach the coast as storms.

As the fetch in the North Sea is not long enough to generate high swells, the big waves observed are storm related. On the Dutch coast, this scenario is reinforced once the mid-latitude atmospheric low pressure travels just on the northern border generating strong northwesterly and westerly wind. This wind field can result in very rough sea states with waves up to 7m [Herman et al. 2009].

Nevertheless, this is not the average sea state. Bukhanovsky et al [Boukhanovsky et al. 2007] developed a new wave climate classification based on multiple wave spectra analysis. From this approach the predominant wave direction is north/north-west/west and most of the time does not exceed Hs=2m with T=5sec (Figure 2.5). Approximately 11% of the waves reach the coast as swell against 60% as storm.

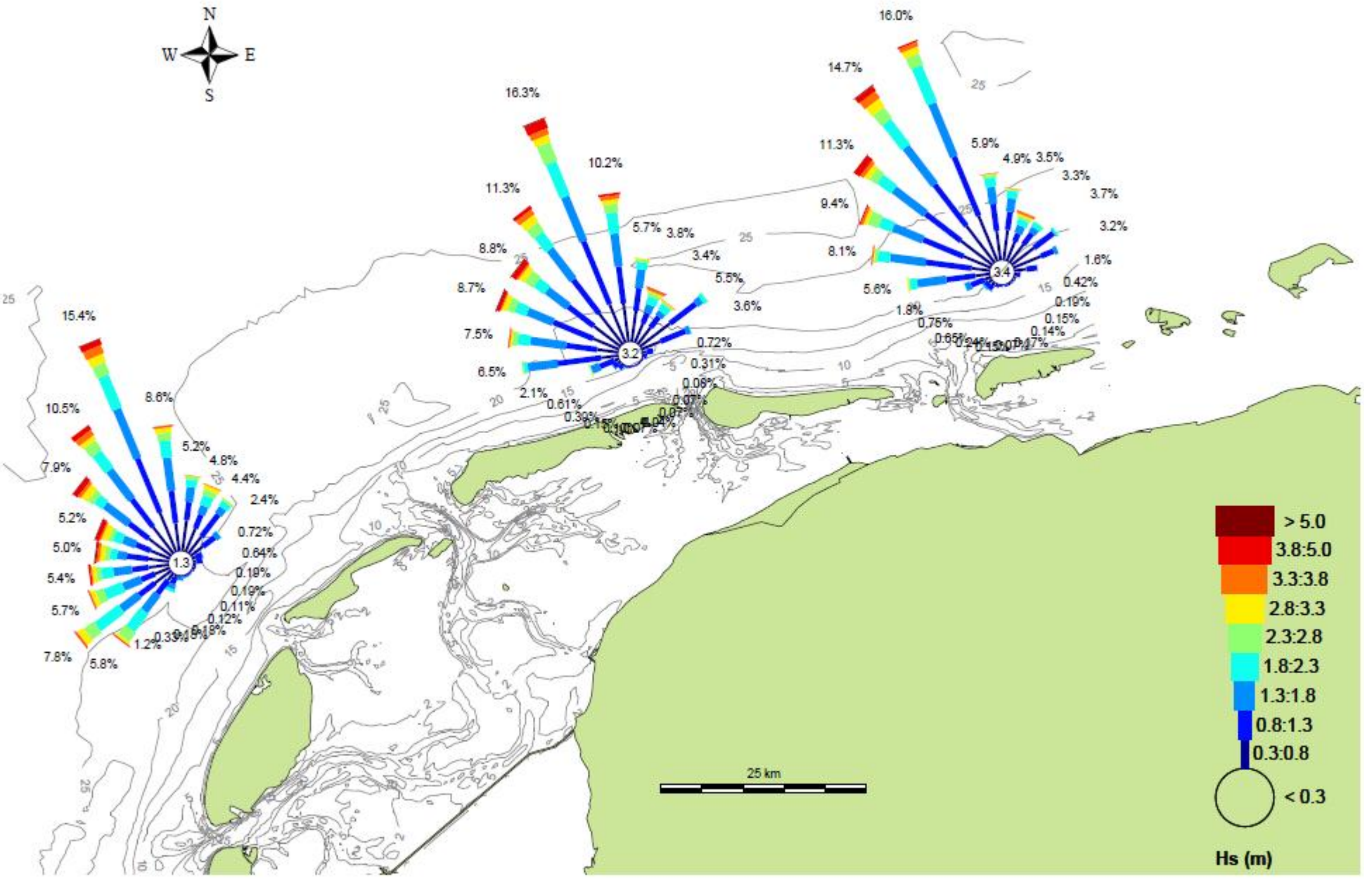

Figure 2.5: Wave rose for 3 locations in the Wadden sea. It can be seen that the rose in front of Ameland is similar to the one east-northward.(source: de Fockert, 2008)

2.2.3 Wave induced Sediment Transport

Sediment transport mainly driven force are the wind induced near-shore current, tides and waves. As the waves are the most important forcing of the Bornrif morphodynamics, the transport induced by waves is going to be described in this section.

The waves trigger a number of different processes that can lead to sediment transportation, as follow [Bosboom 2010]:

- Approaching the shore, the waves become more and more asymmetric. This asymmetry is caused by higher harmonic sinusoidal waves and is represented as the third order of the wave height. This non-linearity leads to a transport in the wave direction.

- Nevertheless, the onshore wave induced mass flux is not related only to wave asymmetry. Take into consideration a perfect sinusoidal wave, under the crest the particle moves faster than under the wave trough. The differences in velocity results in a not completely close orbital movement and consequently a shoreward mass flux, known as Stokes drift.
- Considering wave incident normal to the shore, the Stokes drift has to be counteracted otherwise the water starts to pile up on the coast. This counteraction is done by an undertow current that transport sediment seawards.
- On the other hand, the waves coming obliquely to the coast generate an alongshore current. This current is the result of energy dissipation due to wave breaking. During the breaking process, there is a setup in the breaking zone due to energy concentration; producing pressure gradient that induce the alongshore current.
- The tides play role stirring sediment. Before being transported the sediment has to be put in movement, so overcome the inertia via bed shear stress (τ). It can be done by waves, current or a combination of waves and currents. Considering the last case, the bed shear stress components have to be sum up, however it is non-linear interaction leading to sediment transport not necessarily in the current direction.

In the case where there is an estuary, another variable is included in the system; source/sink of sediment (Figure 2.6). The estuary is in equilibrium following the Escoffier theory, although in the Wadden Sea this dynamic equilibrium is disturbed by human interference as nourishments and poldering. Van de Kreeke [van de Kreeke 2006] estimates that the period required for the estuaries in the Wadden Sea reach a new equilibrium between the tidal prism, the inlet and the shoals after a poldering is in order of 70 years. The changing in the estuary equilibrium leads to morphological impacts in the whole system including the ebb tidal delta and adjacent coast.

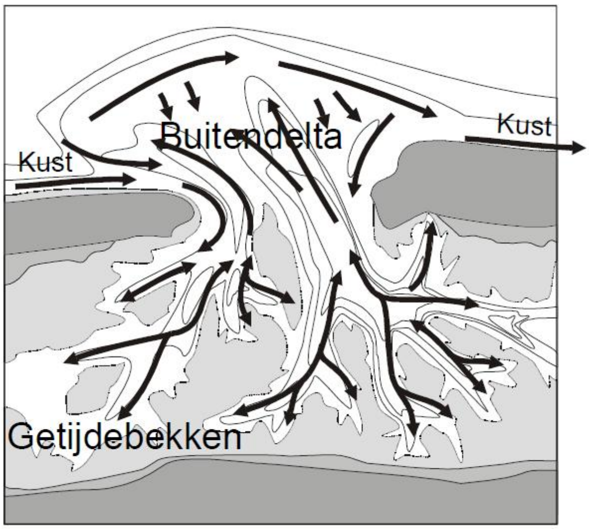

Figure 2.6 Schematic sand transport in the outer delta and estuary, of the Frisian Islands. Buitendelta – outer delta; Kust – Coast; Getijdebekken – tidal basin (source: Cleveringa, 2004)

Sha [1989] observed that, for the Frisian Island, while the wave-induced alongshore current control the ebb-tidal delta asymmetry the tidal current controls its seaward extension. In the Ameland inlet case, it is important to know the ebb-tidal delta extension as it acts as a seaward-protruding groin deflecting the parallel tidal current generating a vortex down-drift eventually increases the sediment by pass. This eddy enhances the sediment supply to the Bornrif but does not shape it [Sha 1989]. The shape force comes from the waves, so the delta is important because it acts as a wave induced breaking generating current that carries and redistributes sediment in the Bornrif.

2.3 Theoretical Model

In order to describe the Bornrif dynamic two conceptual models were analysed:

1. bar evolution in deltas;
2. sand spits.

The Bornrif dynamic can be, to some extension, explained as the mixture between the two models above. The bar evolution can better explain the Bornrif starting stages while the evolution of the Bornrif is better understood considering the spit characterization.

2.3.1 Tidal Inlet Dynamics

The bar concept arises from the necessity to understand the sediment dynamics in inlets that present a complex system of alongshore currents, ebb- flood channels and shoals. De Vriend et al. [1994] developed a conceptual model to the sand bypass that was later improved by van de Kreek [2006] and Kraus [2000][3].

All authors assumed mass-conservation nevertheless this conservation is dynamic; it is possible due to the exchange within other elements or with the open sea [de Vriend et al. 1994]. This exchange is feasible because of the inlet dynamics that is influenced by: the wave induced longshore current; and the interaction between the longshore tidal current and the transversal current (generated in the inlet).

From the bar concept, the follow main features can be drawn. Kraus [2000] (Figure 2.7):

- up- and down-drift Barrier Island;
- ebb- and flood-tidal shoal/delta;
- bypassing bar;
- attached bar.

Sediments from the littoral drift and from the estuary carried out by the ebb-tidal channel supply the ebb-tidal delta. Once the shoal reaches its equilibrium, all the sediment is bypassed down drift through the bypass bar.

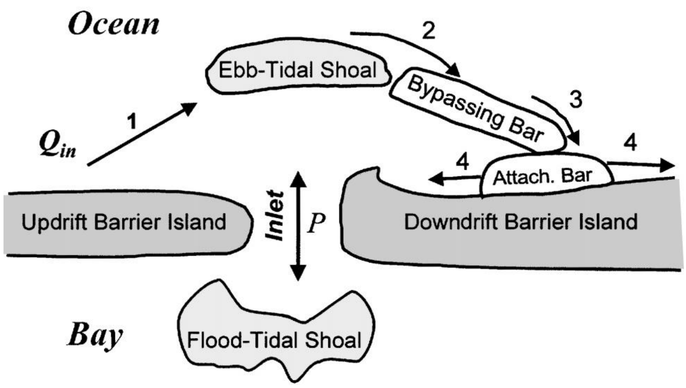

Figure 2.7: Sketch of the inlet morphodynamics and its main features. (source: Kraus, 2000)

3. *Considerations for the bar conceptual model:*
   1. Mass (sand volume) conservation
   2. Morphological forms and sediment pathways among them can be identified, and the morphologic forms evolve while preserve identity.
   3. Stable equilibrium of the individual aggregate morphologic firm(s) exists.
   4. Changes in mesomorphological and macromophological forms are reasonably smooth

Briefly, the bypass bar receives sediments mainly from the ebb-tidal shoal. Two processes are involved in this transport: the first one is the wave-induced current due to breaking; the second is due to wave set-up in the shoal, generating a current that goes around the shoal and reaches the bar [Wilkens 1999; Fockert 2008]. These bars further on are going to attach to the mainland, developing the attached bar. The Bornrif formation consists mainly in the steps described so far.
After merging with the western edge of Ameland this big volume of sand begins to be reworked, spreading sediments eastwards mainly by waves induced currents [Cleveringa et al. 2005], starting to behave as a spit.

2.3.2 Spit Dynamics

Spits are particularly dynamic sand features attached to the edge of a mainland or an island, they are found in sheltered coastal stretches that suddenly change direction. The alongshore sediment transport is extremely important to maintain the spit with its original characteristics. A lack of sediment can cause erosion of the spit and too much sediment input may lead to accretion even creating another spit [Petersen et al. 2008].

Waves play an important role in the spit dynamics; the waves are responsible for shaping the spit. Though the wave depends on the water level, since higher waves can dissipate the energy in the shoal that shelter the spit if the water level is not high enough [Vinther et al. 2004]. Beyond the general sediment transport due to waves induced alongshore current, the waves have other influences as:

- The spit width is proportional to the surf zone;
- the curvature radius depends on the wave height;
- the overwash processes accelerate the spit migration shoreward [Dan et al. 2009].

It follows that spits show cyclic behaviour, where the spits form, grow and merge with the main land creating bays and further on lagoons. The spit cycle concept is developed considering river mouth spit evolution in micro-tidal environments and wave climates dominated by one direction. It is divided in four stages (Figure 2.8) [Nicholas 2000]:

1 submarine accumulation;
2 emerging;
3 evolution;
4 and merging with the main land.

The first and second stage, submarine accumulation and emerging spit, are quite similar to the ebb-tidal delta formation. In the third stage, the spit evolution, the emerging bar merges to the main land and starts to grow. In this process it is needed a continuous big amount of sediment supply to develop the spit parallel to the shore, forming a bay. In the final stage, the tip of the spit merges with the land and the bay becomes a coastal lagoon [Dan et al.] (Table 5).

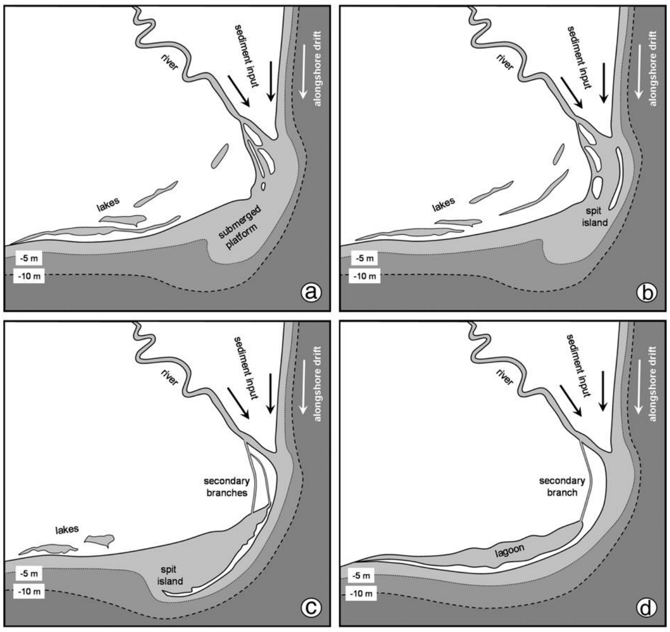

Figure 2.8 The main four stages describing formation and evolution of a spit: a) submarine accumulation; b) emerging spit; c) intermediary stage and d) final stage.(source: Dan et al. 2011)

Even if there is a common evolution history, the spits can be also be classified into 3 categories, depending on the angle in relation to the up-drift coast(Figure 2.9)[Petersen et al. 2008]:

1. small angle, the spit will erode (E1)
2. too big there is accretion (E2)
3. the perfect spit is going to develop and grow in length (E3).

The Bornrif is comparable to E2, where the angle between the wave direction and the Bornrif is so low that the transport capacity is also too low quickly accreting the spit that merges with the mainland. It is worth to note that in the Bornrif case, there is not a proper up-drift coast, and the sediment supply comes from the bypass trough the ebb tidal delta and from the Ameland estuary.

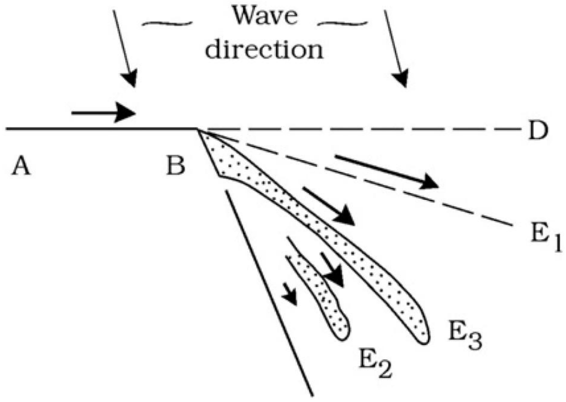

Figure 2.9 Spit orientation in relation a hard point B (source: Petersen et al., 2008)

2.4 Data Analysis

The Dutch Wadden Sea has been monitored for many years, however since 1993, with the SBW-project (Sterkte en Belastingen Waterkeringen); this effort has increased in time and space. The data used in the present work is mostly described in de Fockert [2008], though data from subsequent years (from 2006 to 2009) was added.

The two main bathymetric databases used were the JARKUS ('JAaRlijkse Kustlodingen', Ruessink, 1998) and the Vaklodingen. The JARKUS is one of the biggest beach profile dataset in the world, dating from 1963 of annual soundings from the dunes reaching until 16 meters depth cross-shore. The Vaklodingen dataset is the standard Rijkswaterstaat (RWS) monitoring soundings, performed every three years for delta environments. It is stored in a resolution of 20x20 meters and reaches 35 meters depth since 1987 [Elias 2007]. Both data sets are based on the NAP (Normal Amsterdam's Peil, close to the means sea water level) and are performed during summer, aiming observe inter-annual and not the seasonal variability.

As mentioned in the previous sections the Bornrif has several similarities with bar and spit evolution models, these similarities can be better understood studying the estuary phases as presented below.

2.4.1 Ameland Estuary Phases

The Ameland inlet is a dynamic coastal system, consisting of channels. It flats, and shows a morphological cycle of 50 to 60 years described by Israel [1998]. The proposed classification for the Amelander estuary cycle consists on four transitional phases, which depends on the channels and flats characteristics. It is a modulated cycle where the flood channel modulates the bypass rate that in its turn influences the ebb-tidal channels and flats (Figure 2.10) [Israel 1998].

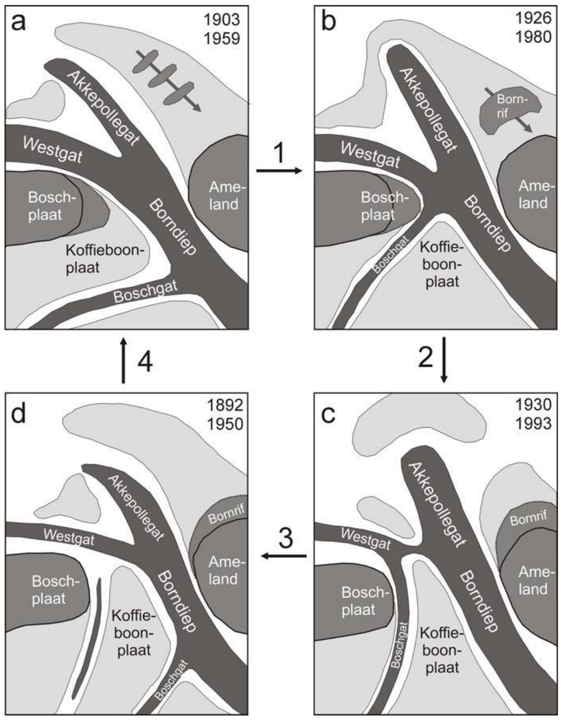

Figure 2.10 Morphological cycle of the Amelander estuary (source: Israel, 1998). The phase a, b, c and d are described in this report as phase 1, 2, 3 and 4 respectively.

During phase 1 (1903 & 1959) just one channel is present in the inlet, allowing the coast of Ameland to stretch westward and the Terschelling to stretch eastward. From the Bornrif point of view, phase 1 is where the sand waves from the ebb tidal delta starts to move towards Ameland western edge.

In phase 2 (1926 & 1980) an intersection of two channels in the inlet can be observed. At this time, Terschelling accretes more eastward, while Ameland west coast starts to erode. The sand waves, a part of the ebb-tidal delta, merge into one big sand flat (bypass bar) and migrate southwards.

Phase 3 (1934 & 1993) is characterized by the presence of two channels in the inlet so there is a drop in the space to the Boschplaat and to the western Ameland coast. On the other hand the Bornrif lands in Ameland northwestern edge forming the attached bar and increasing the island width. It is in this phase that the changes in the Bornrif as an attached bar happens and so the phase of interest of this work.

The last one, phase 4 (1892 & 1950), the two channels start to merge into one, creating more space between the two islands once again. The time line of the transitional phases is represented in Figure 2.11.

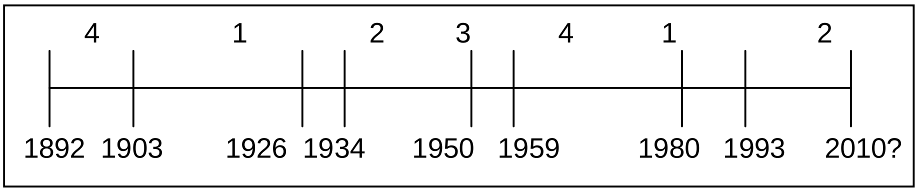

Figure 2.11: Transitional phases. The numbers in the up to the line represent the phase number and below the correspondent year (source: Israel, 1989)

The cycle development of the estuary is possible due to the combination of wave and tide-driven sand transport (Israel, 1998), the estimated mean wave-driven transport is 0.5-1 Mm^3/y [Táncoz et al. 2001; Cheung et al. 2007]

2.4.2 Ameland volume calculation

Following de Vriend's [1994] reasoning, about outer delta bypass, it is possible to define elements that have a dynamic volumetric equilibrium. With the purpose of studying the equilibrium volume over the years and define the best area the test performed was:

- Take the 1993 bathymetry as basal level
- The total volume of 1993 is considered to be equal zero (reference volume)
- For each year, from 1994, calculate the bathymetry difference for each grid point
- Integrate spatially generating a difference volume value (the anomaly between 1993 and the current year)
- plot all the values in a graph of volume changes (Figure 2.13)

These tests were repeated for several different areas in order to find the best equilibrium volume. The tests performed considered: the whole island; just the Bornrif; 30 meter depth contour line; the full ebb-tidal delta etc. For the selected area besides the volume equilibrium, the necessity of keeping the modelling area small enough to be able to reproduce the Bornrif features, as the attachment to the land and the intertidal channel were taken into account

(Figure 2.12).

The most sensitive area is associated with the bypass bar region including the western Ameland edge (Figure 2.12). This result is likely, once the bypass bar region is the most dynamic area with big rate of sediment flux.

After defining the basic element, three general analyses were done:

1. considering the whole element;
2. alongshore partition in 3 smaller elements and
3. cross-shore sub-division.

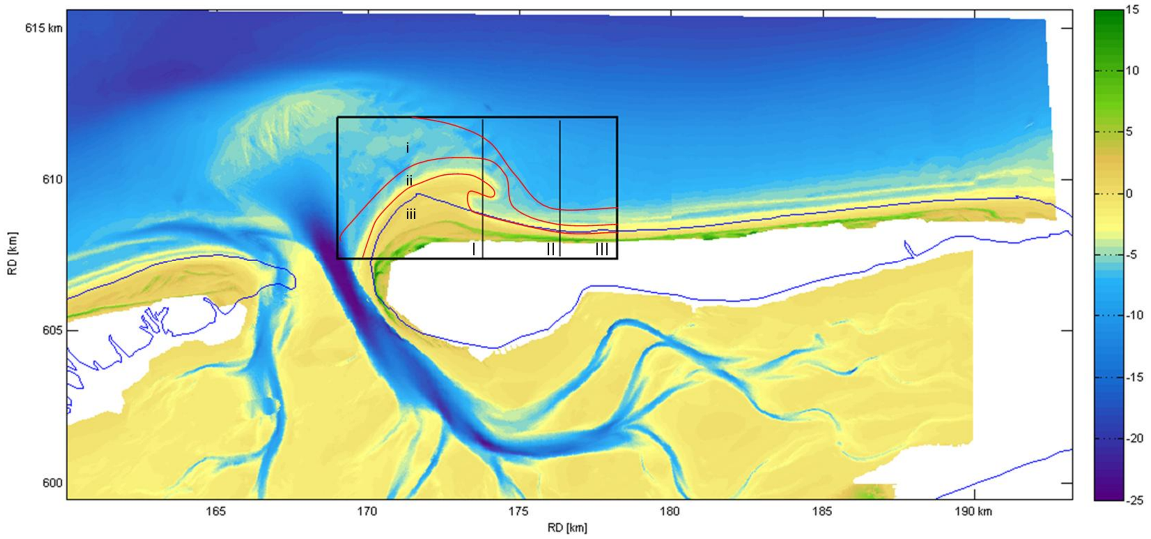

Figure 2.12: Bathymetric map for the year 1993. The big rectangle shows the defined element, the black lines show the alongshore partition and the red the cross-shore subdivision

The first analysis considers the equilibrium volume development. A volume equilibrium is observed varying around +-2.5 Mm^3 (Figure 2.13), even being a high value it is in agreement with the active sediment volume inside the Ameland inlet that is estimated as 25 Mm^3 [Cheung, 2008]. This is the basic element for the rest of the data analysis as for the numerical modelling.

In the second analysis, the basic element was divided in 3 smaller areas in order to characterize, in general lines, the erosion/accretion pattern. The areas are distinguished as follow: I – the Bornrif, from km 169 to 173; II – from km 174 to 176 and III – from km 177 to 178 (Figure 2.12).

Analysing the volume development series three different trends can be observed (Figure 2.13):

A. from 1993 to 2000
B. from 2001 to 2004
C. from 2005 to 2008

During time interval A (1993 - 2000), region I erodes at a rate of 1.14 Mm^3/year while region II accretes in a large rate, 2.1 Mm^3/year. This erosion is due to the angle between the outer Bornrif edge and the incident wave crest, generating alongshore current that is reinforced by tidal current. Region III does not present any major sediment variation, probably because the Bornrif tip traps almost all of the available sediment.

During B (2000 - 2004), the smoothing of the Bornrif is translated in less sediment transport. It remains the erosion/accretion pattern, observed in A, although in a much lower rate. From the total area volume analysis, it is possible to observe that there is some exchange of sediment with the open sea, probably associated with new sand waves coming form the ebb-tidal delta.

The last interval C (2004 – 2008), is when region I archive equilibrium state in relation to the incident waves and region II start loosing sediment to region III. The former Bornrif sediment is redistributed along the Amelander coast due to the alongshore current restoration (Figure 2.13).

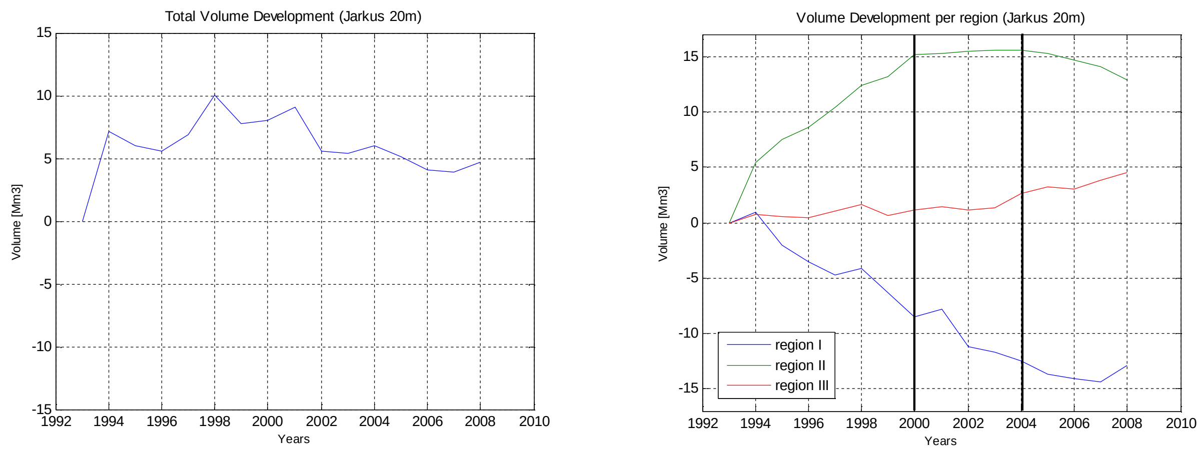

Figure 2.13: Volume development in relation to 1993. Left the total area volume development. Right the volume development for each region (I – the Bornrif from km 169 to 174; II – from km 174 to 177 and III – from km 177 to 178), the vertical line splits the periods A, B and C.

The last volumetric analysis was focus on cross-shore volume exchange over time. The objective was to determine from each region of the beach profile the sediment it is being eroded and where it is deposited. From the basic element, three reference topo/bathymetric regions were defined, considering its 1993 position (Figure 2.12):

i. from -6 to -2 meters depth
ii. from -2 to 1 meter
iii. from 1 m to the dune foot

In this step, the 3 alongshore regions (region: I, II and III) were kept. For region I, the biggest erosion occurs between -2 to 1 meter. This sediment is mainly deposited in the shore face from -6 to -2 meter from region II and III. This behave can be explained by the advance of the spit that reach the coast coming from the sea, and can be clarified in the beach profiles analysis (Figure 2.14).

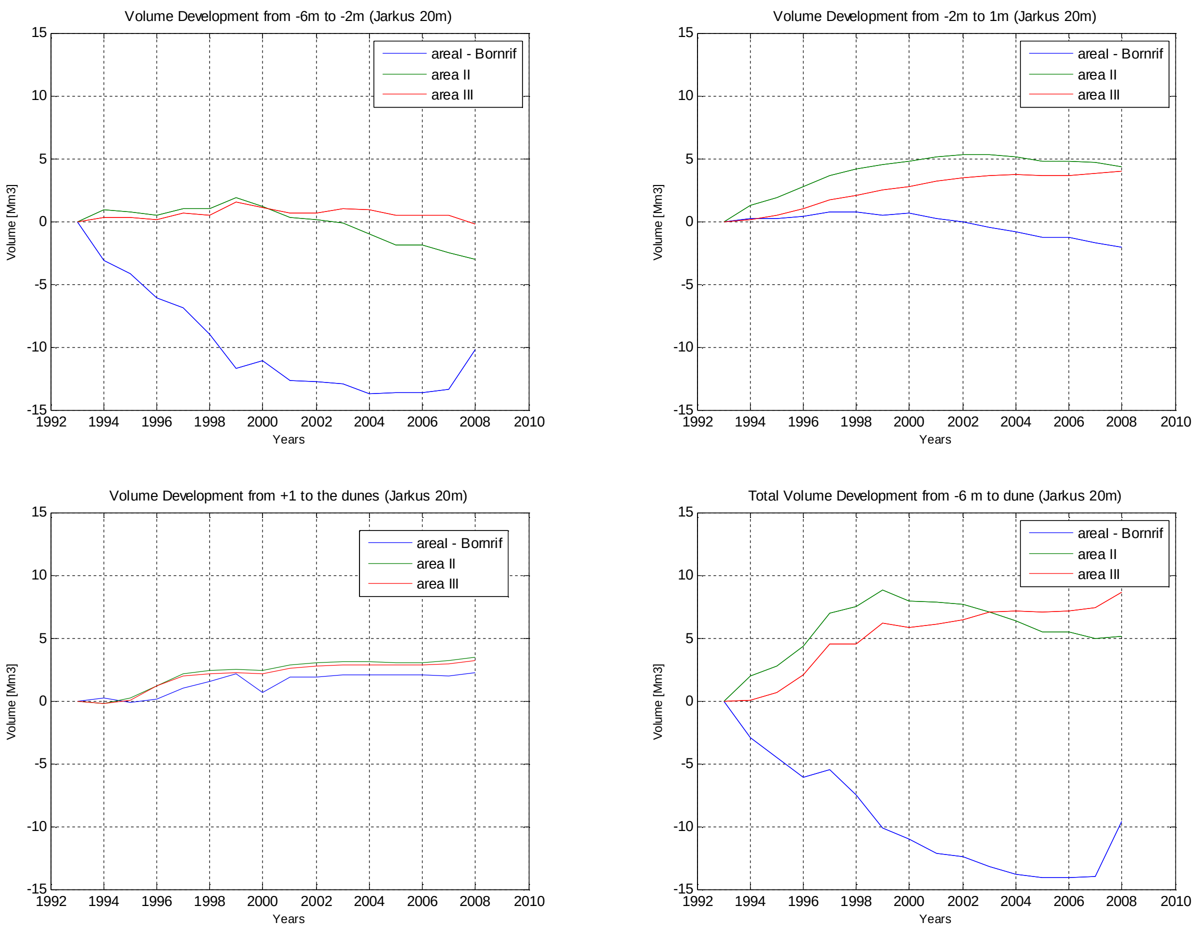

Figure 2.14: Volume development in relation to 1993 for the cross sections.

The conclusion that can be taken from this volume analysis is the stability years that goes from 1993 to 2003 and the area. This element is going to be the numerical simulation region and all the other analysis performed in this work is going to be based on this region/period.

2.4.3 Profile Analyses

In order to better understand the Bornrif evolution in cross-shore direction 3 profiles were selected: A (at km 172); B (at km 174) and C (km177) (Figure 2.15).

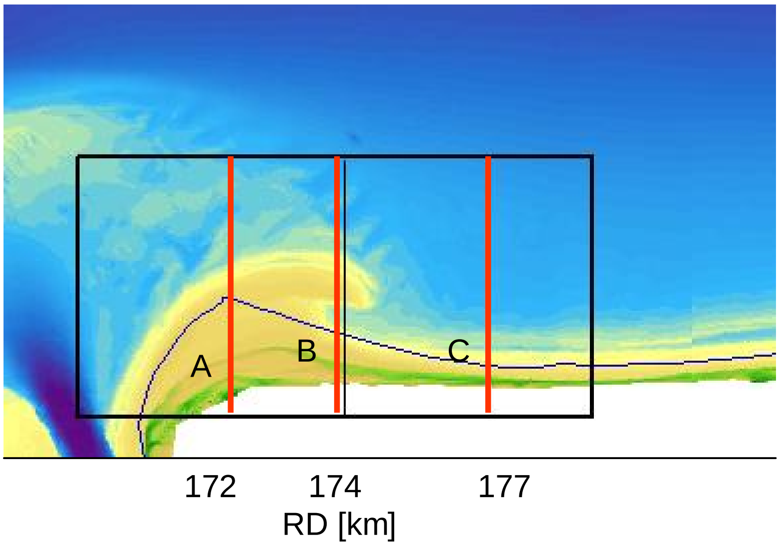

Figure 2.15: Profile locations

Profile A is representative of the Bornrif edge, where severe erosion process takes place. The erosion in the shore-face, between 0 and 6 meters depth, is order of 750m in 15 years. From the eroded sediment, part is exported downdrift and part of it is transported onshore nourishing the dune foot. In profile A, it is possible to visualize submerged sandbars and a big bar coming from the ebb-tidal delta (year 2008), that probably is the formation of the new bypass bar (Figure 2.16).

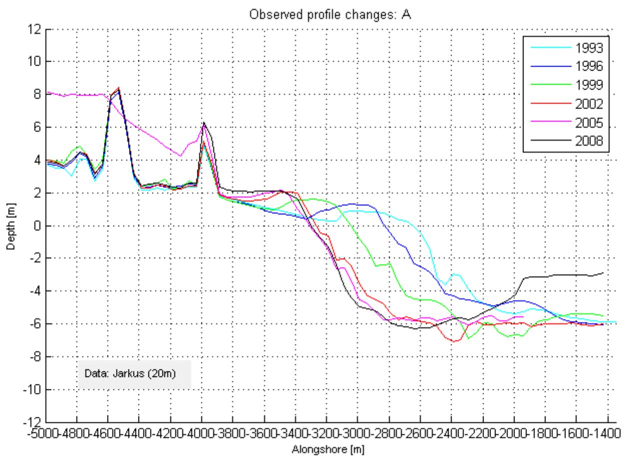

Figure 2.16 : Cross-shore section A, on km 172, over the years

The profile B was chosen in order track the spit tip evolution. It is possible to distinguish a 4 meter height emerged bar approaching the main land; it is the sand spit. The spit reaches the coast around 1996, when a channel linking the inside tidal bay to the open sea is formed. The complete merge with the mainland arise by 2000 when the channel is closed (Figure 2.17).

In B, the erosion takes place in deeper part of the profile, around -4 and -6m that get steeper over the years. As in profile A, it is possible to observe sand bars other then the spit.

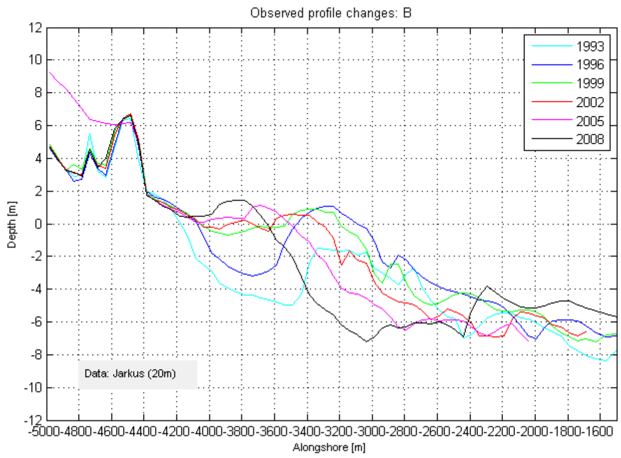

Figure 2.17 Cross-shore section B, on km 174, over the years

The last profile is C, it represents the eastern sheltered part of the domain. Here the main process is deposition of sediment coming form the Bornrif; however, some erosion event can be distinguished. In average, the entire profile has advanced around 200m seawards with a higher rate from 1996 to 2000. Around the year 1997 the sand bars start to reach the area where the profile C is located, one of the reasons to the higher deposition rate. It is important to reinforce that the accretion state is the profile tendency that can varies from year to year (Figure 2.18).

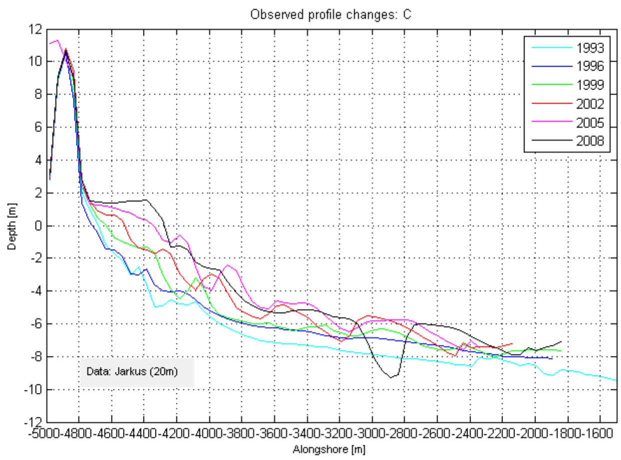

Figure 2.18 Cross-shore section C, on km 176, over the years

Concerning the dune erosion its analysis was performed separately, since the erosion and accretion observed on dunes are in order of 10 to 50 meters so, one order of magnitude lower than in the profile shore-face. For the profile A, was observed in 2005 a 15-meter retreat in the upper part of the dune (form 4 to 6). On the other hand, in profile B observed 80 meters retreat of the dune foot around 1996 due to the inlet channel formation and meandering, the channel meanders advance shoreward creating an erosive region. In 2000 with the closure of the inlet, the erosion stops; and the dune foot starts to recover from 2005. In profile C no substantial (more than 5 meters) dune erosion was observed.

2.5 Coastal Nourishments

As discussed above, Ameland shows an erosion/accretion cyclic behaviour; this natural cycle is kept over the years since it does not cause any damage to the local population. However, during the Bornrif evolution, some populated areas experience intense erosion; in order to mitigate the erosion and maintain the population safety, the Dutch government performed several beach nourishments in two main areas (Figure 2.19):

- the western coast, in front of the Borndiep – 1997, 2000 and 2004.
- the northern coast around the km 175, where the spit reaches the coast and developing a meandering channel – 1996 and 2003.

Figure 2.19 : Nourishments overview. The control volume is represented in the white rectangle, the green rectangles show the shoreface nourishment and the red the beach. . (source: Open Earth Tools)

The total nourished volume from year 1993 to 2003 was approximately 4.26 Mm^3 (Table 2.2), this volume is comparable to the volume variation found in section 202.4.2, when was studied the equilibrium element to define the study domain and the balance was not zero.

Table 2.2: Overview of the nourishment performed inside the control volume from 1993 until 2003

Year	x (RD [m])	y (RD [m])	Volume (Mm^3)
2003	177078 - 181269	608311 - 608554	1.43
1996	174883 - 178894	608237 - 608351	1.55
2004	170084 - 170895	607062 - 607869	0.39
1997	170071 - 170726	606702 - 607812	0.52
2000	170064 - 170477	606502 - 607521	0.40
Total			4.26

It is important to notice that the bathymetric surveys measure the bed level, not taking into account human interference. Therefore, the direct comparison between the model results and the data must be careful, especially when analyzing erosion in the lee side of the Bornrif, place where most of the nourishments were performed.

2.6 Conceptual model

In this section is presented the Bornrif morphodynamics state of art, derived from the literature review and the data analysis. The conceptual model shows and describes, for the time interval from 1993 to 2003, which are the main features and processes related to the Bornrif development.

Four stages (1, 2, 3 and 4, explained below) were distinguished according to the Bornrif shape and erosion/accretion regions. The year of 1993 was chosen as start point to the analysis for two reasons:

1. It is the most similar shape to the Sand Engine design
2. The sand volume equilibrium is more stable from 1993, mainly due to the complete detachment from the ebb-tidal delta.

Before beginning with the stages characterization, it is important to explain the main driving force of the Bornrif dynamics, the waves. As mentioned in 2.3 the principal wave direction, is N/NW so when the wave front reaches the Bornrif west outer edge creates a divergence area

(Figure 2.20). The wave action is reinforced (depleted) by the vertical tidal action, which changes the mean water level letting more (less) wave penetration.

Having the above mentioned process in mind the stage 1 starts in 1993 and goes until 1995, is the stages where the wave divergence in the outer edge is more intense. Due to the wave divergence, the northwestern Bornrif coast is intensively eroded (B), in an average rate of 1m/y. From the total eroded sediment, less than 15%, is transported southwards and the rest 85 % is transported eastward [Chenug et al. 2007]. The southward branch is going to accrete at the western Amelander coast (A) and the eastward is going to be deposited in the hook formation, which is growing southeastwards (C) (Figure 2.20).

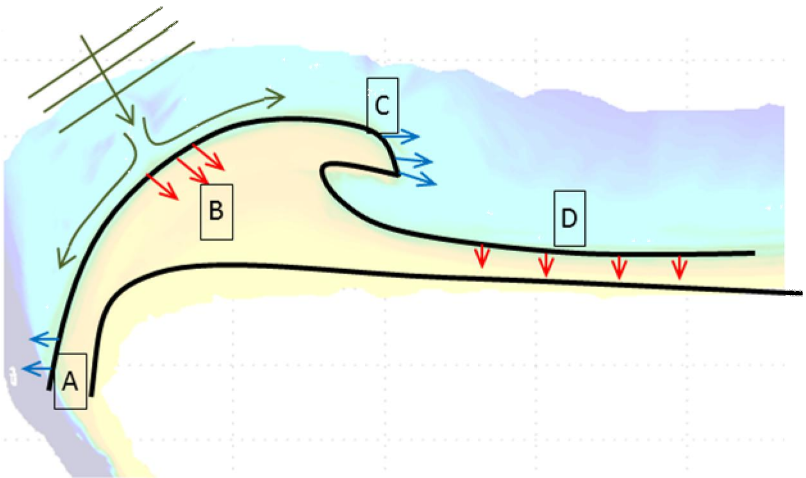

Figure 2.20 : Schematic draw of phase 1. Red arrows shows erosion and blue accretion, the gray arrows show incident wave and the divergence point.

Still in phase 1, the eastern coast behaves as an erosive coast (D). One reason for the erosion is that the Bornrif traps most of the sediment that suppose to reach the eastern coast; the attached bar act as a big groin for the alongshore current.

Stage 2 (1996-1997), is similar to stage one concern the main forcing and accretion/erosion patterns. However, the spit reaches a point where a clear narrow tidal channel is shaped; it is the inlet for the tidal lagoon formed landward of the spit (E) (Figure 2.21) [Cleveringa, 2005].

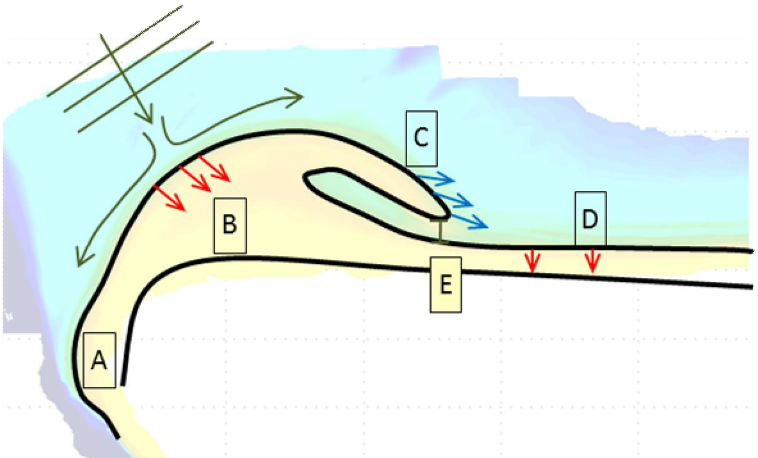

Figure 2.21 : Schematic draw of phase 2.. Red arrows shows erosion and blue accretion, the gray arrows show incident wave and the divergence point.

The stage 2 develops into stage 3 (1998-1999) as the channel increases in length due to the sediment input. As the channel gets longer, it becomes less efficient, leading to meandering (F). This meandering process erodes the shoreline reaching the dune foot. In stage 3 the Bornrif is smoother, less prominent, consequently the erosion/accretion process is damped out too; this trend is the result of the Bornrif coastline achieving an equilibrium state in relation to the wave direction therefore the sediment transport capacity decreases. The third aspect of stage 3 is the sand wave penetration, as the Bornrif is smoothed; it lets more space to the sand waves propagate inside the study domain (Figure 2.22).

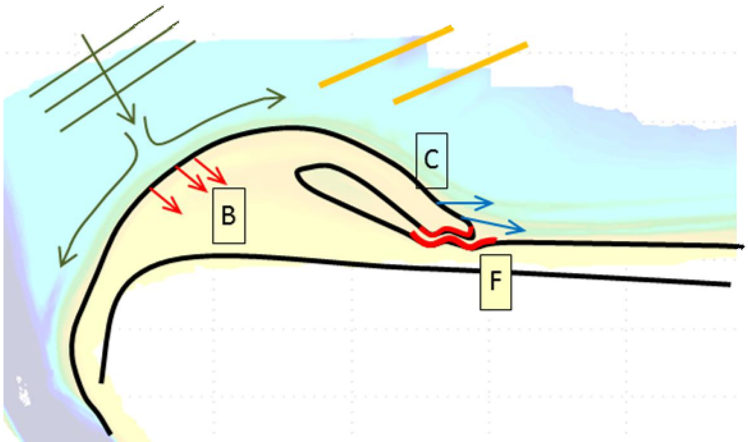

Figure 2.22 Schematic draw of phase 3. Red arrows shows erosion and blue accretion, the gray arrows show incident wave and the divergence point, the yellow lines represent the sand waves.

The spit merging with the mainland characterizes stage 4 (2000-2003). The loss of hydraulic head due to siltation leads to inlet closure. Afterwards, probably due to storms events, a new channel is opened in the north coast; as a dynamic region, this channel is constantly being closed and opened again, in a weaker point of the Bornrif coastline (Figure 2.23).

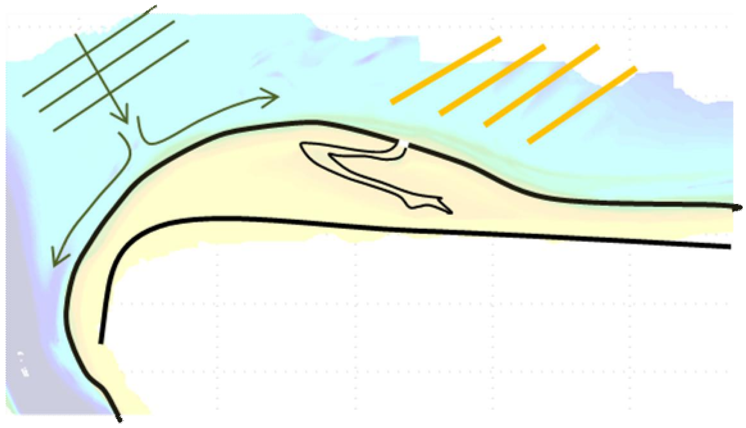

Figure 2.23:Schematic draw of phase 4. Red arrows shows erosion and blue accretion, the gray arrows show incident wave and the divergence point, the yellow lines represent the sand waves.

The difference between the selected start point, 1993 and the final one, 2003 is presented in Figure 2.24.

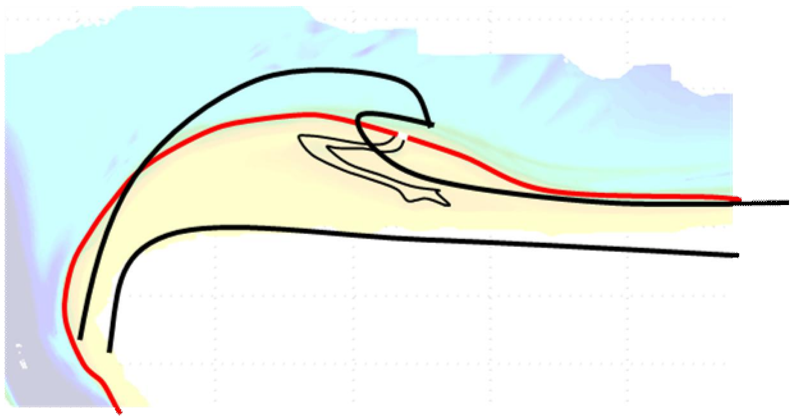

Figure 2.24 : Schematic representation of the coastline in 1993, in black, and 2003 in red.

2.7 Plunging wave X Bornrif

Figure 2.25: Morphological similarity between the Bornrif (left) and a plunging wave (right).

Observing the Bornrif development throughout the time, a clear similarity with plunging wave arises. Nevertheless, the similarity is not restricted to the general shape but also some wave characteristics are present in the Bornrif, the wave of sand.

Mead and Black [2001], developed a classification system for the plunging wave intensity, where the vortex characteristics are investigated (Figure 2.26 and Table 2.3). In their classification, the ration between the vortex length and the width is the parameter descriptive term. They found that as lower the vortex ratio more intense is the breaking; from this system, the Bornrif can be comparable to a medium intensity breaking, presenting vortex ratio of 3.2.

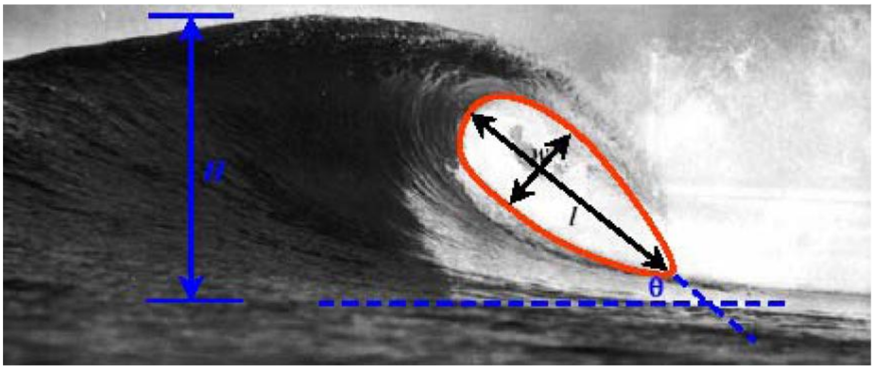

Figure 2.26: Curve fitting applied to the forward face of a crest parallel wave. Used to calculate the vortex length (l), width (w) and angle (θ). (source: Mead and Black, 2001)

Table 2.3: Classification of plunging wave intensity. (source: Mead and Black, 2001)

Intensity	**Extreme**	**Very High**	**High**	**Medium/high**	**Medium**
Vortex Ratio	1.6-1.9	1.91-2.2	2.21-2.5	2.51-2.8	2.81-3.1
Descriptive Terms	Square, spitting	Very hollow	Pitching, hollow	Some tubes sections	Steep faced, but rarely tubing

Another similarity concerns the wave energy dissipation area and the sediment influence in the Bornrif. When the Bornrif spit reaches the mainland, the sand accumulates close to the tip and afterwards starts to spread sediment along the coast. The accumulation and spreading of sediment cause a "turbulence" in the mainland, disturbing the initial condition of the coast, where close to the attachment presents a high level of disturbance and the level decrease further away. This process is also similar to a plunging wave behave; the falling jet forms a splash when it touches the water then starts to propagate as a turbulent flow, in big eddies that become smaller as they propagate [Ting and Kirby 1995; Lubin et al. 2006]

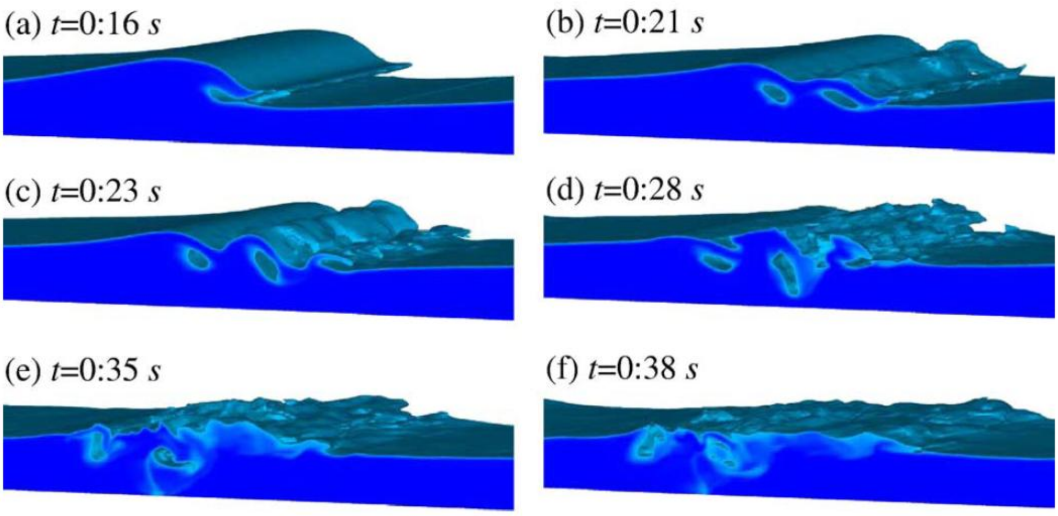

Figure 2.27 : Snap shot of plunging wave breaking simulation. Similar process to the one that occur with the Bornrif with completely different time scale. (source: Lubin, et al.2006)

3 Numerical Model

3.1 Process Based Model

The second approach to the Bornrif evolution study is the numerical model using the DELFT3D software, developed by [Deltares]. DELFT3D is a process-based model; this means that it reproduces the physical problem by solving the horizontal momentum equations, continuity equation and turbulence closure model with a robust drying and flooding scheme.

The core of DELFT3D is DELFT3D-FLOW, which account for a number of processes such as wind shear stress, wave forces, tidal forces, drying and flooding of intertidal flats, etc. The FLOW model can be coupled with other models as the DELFT3D WAVE module. The coupling is done by a dynamic interaction between them, this means two-way interaction; the FLOW model uses the WAVE output to calculate the hydrodynamics and the sediment transport conversely WAVE get as input the FLOW output to calculate the wave height, wave direction, dissipation among other parameters.

SWAN is the model behind the DELFT3D-WAVE module. It calculates: the evolution, the non-linear wave-wave interaction and wave energy dissipation of random, short-crested wind generated waves. The coupling with the FLOW model can be done online through the communication file that stores the most recent flow and wave computations every given time step.

The FLOW model calculates the morphological change by the ‘parallel online’ approach [Roelvink, 2006]. The idea is to run each hydrodynamic condition (for example Wave direction in combination with wind) in parallel and calculate the bed level change. Then each bed level enters in the merge process, is multiplied by the weight factor giving as output the averaged bed level change, which is going to be the input bathymetry for the new parallel computation step (Figure 3.1). Each time step, the computed bed level changes of the individual conditions are merged using weight factors based on the average bed level change of all conditions that is the next computational step.

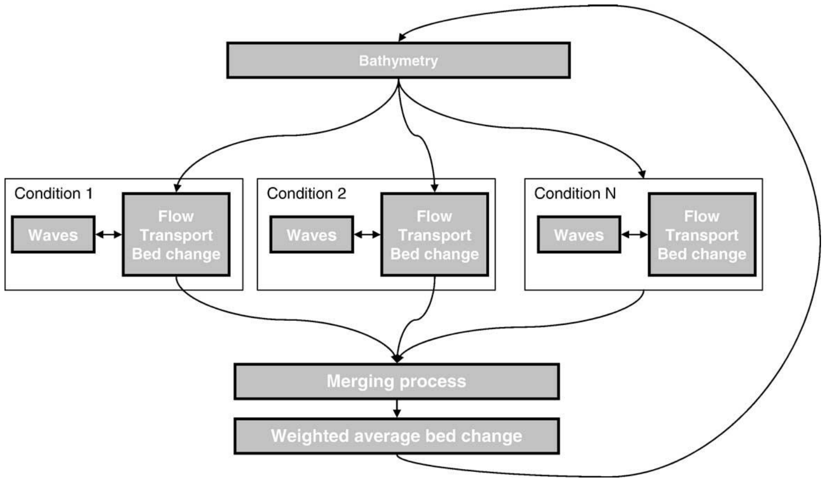

Figure 3.1:Computational flow scheme of "parallel online" approach. (source: Roelvink, 2006)

Further information and formulations can be found in the DELFT3D FLOW and WAVE manual [Deltares, 2010] and in Lesser et al.[2004].

3.2 Model Set-up and Settings

3.2.1 Parameters

The hydrodynamic model applied is 2DH (averaged over depth) since the full 3D scheme could be too computational expensive. The time step is based on the courant number criteria and is set as 15 seconds [Stelling, 1984].

The communication time step between the FLOW and WAVE model is 20 minutes, this time step defines how often the two models are changing information. Thus the FLOW model provides water level, currents and bed levels to SWAN computations; while SWAN gives waves field as output to FLOW computations, including wave driven current, setup and sediment transport.

3.2.2 Grid

For the Bornrif model three computational grids were applied (Figure 3.2), two for the WAVE model and one for the FLOW model. The flow and morphological grid extension was set based on the volume calculation study (section 2.4.2) and the resolution according with the main features defined in the conceptual model (section 2.6), the boundaries are:

- west: the Borndiep (ebb-tidal channel);
- east: was considered where the Bornrif sediment input is not varying on time (km 179);
- north: approximately the 7 meters depth contour line;
- south: is the Ameland island shoreline.

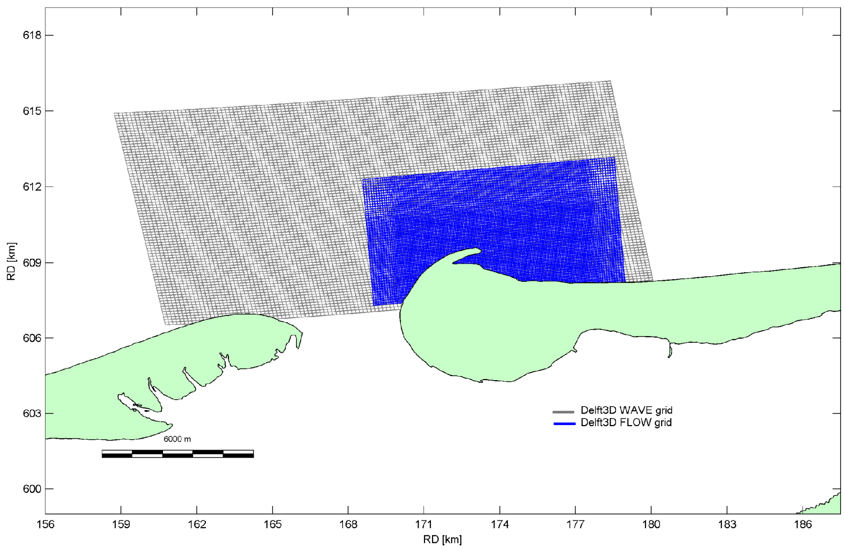

Figure 3.2: Numerical grid representation. In blue the flow grid and in gray the wave grid.

The flow grid extension is 87 by 182 in x and y respectively, with 50 by 50 meters resolution closer to the Bornrif to 100 by 50 meter at the boundaries. The wave grids setting were based on the flow grid. Two grids were required one with the same grid size as the flow model and focused in the flow model region the second one covering the whole ebb-tidal delta and 3 times coarser than the flow grid. The numbers of points in the wave grids are respectively 95 - 185 and 86-181 (Figure 3.2).

3.2.3 Initial and Boundary Conditions

Uniform values were considered as initial condition for the entire domain. Three initial conditions were required as input for the model: water level, sand and mud concentration. All of them set as zero initial value. For the water level case, the zero was the value that showed the smallest spin up time as well as less instability in the flow.

Two types of boundaries were defined for the FLOW model: water level and Neumann. In the North and West boundaries, the water level type applied was a harmonic (M2) vertical water level of 1 meter. The definition of these two boundaries was based on:

- the tidal forcing in the North Sea, entering in the North and
- due the inlet flux penetrating the Western boundary.

In the South and Eastern boundaries, Neumann conditions were applied, which calculate the gradients inside the model and reproduce it in the boundary. Neumann boundaries lead to a more stable flow inside the domain and simplifies the model settings. This type of boundary is applied when the cross-shore length is limited and can be considered that the gradient does not vary in this dimension [Roelvink 2006].

3.2.4 Morphological Settings

The bed level change is calculated for each wave condition and each FLOW time step, following the parallel online approach. However, the morphological time scale development is several times longer than the flow. To adjust this bias between them one alternative is to use a speed up factor, the so-called the “morphological time scale factor” (MorFac). The principle is to multiply the morphological processes, erosion and accretion, by a factor fmor, leading to after one hydrodynamic time-step: $\Delta t_{morphological} = fmor * \Delta t_{hydrodynamic}$.

A phase shift in the hydrodynamic conditions was applied, so that ebb and flood transport in various conditions counteract, which allows for higher MorFac values (30).

The sediment data available indicates that the D_{50}[4]. varies from 180μm to 240 μm, so the D_{50} prescribed was 200 μm uniform distributed in the domain for the sand. A fraction of mud was added because the siltation in the Bornrif inlet depends on this sediment class (Figure 3.3). The mud content atlas shows that the region presents around 1% of mud content, although in the model was considered 10% otherwise the mud would be washed away too fast. The cohesive fraction is important to the tidal basin dynamics as for the vegetation growth.

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4. *D_{50} is defined as the grain diameter at which 50% of the sediment sample is finer than.*

Figure 3.3: Mud content, browner higher the mud fraction. Can be notice that inside the Wadden Sea the mud content is much higher.

3.3 Model Schematization

3.3.1 Bathymetry

The initial bathymetry is a parameter influences the further development of the spit. To build the initial bathymetry map, JARKUS ('JAaRlijkse Kustlodingen', Ruessink, 1998) data from 1993 in combination with the Vaklodingen database were selected.

The JARKUS bathymetry was projected using triangular interpolation to build the flow grid initial bathymetry. This dataset was chosen due to its frequency in time, becoming easier to validate the model afterwards. However for the wave grid the JARKUS does not cover the whole domain that includes depths over 20 meters. In this case, the Vaklodingen dataset was applied.

3.3.2 Tides

Herein, only vertical tides were considered, 1 meter of harmonic water level variation with the same frequency as M2 (28.98 ^{o}/hour). This is allowed since the main sediment driven forces are the waves and wave induced currents, leading to the conclusion that the horizontal tides are not that important. However experiments without any kind of water level changes results in unrealistic sedimentation patterns [Grunnet et al. 2005].

Grunnet et al. [2005] performed several experiments to test the influence of tides, wind and waves in sediment redistribution in Terschelling, and concluded that for a local model in the western Dutch Wadden Sea the transport capacity of horizontal tides in local models is negligible (Table 3.1). Therefore, the consideration of vertical tides only, is justified here.

Table 3.1: Volume change and root mean square differences derived from bed level change. It shows the results from an experiment about local model in Terschelling, where the influence of horizontal tide was assessed. Experiment 1 includes tides, waves and wind while experiment 3 just vertical tides waves and wind.

Section	Model experiment			
	ΔV (m^3/m)		$\delta_{rms}{}^{a}$ (m)	
	1*	3b*	1*	3b*
A0	5	5	0.07	0.07
B0	8	8	0.07	0.08
C0	6	7	0.06	0.08
A1	10	8	0.06	0.07
B1	98	95	0.05	0.06
C1	29	27	0.06	0.06
A2	84	82	0.05	0.05
B2	153	152	0.06	0.07
C2	70	69	0.05	0.06
A3	−91	−94	0.06	0.06
B3	−86	−90	0.04	0.05
C3	−8	−9	0.05	0.06

[a] δ_{rms} is the root mean square difference of Δz relative to experiment 1 (i.e. results from the larger model).
* Indicates experiment with local model.

3.3.3 Waves and wind

Within SBW, wave data starts collecting in the Ameland Inlet from 2003. However, this work is focusing on a previous period, from 1993 to 2003, similar to the work of de Fockert [2008]. The wave data schematization prescribed in this work is based on the analysis performed by De Fockert [2008].

Briefly, de Fockert [2008] compared the overlapping time between the AZB12 buoy, located in the Amelander inlet, with the SON and ELD buoys (Figure 2.5). Getting the conclusion that the incident wave in the Ameland is comparable to the SON buoy.

As applying the whole wave climate is not computational possible, hence a wave schematization was performed. The first step was to take off the waves that are not significant for the sediment transport. These are waves with wave heights below 0.25m and the ones coming from the south; leading to a 126 wave conditions. That still is too many wave conditions, thus a morphological wave climate is derived applying *Opti* (developed by Roelvink), where the morphological conditions are reproduced by a reduced number of wave conditions. Twelve wave conditions results from this process with respective setup, wind direction and time persistence (the weight factor for the online approach) (Figure 3.4).

Wave condition [#]	Hm0 [m]	Tp [s]	Dir [°N]	Setup [m]	U_{wind} [m/s]	Dir_{wind} [°N]	Weight [%]
002	0.49	4.84	22.77	-0.13	4.65	88.04	17.58
009	0.52	4.87	292.97	0.03	5.08	224.09	11.35
020	0.99	5.06	264.07	0.10	9.17	215.45	13.21
024	0.99	6.29	322.68	-0.01	4.88	267.05	24.50
030	1.49	5.73	53.63	-0.38	9.60	80.80	8.22
051	1.98	7.13	338.01	0.03	6.99	332.86	6.67
052	1.98	6.98	351.21	-0.05	7.52	5.99	4.35
060	2.47	6.94	278.78	0.57	13.81	252.61	2.37
061	2.47	7.26	293.40	0.48	11.14	262.90	7.35
087	3.45	8.59	336.61	0.33	11.10	336.12	2.02
102	4.47	9.44	307.05	1.06	15.00	284.07	0.99
118	5.88	11.26	324.60	1.35	14.60	315.92	0.23

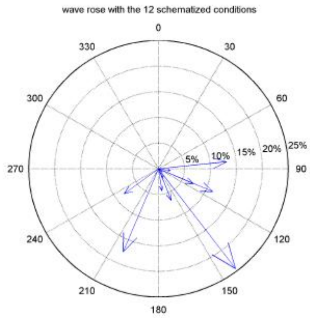

Figure 3.4: Schematized wave scenario for the years 1989-1999. Wind rose for each wave condition.(source: de Fockert, 2008)

4 Hindcast short term 1993-1997

The short-term hindcast focuses on the period from 1993 to 1997. As mentioned already, 1993 is the year when the Bornrif shows the most similar shape to the Sand Engine project; and therefore is so the starting point for the analysis. On the other hand, the choice of the year 1997 as ending time for the hindcast is based on the spit development stage; described in stage 3 of the conceptual model (section 2.6) and it is when the spit reaches the coast. The most critical period that we are interested in now is the early years development, so how and how long is it going to take for the spit to merge with the mainland and how accurate is the representation.

4.1.1 Basic Setting

A basic model setting was defined in order to have a reference simulation and on top of that include more variables. This approach was applied in order to reproduce and identify the Bornrif morphology driving forces one by one. In this step was considered:

- The wave schematization with the 12 wave conditions, waves are the most important driving force for the western Bornrif;
- Vertical harmonic tides with 1 meter amplitude; following Grunnet [2005] reasoning that the waves are the most important force however not considering vertical tide leads to unrealistic bed-forms;
- Uniform sediment distribution where the D50 is equal to 200µm;
- TRANSPOR2004 sediment transport formulation, in combination with the bed roughness predictor. The choice of this formulation explained further in Sensitivity Analysis section (5.1);
- The setup represents the water level rising due to waves and wind shear stress pilling up water at the coast. The setup height is derived from the wave schematization procedure. In the simulation, the setup is implemented as additional water level specific for each wave condition
- The simulation time frame is 1 month with Morfac equal 30, which reproduces around 3 years of morphological changes.

The base model, in general lines, does reproduce the Bornrif dynamics, that is shown next. The simulations analysis is based on: bathymetric maps comparison; erosion/sedimentation patterns: bathymetric maps, bed level changes map, profile change throughout the years and volume development per alongshore section (one kilometre) per year. The results and features reproduced are discussed below:

- The spit propagates east-southwards, until hits the coast forming a bay. However, the rate between the propagation eastward over southwards in the simulation is lower than the rate observed in the data, leading to a quicker land attachment and so a smaller bay (Figure 4.1).

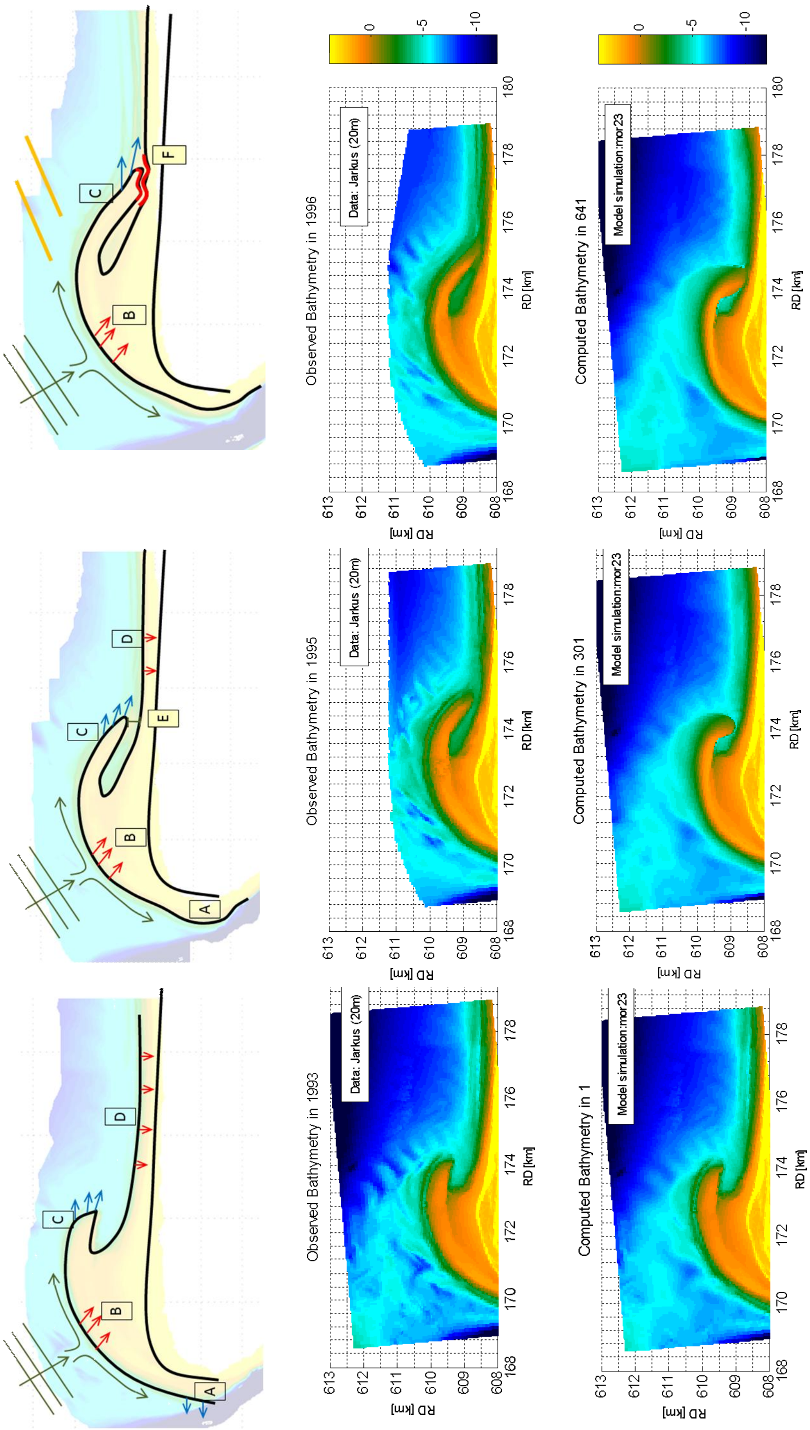

Figure 4.1: The first line is the conceptual model phase 1, 2 and 3 (the simulation does not reach phase 3, but is half way); second line data and third line simulation. Each row represents one period 93, 96 and 97 respectively.

This early "breaking" of the spit can has two complementary explanation:

– Kraus [1999] state that the length of the spit depends on the alongshore sediment transport rate and the inlet currents. As the model does not consider the estuary this inlet currents are not reproduced leading to a shorter evolution of the hook; though in reality these are strong currents (1m/s) and able to mobilize a large amount of sediment.
– As described in section 2.3.2, the Bornrif present a receive sediment form the ebb tidal delta (E2 type, Figure 2.9) rapidly accreting and turning towards the mainland (Table 4.1) [Petersen et al., 2008].

Table 4.1 Parameters controlling inlet spit geometry and evolution, and the associated processes. (source: Kraus, 1999)

Spit Parameter	Short Term	Long Term[1]
Length	Longshore transport rate; proximity to inlet channel; strength of channel current	Sediment supply; geologic controls; breaching (bayward or seaward); cyclic & intermittent forcing
Elongation speed	Longshore transport rate; grain size; proximity to inlet channel; beach slope and depth-contour gradients parallel to spit	Cyclic and intermittent forcing[2]
Width	Run-up elevation; tidal range; depth-contour gradients perpendicular to spit	(see Overwash fans below)
Overwash fans	Storm surge; frequency of storms	Dunes and other blocking features; depth of receiving bay or lagoon
Elevation above MSL	Run up; tidal range	Aeolian transport; relative sea-level change; tsunami
Depth of closure	Wave height and period; tidal range; grain size	Extreme storms; elapsed time
Tendency to recurve	Proximity to channel; channel current; wave focussing; extreme storms	Cyclic and intermittent forcing

1. Long-term processes encompass those of short-term processes in same category.
2. Cyclic and intermittent forcing arises from seasonal and annual changes in wind and waves, arrival of storms and weather fronts, annual and inter-annual change in water level, etc.

• The erosion/sedimentation pattern is similar, but the simulation shows stronger erosion in the northern edge of the Bornrif. This erosion is reflected in a slightly flatter outer edge that does not fully correspond to the field observations (Figure 4.2).

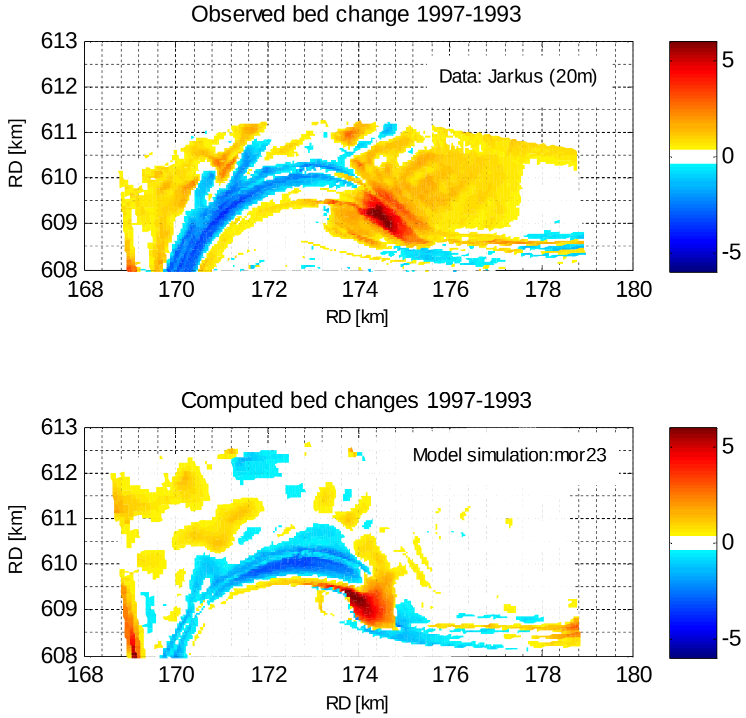

Figure 4.2: Bed level change between 1993 and 1997, upper plot data and lower simulation. In 1996 there is a nourishment in the lee side (from km 174 until 178) of 1.55Mm^3 that is not included in the simulation.

- Analysing the volume development two main differences are observed. The first westwards concern the inlet channel. As no horizontal tide is considered accretion in the flood channel occurs leading to a misinterpretation in the most eastward volume development section (km170) (Figure 4.3).

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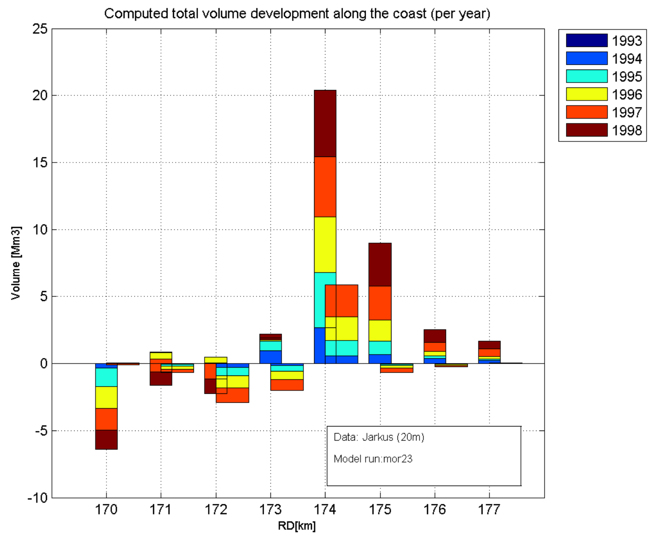


Figure 4.3: Volume development per alongshore section (one kilometre) per year. The left hand side the thinner bar represent the data analysis and the right hand side wide bars the computed volume. Each colour represents one specific year as described in the legend.

- The transport pattern trough the transect (not shown) is in order of 1Mm3/year for the lee side far from the Bornrif, which is coherent with previous works. On the other hand, the transport in the tip and northern coast of the Bornrif can reach values 2 times bigger.
- The second divergence about the volume development concerns the spit region. Measurements reveals that the spit goes further eastward this process is reflected in the volume development analysis with two main accretions regions in km 174 and 175. As the spit in the simulation does not reach the km 175, no accretion is observed for this area (Figure 4.3 and Figure 4.1).

- The profiles are steeper landward and smoother seaward. It looks like more as an advection plus diffusion process than a purely advection as observed in the data, when the spit is approximating the coast.

Considering this first simulation, some points should be improved such as: the northern coast flattening; the Ameland estuary flood channel accretion; the profile steepness and the eastward spit development. In order to improve the hind cast simulation some sensitivity analysis test are done (chapter 5) and further some additional parameters were applied (chapter 6).

5 Sensitivity Analysis

Sensitivity analyses were performed in order to validate and improve the simulation. The simulations performed for each of the sensitivity analysis test have the settings of the base simulation as starting point. The time frame is 15 days with a Morfac of 30, resulting in approximately 1 year and a half of morphological changes.

5.1 Transport formulation

In literature, there is an extensive discussion about which sediment transport formulation should be applied to calculate morphological changes. The default transport formulation implement in the model DELFT3D is TRANSPOR1993 and calculates the time-averaged sediment transport over the wave period (Van Rijn, 1993). Nevertheless, Van Rijn and Walstra (2003) presented a new formulation, TRANSPOR2004, which includes the intra-wave processes divided in current-related and wave-related bed load transport.

This section discusses which one of these two formulations is more recommendable for the Bornrif simulation.
TRANSPOR2004 has as basic formulation the TRANSPOR1993, however some modification were done concerning the following points [Brière 2006]:

- Bed roughness predictor
- Suspension sediment size predictor
- Grain roughness and friction factor
- Wave-induced orbital velocities and streaming near the bed
- Shields criterion for fine sediment

As cited above the main modifications are about wave-induced transport, and the waves are the most important driving force for the Bornrif development. Consequently, it is important to verify if whether the TRANSPOR2004 implementation improves the hindcast.

In order to verify which of the formulation fits better for the Ameland region, two tests were performed each one considering one formulation (TRANSPOR1993 and TRANSPOR2004 with bed roughness predictor). For this analysis, the mud was taken into consideration.

The analysis is based on: erosion/sedimentation patterns; bathymetric evolution; transport through sections and volume development per alongshore section (one kilometre) per year. The main results are:

- The Van Rijn 2004 takes longer in two aspects:
  - it takes at least 15% longer to run each simulation day
  - the morphological changes are slower, this means that the tip takes longer to advance eastwards
- The erosion/sedimentation pattern in TRANSPOR2004 is more similar to the data especially on the western coast, where the 1993 formula is presenting too much accretion (Figure 5.1).
- The sediment transport volume is approximately 20% higher in the 1993 formula.. Although, for both formulations, the values are inside the predicted value by previous works that varies from 0.5 to 1 Mm^3/year.
- In TRANSPOR2004, the Bornrif developing shape is smoother, as observed in the data. The Bornrif keep a “round” coastline, showing the same shape as a plunging wave that does not has edges.

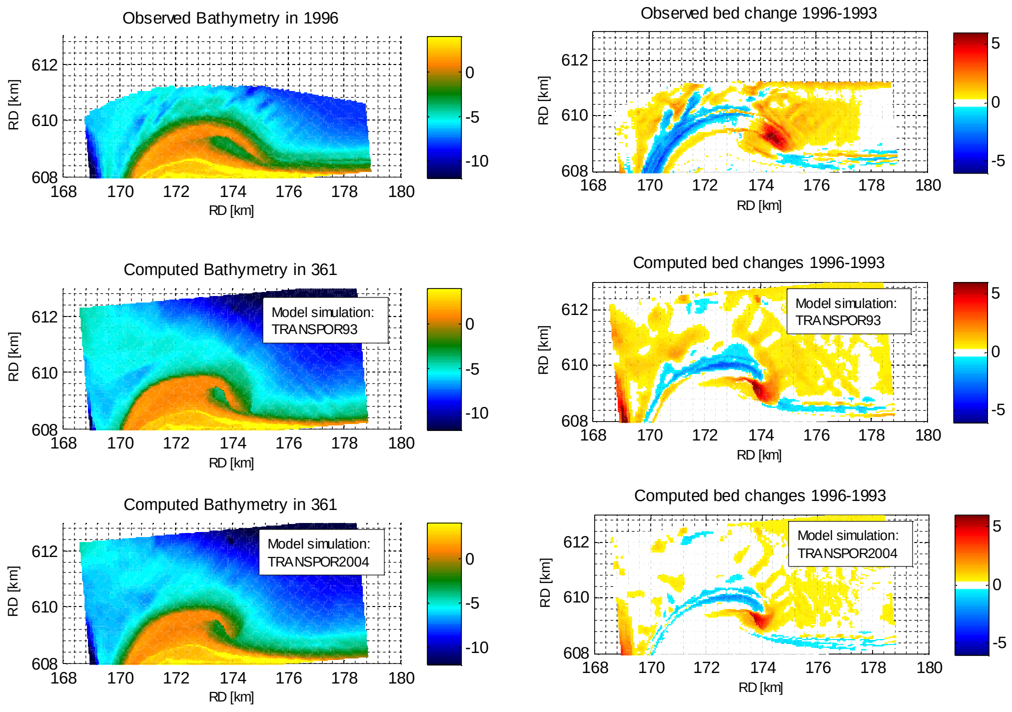


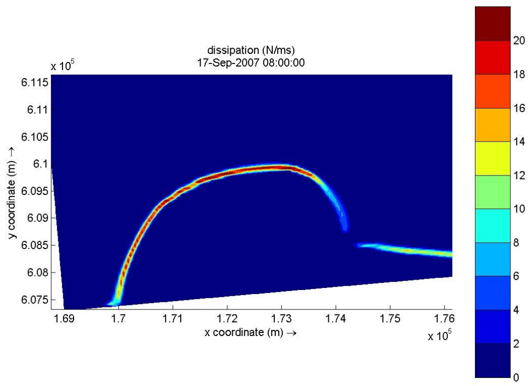
Figure 5.1: Left: Bathymetric maps in the top Jarkus data for 1996, in the middle the computed bathymetry applying transport formulation TRANSPOR93 and in the bottom TRANSPOR2004. Right: Observed and computed bed level change, red shows accretion and blue erosion, following the same order of the left.

5.2 Wave Direction

To a better understand of how changes in the wave climate could influence the Bornrif two tests were done varying the incident wave direction of all wave conditions: in mor-12 10^{o} was added to each wavecon file and in mor-13 10^{o} was subtracted. For example, the wave direction in condition wc002 is 22.77 ^{o} in mor-12 the direction is set as 32.77 ^{o} and in mor-13 12.77 ^{o}.

The analysis is based on: dissipation region; the shoreline position; erosion/sedimentation patterns and transport through sections. The differences in the development are described below.

- A shift of the maximum dissipation region is observed. The wave condition presented here is the wc024, it is the most frequently occurring condition, accounting 25% of the total wave climate. It can be observed that the region of maximum dissipation is shifted and concentrated more southwards, leading to a different transport pattern (Figure 5.2).



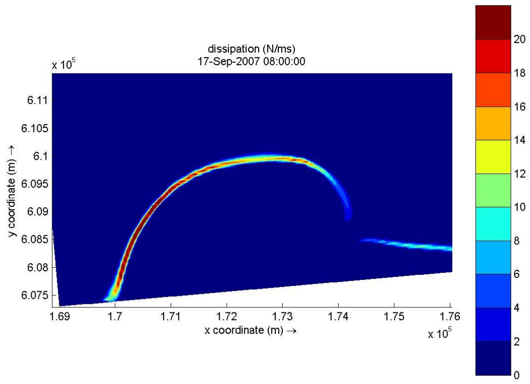


Figure 5.2: Wave dissipation for plus 10^{o} (mor-12, left) and minus 10^{o} (mor-13, right).

- The net transport rates do not vary much; they are in the same order of magnitude. However the distribution changes, the divergence point shift southward approximately 1500 meter comparing from mor-12 to mor-13 (Figure 5.3).

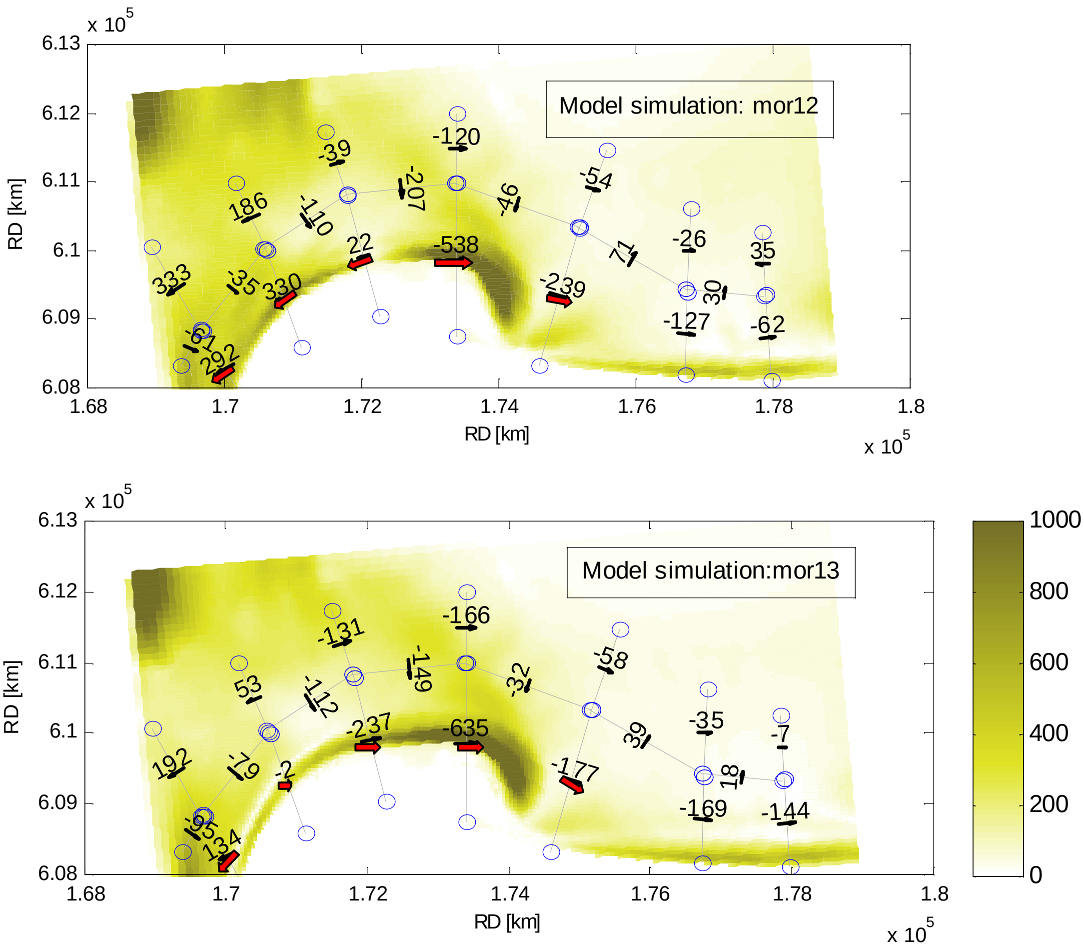


Figure 5.3:Yearly total transport trough transects ($10^3 m^3$/year).

- The change of the divergence point is reflected in the spit position. In mor-13 the spit goes further eastwards, with a distance difference of approximately 100 meters. At first glance, this seems counterintuitive because the divergence point for mor-13 is further from the spit than at mor-12; but as in mor-13, the most frequent scenarios the waves approach the shore with a bigger angle resulting in a stronger alongshore current. (Figure 5.4).

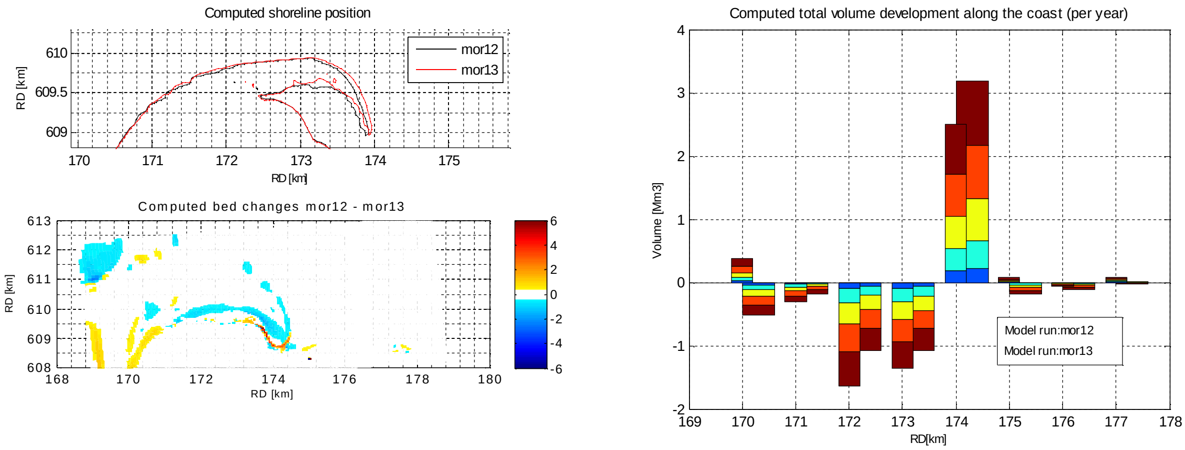


Figure 5.4: Left: upper shoreline position for the experiment mor12 and down mor13. Right: Volume development per alongshore section (one kilometre) per year. The left thinner bar represent the mo12 and the right hand side thicker the mor13. Each colour represents one specific year as described in the legend.

From this analysis, it can be concluded that the wave direction is an important Bornrif morphodynamics forcing. The refraction due to the ebb tidal delta does not filter the changes in wave direction and therefore it is important that the waves be well schematized, as they determine the Bornrif erosion/accretion process.

5.3 Sediment Size (D_{50})

This analysis aims to quantify how much the sediment diameter (D50) influences the Bornrif dynamics. Two simulations were conducted varying the D_{50}: one with D_{50} equal100 µm (mor-18) and one with 300 µm (mor-19). In both cases, the sediment is uniformly distributed and the boundary profiles are in equilibrium, so there is no lack of sediment.

The simulations analysis is based on: the shoreline position; bathymetry development; erosion/sedimentation patterns; transport through sections and volume development per alongshore section (one kilometre) per year. The two experiments show different evolution patterns as discussed below.

- The simulation mor-18 shows a much faster evolution than mor-19. Drawing a parallel between the experiments and the bathymetric data, in the end of the simulation time, mor-18 can be compared with the year 1999, this means a 6 years evolution; while mor-19 could not even reach the shape observed in 1994, less than 1 year (Figure 5.5).

- In mor-18 the Bornrif spit reaches further west than mor-19, even if the simulation time was extended the tip in mor-19 shows a trend to go southwards instead of east-southwards as is observed in mor-18 and in the bathymetric data. In mor-19, the “wave breaking” shape is more truncated, as the sediment is too heavy there is not enough force to carry them further away.
- As 300µm is too coarse for the local hydrodynamics conditions, the transport capacity of this sediment diameter is low. On the Bornrif tip, the transport is 0.3Mm^3/year and in km 176 0.09 Mm^3/year, while for D_{50} equal 100µm the values are 4.3 Mm^3/year and 1 Mm^3/year respectively.

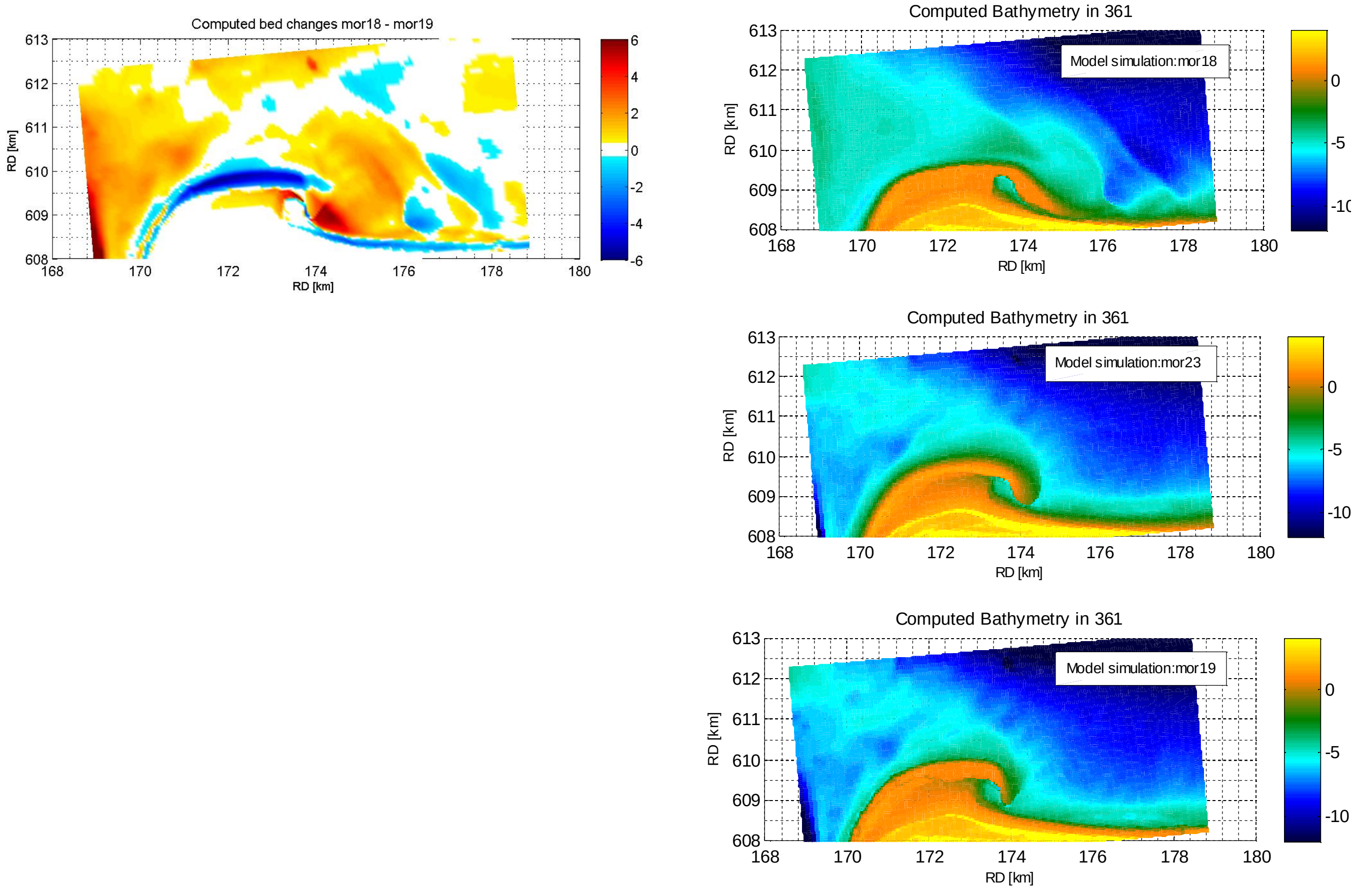


Figure 5.5: Left: Bed level difference between mor18 (100 µm) and mor 19 (300 µm). Right: Computed bathymetry for upper mor 18 (100 µm), middle mor 23 (200 µm, base simulation) and lower mor19 (300 µm).

Even if the chosen sediment diameter range is not fully realistic, it gives the idea of the D_{50} importance. From this analysis is possible to define reasons to take into consideration other sediment fractions than just sand (200 µm) once the sediment characteristics are going to define: how the morphological Bornrif simulation is going to develop, how far the spit can reach and how the intertidal basin is going to behave. So the D_{50} has a key role in the period of the Bornrif development.

5.4 Sensitivity of including wind setup

The setup implementation has a positive influence in the spit migration, which goes eastward and leads to a slight smoother outer edge. Besides, it does not improve the profile steepness neither the Amelander inlet channel accretion that still requires the implementation of others parameters. Concluding it is important the inclusion of setup in any further study, once this parameter influences positively the morphodynamics.

6 Additional Processes

6.1 Mud Implementation

As part of an estuary inlet, the Bornrif receives fine sediment from inside the Amelander estuary. The mud and sand have different properties for instance: cohesiveness, lower settling velocity and critical bed shear stress. As a result, the morphological response of each type of sediment is going to diverse. In this section is analysed how the mud influence in the Bornrif development.

The implementation of mud in the simulation is done by adding a mud fraction as a percentage of the sediment layer, in this case a 10% of mud comparing with the sand. The measurements shows, for the year 2008 a 2-3%. However with the low percentage and with no input from the estuary was a possibility of this sediment be washed away.

The analysis is based on the comparison with the data and with the sand-only simulation. Analysed were: bathymetric maps comparison, bed level changes difference; shoreline position difference (how far goes the spit); profile change throughout the years and volume development per alongshore section (one kilometre).

- Comparing the coast line evolution of mor-23 (just setup) and of mor-30 (setup + mud), in mor-30, the spit is about 50 meter more westwards than in mor-23. This difference can be the result of a sediment loss. As fine sediment needs a calmer environment to settle.
- Following the same reasoning, washed away mud, the western Bornrif coast is more eastwards than in mor-23. In fact, the entire outer contour in mor-30 is smaller when compared with the outer contour of mor-23 (Figure 6.1).

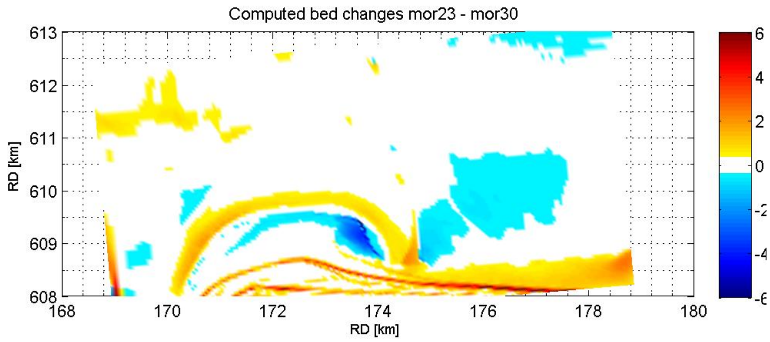


Figure 6.1: Bed level change between mor-23 (just setup) and mor-30 (setup + mud).

- The mud inclusion solves the problem of the profile steepness. Inside the bay, formed between the spit and the island, there is hydrodynamics condition to mud deposition. This sediment is going to nourish the profile foot keeping it smoother. This deposition is observed in the data, and is found not just inside the bay as in the bay channel; it is the responsible for the channel siltation and loss of hydraulic head and further closing.

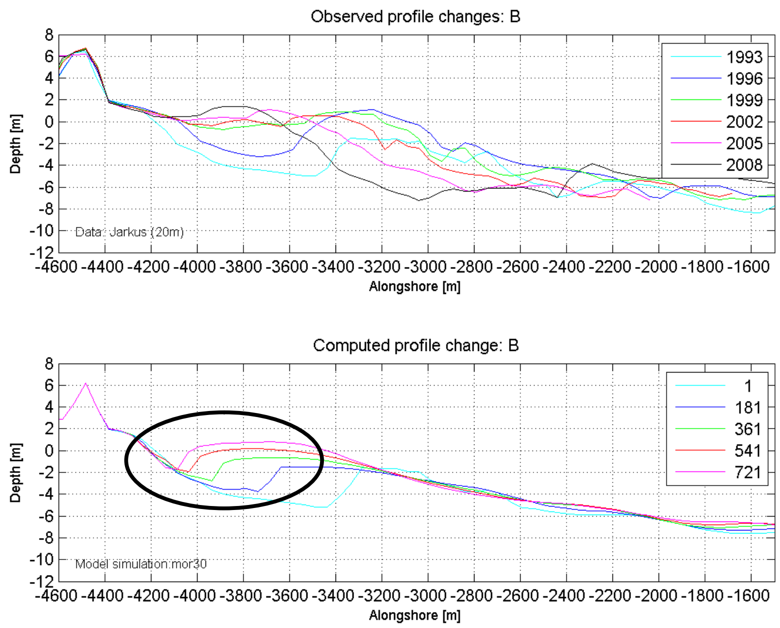


Figure 6.2: Profile time evolution. Upper: Jarkus data. Down: Model simulation mor30. The black circle shows the smoother profile.

- The accretion in the Borndiep is damped out too, probably due to the high energy of the region.

The impact including cohesive sediments has been widely discussed, in this chapter becomes clear that it influences the morphodynamics. Apart from the dynamics, the mud fraction is also extremely important to ecological models; which are the new step for a better reproduction of these large features.

6.1.1 Bornrif Morphology comparing with Waves parameters

As described in section 2.7 the Bornrif is comparable, in many ways, with a plunging wave. In order to verify if these aspects also can be reproduced in the model the vortex ratio was calculated. The model results vortex ratio is inside the classification developed by Mead and Black [2001], however as a high intensity breaking (vortex ratio equal 2.36) and not medium intensity as in the data. In the previous sections, the not completely reproducing of the lagoon was already described when state that the spit does not reach as westward as in the data. Nevertheless, it is an interesting result, once it can become one more parameter to a quick evaluation of the spit reaching point. It is expected that the Sand Engine Delfland form a lagoon within the range of the vortex ratio parameter most probably varying from 2.5 to 3.5 once in the project a long hook is predicted.

6.2 Long term hindcast

The long-term running is set to reproduce the Bornrif evolution from 1993 to 2003, so 10 years of morphological development. As it is the continuation of mor30, the same settings are applied. The previous section (6.1) already discusses about the features and processes from 1993 to 1997; the focus in this section is from 1998 to 2003. Following the conceptual model stages this period comprises the stages 3 (1998-1999) and 4 (2000-2003).

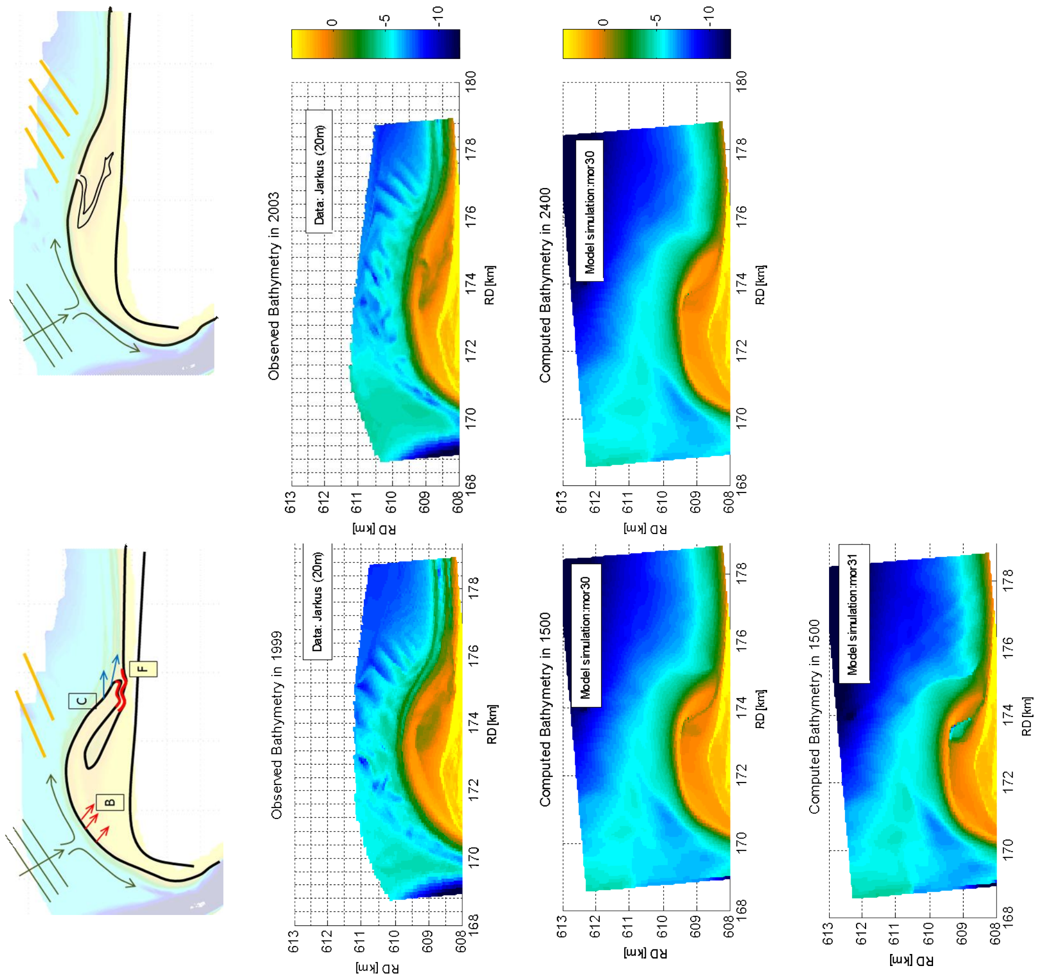
Concern stage 3 the three aspects are the most important ones: the channel increase; the channel meandering and the slower erosion/accretion process. The increasing of the channel is well reproduced and so the accretion inside the bay due to the fine settling as well the smaller rate in the accretion/erosion patterns due to the wave direction oriented coast.

However the channel meandering is not reproduced in the simulation, it is observed some erosion in the island coast in front of the channel but it is milder than in the data. A plausible explanation, for the channel morphology, is the meandering could be forming during longer slack water period, if considering horizontal tidal current as well as asymmetry that is not the case in the scope of this work. This results show that the simulation output for the Sand Engine must be carefully analyzed once more severe erosion can be cause than the expected one. (Figure 6.3).

Another discrepancy concerns the accretion inside the bay. In data analysis, is observed deposition in this region, though too much accretion takes place inside the bay in the simulation. This problem probably arises due to the high volume of fines available; a better knowledge on sediment availability and distribution could improve this scenario.

In stage 4 the main patterns are: the merging with mainland and the opening of new channels in the North coast. The siltation and further channel closures is well reproduced in the long-term simulation. However, the opening of new channel up north is not observed; probably due to the high siltation in the lagoon that is almost filled up.

One important remark is the development period; after the spit merging with the mainland the development become much slower, so the same shape resides for longer periods. This behaviour is the same as the observed on data, where the entire process from the hook formation (1993) until the channel formation/siltation (1998) takes in average 5 years and after the merging until all the entire spreading of sediment takes more than 10 years, the spreading process is still incomplete until the last measurements 2010.



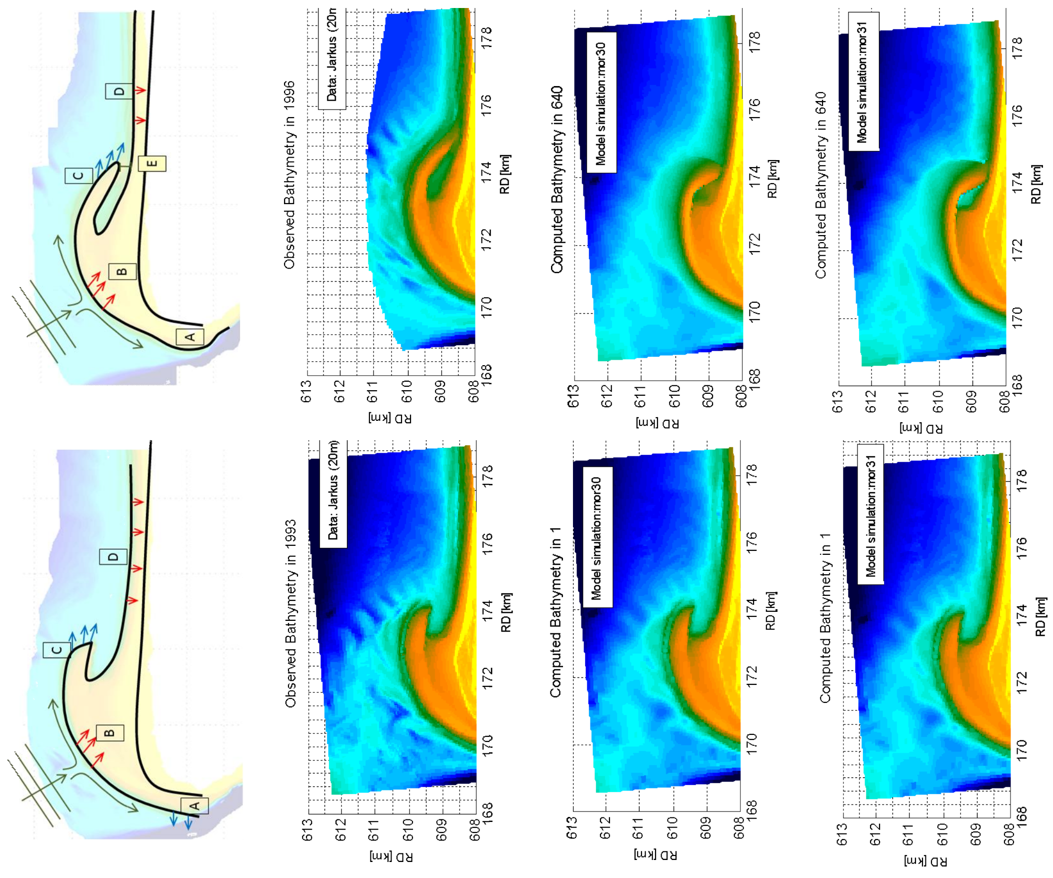


Figure 6.3: The first line is the conceptual model phase 1, 2, 3 and4; second line data and third line simulation. Each row represents one period 93, 96, 99 and 2003 respectively.

A long term simulation without mud was performed in order to analyse the coastal lagoon development. In the cohesive sediment simulation, the lagoon silts up faster than the observed in the data analysis, on the other hand in the only sand simulation, there is no deposition in the lagoon. Leading the conclusion that the Bornrif environment has mud, however 10% of the total sediment is far too much.

7 Projection of findings on the Sand Engine Delfland

This section discusses which conclusions from the Bornrif can be extended to the Sand Engine pilot project. The morphological development in general is expected to follow the same trend taking into consideration the findings in this study.

Several patterns can be highlighted from the comparison (Figure 7.1):

- The hooks develops in a similar way, as a plunging wave. The tip of the hook heads towards the coast forming a bay. The time for the spit to reach the coast the coast is around 3 years.
- As the spit approaches the mainland, it forms a coastal lagoon, the connection with the open sea is maintained via a channel. The channel extends in length due to the accretion in the spit, with sediment coming from the Bornrif.
- The shape of the lagoon can be assessed applying the vortex ratio. It is expected that the ratio be between 2 and 3.4, most probably closer to 3.4 as the hook length is big.
- After the merging with the mainland, the resulting emerged and submerged shape reaches equilibrium with the wave directions. In this phase the morphological changes slow down. Therefore, the period to spread the sediment after that is almost 2 times the period taken to the spit reach the coast (observed in data and in the Bornrif simulation).
- Comparing the western edge behaviour it is necessary to keep in mind that are some main differences between the Bornrif and the Sand Engine Delfland. The edge of the Bornrif ends is part of the estuary inlet and in the Sand Engine case, is located in a continuous sandy coastline.

  However, in both cases the western edge is the side where the most waves reach the coast, so a divergence point appears resulting in transportation of sediment southwards as eastwards. In the Bornrif case, the sediment transported southwards is carried trough the Borndiep but in the Sand Engine, a recirculation cell is formed.
- Another remarkable point concerning the estuary, is the presence of an ebb-tidal delta in the Bornrif case and not in the Sand Engine. As discussed in the report the ebb-tidal delta influences the wave breaking and the wave induced current. The modification of these two forces can lead to different evolution, mostly on the tip propagating behaviour observed in the Bornrif, the Sand Engine can show a more diffusive pattern (Figure 7.1, top line).

- The ebb-tidal delta releases cyclic sand waves that propagates in the Bornrif direction, and will not be observed in the Sand Engine. This bars can influence the morphodynamics by nourishing the Bornrif, in this case the period of the Sand Engine spreading can be smaller than the observed for the Bornrif. On the other hand this bar can only provide the amount of sediment that is lost to the estuary, keeping the equilibrium, in this way does not have any influence in the findings for the Sand Engine.

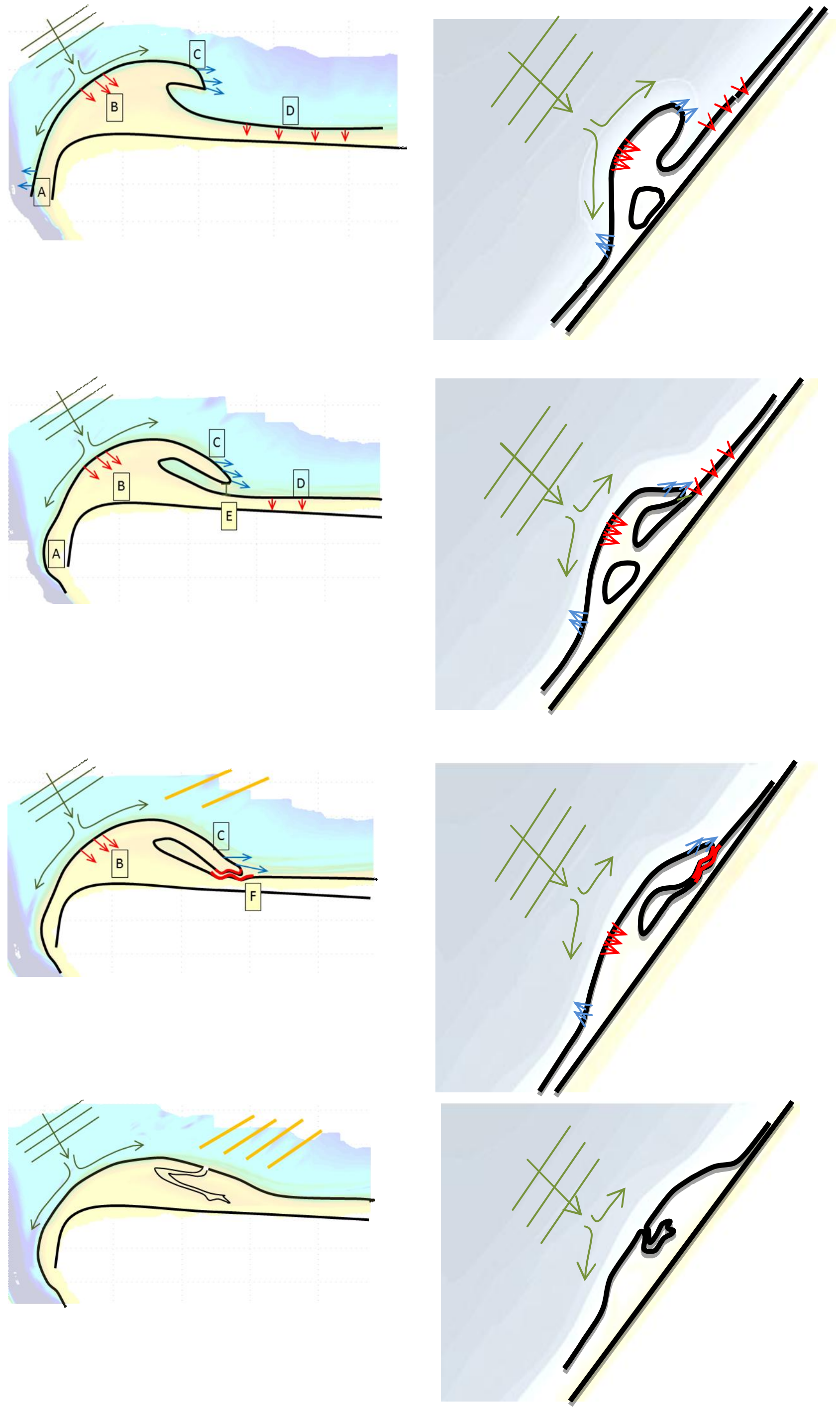


Figure 7.1: Sketch of the conceptual model of the Bornrif left and the Sand Engine right. Red arrows menas erosion and blue accretion, the green represent the waves and waves induced current.

8 Conclusions and Recommendations

This report assessed the morphodynamics of the Bornrif using data analysis and numerical modelling. From the knowledge acquired with the Amelander Bornrif a parallel was drawn between the Bornrif and the expected Sand Engine behaviour.

8.1 Conclusions

The conclusions are categorized in the several sections studied in this report:

8.1.1 Data Analysis

From the data analysis it was found that the following simplifications can be done:

- The Bornrif morphodynamics are comparable with the inlet bar migration model and with the sand spits model in other instance. The importance of finding similarities with other features is being able to compare with other cases and confirm whether the results are consistent or not.
- The definition of a control element that has a dynamic equilibrium leads to the possibility to define a local model and so several variables can be excluded as: the estuary inlet, horizontal tide and the entire ebb-tidal delta. This approach has proven to be effective and efficient in reproducing the Bornrif features.
- In the conceptual model, the main features defined were: the wave divergence point; the spit migration; the meandering channel that cause erosion in the mainland; the merging and further sediment distribution alongshore.

8.1.2 Modelling

The process based model Delft3D is able to reproduce the Bornrif morphodynamics well. Main remarks are the following:

- It is possible to apply local model with vertical tides only to reproduce most of the main features observed in the data analysis.
- The waves are the main driving force for the Bornrif morphodynamics, therefore a good representation of waves is required; as well as the setup implementation as this defines to define the wave penetration.

- The mud implementation has an important role in the dynamics of the Bornrif. Firstly, the outer shape, becomes more round. Secondly, for the lagoon and the lagoon inlet, without mud there is no deposition inside the lagoon and the channel is too steep.

8.1.3 Bornrif and Sand Engine

The Bornrif processes that could be projected on the Sand Engine were already described in section 7, nevertheless the most important are:

- The period for the hook reach the mainland, is forecasted to be about 3-4 years.
- A coastal lagoon will be formed, and most probably (severe) erosion of the coast adjacent to the channel as was observed in the Bornrif data and model.
- A quick assessment of the shape and extension of the lagoon can be made applying the wave breaking intensity parameter.

8.2 Recommendations

To ensure the validity of the wave breaking intensity parameter it is advisable to test it in others natural cases, which could result in a new methodology.

In order to simulate as well predict the Sand Engine morphodynamics it is extremely important to apply a good wave schematization. The sensitivity analysis shows that this schematization has a major impact on the development of the feature.

It is important to have a good knowledge of the sediment that is used in the nourishment in order to be able to predict the time evolution and the shape of the feature, as well as sedimentation in the lagoon.

In order to improve the Bornrif hindcast:

- A better representation of the estuary inlet is necessary, such as maintaining the channel depth and study if it is possible to apply a current boundary condition in the south; representing the tidal current in the inlet. This probably, fits better the outer edge shape and the accretion/sedimentation westwards.
- Coupling with an aeolian transport model, as the Bornrif is a large sandy area the wind could plays an important role in the sediment transport.

- Including the effect of individual storms should be carefully investigated too, since it is the strongest forcing in the region [van der Molen 2002]
- Inclusion of vegetation. From the aerial photography (kustfoto.nl), can be seen that by 1999 starts some vegetation colonization. The vegetation traps sediment, so an understanding of them could clarify the channel dynamics as the by pass of sediment to the down-drift coast (Figure 8.1).

Figure 8.1: Aerial photography of the Bornrif inlet, 1993, 1999 and 2007.

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