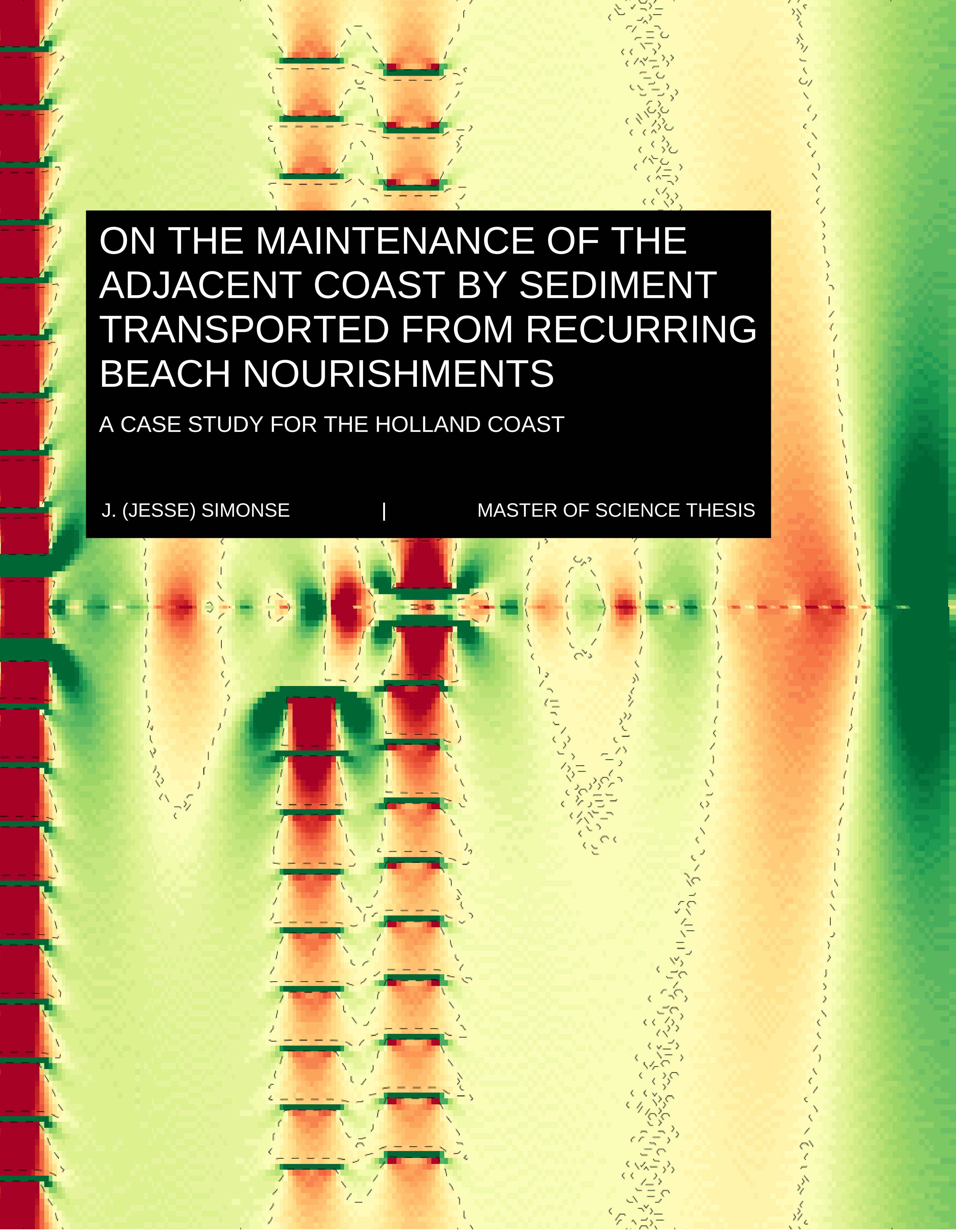

ON THE MAINTENANCE OF THE ADJACENT COAST BY SEDIMENT TRANSPORTED FROM RECURRING BEACH NOURISHMENTS

A CASE STUDY FOR THE HOLLAND COAST

J. (JESSE) SIMONSE | MASTER OF SCIENCE THESIS

Rijkswaterstaat
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TUDelft

Deltares
Enabling Delta Life

On the maintenance of the adjacent coast by sediment transported from recurring beach nourishments

A case study for the Holland coast

By

J. Simonse

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Preface

In this thesis report, the results of the final part of the Master of Science program in Civil Engineering at the Delft University of Technology are presented. The thesis is carried out in collaboration with Rijkswaterstaat and Deltares and focusses on the maintenance of the adjacent coast by sediment transported from recurring beach nourishments along the Holland Coast.

First I would like to thank Rijkswaterstaat and Deltares for the opportunity to work on this interesting topic. Especially with my roots in Westkapelle, where the effort needed to preserve the coast is always visible, I am thankful for the opportunity to dive into the world of coastline preservation. Furthermore I would like to thank Marian Lazar for the feedback, knowledge, and life lessons he taught me during the seven months that I worked at Rijkswaterstaat Zee & Delta in Middelburg. I would also like to thank Pieter Koen Tonnon for the feedback and help with especially the modelling part of this thesis. Finally I would like to thank Stefan Aarninkhof, Quirijn Lodder, Ad van der Spek and Bram van Prooijen for the valuable feedback during the process from kick-off towards the completion of this final thesis report.

J. (Jesse) Simonse
Delft, November 2017

Summary

Since 1990, the Dutch coastline is maintained within the 'Dynamic Preservation' program, according to which the coastline is maintained seawards from a reference line, mainly by applying nourishments. Research into the maintenance of the Dutch coast is continuous and causes the content of the coastline preservation program to change constantly since the initiation in 1990. In recent years, the switch was made from yearly nourishment programs to the use of multiannual nourishment programs, in which an interim nourishment planning is included for 4 years. Next to the nourishments following the 'Dynamic Preservation' program, ten large reinforcements were applied along the Dutch coast in the past decade according to the 'Zwakke Schakel' project. A project wherein several locations were thoroughly reinforced in order to comply to the safety standards. In most of the reinforcement projects large (beach) nourishments were included, which led to a large local seaward migration of the coastline. As a consequence, the coastline at these locations needs continuous maintenance to remain at the desired position.

The combination of the long term maintenance at the 'Zwakke Schakel' locations and the multiannual nourishment program, leads to a more or less fixed character of the nourishments program with recurring maintenance nourishments in each period. The question is to what extent also the adjacent coast is maintained by sediment transported from these recurring maintenance nourishments. A situation in which the adjacent coast can be sufficiently maintained by long term application of nourishments at the 'Zwakke Schakel' locations, would lead to an even more fixed character of the nourishment program. At this moment, knowledge on the contribution of sediment transported from beach nourishments to the maintenance of the adjacent coast is insufficient. Therefore research into this process is needed to be able to answer the following research question.

To what extent is the adjacent coast maintained by sediment transported from recurring nourishments at fixed locations along the Holland coast?

The research presented in this thesis focusses on one case study. Along the coastal stretch between Scheveningen and IJmuiden, three distinct 'Zwakke Schakel' reinforcement nourishments were applied at Scheveningen, Katwijk and Noordwijk. At all locations the coastline was migrated seawards, with varying distances of 60 to 100 meters. To maintain this coastline, maintenance nourishments are already applied or planned at all locations. The coastal stretch between Scheveningen and IJmuiden is part of the Holland coast and bounded by the breakwaters of the Scheveningen and IJmuiden harbours. Along the Holland coast, sediment transport is dominated by wave related processes wherein longshore transport is the most important sediment transport process. Gradients in longshore sediment transport are therefore an important cause of erosion and accretion. These gradients are caused by amongst others varying angles of incidence of the waves and variations in the coastal profile, which both can be related to the application of nourishments. Also the breakwaters at the Scheveningen and IJmuiden harbours have a large influence on the local sediment transport gradients.

Results of the yearly measurements done along the entire Dutch coast already show a positive effect of the maintenance nourishments in the area. With a refined version of an existing Unibest-CL+ model the effect of the recurring maintenance is further assessed for the long term. In the model, the longshore sediment transport volumes and resulting coastline evolution are modelled for a timescale of 55 years, starting in 2006 before application of the 'Zwakke Schakel' reinforcement nourishments and including the effect of possible sea level rise of 0.2 to 1.5 cm per year. At all 'Zwakke Schakel' locations, a long term nourishment scheme is

applied providing maintenance of the coastline at a constant position. Erosion is allowed for 5 to 8 years after which a nourishment is applied to compensate the erosion and maintain the coastline at the constant position. The model is validated by comparing transport quantities (volumes and gradients) and coastline development with real measurement results and results from earlier research.

Model results show that the long term application of maintenance nourishments at the ‘Zwakke Schakel’ locations has a significant impact on the sediment transport gradients. Without nourishments, gradients tend to go to zero due to the development towards an equilibrium coastline. Maintenance of the coastline thus also leads to maintenance of large sediment transport gradients. Gradients in sediment transport near the boundaries of the nourishment location lead to accretion at the adjacent coast. The region over which a positive effect of the maintenance nourishments (accretion) can be observed increases over time.

In order to maintain a positive coastline position along the adjacent coast, the autonomous erosion needs to be sufficiently compensated by the accretion related to the long term maintenance. At several locations in the area of interest initial erosion is expected, after which the erosional trend switches into a seaward migrating trend on the long term, partly under influence of the maintenance nourishments. This process is expected to occur at both Wassenaar (between Scheveningen and Katwijk) and Noordwijkerhout (north of Noordwijk) in the upcoming decades, although the inclusion of some uncertainty in amongst others sea level rise shows that it is unsure whether a positive development at Noordwijkerhout will really occur. The erosional trend at Bloemendaal and Zandvoort, close to IJmuiden, cannot be compensated by the sediment transported from maintenance nourishments. On the time scale of 55 years, the region of influence of the maintenance nourishments does not reach Bloemendaal and Zandvoort. The regions of influence of all ‘Zwakke Schakel’ maintenance nourishments are expected to cover the area from Scheveningen up to around 10 kilometres northwards from Noordwijk in 2060. Individual regions of influences are expected to reach a size of 15 to 24 kilometres up to 2060.

Although in most cases the trends of coastline development within the regions of influence are expected to become positive on the long term, the coastline position itself may be located too much landwards due to the initial erosion. In order to solve this problem, additional (shoreface) nourishments need to be applied at Wassenaar and Noordwijkerhout. At both locations shoreface nourishments are already applied in the past decades, which supports the outcome of the model results. At Bloemendaal and Zandvoort, additional (shoreface) nourishments will surely be needed in order to maintain the coastline.

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List of acronyms

BKL	Basal coastline, ‘Basis KustLijn’ in Dutch, which is the reference coastline position which may not be exceeded according to the Dutch coastline preservation program.
JARKUS	Yearly measurements along the Dutch coast, following a documented procedure. ‘JAaRlijkse KUStmeting’ in Dutch.
MKL	Instantaneous coastline, ‘Momentane KustLijn’ in Dutch, which is the measured coastline position.
MLW	Mean Low Water.
NAP	Amsterdam Ordnance Datum, ‘Normaal Amsterdams Peil’ in Dutch, which is approximately equal to the mean sea level.
RSP	A documented reference line along the Dutch coast. ‘RijksStrandPalenlijn’ in Dutch.
TKL	Coastline to assess, ‘te Toetsen KustLijn’ in Dutch, which is the predicted coastline position based on at least three years of MKL measurements.
TSHD	Trailing Suction Hopper Dredger.

1. Introduction

1.1. Background

Research on the effect of nourishments along the Dutch coast is continuous and causes the nourishment strategy to change constantly over time since the application of the first nourishments in the early 1950s. In figure 1.1, the applied nourishments for the past ten years are visualised per coastal reach along the Dutch coast (Rijkswaterstaat, 2016a). Tens of millions cubic meters of sediment are supplied to the Dutch coast in order to maintain the coast according to the coastline preservation program. In the past decade, additionally ten locations along the Dutch coast are extensively reinforced as part of the ‘Zwakke Schakel’ project. The applied reinforcements at many of these locations will need regular maintenance by nourishments, which will have its influence on the content of the future nourishment programs.

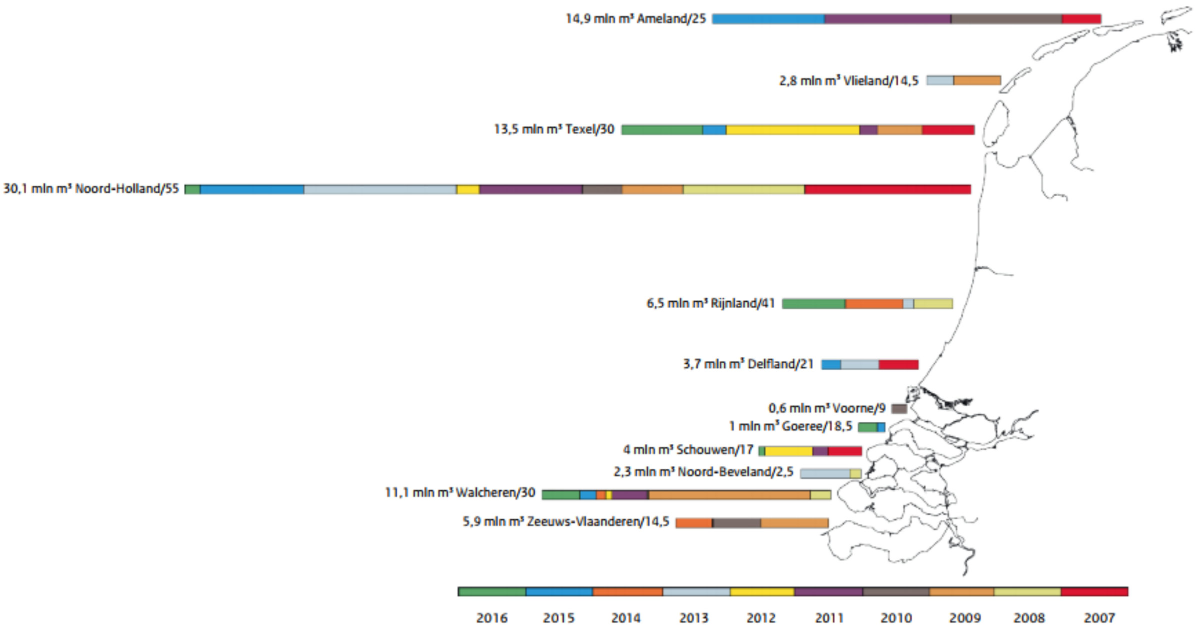

Figure 1.1: The Dutch coast with applied nourishment volume per section in the past ten years (2007-2016) (Rijkswaterstaat, 2016a).

In recent years, new nourishment plans have been set up in which nourishments are planned for 4 years (Rijkswaterstaat, 2016b). The present nourishment program (2015-2019) has two goals. At first, maintaining a documented reference coastline, and secondly, increasing the sediment volume in the coastal foundation in order to keep up with the current forecasted rate of sea level rise. Ongoing research aims for acquiring an optimal and future proof nourishment strategy. Part of the research, including this research, is since 2011 united in the project ‘KPP B&O kust’, Knowledge on Primary Processes regarding Management and Maintenance of the Dutch coast, by Rijkswaterstaat and Deltares (Deltares, n.d.-a).

The focus of this research is on the Holland coast (including the coastal reaches of Delfland, Rijnland and Noord Holland, figure 1.1), where sediment transport is dominated by wave related longshore transport processes (Bosboom & Stive, 2015). Part of the research is done with the help of the UNIBEST-CL+ model (Deltares, n.d.-b), wherein the (longshore) transport of sediment and resulting patterns of erosion and accretion can be modelled. The gained insight into sediment transport and coastline evolution may lead to a better understanding of the effect of long term maintenance at the ‘Zwakke Schakel’ locations.

1.2. Problem description

The history of the Dutch nourishment program goes back to 1952, when the first nourishment was applied near Vlissingen (Pilarczyk et al., 1988). Since 1990, applying nourishments is the main method for preserving the Dutch coast, which suffers from structural erosion (see paragraph 2.1). In 1990 a new nourishment strategy was presented to maintain a reference coastline along the entire Dutch coast, the BKL. This reference coastline is composed based on the results of ten years of measurements before 1990 (Hillen, de Ruig, Roelse, & Hallie, 1991).

Although the present nourishment program succeeds in preserving the Dutch coast (Roelse, 2002; van der Spek & Lodder, 2015) increasing knowledge is crucial to be prepared for the future. Possible extreme sea level rise (Le Bars, Drijfhout, & de Vries, 2017) and an increase of the population and activities in the coastal region (Bestuurlijk Overleg Kust, 2003) increase the challenge of coastline preservation on one side, while the wish to improve efficiency and decrease costs remains a challenge on the other side. Research is ongoing within amongst others the project 'KPP B&O Kust' to acquire an optimal and future proof nourishment program, wherein not only the safety of the hinterland is taken into account, but also preservation of important values in the coastal region like nature and recreation remains essential (Deltares, n.d.-a).

With the experience and research of the past decades, knowledge on the evolution of the Dutch coastline and the behaviour of nourishments increased, which lead to changes in the trend of the nourishment program since 1990. Nourishments volumes increased over the years and more variations are nowadays present in the type of the applied nourishments. The experience and research also leads to a situation in which nourishments can be planned more in advance. Since 2012, nourishments are presented in a multiannual planning of 4 years. Due the recurring pattern of nourishments, the multiannual planning leads to a more fixed character of the nourishment program. Additionally, the reinforcement of 'Zwakke Schakels' along the Dutch coast strengthened the fixed character of the nourishment program. At most of the 'Zwakke Schakel' locations, regular maintenance nourishments are and will be needed. In the history of planned and applied nourishments, locations where recurring nourishments are planned or applied are clearly present (Rijkswaterstaat, 2014; 2016b; 2016c).

Although new knowledge is gained continuously, knowledge on the transport of sediment from especially the recurring beach nourishments towards the adjacent coast is insufficient and the question is to what extent the adjacent coast is maintained on the long term by sediment transported from the recurring nourishments. If the recurring beach nourishments at the 'Zwakke Schakel' locations provide enough sediment for the considered system, a situation in which no additional nourishments are needed may be reached. Increasing knowledge on this transport of sediment will help to better understand what the effect of the chosen preservation strategies is, and therewith help to optimize the coastline preservation program and be prepared for the challenges of the future.

1.3. Objective

The objective of this research is to quantify the contribution of sediment, transported from recurring beach nourishments, in the development of the adjacent coast. Therewith can be assessed to what extent the adjacent coast is on the long term maintained by the sediment transported from the recurring nourishments. Additionally, suggestions can be made about the effects of different nourishment strategies. Expected is that the contribution of sediment which is transported from the recurring nourishments is insufficient to maintain the adjacent coast, but the quantities, spatial scales and time scales for this contribution are difficult to guess and have to become clear within the research. The outcome of the research may give a guideline for the expected effect of long term recurring beach nourishments along the Holland coast.

1.4. Research questions

The objective of this research can be summarized as finding the answer on one main research question. To answer this question , several sub questions are made up. The answers on these sub questions will contribute to answer the main research question, which is as follows.

To what extent is the adjacent coast maintained by sediment transported from recurring nourishments at fixed locations along the Holland coast?

The sub questions which support the main research question are presented below. Questions a) to e) need to be answered in order to be able to gain insight in the effect and the consequences of sediment transported from recurring nourishments towards the adjacent coast.

a) *How can the local morphology be described*?

b) *What is the effect of the 'Zwakke Schakel' (maintenance) nourishments on the coastline development of the adjacent coast in the present situation*?

c) *What is the effect of the recurring maintenance nourishments on the coastline development of the adjacent coast on the long term*?

d) *How is the amount of sediment transported towards the adjacent coast related to nourishment volume and frequency*?

e) *What are the consequences of long term maintenance at the 'Zwakke Schakel' locations for the future nourishment programs*?

1.5. Approach

The approach can be split up into four parts, including literature review, data review, model research and the conclusion. The literature review includes research on the local hydro- and morphodynamics and the history of coastline preservation with the help of books, reports and measurement data and is used to answer research question a. In the data review, the nourishment data and development of the coastal profiles are analysed. At the end of the data review, a first conclusion on the sediment transport from the (maintenance) nourishments towards the adjacent coast is formulated to answer research question b. In the modelling part of the research, the insight gained in the first part has to be used to adequately set up the UNIBEST-CL+ model (Deltares, n.d.-b) and investigate the long term effects of maintaining the 'Zwakke Schakel' reinforcements (research question c). Additionally the roles of different nourishment parameters, such as size and frequency, are assessed to answer research question d. The model results are also used to give a prediction on the future of the nourishments programs (research question e). Important in the model research is the evaluation of the model results, in which the consequences of uncertainty in the most important assumptions are assessed and therewith the value of the model results can be determined. In the conclusion all results are combined and discussed. The approach is summarized in the outline as presented in figure 1.2. More information on the Unibest-CL+ model can be found in chapter 4.

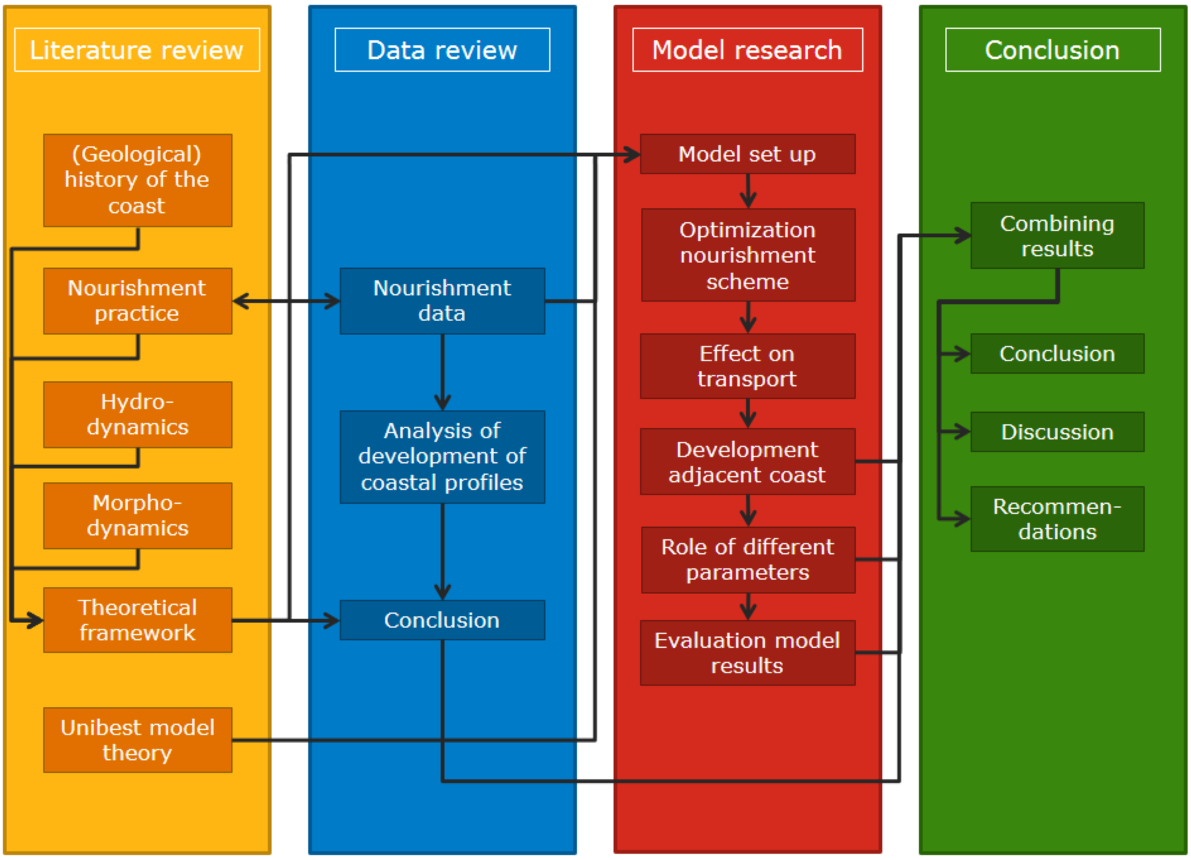

Figure 1.2: Thesis outline.

1.6. Area of interest

The Dutch coast can be split into three areas, the Wadden Sea region, the Holland coast and the Delta region (see figure 2.1). The initial area of interest in this research is the Holland coast. Along the Holland coast, the sediment transport is dominated by wave related longshore transport (Bosboom & Stive, 2015), which makes this region suitable for research into nourishment effects. In the Wadden Sea and Delta region more complex processes play a significant role, with the influence of the tide and tidal channels becoming more important. Additionally in the Delta region, the morphology is highly influenced by the construction of hard structures like the Delta works (Elias, van der Spek, & Lazar, 2016).

The Holland coast can also be split into three different sections. Mainly divided by harbours and breakwaters, which is the case near Hoek van Holland, Scheveningen and IJmuiden. In the north the most northern section is bounded by the tidal inlet of the Wadden Sea at Den Helder (figure 1.3). The characteristics of the three sections and the resulting suitability for this research are discussed in the remaining of this paragraph.

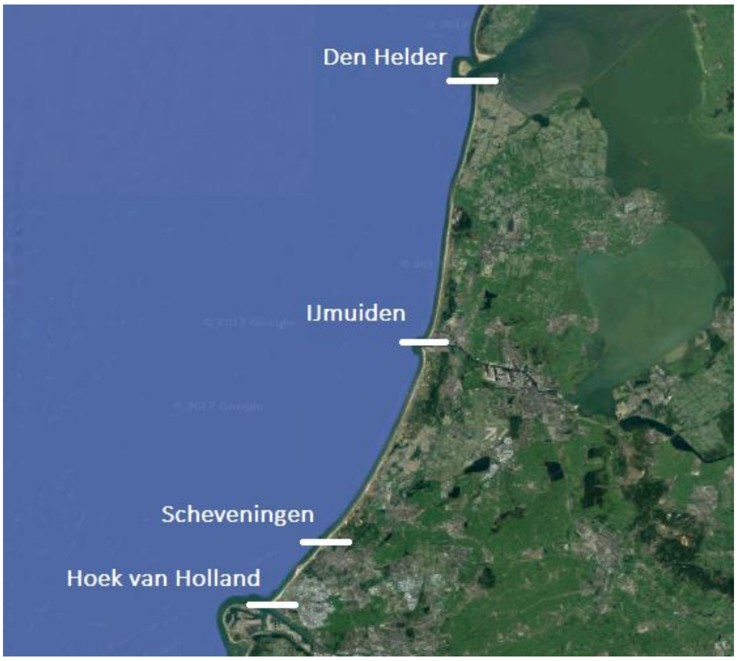

Figure 1.3: Division of the Holland coast in three sections (Google, 2017).

Hoek van Holland - Scheveningen

In 2011, the 'Zandmotor' is constructed between Hoek van Holland and Scheveningen, a mega nourishment of 21,5 million cubic meters of sand. In line with the 'Building with Nature' philosophy, the sediment from the sand motor is expected to be distributed over the reach over a period of 20 years (Mulder & Stive, 2011; Provincie Zuid-Holland & Rijkswaterstaat, 2015). Since construction of the Zandmotor, the Delfland reach is extensively monitored and the effect of the mega nourishment on the adjacent coastline is repeatedly evaluated and labelled as positive. For more information on the influence of the Zandmotor on the regular coastline preservation program, reference is made to the summary of the 2016 evaluation report (Taal et al., 2016). The section between Hoek van Holland and Scheveningen is not included in this research.

Scheveningen - IJmuiden

Between Scheveningen and IJmuiden three distinct locations with large 'Zwakke Schakel' nourishments are present where in the past and coming years regularly nourishments were and are needed. The presence of these three comparable 'Zwakke Schakel' locations makes the area very suitable for this research. Next to the 'Zwakke Schakel' nourishments, a couple of large shoreface nourishments are applied which will have its influence on the regional sediment transport. The main interest in this case will be on the transport of sediment from the three nourishment locations from the 'Zwakke Schakels' project towards the adjacent coast, in line with the research objective. The southern boundary of the area of interest is the northern breakwater of the Scheveningen harbour, the northern boundary is the southern breakwater of the harbour of IJmuiden. For more information on these structures and the morphological consequences, see paragraph 2.7.

Between Scheveningen and IJmuiden, the first nourishment within the 'Zwakke Schakels' project is applied in 2007 in Noordwijk. A summary of all recent applied nourishments is presented in figures 1.3 and 1.4. In Appendix B the details of all nourishments are given. It is chosen to include all nourishments starting in 2002 in order to give an overview from the measures taken in the research area in recent years. The distance in both figures is measured in distance from Den Helder, the most northern location of the Holland coast (see figure 1.1). The distance from Den Helder is a regularly applied distance parameter in the field of Dutch coastal engineering.

IJmuiden - Den Helder

Along the coast of North Holland, between IJmuiden and Den Helder, in 2014/2015 the Hondsbossche and Pettemer sea defence is reinforced with 35,000,000 cubic meters of sand, leading to a large beach and dune area over a stretch where previously no beach or dune was present. This situation shows similarities with the Zandmotor due to its large nourishment volume. An important difference is present in the fact that the mega nourishment in this case will need regular maintenance according to the Dutch coastline preservation policy, while the Zandmotor is part of an extensive research program and is not regularly maintained. The effect of regular maintenance of the mega nourishment on the adjacent coast fits within the framework of this research. However, the coast near the tidal inlet of the Wadden Sea in the north of the region IJmuiden – Den Helder is not wave dominated and therefore less suitable for this research. The Wadden Sea is sand demanding, leading to a situation in which the northern part of the coast of North Holland supplies sediment to the Wadden Sea (Elias, van der Spek, Wang, & de Ronde, 2012). Taking this condition into account, it is chosen to exclude this part of the Holland coast from research and focus on the coastal stretch between Scheveningen and IJmuiden. In addition to the research presented in this thesis, it is recommended to investigate the effect of regular maintenance of the Hondsbossche and Pettemer mega nourishment on the development of the adjacent coast (see chapter 8).

Figure 1.4: Nourishment locations since 2006 in the area of interest. In blue shoreface nourishments, in red Zwakke Schakel (maintenance) nourishments. Numbers correspond with the distance from Den Helder in decametres (Google, 2017).

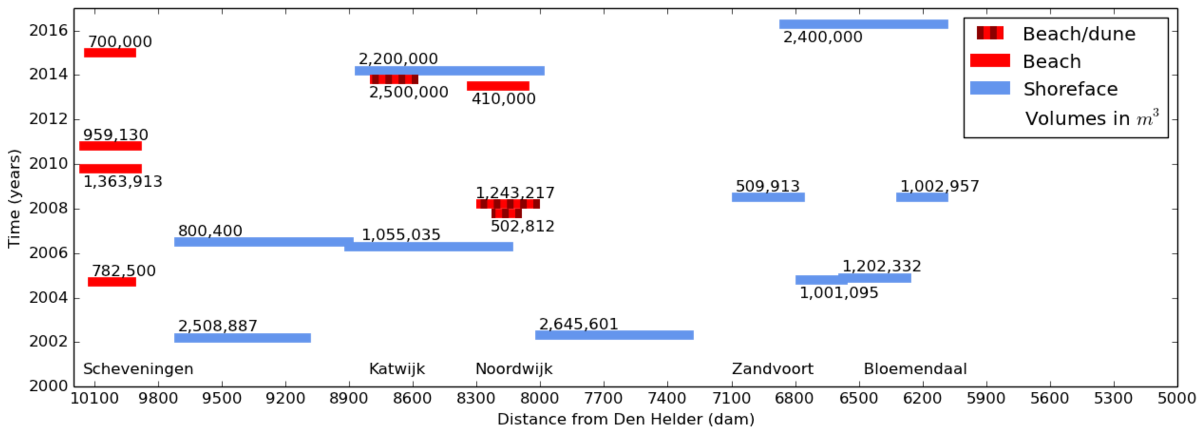

Figure 1.5: Graph for nourishment locations and size along the coastal stretch from Scheveningen to IJmuiden.

2. Literature review

The results of literature review as presented in this chapter focus on the history of the Dutch coast and the history and characteristics of nourishments. Furthermore characteristics of the sediment transport around nourishments in general and on a larger scale in the area of interest are discussed. The details of theory and formulae behind sediment transport and coastline evolution, which are also part of the Unibest-CL+ model, can be found in Appendix E.

2.1. Long term development of the Dutch coast

In terms of morphology, the Dutch coast can be divided into three areas (figure 2.1). The Wadden Sea area in the north, in the centre the Holland coast, and in the southwest the Delta region. The Wadden sea area is characterized by barrier islands, inlets and a back-barrier intertidal flat. The Holland coast (350 km) can be characterized by beaches and dunes (290 km), interrupted by human structures like seawalls, dams, breakwaters and storm surge barriers (60 km) (de Ruig & Hillen, 1997). The southwest Delta region is formed by the rivers Meuse, Rhine and Scheldt and consists of several islands with four estuaries in between, of which three are (semi-)closed due to human intervention. Only the Western Scheldt is an open estuary (van der Spek & Lodder, 2015; Wang, Elias, & Briere, 2007).

Figure 2.1: Division of the Dutch coast into three morphological areas (Google, 2017).

When starting back in time at approximately 5500 BP, the Dutch coastline showed a fluctuating trend of regression and transgression over the past thousands of years. Around 5500 BP, the sea level rise which initially caused the North Sea to flood and the coastline to retreat, declined significantly. The coastline stabilized and the tidal basins in the north and in the south started to silt up. The Holland coast even regressed until 1000 BP, leading to a more or less closed coastline with only river mouth interruptions. Due to the lack of sediment input and subsidence of the land (partly caused by human influences from 1000 BP), the regression stopped and the coastline slowly began to transgress, while the rate of sea level rise also decreased further. In Zeeland, the present estuaries were formed, while in the north the Wadden Sea started to develop. Although in general erosion continued, from 1000 AD the first dunes ('Young Dunes') began to develop during more calm conditions, probably with sediment eroded from the coastal profile. Especially in the centre of the Holland coast dunes were developing, while in the north the coastline still retreated. The dunes have dominated the development of the Holland coast from that moment onwards. The combination of dune development, erosion and land subsidence caused several flood disasters in the Middle Ages. Under threat of these disasters, the inhabitants of the coastal region started with coastal protection and formed 'Water Boards', these were the first steps of the Dutch coastline preservation program. Together with the continued threat of the North Sea over the centuries, also the amount of human interventions along the Dutch coast increased (Bosboom & Stive, 2015; van der Spek, 1999).

In the 15th century, the Hondsbossche Zeewering, nowadays lying below a large nourishment and the Westkappelse Zeedijk were one of the first and only (hard) measures to stop coastline retreat in that time. About 300 years ago, less radical measures were taken to fight coastline retreat, wooden piles were placed in cross shore direction to decrease the coastal erosion. Various other structures with the same principle and different materials, impermeable and permeable, were applied in the past centuries, but never succeeded in completely stopping the erosion (Pilarczyk et al., 1988). In the beginning of the 20th century, the first large scale work in Dutch coastline preservation history was constructed, the closure of the Zuiderzee with the Afsluitdijk. This closure still affects the sediment transport around the Wadden Sea (Wang et al., 2007).

In 1953, a large flood disaster hit the southwest Delta area of the Netherlands, with many casualties as a consequence. After the disaster, the Delta commission was formed in which new norms for flood protection were discussed. The result was a new method based on statistical analysis. A flood level with a probability of exceedance of 10^{-4} was taken as the new norm for flood protection. The subsequent project, the Delta project, took 25 years, after which the Delta region was protected according to the new safety standards. In this project, part of the estuaries in the Delta region were (semi-)closed off, with interesting consequences for the sediment balance in the region.

Despite (or due to) all human measures, coastal erosion continued along many parts of the Dutch coast, even more than half of the Dutch coast suffers from coastal erosion (de Ruig & Hillen, 1997). Furthermore, in the years before 1990, yearly 20 ha of dune area disappeared due to coastal retreat (de Ruig, 1998). After successful, small scale, application of nourishments in the period between 1952 and 1990, the ongoing erosion lead to a new plan in which the Dutch government decided to stop the coastal erosion by soft measures only, this was the beginning of the nowadays still present Dutch nourishment program (Bosboom & Stive, 2015; Roelse & Hillen, 1993).

2.2. History of the Dutch nourishment program

In 1990, the Dutch government presented a new plan for coastline preservation along the entire Dutch Coast, so called 'Dynamic Preservation'. This new preservation policy aims for a combination of maintaining safety against floods, and preserving other values and interest on the beach and in the dunes like nature and recreation (de Ruig & Hillen, 1997). Before 1990, several nourishments were already applied from which it was concluded that preserving the coast dynamically had many advantages compared to preserving the coast with hard structures (Pilarczyk et al., 1988; Roelse & Hillen, 1993). In the 90's, the Dutch coast was nourished annually with 5 to 7 million cubic meters of sand in accordance with the new program.

The nourishments were executed based on the new norm presented with the 'Dynamic Preservation' program in 1990, the 'BKL' (Basis Kust Lijn in Dutch) or 'BCL' (Basal Coast Line in English) (Hillen et al., 1991). The BKL is a reference coast line, documented for almost the entire sandy part of the Dutch coast, based on the regression trend of 10 years of measurements before 1990. This reference coastline is since 1993 officially the norm for 'Dynamic Preservation' (Rijkswaterstaat, 2016a). Yearly, measurements are done along the Dutch coast according to the JARKUS program, for which the coastal profile is measured from the landward side of the first dune row up to a seaward distance of approximately 800 m from the beach. From these measurements result the MKL is computed, the location of the instantaneous coastline. In longshore distance the measurements generally are done each 250 m (de Ruig, 1989). With the help of MKL measurements from at least three years, a trend can be computed leading to a TKL, the coastline to assess. If the BKL is exceeded by the TKL, in most cases a nourishment is planned to maintain the BKL. Sometimes it is decided to accept the exceedance of the BKL in consultation with local government and therewith prevent unwanted nourishments. By computing trends over multiple years, the influence of temporary erosion, due to for instance storm surges, on decision making is decreased (de Ruig & Hillen, 1997). In principle, the location of the BKL is fixed, however, if maintenance of the documented BKL is (morphologically) not realistic, changes can be made.

If uniformity in decision making has to be guaranteed, a standard method for the computation of the MKL is needed. In figure 2.2, the standard method for computation of the MKL ('momentane kustlijn') after measurements is presented. Important in this figure are the RSP ('rijksstrandpalenlijn'), a documented reference line along the entire Dutch coast, the dune foot ('duinvoet') and the mean low water level ('laagwaterlijn'), which form the base for computation of the MKL. From the measured location and height of the dune foot and the MLW level, the yellow area can be computed from which the MKL is determined, relative to the RSP.

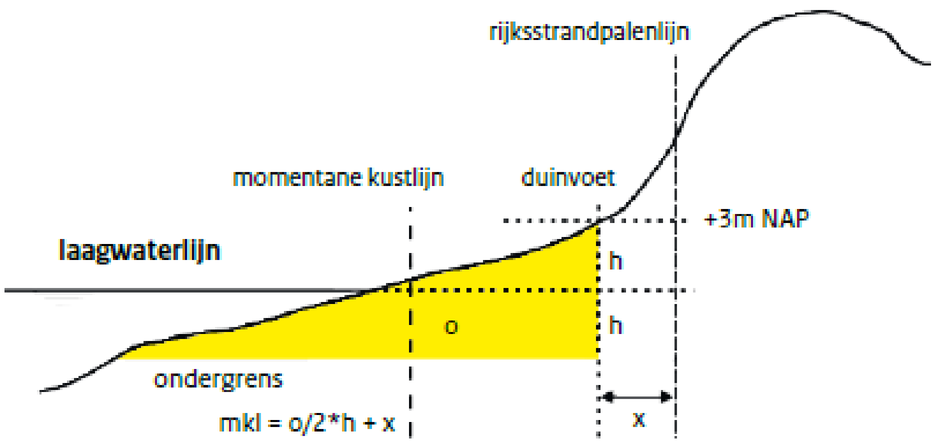

Figure 2.2: Method for computation of the MKL ('momentane kustlijn') (Rijkswaterstaat, 2016a).

In the years after 1990, many research is done on the efficiency of the new 'Dynamic Preservation' program. In general, the new strategy is proven to be a success and the goals set at the beginning of the program are reached. Structural coastal erosion was stopped and also other important values like nature and recreation mainly did benefit from the new policy. Still the BKL was yearly exceeded at some locations, but the percentage decreased from 30% exceedance in 1992 to 10% exceedance in 1998. Within the dynamic character of the 'Dynamic Preservation' policy the 10% exceedance of the norm is accepted. Further decreasing the exceedance percentage would mean an increase of the amount of nourishments, which is economically and ecologically not favourable (Roelse, 2002).

Although the conclusion in 2002 was positive, important side notes were made about the overall sediment balance of the Dutch coastal system. Especially steepening of the shoreface due to nourishments at the beach and migration of tidal channels would likely lead to problems in the future (Roelse, 2002). If the sediment balance in shallow water over the period between 1965 and 1995 is computed including nourishments, a loss of 1.5 million cubic meter of sediment per year is found. When the sediment balance is computed for deep water, a loss of 5 million cubic meter is found, partly caused by sea level rise (Mulder, 2000). To compensate the losses, it was recommended to increase the yearly nourishment volume from 9 million cubic meter to 12 million cubic meter, or with maximum sea level rise scenario, to 16 million cubic meter per year. Part of the additional volume had to be used for nourishments in the deep water at the lower shoreface up to -20 m NAP. The amount of sediment volume available for these nourishments depended on the remaining available volume after nourishments at the beach or upper shoreface. Furthermore, recommended was to, if possible, nourish below the water at the upper shoreface instead of at the beach, and let nature distribute the sand towards the coast (Mulder, 2000; Roelse, 2002).

More recent research on the sediment balance up to 2005 shows that, due to the nourishment program, in general the sediment volume of the upper shoreface and beach area (above -8 m NAP) increases. In the region between -8 m and -20 m NAP, the lower shoreface, the sediment volume remains decreasing and erosion is present. Nevertheless, the 'Dynamic Preservation' program still succeeds in stabilising the coastline and stopping coastal erosion (van der Spek & Lodder, 2015). The area between -20 m NAP and the landward border of the dunes is the so-called coastal foundation. In 2009, the Dutch government officially presented the ambition to let the entire coastal foundation grow according to the sea level rise. A consequence of this ambition was that the yearly nourishment volume for the Coastal Foundation had to increase from 12 million m^3 to 20 million m^3 (Ministerie van V&W, Ministerie van VROM, & Ministerie van LNV, 2009).

2.3. The Dutch nourishment program in the present

In the past years, the 'Dynamic Preservation' program is further improved and a new nourishment program for the years between 2016 and 2019 is made in 2015. For the second time, after the 2012-2015 program, nourishment plans for 4 years are included based on the predicted trends of coastal erosion. In the past, only yearly plans were presented based on the trends of yearly measurements. Although the planning of the program is nowadays multiannual, still yearly the program can be changed. With the measurements of 2016, a first actualisation of the 2016-2019 nourishment program is made last year (Rijkswaterstaat, 2016b).

Next to improving the coastline preservation policy, the main goal of the multiannual planning is to decrease costs. Efficiency in planning of the nourishments increases as the overview of nourishments is better, which makes it interesting for a contractor to sign up for (a series of) nourishment project(s). When a nourishment is put out to contract, the contractor has 2 years to complete the nourishment instead of the shorter time period in the past, further increasing the contractor's planning efficiency. In combination with the set upper limit of the price per cubic meter of sand, this leads to a decrease in costs for Rijkswaterstaat (Rijkswaterstaat, 2017a). A disadvantage of this method is that regional stakeholders have to deal with the uncertainty of the flexible implementation period of 2 years.

For 2017, at 7,9% of the measurement locations the BKL is exceeded. Part of this exceedance is caused by a BKL which is located at a distance too far seawards, the BKL in these cases will be evaluated in 2017. The exceedance value lower than the accepted 10% (Roelse, 2002), is structural since 2005 (see figure 2.3). Furthermore, according to the present nourishment program only 7 million cubic meter per year will be nourished on the Dutch coast, which is significantly less than the previously advised annual volume of 20 million cubic meters per year (Ministerie van V&W, Ministerie van VROM, & Ministerie van LNV, 2009) and the yearly nourishment volume of the 2012-2015 program which was equal to approximately 12 million cubic meters per year (Rijkswaterstaat, 2014). The decrease in volume is possible because plenty of sediment is available in the Dutch coastal system, mainly due to large 'extra' nourishments in recent years, for especially the 'Zandmotor' and 'Zwakke Schakels' projects (Rijkswaterstaat, 2017a).

For the near future (up to 2035), relatively few changes in morphology along the Dutch coast are expected, leading to the nourishment volume to remain almost the same. Only for maintenance of the 'Zwakke Schakels' and compensation of sea level rise around tidal inlets (especially near the Wadden Sea) additional volume will be needed, this volume is expected to fit in the regular yearly nourishment volume of 12 million m^3 (van der Spek, Elias, Lodder, & Hoogland, 2015). However, especially with the possibility of extreme sea level rise in the coming century (Le Bars et al., 2017), continuous research and evaluation remains important, as the challenge of coastline preservation may become even bigger than before.

2.4. Project 'Zwakke Schakels'

'Zwakke Schakels' (Weak Links in English) are locations along the Dutch coast at which safety is at risk according to research from Rijkswaterstaat in 2003, based on new insight in wave heights and wave periods (Bestuurlijk Overleg Kust, 2003). Within this project, 10 locations were marked as weak link and needed to be reinforced. For each weak link, a separate project is set up as collaboration between the relevant provincial government and the water board. In most cases, a beach or shoreface nourishment is performed as part of the project. These nourishments are not included in the previous described nourishment programs, but of course do influence the planning of the regular nourishment program.

In the period between 2003 and 2016, the 'Zwakke Schakel' project was finished and the Dutch coastline was protected against a once in 10,000 years water level and wave scenario according to the safety standards (Bestuurlijk Overleg Kust, 2003). In most cases where a nourishment was part of the project, the maintenance of the coastline after project completion became again the responsibility of Rijkswaterstaat and thus part of the regular nourishment program (Rijkswaterstaat, n.d.-b). Details on the 'Zwakke Schakel' reinforcements applied in the area of interest (at Scheveningen, Katwijk and Noordwijk) are presented in Appendix C.

2.5. Nourishments in general

Various reasons can be given for applying a nourishment. Mostly a nourishment is applied to compensate for structural erosion, these nourishments usually have to be repeated within a time frame of 5 to 10 years. A nourishment can also be used to improve the safety of the coastal region by increasing the beach area or decreasing the shoreface depth. Finally, a beach nourishment can be applied to create a new beach, enlarge a present beach or create artificial islands, mostly for recreational use (Bosboom & Stive, 2015).

Nourishment types

With respect to the location, four different types of nourishments can be distinguished. A dune nourishment, a beach nourishment, a shoreface nourishment (Bosboom & Stive, 2015) and recently a channel wall nourishment (Lazar, Elias, & van der Spek, 2017).

A dune nourishment is not applied very often, only in cases of damage at the dunes after storm surge, when the entire coastal profile is adapted to compensate for sea level rise or after changes in safety standards. Sometimes new dunes are created to heavily reinforce the coastline, which was the case in some of the ‘Zwakke Schakels’ projects. When it comes to maintenance of the existing dunes, dune nourishments can be applied either at the seaward side of the dune, on top of the dune or at the landward side of the dune. In general, widening the dune leads to a larger increase in safety then heightening the dune, however, for widening the dune in landward direction, often no space is available. Furthermore, widening the dune in seaward direction leads to a deviation of the coastal equilibrium profile. Therefore, if a reinforcement of the dune in seaward direction is performed, the remaining of the coastal profile also has to be nourished in order to reach an equilibrium profile and prevent large sediment losses (Bosboom & Stive, 2015).

Beach nourishments were initially the most applied form of nourishments (Roelse, 2002). After dredging the sediment from a borrow area, the sediment is in this case transported to the beach via pipelines and redistributed between the low water line and the dunes by land-based equipment like bulldozers. An advantage of this method is that the beach is directly enlarged which is in most cases beneficial for recreation, also the sand can be evenly spread over the beach according to the equilibrium profile. A disadvantage of this method is that placing the sand on the beach (and also in the dunes) is relatively expensive as the breaker zone needs to be crossed with pipelines and additional equipment is needed on the beach. Furthermore the beach is not accessible during construction and the disturbance for people and animals living in the surroundings is relatively high (Bosboom & Stive, 2015). The lifetime of a general beach nourishment is in the order of 5 years (Roelse, 2002).

Due to these disadvantages and growing knowledge on coastal morphology, nowadays a shoreface nourishment is preferred over a beach nourishment and used in approximately 70% of all cases (see figure 2.3) (Rijkswaterstaat, 2017a). With a shoreface nourishment, the sand is nourished in deeper water and redistributed by natural processes. Depending on the goal of the nourishment, the exact location is variable. If the nourishment is applied to strengthen the coastal foundation, the nourishment can be applied in deep water. When the goal of the nourishment is to reinforce the beach area over time, the nourishment is placed in more shallow water (Roelse, 2002). Opposite to the case of beach nourishments, sediment from shoreface nourishments does not directly, or only slowly, start diffusing. The lifetime of a shoreface nourishment can vary between 2 and 10 years (van Rijn & Walstra, 2004). In case of severe and fast erosion at the beach, the distribution period of a shoreface nourishment takes too long and a beach nourishment is preferred to be directly effective. There are also cases in which a shoreface nourishment cannot be applied successfully due to the local morphology, for instance near tidal channels (especially in the Delta region) (van der Spek, de Kruif, & Spanhoff, 2007).

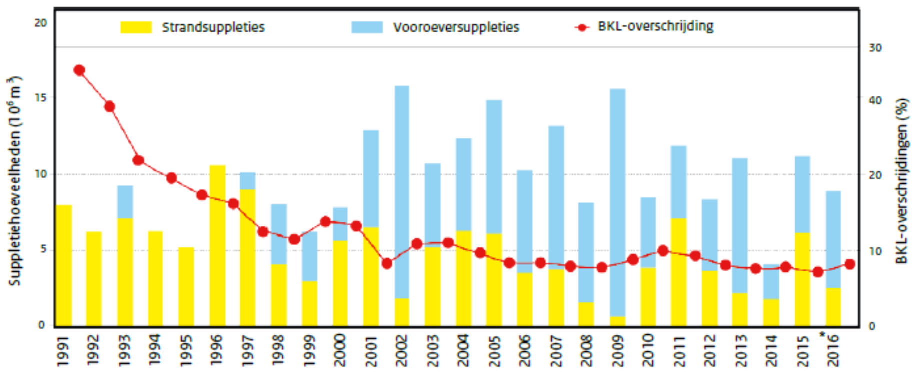

Figure 2.3: Volumes of beach nourishments (‘strandsuppleties’) and shoreface nourishments (‘vooroeversuppleties’) of the past 25 years. In red the percentage of BKL exceedance (‘BKL-overschrijding’) which is below 10% since 2005 (see paragraph 2.2) (Rijkswaterstaat, 2016a).

Generally, the cost of a shoreface nourishment is often only half of the cost of a beach nourishment with the same volume (Bosboom & Stive, 2015). To be effective, the size of a shoreface nourishment needs to be more or less equal to the size of natural breaker bars being present in the area. Distinction can be made between feeder berms and breaker berms. The goal of a breaker berm is to reinforce the shoreface and increase friction for waves. In case of a feeder berm, the nourished sediment will move landwards naturally over the first years, leading to an increase in sediment volume in the surf-, beach and dune zone (Roelse, 2002; van der Spek et al., 2007) and an interruption of the naturally present offshore migrating bar cycle (Grunnet & Ruessink, 2005). In both cases but especially in case of a breaker berm, also lee side effects will be present, which means that sediment will be deposited at the landward side of the breaker berm due to the reduced wave-induced longshore current (Grunnet & Ruessink, 2005). Both breaker- and feeder berms contribute in the reinforcement of the shore.

A solution for the problem of tidal channels migrating towards the nearshore region is to apply a more specific nourishment at the wall of the tidal channel which supports the beach and stops the tidal channel migrating landwards. Migration of a tidal channel in landward direction is a potential problem as it may undermine the foreshore and beach area, reducing the area available for nourishments and recreation, or even leading to instabilities of the channel embankment. In 2005, for the first time a channel wall nourishment was executed in the Oostgat channel near Walcheren, Zeeland. This nourishment succeeded in stabilizing the coast and is since then used as example for three more channel wall nourishments in the Delta region (Lazar et al., 2017)

Nourishment execution

The execution of nourishments along the Dutch coast can be characterized by three phases, the mining of sediment at the borrow area, the transportation to the coast and the placement of the nourishment sand. Details of these phases depend on the location of the borrow area and the type of nourishment (Pilarczyk et al., 1988)

Mining of sand generally happened as close as possible to the project location up to the year 2000. Since 2001 sand mining takes place at a location seaward of the -20 m NAP depth contour, beyond the Coastal Foundation. Along the entire Dutch coast, borrow areas are located just seaward of the -20 m NAP depth contour. In principle, sand mining at a borrow area is only allowed until a depth of 2 m below bottom level. When this depth is reached, the borrow area is closed until the area is filled up again (Rijksoverheid, n.d.). In case of shoreface nourishments, the grain size distribution depends on the goal of the nourishment. For breaker berms, larger grain sizes can be used, leading to a more stable the berm. For feeder berms, the sediment characteristics need to be more or less equal to the sediment characteristics of the surrounding area. The grain size of sand in beach nourishments is generally larger than the grain size of the naturally present sand. Together with the presence of shells, this sand forms a layer which covers the native top layer leading to a decrease in (aeolian) transport. Only the fractions with small grain size reach into the dunes (Van der Spek et al., 2007; van der Wal, 2000).

Nowadays in most cases, a Trailing Suction Hopper Dredger (TSHD, ‘sleephopperzuiger’ in Dutch) is used as main equipment for the nourishment. Other possible equipment is a stationary suction dredger (d’Angremond, 1992; Roelse, 2002). A TSHD is able to loosen and pump the sediment from the seabed, load the sediment into the hopper, transport the sediment to the nourishment area and subsequently discharge the water sediment mixture. Discharging the sediment can be done by either pumping via pipelines, dumping via rainbowing or dumping via bottom doors. Dumping via bottom doors or rainbowing is generally preferred as costs are lower when no pipelines have to be used (Roelse, 2002). The disadvantage of dumping the sediment mixture via rainbowing is that considerable losses are found, up to 30% (d'Angremond, 1992). The main advantage is that the breaker zone can be crossed without the use of (expensive) pipelines. Benefits of the use of a TSHD are amongst others great maneuverability, the high level of seaworthiness, the mobility when sailing with own engines, flexibility in discharging the sediment and high productivity. A large TSHD has a capacity in the range of 20,000 to 30,000 m3 and is both suitable for projects with beach nourishments as well as shoreface nourishments (van der Schriek, 2016).

Ecological effects of nourishments

The ecological impact of nourishments can be split in two parts, during sand mining the ecology is affected by the dredging activities and during nourishing the sand has its impact on ecology in the coastal region. The ecological effects of nourishments are important to take account and ecology plays a significant role in the decision making of nourishments, however, in this research, ecology will not be further addressed.

Research about ecological effects of sand mining is ongoing. According to the North Sea Foundation, effects on ecology are limited and time scales of recovery are short, however, mitigation of negative effects and monitoring remains important. Certain areas with high ecological significance need to be avoided as borrow area. Furthermore, research into the difference in ecological effects between shallow dredging (large areas, small depth) and deep dredging (smaller areas, larger depth) is recommended. Yet no clear conclusion on which method is preferred for ecology can be taken (Bosboom & Stive, 2015; Phua, van den Akker, Baretta, & van Dalfsen, n.d.).

Directly at the nourishment dumping location below water, ecological effects of the nourishment are relatively short term. Most of the short living species recover within one year, longer living species recover within 2 to 5 years. Favorable for the (low) influence of nourishments on ecology is that the species in the sea bed are well-adapted to a dynamic environment due to the effects of storms, wave action and fishing activities (Baptist, Tamis, Borsje, & van der Werf, 2009).

One of the goals of the in 1990 introduced 'Dynamic Preservation' policy was to protect the natural value of the dune area. The policy succeeded in protecting the value and even contributed to an increase of the dune area with more than 500 ha over the years between 1980 and 1998. In years with a high nourishment volume, the amount of increase in dune area also increases (Roelse, 2002). This observation is supported by results of research by van der Wal (2004) which shows that transport into the dunes increases in the years after the application of a nourishment.

2.6. General sediment transport processes around nourishments

Division in transport processes is made between longshore transport due to waves and currents, cross shore transport due to waves and currents, and aeolian transport (land-based) due to wind. Important to know is that many processes in the field of sediment transport are still poorly understood. Modelling of sediment transport is therefore highly empirical (Bosboom & Stive, 2015). Nevertheless, sufficient research is done on the transport of sediment around nourishments to discuss the importance of the different processes for the research in this paragraph.

Longshore transport

Longshore transport is the transport of sediment parallel to the shoreline, mostly concentrated in the surf zone. Gradients in longshore transport are an important contributor to coastal change and the distribution of sediment from nourishments towards the adjacent coast. At a high energy coast like the Dutch North Sea coast, coastline change is even dominated by longshore transport processes (Bosboom & Stive, 2015). Therefore longshore transport is the main sediment transport process to take into account in this research. Gradients in longshore sediment transport can be caused by human interventions, by gradients in nearshore wave height caused and by gradients in angle of incidence of the incoming waves.

Zooming in to the application of a nourishment, the following representative situation can be sketched for the Holland coast regarding longshore transport (figure 2.4). The coastline orientation changes due to the placement of the nourishment (top part). Following the S-ϕ curve, which describes the relation between angle of incidence of the waves ϕ and annual sediment transport volume S. The sediment transport volumes changes as a consequence of changing coastline orientation (figure 2.4, centre part). The maximum sediment transport volume is found at the location with the highest difference between angle of incidence and coastline orientation. The minimum is found at the location with the lowest difference. From the alongshore variation in transport volumes, the longshore transport gradient can be computed (figure 2.4, bottom part). Decreasing transport in the positive x-direction means a negative gradient and leads to accretion. This phenomenon is found around the edges of the nourishment. At the centre of the nourishment, the sediment transport gradient is positive, leading to erosion. On the long term, these processes lead to flattening of the nourishment and transport of the nourishment sediment towards the adjacent coast.

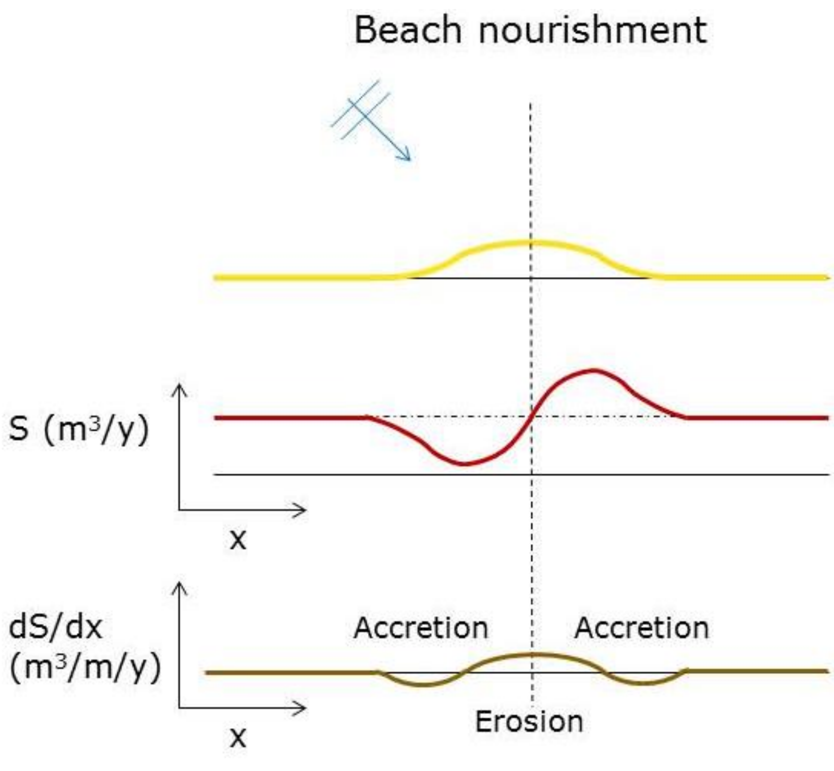

Figure 2.4: Erosion and accretion around nourishments.

Cross shore transport

Although longshore transport dominates coastal changes along the Holland coast, also cross shore transport plays a role, especially when dealing with shoreface nourishments and bar migration. As described in paragraph 2.5, breaker- or feeder berms can be applied in case of a shoreface nourishment. A feeder berm aims at providing cross shore transport of sediment from the berm into the breaker zone and onto the beach. Furthermore, shoreface bar nourishments interrupt the natural (cross shore) offshore directed bar migration and therewith stabilise the coastal region (Grunnet & Ruessink, 2005). A relation between cross shore transport, bar migration and shoreface nourishments is clearly present. The role of cross shore transport in the development of beach nourishments is however relatively small and therefore cross shore transport is not taken into account in this research.

Aeolian transport

Aeolian transport is the transport of sediment forced by wind and is interesting for both sediment transport across the beach as well as beach-dune interaction. Aeolian transport also takes place in offshore direction, but in relatively small amounts compared to non-offshore transport. According to Hoonhout (2017), the amount of offshore aeolian transport for the Sand Motor area is estimated on only 10% of the landward deposition.

Different research made clear that the aeolian transport into the dunes increases in the years after a nourishment (Roelse, 2002;van der Wal, 2004). Important is that this increase of aeolian transport is not caused by changes in susceptibility of the nourishment sand with respect to the native sand, but solely caused by the increased area and height of the beach after a nourishment (van der Wal, 2004). Remarkable is that the amount of aeolian transport from the intertidal and supratidal areas is larger than from the dry beach area. At the Sand Motor nourishment this ratio is even 67% to 33%. This difference is partly caused by armour layers formed at the surface of the dry beach, decreasing the aeolian transport from this region and therewith decreasing the share in overall aeolian transport (Hoonhout, 2017).

According to the findings, nourishments have a significant influence on the transport of sediment from the nourishment locations towards the adjacent coast and into the dunes, and therewith contribute to the preservation of the Dutch coast. Unfortunately, especially the research on the aeolian transport across the beach is a very extensive research which does not fit in this research. Therefore it is chosen to exclude aeolian transport from this research and focus on the longshore transport processes. Recommendations on additional research taking into account aeolian transport are presented in chapter 8.

2.7. Local hydrodynamics

The hydrodynamics along the Holland coast are determined by the tide and the wind, with resulting currents and waves. The tide is semi-diurnal, which means two times a day high water, and two times a day low water. The magnitude of the tidal currents varies between 0.8 m/s at maximum during spring tide in northern direction, and 0.7 m/s at maximum during neap tide in southern direction, leading to a residual net current with a velocity of 0.1 m/s in northern direction. The tidal amplitude varies between 1.3 m and 1.9 m, and decreases when moving to the north (Kuijper et al., 2015; van Rijn L. , 1995; Wijnberg, 2002).

Wave directions along the coastal stretch between Scheveningen and IJmuiden vary between south west and north-north west, mainly generated by the wind climate at the North Sea. Due to the shape of the North sea, swell will always approach the Dutch coast from northwest direction. As a consequence of the available fetch in this direction, also the largest waves are coming from western to north western direction. Wave heights and frequencies along the Holland coast are highly variable over time. The dominating wave height in the surf zone is between 1 and 1.5 m, with a wave period of average 5 seconds. The dominant wave direction is between south and west. The smallest waves are present in summer, while the largest waves are present in winter. Offshore wave heights exceed 3 m approximately 2% of the time (van Rijn L. , 1995; Wijnberg, 2002).

2.8. Local morphodynamics

The focus in this paragraph is on large scale transports in the area of interest, including a qualitative description of the gross and net sediment transport volumes. Details about smaller scale sediment transport around nourishments can be found in paragraph 2.6.

In line with the tide and waves, the morphodynamics along the stretch of the Holland coast between Scheveningen and IJmuiden are characterized by a net sediment transport in northern direction. The direction of this transport is however a very sensitive parameter. The net sediment transport is a result of large amounts of sediment transport both in northern and southern direction and therefore the (small) residual transport is highly variable both in terms of size and direction (Kuijper et al., 2015). The bulk net longshore transport is in the order of 100,000 to 300,000 m^3/year, based on several studies by different authors (figure 2.5) (van Rijn L. , 1995).

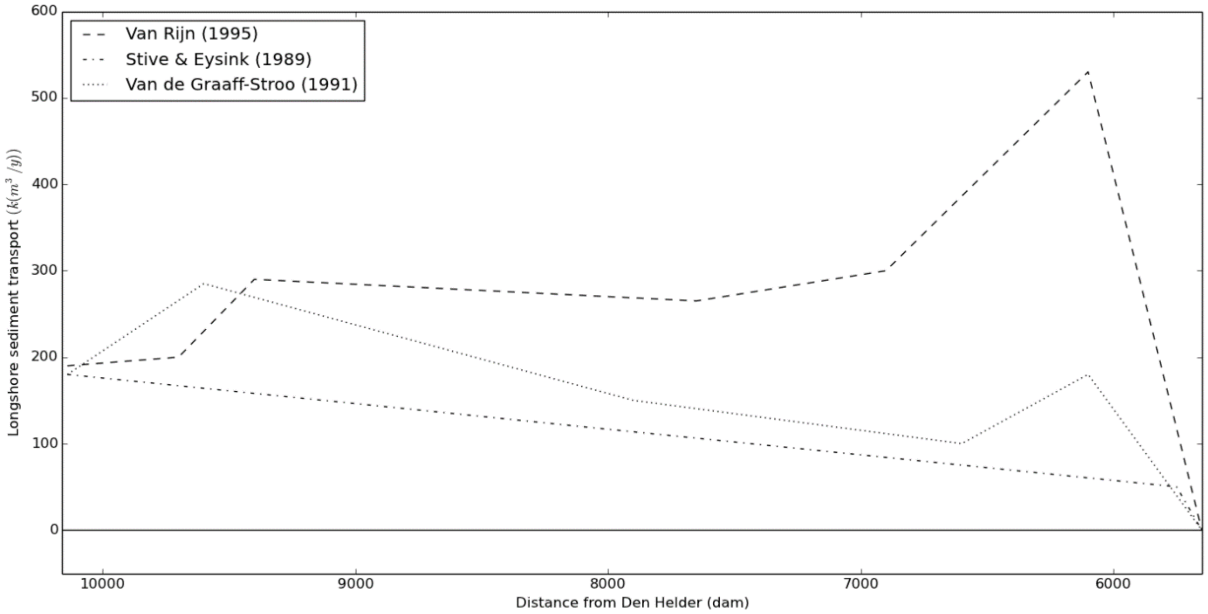

Figure 2.5: Predicted longshore transport volumes (van Rijn L. , 1995).

The coastline between Scheveningen and IJmuiden consists almost purely of a sandy beach-dune system, with the discharge sluice of the Old Rhine near Katwijk as exception. The northern side of the area of interest is bounded by the breakwater of the IJmuiden harbour. The longshore sediment transport is, even on the upper shoreface, almost fully blocked by the breakwaters of the IJmuiden harbour which have a cross shore length of 2.5 to 3 kilometre. On the southern side the area is bounded by the breakwater of the Scheveningen harbour, which has a length up to 800 m (Giardino & Santinelli, 2013; Kuijper et al., 2015). The amount of sediment which still passes the breakwater is related to the cross shore distance of the breakwater and is therefore larger at the southern boundary than at the northern boundary. Both breakwaters are presented in the aerial photographs of figure 2.6. Around the Scheveningen harbour breakwater, clearly sediment is transported. As a consequence of the presence of the harbour breakwaters, the areas close to the breakwaters are subjected to an accumulation of sediment.

Figure 2.6: The breakwaters at IJmuiden (left) and Scheveningen (right) (Rijkswaterstaat, n.d.-c).

In general, the entire beach area along the coastal stretch accretes, with maximum accretion volume near IJmuiden. Only near Scheveningen, Wassenaar, Bloemendaal and Zandvoort, regular erosion is found (Rijkswaterstaat, n.d.-a), in line with the positive gradients in the longshore sediment transport distribution of figure 2.5.

For the Rijnland coastal reach (which does not include Scheveningen) the nearshore (surfzone and beach) accumulation is 8.5 million m^3 of sand per year. The accumulation of sediment in the nearshore is compensated by the loss of sediment at the shoreface (-8 m to -12 m NAP), for Rijnland this yearly amounts up to 7.4 million m^3. Only near the breakwaters of the IJmuiden harbour, sedimentation is found in the shoreface region. Summarizing the erosion and accretion volumes over the Rijnland reach, a net sediment gain of 1.1 million m^3 is found, including nourishments (Kuijper et al., 2015).

The net gain of sediment is earlier discussed in a report by van Rijn (1995), in which sedimentation was found in the surfzone and beach area (-8 to 3 m NAP) as well as in the dune area (3 to 10 m NAP) for the coast between Hoek van Holland and IJmuiden. However, when excluding the areas close to the IJmuiden and Hoek van Holland harbours, the beach area shows only minor sedimentation, while the surfzone (and the shoreface) show(s) erosion.

Next to the pattern of sedimentation in the nearshore, bar migration in seaward direction can be observed. Along the area of interest, mostly two or three breaker bars can be distinguished which move from the landward edge to the seaward edge of the surfzone over a period of roughly 4 years. The migration of these bars is probably forced by gradients in longshore transport along the coastline (van Rijn L. , 1995). The application of shoreface nourishments disturbs the migrating trend of the natural breaker bars, after which the bars stabilize for a couple of years and start migrating again when the effect of the nourishment is faded out.

The final important process regarding sediment volumes in the coastal zone is sea level rise. Sea level rise can be converted to a loss of sediment in the coastal zone. To retain the same level of safety, the increase in sea level has to be compensated by an increase in sediment volume. According to the present Dutch coastline preservation policy, compensation of sea level rise in the area up to -20 m NAP is desired (paragraph 2.2).

Gross sediment transport

Based on the hydro- and morphodynamics, an overview of expected gross and net sediment transports in the area of interest, between Scheveningen and IJmuiden, is made. The area of interest reaches in cross shore direction from the dunes towards the -20 m NAP depth line, which is the boundary of the coastal foundation. This same area is part of the Coastline Preservation policy, as discussed in paragraph 2.2. The most important sediment transport processes can be summarized qualitatively as follows (figure 2.7).

- Longshore sediment transport in the nearshore and on the shoreface in both directions, with slightly larger transport in northern direction (orange).
- Significant import and export of sediment at the southern boundary. Import is expected to be larger than export due to the dominant tidal flow in northern direction . On the other hand almost no import or export of sediment is expected at the northern boundary. The small amount of transport is expected in the shoreface area, as transport in the surfzone is fully blocked by the IJmuiden harbour breakwaters (Kuijper et al., 2015) (green).
- Net sediment loss on the shoreface (up to -12 m NAP) and net sediment gain in the surfzone and on the beach (Kuijper et al., 2015) (red). This includes the effect of nourishments in all areas. The related cross shore transport quantities are yet unknown.
- Import and export at the cross shore boundary. Taking into account sea level rise, the volume loss is expected to be much higher than the sediment import (blue).

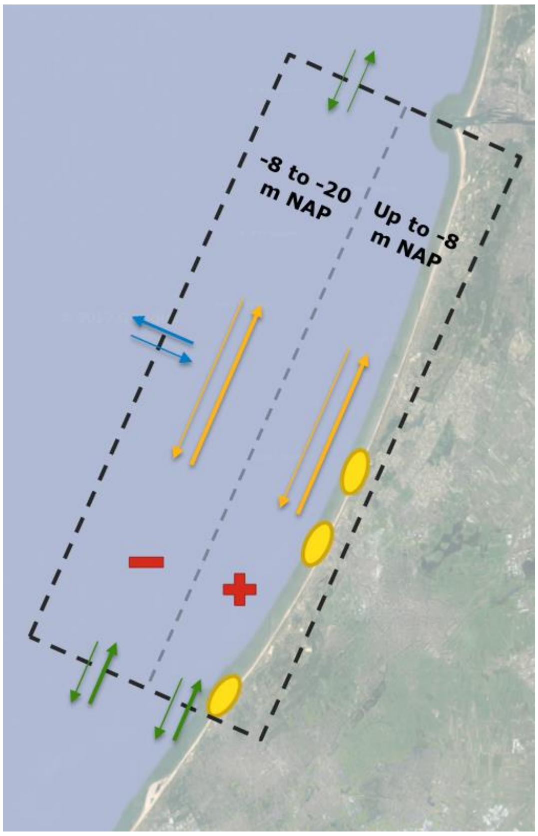

Figure 2.7: Large scale gross sediment transports.

Important to note is that the aim of the research is on the maintenance of the adjacent coast, therefore the beach region is the most important part of the area of interest. In figure 2.8 (left), the expected gross sediment transports around the nourishment locations are presented. When combined with figure 2.7, most important gross sediment transport processes are visualised. For the nourishment locations (Scheveningen, Katwijk and Noordwijk) and the adjacent coastal stretches, the following summary on gross sediment transports can be made.

- Longshore transport from the nourishment locations towards the adjacent coast, with slightly larger transport in northern direction than in southern direction. Also longshore transport of sediment from the adjacent coast towards the nourishment locations is present. The resulting accretion volume around nourishments is however expected to be much smaller than the erosion volume caused by the opposite process.
- Cross shore transport from the nourishment locations towards the surfzone. It is expected that in general, transport towards the surfzone is larger than sediment transport from the surfzone to the nourished beach.
- Cross shore transport from the surfzone towards the beach along the adjacent coast, with in general larger transport towards than beach than vice versa.

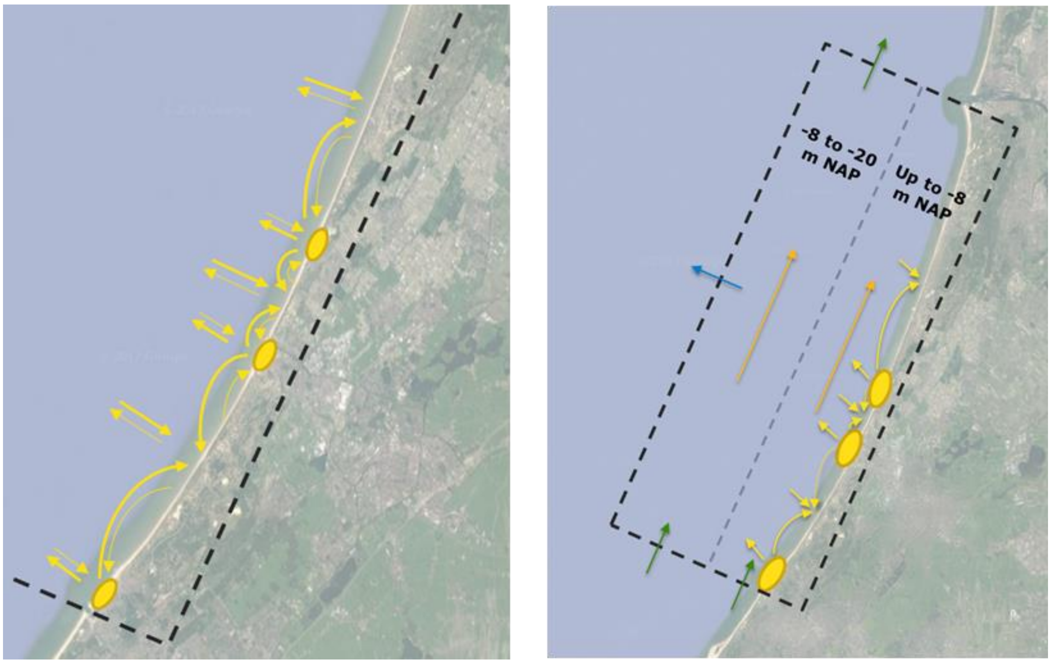

Figure 2.8: Gross sediment transport close to the beach (left) and net sediment transport directions (right).

Net sediment transport

In line with the previously discussed gross sediment transport volumes and processes, the following net sediment transports are expected (figure 2.8 (right)).

- Net longshore transport in northern direction.
- Net sediment import at the southern boundary, both in the surfzone as well as in the shoreface area.
- Net export of sediment from the shoreface area in northern direction at the northern boundary.
- No import or export of sediment at the northern boundary in the surfzone.
- Net cross shore transport from the surfzone towards the beach area at locations where no beach nourishment is applied.
- Net longshore transport from the nourishment locations towards the adjacent coast in northern and southern direction.
- Net cross shore transport from the nourishments towards the surfzone.
- Net loss of sediment at the cross shore boundary, with sea level rise as most important process.
- Unknown cross shore transport quantities between the shoreface and the surfzone.

3. Measurements

To be able to assess the state of the coastal profile and consequently plan or act according to the findings, yearly measurements are done along the entire Dutch coast, called the JARKUS measurements (paragraph 2.2). The results of these measurements (Rijkswaterstaat, n.d.-a) are analysed in this chapter to give a first insight in the transport of sediment from the locations of interest towards the adjacent coast. The trend in the position of the coastline and the trend in MKL volume (3 m NAP to -4.4 m NAP) for the years 2009 up to 2017 (volume) or 2018 (coastline position) are the two characteristics taken into account. The development of the shoreface itself is not included, but the effect of shoreface nourishments is visible in the development of the coastline and MKL volume. Since both considered characteristics show almost the same behaviour, only figures of the coastline position are presented in this paragraph. Additional figures can be found in Appendix D.

Trends in coastline development are based on at least three years of measurements, therefore new trends after nourishment application only become visible when three new measurements are available (see figure 3.1). For the trend in the first two years after nourishment application, the amount of available new measurements is insufficient and therefore the old trend, computed from measurements before nourishment application, is used. This only holds for the nourishment location itself. For the adjacent coast, the effect of the nourishment may already become visible in the first year. Table 3.1 gives an overview of all nourishments, the presence in measurements and the resulting visibility in the predicted trends.

Nourishment	**Application year**	**Present in measure-ments**	**Present in predicted trend at location**	**Present in predicted trend along adjacent coast**
Noordwijk 'Zwakke Schakel'	2007/2008	2008	2011	2008
Noordwijk maintenance	2013	2014	2017	2014
Katwijk 'Zwakke Schakel'	2013/2014	2014	2018	2014
Scheveningen 'Zwakke Schakel'	2009/2010/ 2011	2011	2014	2011
Scheveningen maintenance	2015	2015	2018	2015

Table 3.1: Applied nourishments and the presence in yearly measurements.

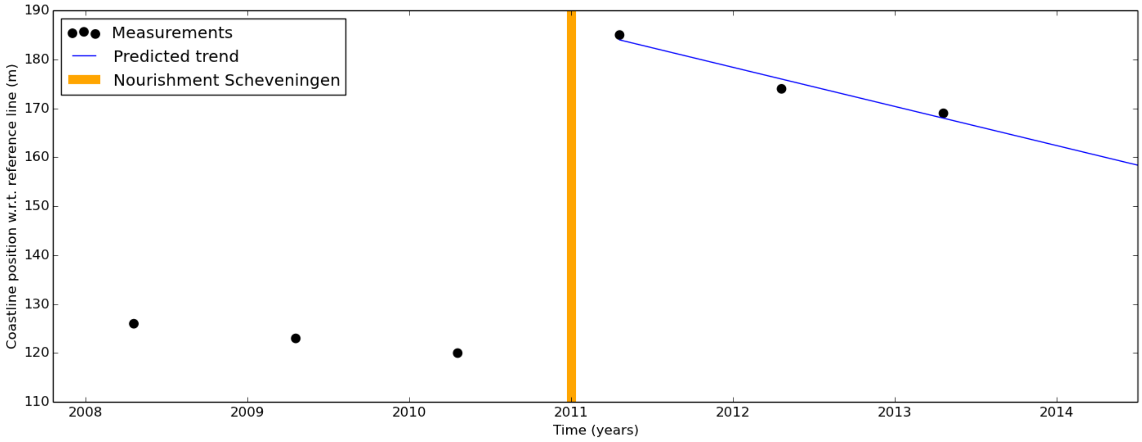

Figure 3.1: Example of the computation of a trend after nourishment application for Scheveningen.

A positive trend in coastline development indicates that the coastline position is migrating in seaward direction, while a negative trend indicates landward migration. A positive, and increasing trend at a certain location along the adjacent coast in the years after nourishment application may be related to the sediment transport from the nourishment location towards the adjacent coast. In the graphs used in this paragraph, a dashed black line is placed at the year and location were the application of a nourishment is first visible in the measurements. In the trend at the nourishment location itself, the first effect is thus expected 3 years later, when at least 3 measurements are available, while along the adjacent coast the trends may become visible from the dashed line onwards (see table 3.1 and figure 3.1).

3.1. Scheveningen

Around Scheveningen (figure 3.2), close to the nourishment location on the northern side, a positive change in trend is clearly visible over a length of approximately 2000 meter for 2018, from 97 to 99 kilometre from Den Helder. At the nourishment location, a negative change in trend is found in year 4 (e.g. 2014) after nourishment application due to increased erosion, which is according to the expectation. The trends for the years 2009 up to 2013 make clear that also without beach nourishments, the coast is continuously eroding. This result matches with the longshore sediment transport distribution as presented in figure 2.5, where the longshore sediment transport increases around Scheveningen with erosion as a consequence.

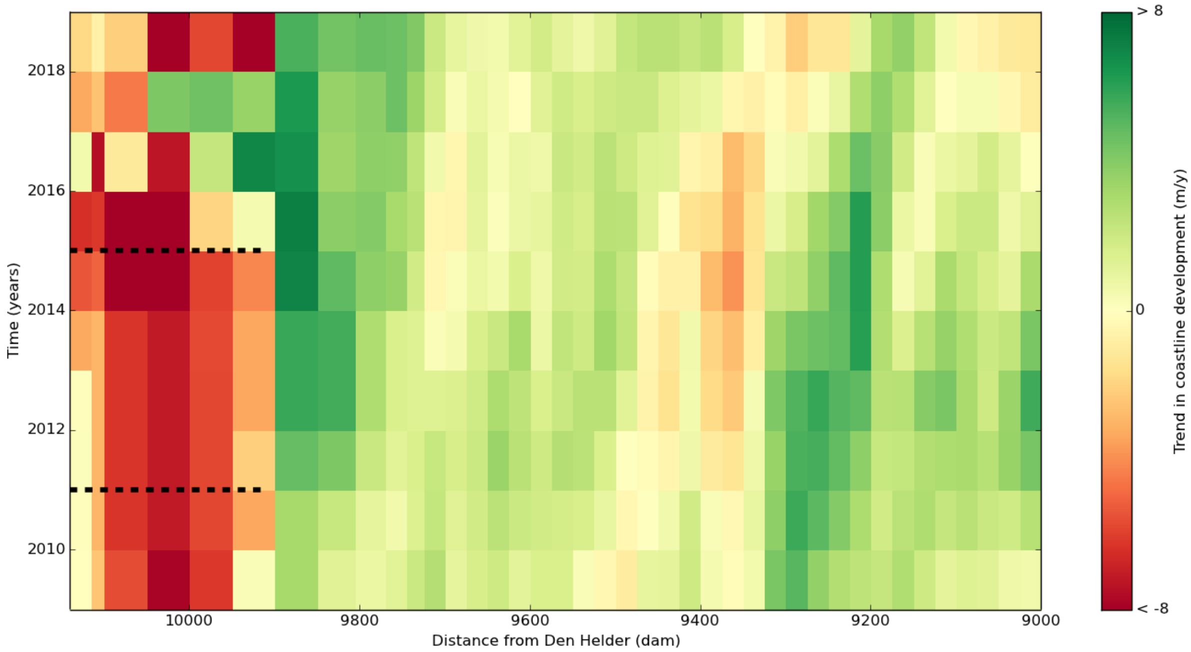

Figure 3.2: Trends in coastline development around Scheveningen.

3.2. Katwijk

The ‘Zwakke Schakel’ reinforcement nourishment at Katwijk is applied in the years 2013 and 2014, and the effect is for the first time visible in the measurements of 2014 (table 3.1). Although three years of measurements are available for the predicted trend of 2017, the effect of the Katwijk reinforcement is only included in the predicted trend for 2018 (figure 3.3). A clear negative erosion trend is visible in the centre of the nourishment location. This observation is, in contrast to most of the erosion at Noordwijk, nicely in line with the theory on erosion and accretion patterns around nourishments (see paragraph 2.6).

The region around the Katwijk reinforcement also shows clear changes in trend. Small increase in sedimentation trend can be observed both north and south of the nourishment location along the adjacent coast. Similar to the Noordwijk case (paragraph 3.3), the positive influence along the northward adjacent coast is more clear than the positive influence in the south. In the north, a clear increase in positive trend is found over a distance of more than 1 km in 2018.

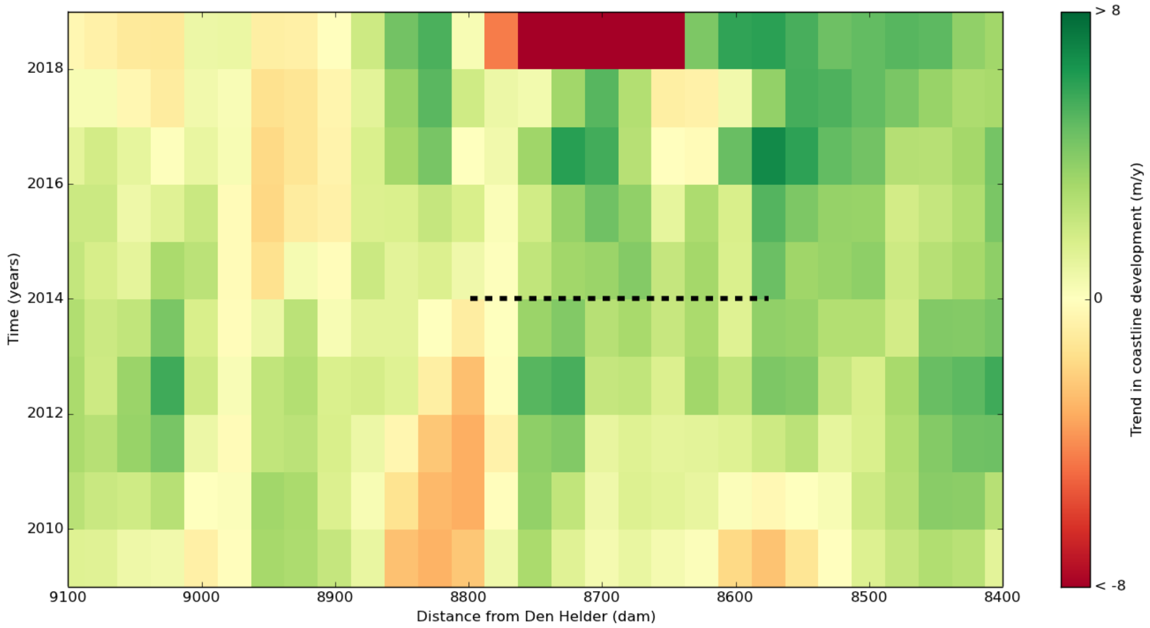

Figure 3.3: Trends in coastline development around Katwijk.

3.3. Noordwijk

The ‘Zwakke Schakel’ nourishment at Noordwijk is applied in the winter of 2007/2008. Similar to the Scheveningen and Katwijk cases, an erosional trend comes up after three years (2011) at the nourishment location (figure 3.4). Remarkable is that the erosion mainly occurs around the edges of the nourishment, while the centre part of the nourishment mainly shows a trend of accretion. The stretches with an erosional trend slowly move northward over the years. The varying erosion and accretion patterns, which are not only visible in the trends but also in the direct measurements, may be related to the nourishment design. From 2017 onwards, a new erosion pattern is found in which the erosion mainly takes place in the centre of the nourishment location. This new trend is related to the maintenance nourishment applied in 2013, which was first measured in 2014. Probably the design of this maintenance nourishment is less complex and therefore the erosion and accretion patterns are more straightforward than after the ‘Zwakke Schakel’ nourishment. Finally important to note is that also in the years before the effect of nourishment application was present, before 2011, a negative trend was present in some sections.

Along the adjacent coast, in the north an increasing trend of sedimentation is found between km 81 and 79, over a distance of almost 2 kilometres in 2018. The magnitude of the positive trend slowly decreases over time, which may be caused by decreasing sediment transport gradients over the years due to smoothening of the coastline. In the south it is more difficult to find in clear increasing trend of accretion, but in general the trends in 2018 are more positive than in 2010.

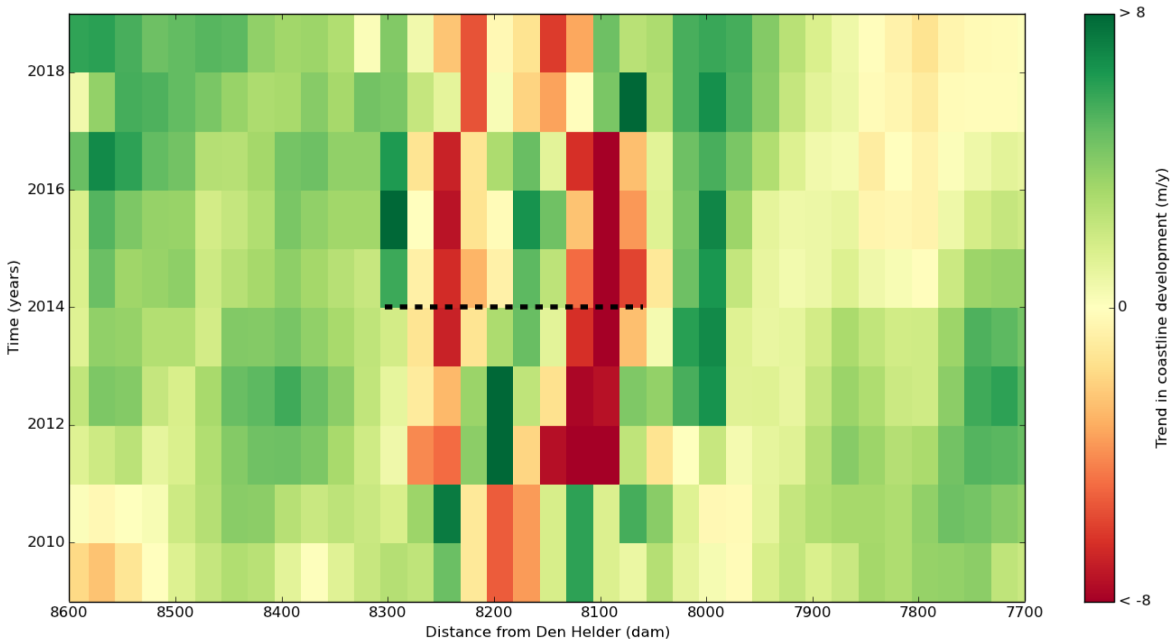

Figure 3.4: Trends in coastline development around Noordwijk.

3.4. Overall

In figure 3.5 the trends in coastline development are presented for the entire research area. Next to the already discussed effects around the nourishments locations, some additional interesting observations can be done. Erosion is found in the area around Bloemendaal and Zandvoort (km 65) from 2015 onwards. Looking at the applied nourishments (Appendix B), this may be related to the lifetime of the 2004 shoreface nourishment in this area. The increasing positive trends northwards and southwards from this area may be related to the applied shoreface nourishments late 2008. Around Noordwijkerhout (km 75) and Wassenaar (km 95) negative trends are found. These two locations also correspond with locations where in the past decade shoreface nourishments are applied.

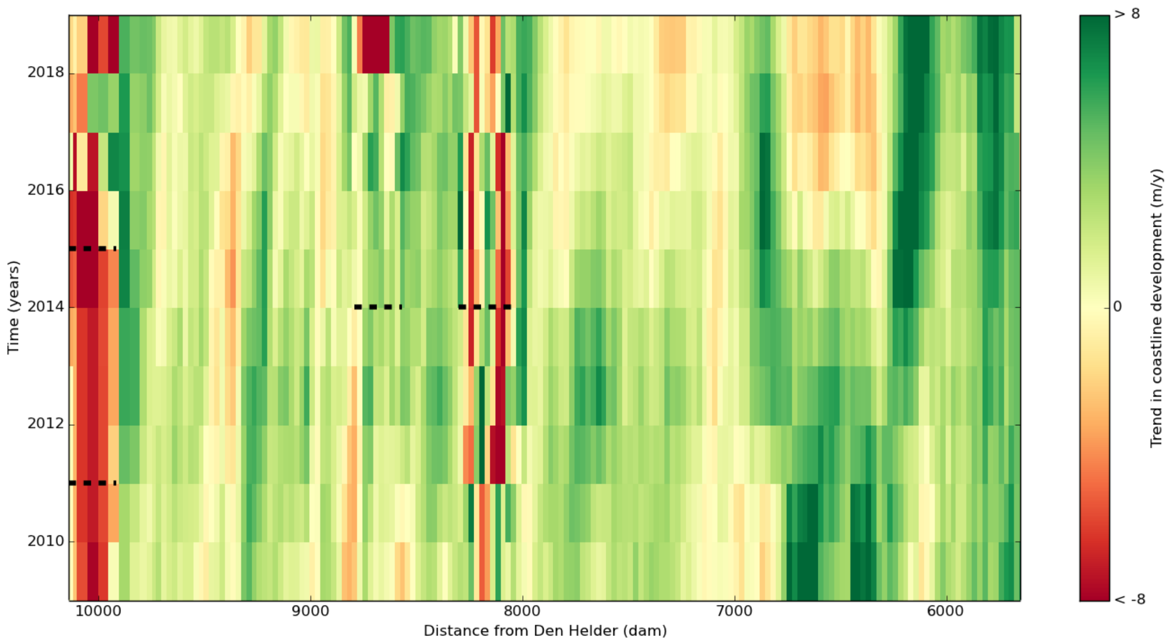

Figure 3.5: Trends in coastline development over the entire area of interest.

3.5. Conclusion

Based on the results of the yearly assessment on the development of the coastal profiles, a first conclusion on the sediment transport from recurring nourishments towards the adjacent coast can be made. This conclusion forms a first hypothesis on the long term development of the adjacent coast.

Measurements at Scheveningen, Katwijk and Noordwijk all show a positive influence of the (maintenance) nourishments on the adjacent coast, generally the trend north- and southwards of the nourishment location becomes (more) positive in the period after nourishment application. This effect is visible over roughly a distance of 1 kilometre per 4 years in northern direction. The effect in southern direction is more difficult to observe, possibly because the magnitude of the positive effect is lower. Clear erosion is present in the years after nourishment application at all 'Zwakke Schakel' locations. At Scheveningen, continuous erosion is present also without nourishment application. The same holds for Noordwijk although the autonomous negative trend here is much smaller. Next to the nourishment locations, erosion is present in the region of Bloemendaal, Zandvoort, Noordwijkerhout and Wassenaar, which is in line with the locations of shoreface nourishments in the past decade.

4. Model setup

An existing Unibest-CL+ model Unibest for the Holland Coast (Huisman & Luijendijk, 2010) is used as starting point for the model research. This model is used in various previous studies by Deltares and for that purpose already calibrated and validated (Huisman & Luijendijk, 2010; Tonnon, van Rijn, & Schrijver, 2012). However, detailed information on the background of especially Unibest-LT input parameters is limited in these studies. The model setup is therefore examined again for this research with the help of the research reports, several papers and the Unibest-CL+ manual (Deltares, 2011). For most parameters in Unibest-LT, no changes are made in this research with respect to the original model. The setup of this part of the model can be found in Appendix F together with a simple sensitivity analysis.

Additionally, a small literature review into the theory and formulae behind the Unibest-CL+ model is done with the help of the Unibest-CL+ manual and multiple papers, in order to be able to judge the input parameter values properly. Results of this review can be found in Appendix E. The refinements made in Unibest-LT model as well as the setup of the Unibest-CL model are elaborated in this chapter, together with the validation of both parts of the model.

4.1. Model background

For this research, version 7.1 of the Unibest-CL+ model is used. Most of the information provided in this paragraph is based on the Unibest-CL+ manual (Deltares, 2011). The Unibest-CL+ model is split in two separate models, Unibest-LT to compute Longshore Transport and Unibest-CL to compute the CoastLine development.

Capacities

The Unibest-CL+ model can be used for simulating the evolution of the nearshore zone when effects of longshore transport are dominant. This longshore transport can be either caused by wave breaking, wave-driven longshore currents and/or tidal currents. The response of the coastline and nearshore profile as a consequence of gradients in longshore transport can be simulated for the period of months to decades. Within this research the focus is on medium to small scale problems, with spatial scales up to tens of kilometres and time scales up to decades. On this scale, the model is capable of assessing the impact of human measures on the coastal system. When decreasing the time and spatial scale to couples of kilometres and up to a decade, coastal engineering structures, including beach nourishments, can be assessed in more detail. The detailed development of a beach nourishments lies however not within the scope of this research.

Suitability

The main focus in this research is on the transport of sediment from nourishment locations towards the adjacent coast. The applied nourishments in this case are beach nourishments and the transport of sediment from these nourishments towards the adjacent coast mainly takes place in the nearshore region. Furthermore the beach nourishments are applied within the active region. Unibest-CL+ is capable of modelling the sediment transport in longshore direction in the nearshore (active region) and the resulting development of the coastline. This capability is in line with the main objective of the research and the corresponding problem description (paragraph 1.2). Therefore it is concluded that the Unibest-CL+ model, taking into account the simplifications (see chapter 7 ‘Discussion’) of the model, is a suitable model for this research.

4.2. Unibest-LT refinement

The main goal of the Unibest-LT model is to compute the longshore sediment transport rate and its cross shore distribution for varying coastline angles, taken into account waves, currents, sediment characteristics and the shape of the coastal profile. The result is an S-ϕ curve, which shows the relation between the longshore transport volume (S) and the relative coastline angle with respect to the average angle of incidence of the waves (ϕ). The dynamics in the surf zone are computed with the help of a random wave propagation and decay model (Battjes & Janssen, 1978; Battjes & Stive, 1985). Offshore wave data from a local wave climate is transformed to nearshore wave data (see Appendix F). When all parameters are known, the longshore current distribution is computed with the (alongshore) momentum equation, taking into account bottom friction, gradients in radiation stress and the alongshore tidal surface slope. The sediment transport, which is forced by a longshore current, can be computed with several different sediment transport formulae and corresponding transport parameters.

The outline of the Unibest-LT model can be summarized as follows (figure 4.1). The longshore sediment transport distribution is computed given a certain cross shore profile, wave scenario and several wave- and sediment transport parameters.

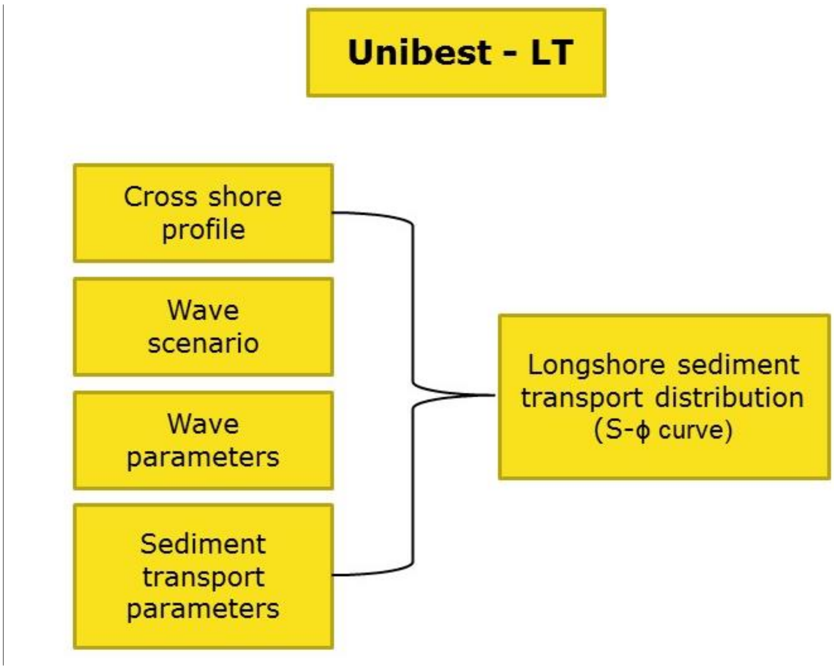

Figure 4.1: Outline of the Unibest-LT model.

Only in the wave parameters, a small change is made with respect to the original 'Holland Coast' model, regarding the bottom friction coefficient. The input for the cross shore profiles, wave scenario, other wave parameters and sediment transport parameters is identical to the original input. The values or types of all these input parameters are reconsidered in Appendix F.

Bottom friction coefficient

The bottom friction coefficient f_w is used to compute the Chézy coefficient for bottom friction (see Appendix E). For the bottom friction coefficient, a value of 0.01 (-) is advised (Deltares, 2011), while no friction is applied in the original model. The effect of applying bottom friction with a coefficient of 0.01 is presented in figure 4.2. In case of applying bottom friction, the annual transport volumes are slightly lower, leading to a decrease in gradients near the boundaries and therefore lower erosion or accretion volumes. Further research into the influence on coastline development makes clear that for instance the erosion rate at Scheveningen decreases with maximum 1 meter per year, near IJmuiden the decrease in accretion rate is in the order of 0.3 meter per year. Decisive in the value of the bottom friction coefficient is the observation that the erosion rate near Scheveningen is likely to be overestimated (see paragraph 4.3). In line with this observation, it is chosen to use the advised value of 0.01 for the friction coefficient f_w and therewith slightly decrease the erosion and accretion volumes.

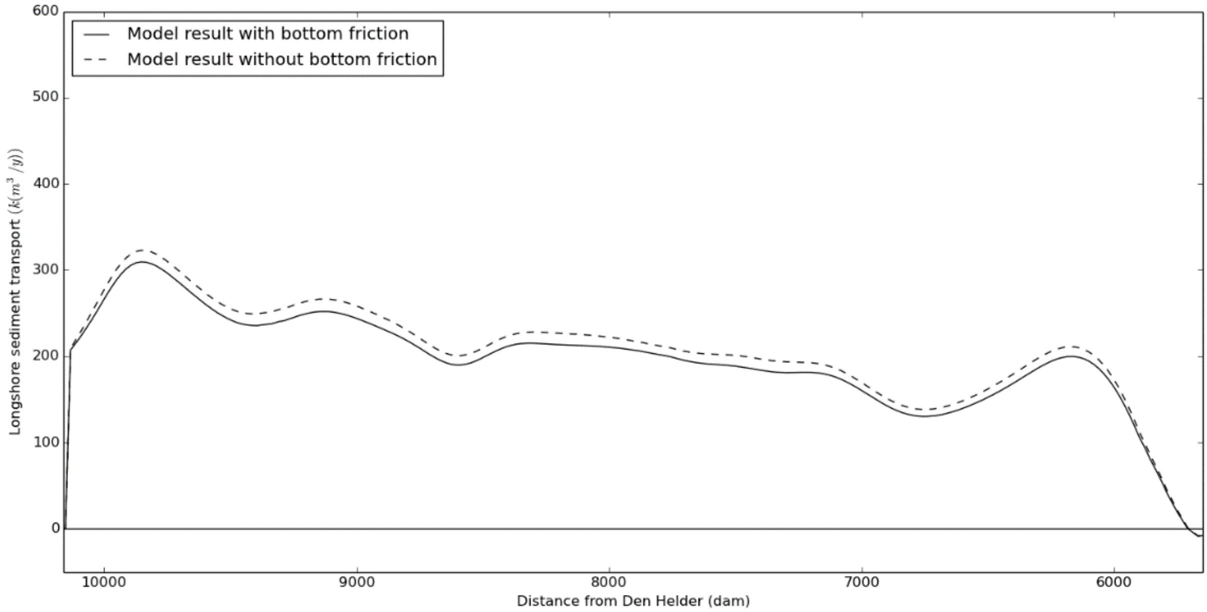

Figure 4.2: Annual longshore sediment transport volumes for model runs with and without friction. Important to note is that the positive sediment transport direction is northwards

4.3. Validation Unibest-LT refinement

The main output of the Unibest-LT model is the net annual longshore sediment transport along the coastal stretch. This net annual longshore transport is composed out of 34 computed S-ϕ curves for 34 different cross shore profiles, evenly distributed over the coastal stretch. It is chosen to use the transport after 5 years of modelling time as representative situation (figure 4.3). The model needs some time to spin up, which makes the first years of the model results unreliable. Along the major part of the coastal stretch, the annual net sediment transport volume decreases in northern direction and is on average around 200,000 m^3/year. Near IJmuiden, around 60 km from Den Helder, the transport volume increases initially after which it decreases to almost zero at the harbour breakwater. Around Scheveningen in the south, the annual transport volume is remarkably large with values between 300,000 and 400,000 m^3/year.

In figure 4.3, the model results are presented together with results from previous studies by van Rijn (1995), Stive & Eysink (1989) and Van de Graaff-Stroo (1991), as summarised in the research by van Rijn (1995). Almost along the entire coastal stretch, the model results lie well within the range of results of previous research. Furthermore, the gradients in all studies are in the same order of magnitude for the major part of the research area. Only near the boundaries, at Scheveningen and IJmuiden, significant differences can be observed. Near IJmuiden, only a large difference between model results and the research by van Rijn (1995) is found. This difference may have different causes. Firstly it can be caused by the fact that in case of the van Rijn research, the (extreme) initial trends of transport after extension of the harbour breakwaters was taken into account (van de Rest, 2004). Furthermore, due to the presence of the harbour breakwaters of IJmuiden, the coastline orientation changed significantly over the past decades since the van Rijn research in 1995.

Close to Scheveningen, the annual sediment transport volume is significantly larger than the expected sediment transport volume. This large peak in sediment transport causes severe erosion at Scheveningen, where the gradient is positive. If nourishments are placed in this area, the gradient increases further, leading to unrealistic amounts of erosion. Similarly, the large negative gradient north of Scheveningen leads to heavy accretion. The sediment transport volumes in this area do not match with previous research, nor with reality and therefore it is chosen to adapt the sediment transport around Scheveningen.

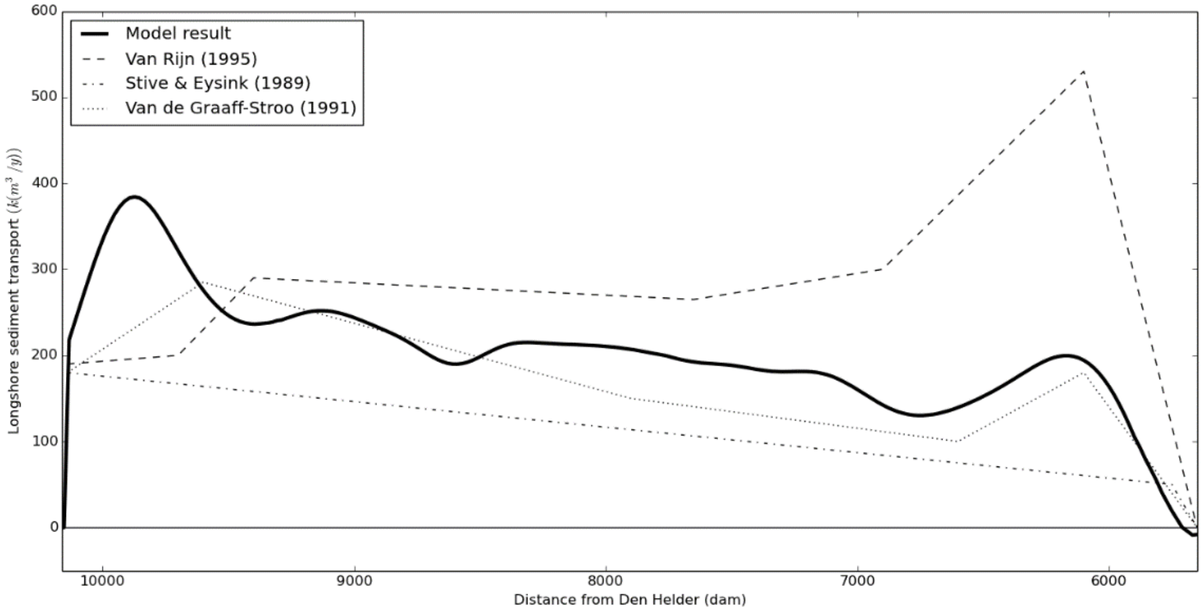

Figure 4.3: Longshore sediment transports volume along the coast without scaling.

In order to adapt the sediment transport in the region of Scheveningen, it is chosen to scale down the sediment transport curves (S-ϕ curves) in such a way that the new gradients are in correspondence with gradients obtained from yearly measurements. By scaling the S-ϕ curve, the behaviour of the sediment transport for different coastline angles is maintained, only the magnitude of the transport is decreased. The transport in the region of Scheveningen is determined by five different cross shore profiles and corresponding S-ϕ curves. In table 4.1, the locations of these profiles are presented together with the scaling factor used to scale the S- ϕ curve. The scaling factor first increases in northern direction to a minimum of 0.7, after which it increases back to normal.

Distance from Den Helder (dam)	Scaling factor (-)
101,100	0.9
100,100	0.7
99,300	0.7
98,300	0.8
97,100	0.9

Table 4.1: Scaling factors at Schevingen as applied in the Unibest-CL+ model.

In figure 4.4 the new annual sediment transport curve is presented, again at t = 5 years. It is clear that in this case the magnitude of the sediment transport around Scheveningen corresponds better with the results from previous research. The gradients are less extreme, leading to a situation with more realistic accretion and erosion volumes around Scheveningen. To find the right scaling factors, gradients are computed from the results of yearly measurements and compared with the model results. From the yearly measurements (see paragraph 2.2) a gradient (m^3/m) is obtained by computing the average yearly volume gradient from volume balance over the period between 2005 and 2009 in the region of Scheveningen. These volume gradients are computed for different volume areas, all corresponding with an active height of 10 m (table 4.2). The considered region corresponds with the region over which the important positive gradient (erosion) is found in figure 4.3 and consists of 6 JARKUS measurement locations. All computed gradients including the gradient in the Unibest model are around 50 m^3/m/y. Given the similarities between the Unibest model transport results and the results of previous research, it is assumed that the model is now sufficiently capable of reproducing the sediment transport along the coast between Scheveningen and Den Helder.

Boundaries active height (m + reference water level)	**Predicted average gradient (m^3/m/y)**
-5 to 5	45.8
-6 to 4	56.1
-7 to 3	51.3
Model result	50.8

Table 4.2: Sediment transport gradients around Scheveningen, based on measurements and the new model transport quantities.

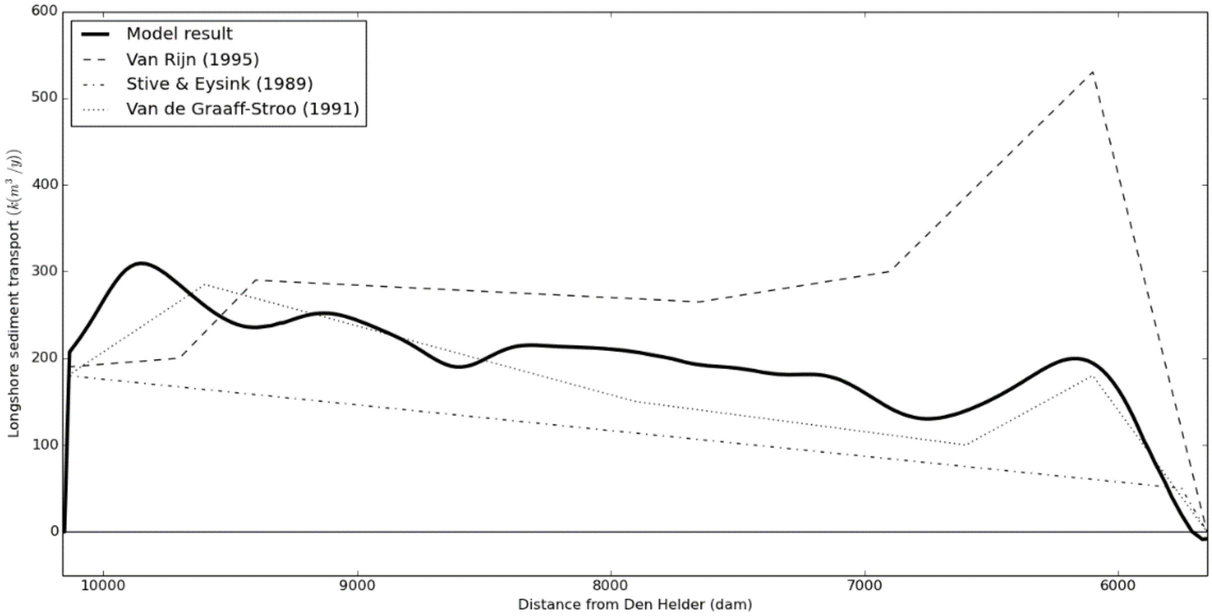

Figure 4.4: Longshore sediment transport volumes along the coast, after applying scaling factors.

4.4. Unibest-CL setup

In Unibest-CL , gradients in sediment transport and resulting coastline changes are computed along a given coastline. The main input is formed by the distribution of the longshore transport rate for all coastline angles, which is computed for each defined profile in Unibest-LT. The base of the coastline changes in the Unibest-CL model is the single line theory, by Pelnard-Considère (1956) (see Appendix E). In this theory, the shape of the coastal profile remains constant under influence of erosion and accretion, while the entire coastal profile moves horizontally as a result of gradients in longshore transport. As a consequence, the coastal profile is assumed to be always in equilibrium. Furthermore, only longshore transports are taken into account and it is assumed that the transport is instantaneously, which means that no time is needed to develop the transport up to full capacity. Sources and sinks, groynes and revetments (not applied in this research) can be added in the Unibest-CL model, which will have its influence on the longshore sediment transport gradients (Deltares, 2011).

The outline of the Unibest-CL model is summarized in figure 4.5. Only the parts of the model which are used in this research are presented.

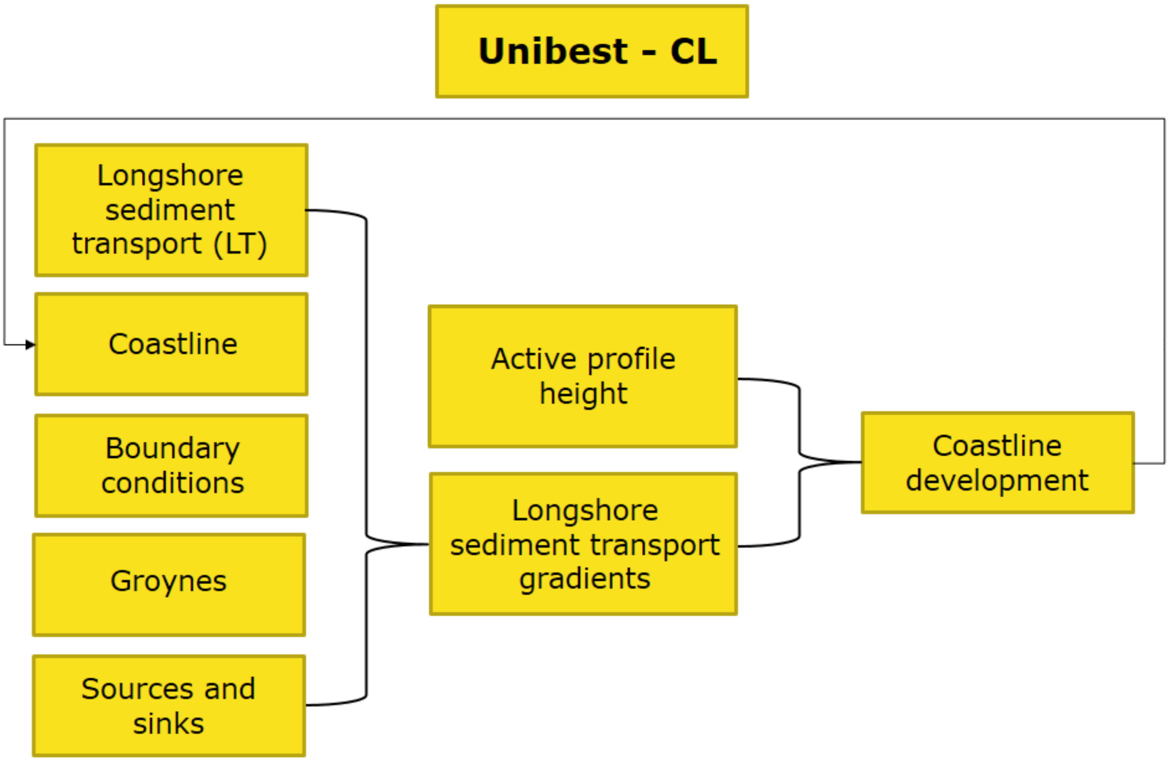

Figure 4.5: Outline of the Unibest-CL model.

Coastline

The base of the Unibest-CL model is the coastline, which has to be defined by the user. In case of the original 'Holland Coast' model, a coastline is constructed based on measurements from the coastline in 2005. For this research, only the part of the coastline between Scheveningen and IJmuiden is used, which has a length of approximately 45 kilometres. This coastal stretch is bounded by the breakwaters at the harbours of Scheveningen and IJmuiden. Along the stretch, the cell width or grid size varies slightly, but is on average around 200 meter. Most cells have a width of 200 meter, while some cells north of Noordwijk and near IJmuiden are larger and some cells at the Wassenaar beach, between Scheveningen and Katwijk, are smaller. For each cell along the coastline, transports and resulting coastline changes are computed based on the imposed S-ϕ curves from Unibest-LT. The discharge sluice of the Old Rhine near Katwijk is neglected.

The reinforcement nourishments of the ‘Zwakke Schakel’ project are added as a sediment source to the coastline. Due to the presence of the source, the coastline in the Unibest model initially migrates in seaward direction after which (new) gradients in sediment transport cause the migrated coastline to erode. Model start is set on 2006, while reinforcement nourishments start in 2007, 2009 and 2014 for Noordwijk, Scheveningen and Katwijk respectively. More information on these nourishments can be found in the final part of this paragraph.

Active profile height

The active profile height has a significant influence on the results of the CL model. The magnitude of the seaward or landward migration of the coastline directly depends on the value of the active profile height. The larger the active profile height, the more volume is needed to migrate the coastline (see Appendix E). To come up with a reasonable active profile height, generally two methods can be applied. The first method is to analyse measurement data and predict the relation between morphological activity (bathymetry change) and time. The second method is related to Hallermeier’s closure depth (1978), which provides a relation between the closure depth and the maximum significant wave height.

Hinton and Nicholls (1998) performed a study on the closure depth for the Holland coast. For the coast of south Holland, closure depth varies between 5 m and 10 m for short term and long term closure respectively, based on the JARKUS measurements. The short term closure depth is mainly determined by sediment transport due to wave breaking, while long term closure depth involves the shoreface and changes in bathymetry which can be observed on a scale larger than 10 years. Based on the Hallermeier equation for closure depth, a value of 9.2 meters is found (Hinton & Nicholls, 1998). Stive, Roelvink and de Vriend (1990) estimated the border of the active zone along the Holland coast on 8 meters water depth, based on morphologic changes visible within one year in the measurements.

The Unibest model used in this research is used to predict coastline evolution on a timescale up to five decades. When taking into account bottom changes on longer time scale, the border of the active zone will move in seaward direction and the closure depth will increase. Furthermore, part of the profile above the mean water level may be included in the active profile height when taking into account longer timescales due to the higher probability that extreme conditions occur during which the water level rises. Originally, an active profile height of 10 meters is used in the ‘Holland Coast’ Unibest model (Huisman & Luijendijk, 2010), which is, taking into account all the previous, a reasonable estimation for the active profile height. During the evaluation of the model results (paragraph 5.6), additional model runs are performed with active heights of 8 and 12 meters to visualise the consequences of the uncertainty in the determination of the active profile height.

Boundary conditions and groynes

At the boundaries of the model, north of IJmuiden and south of Scheveningen, boundary conditions need to be imposed. The possible choices in boundary conditions varies between a constant coastline, a constant coastline angle, a constant sediment transport or a time dependant sediment transport. It however turns out that, due to the effect of the harbour breakwaters at Scheveningen and IJmuiden, the boundary conditions have no influence on the sediment transport in the area of interest. In the area of interest, the sediment transport is determined by the sediment bypass volumes at the harbour breakwaters. These harbour breakwaters are modelled as impermeable groynes, including local wave climates and resulting sheltering effects close to the breakwaters at Scheveningen. The bypass volume at both breakwaters is constant over time.

The amount of sediment transport along the IJmuiden harbour breakwaters is almost zero (paragraph 2.8), while in the original model a bypass of 90,000 m^3/year is used. Models tests are performed with a bypass of 5,000 and 90,000 m^3/year respectively. The difference in coastline development near the IJmuiden breakwater for the different bypass volumes is in the order of 2 meters per year. As a consequence, the yearly rate of change of the coastline increases from approximately 4 to 6 meters per year. According to yearly measurements (Rijkswaterstaat, n.d.-a), the rate of change close to IJmuiden lies between 4 and 8 meters, from which it is concluded that a bypass of 5,000 m^3/year gives better results.

At the Scheveningen harbour breakwater, the sediment transport is not fully blocked (see paragraph 2.8). According to figure 2.5, which is made with the help of several previous studies, a bypass of 200,000 m^3/y seems to be a realistic value. This bypass volume is also used in the original Holland Coast model (Huisman & Luijendijk, 2010) and is retained in this research.

Sea level rise

In the present preservation policy of the Dutch coast, a sea level rise of 18 centimetres per century is taken into account (M. Lazar, personal communication, November 2017). In the past decennia, extensive research is done on the estimations of future sea level rise. Recent research (Le Bars et al., 2017) states that extreme sea level rise in the coming century is a possibility. Taking into amongst others new methods for the computation of Antarctic ice mass loss (DeConto & Pollard, 2016), a sea level rise of 184 cm is predicted for the 21st century. This prediction includes an extreme scenario for greenhouse gases, in the most positive scenario with a very ambitious worldwide climate policy, the contribution of Antarctic ice mass loss may decrease with almost 1 meter (DeConto & Pollard, 2016). Taking the results of recent research into account, the maximum sea level rise predicted by the 'commissie Veerman' in 2008, 130 centimetres in 2100 (Deltacommissie, 2008), is an event which is no longer unlikely to happen. Since sea level rise grows exponentially, it is especially important to take sea level rise into account in research on a large timescale. With the time scale in this research being 55 years, sea level rise cannot be neglected.

As starting point in this research a theoretical sea level rise of 100 centimetres in 100 years is applied in this research. Theoretically this sea level rise may lead to a total loss of sediment of 500 m^3/m, assuming a profile length of 500 meter which has to adapt to the sea level rise. This 500 meter on its term is based on the active profile height of 10 meter and an average slope of 1:50 (figure 4.6). Assuming the sea level rise to be linear instead of exponential (see chapter 7 'Discussion'), per year a loss of 5 m^3/m is found. Given the active height of 10 meters, this volume loss is in the model equal to a coastline retreat of 0.5 meter per year. The assumed slope of 1:50 complies with the average slope of the coastal profiles between Scheveningen and Noordwijk in the model. North of Noordwijk, the slope of the coastal profile increases, however, since the area between Scheveningen and Noordwijk is the main area of interest, it is chosen to use a slope of 1:50. In the evaluation of the model results (paragraph 5.6), further research is done with values for the magnitude of sea level rise varying between 20 and 150 centimetres per century. These cases represent current practice and extreme future scenarios respectively. Additionally, the consequences of using a profile slope of 1:60 is evaluated, which leads to an increase in the effect of sea level rise.

Including sea level rise as a continuous sink in the model leads to instabilities near the boundaries and therefore the effect of sea level rise is included during post-processing of the model results. The sea level rise of 1 centimetre per year is converted to a continuous coastline retreat of 0.5 meter per year. The influence of sea level rise on the results on a timescale of 50 years is therefore 25 meters. Since the effect of sea level rise is uniform over the entire area of interest, the sea level rise has no influence on the coastline orientation and resulting sediment transport volumes. This justifies the implementation of sea level rise after the model runs.

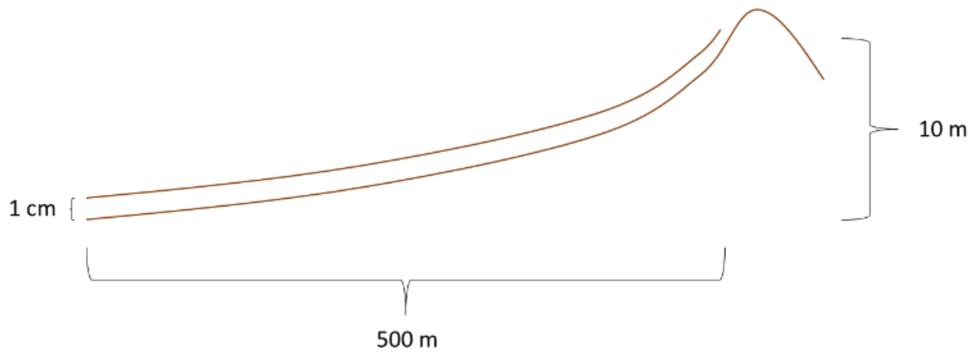

Figure 4.6: Schematised development of the coastal profile under influence of sea level rise.

Nourishments

Nourishments are applied in the model by adding a source to the coastline. For instance, when a maintenance nourishment with a volume of 500,000 m^3 is applied over a distance of 1,000 m in 4 months, a source of 25,000 m^3 per month can be added to five corresponding cells (200 m wide) along the coastline, over a period of 4 months. Important to note is that the nourishment in the model is evenly spread over a certain corresponding distance, while in reality the volume per section may be different. Furthermore, the slope of the coastal profile in the Unibest model is constant and assumed to be in equilibrium, while in reality the slope after nourishment application may change and is not in equilibrium, which has its influence on the coastline position. Due to these simplifications, the total nourishment volume and (longshore) location are together with the imposed frequency the most important parameters of a nourishment and the only parameters which are used in the model for nourishment design.

In table 4.3 and 4.4, the 'Zwakke Schakel' reinforcements and the first (in most cases already applied) maintenance nourishments are listed. These nourishments are applied in each long term nourishment model scenario and form the base for the Unibest-CL model validation, in which the coastline development at the nourishment locations is assessed. Some nourishment volumes are measured after nourishment execution while others are design values, depending on the available data (Rijkswaterstaat, 2016c).

'Zwakke Schakels'	Time (mm/yy)	Volume (m^3)	Distance from Den Helder (dam)	Width (m)	Cells
Scheveningen 1	10/09 – 03/10	1,363,913	9900-10150	2500	12
Scheveningen 2	10/10 – 03/11	959,130	9900-10150	2500	12
Katwijk	10/13 – 03/14	2,500,000	8575-8800	2250	11
Noordwijk 1	10/07 – 10/07	502,812	8085-8230	1450	7
Noordwijk 2	02/08 – 02/08	1,243,217	8000-8300	3000	15

Table 4.3: 'Zwakke Schakel' reinforcement nourishments as applied in the model.

First maintenance	Time (mm/yy)	Volume (m^3)	Distance from Den Helder (dam)	Width (m)	Cells
Scheveningen	01/15 – 02/15	700,000	9925-10125	2000	10
Katwijk	01/19 – 02/19	400,000	8600-8800	2250	11
Noordwijk	05/13 – 06/13	410,000	8075-8325	2500	12

Table 4.4: First maintenance nourishments as applied in the model.

4.5. Validation Unibest-CL

Model validation mainly consists of comparing the erosion and accretion patterns in the model with real values, available from yearly measurements. This comparison is done by computing the predicted trend for the years 2011 to 2018 for both the model results and the measurements. The predicted trend is in both cases based on at least 3 years of available consecutive measurements, without nourishment application between these measurements. At maximum, the trend is based on 10 years of measurements (see paragraph 2.2). In case of the model results, the first fictional measurement is done in the year 2008, which is the first year after 'Zwakke Schakel' nourishment application at Katwijk. If a nourishment is recently applied at a certain location, both the trend as well as the model development are based on the results of earlier years. All validation figures, including discussion, can be found in Appendix G.

As an example, the predicted trends for the year 2018 are used (figure 4.7) since the predicted trends for 2018 are the only trends which contain the development of all 'Zwakke Schakel' (maintenance) nourishments. In earlier years, the development of the 'Zwakke Schakel' nourishment at Katwijk, which is applied in 2014, is not yet included.

At almost all locations the model trend shows similar behaviour as the measurement trend. An important overall difference found in the more variable predicted trend, while the model gives a smoothened result. This has to do with the simplifications in the model, due to which only large scale variations in sediment transport are taken into account. Most remarkable are the positive peaks around km 60 and 70, these peaks are probably related to the shoreface nourishments applied in 2008 at both locations. These shoreface nourishments are not included in the Unibest model and therefore the magnitude of the positive trend at these locations is lower for the model trend. Only the difference between both trends north of Noordwijk cannot be easily explained. A possible reason for this difference may however be the difference in nourishment design and nourishment application. In the model the design and application are simplified, which may lead to differences in results, especially around the nourishment locations.

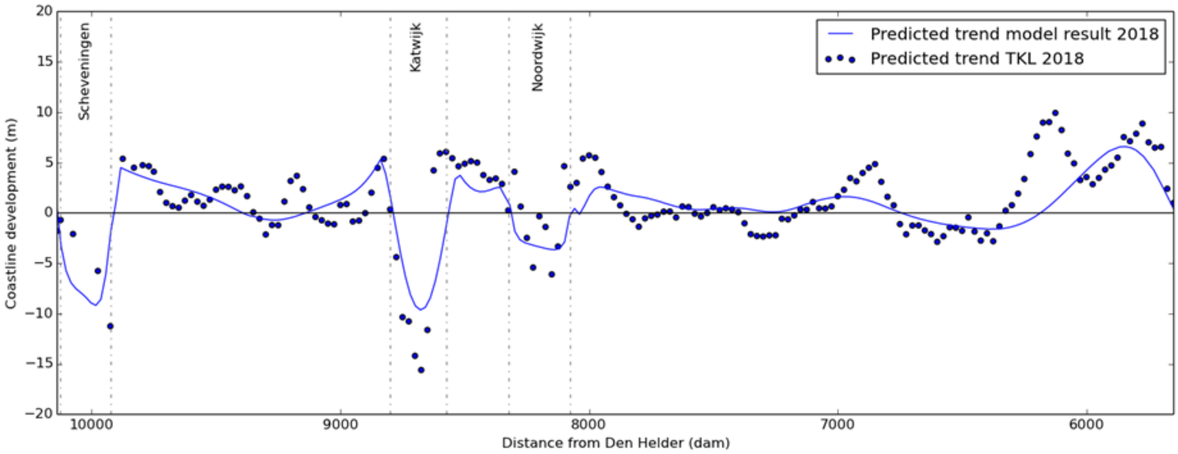

Figure 4.7: Predicted model trend and measurement trend for 2018.

4.6. Conclusion

In the model results often a lower variability in erosion or accretion is found, caused by the fact that the Unibest-CL model is a simplification of reality, with for instance the use of equilibrium profiles and the absence of cross shore transport processes. Furthermore, the effect of shoreface nourishments is clearly visible in the measurement results. Around Bloemendaal and Zandvoort, positive development is found in the measurements, while the model results are much less positive. This observation is however in correspondence with the autonomous erosional development in this region, which is the reason of application of shoreface nourishments in reality. The focus in this research is on the effect of long term maintenance at the 'Zwakke Schakel' locations on the development of the adjacent coast. Following the research objective, the effect of shoreface nourishments on the development of the coast lies outside the scope of this research.

Overall, the order of magnitude of the model results is in the range of the real measurements and the general erosion and accretion patterns are in correspondence as well. Therefore it is concluded that the model, including the refinements and additions with respect to the original model, performs well for the purposes of this research. However, still important to take into account are the simplifications of the model with respect to reality and the consequences of the assumptions made for certain parameters. The most important and most uncertain assumptions are made regarding the active profile height and the effect of sea level rise. The effect of the uncertainty in these assumptions is part of the evaluation of the model results (paragraph 5.6). The consequences of simplifications of the model with respect to reality are further discussed in chapter 7.

5. Model results

In this chapter, first the development of the 'Zwakke Schakel' locations for different maintenance nourishment schemes is presented. Subsequently the influence of the long term nourishments on sediment transport and development of the adjacent coast is assessed, after which the region of influence is discussed and the model results are evaluated. In the results, the effect of sea level rise is generally included by applying an additional coastline retreat at each location of 0.5 m per year (see paragraph 4.4).

5.1. Nourishment scenarios

In order to maintain the coastline at the 'Zwakke Schakel' locations on the long term (up to 2060 in the model), it is chosen to take into account three different long term nourishments scenarios. In table 5.2 to 5.4 the long term maintenance nourishment scenarios are presented. In all scenarios, nourishment volumes and return periods are constant over time, except for the already applied or planned reinforcement nourishments and first maintenance nourishments (see paragraph 4.4). All nourishment scenarios include the compensation of the effect of sea level rise in the nearshore region.

In scenario A (table 5.2), the long term theoretical nourishment scheme is made such that after every maintenance nourishment approximately the same coastline position is reached, while all return periods are equal to 5 years. A constant coastline position over the years means that the erosion rate at the nourishment location is evenly compensated by the nourished sediment. Due to the small erosion trend at Katwijk and Noordwijk, the application of maintenance nourishments is not as urgent as near Scheveningen (see chapter 3). With a return period of 5 years, only small nourishment volumes are needed if a constant coastline position has to be achieved. In scenario B, a different approach is used for Katwijk and Noordwijk with a larger return period of 8 years and larger nourishment volumes (table 5.3). This longer return period is better in correspondence with the real nourishment program, in which no nourishment is planned at Noordwijk before 2020. Scenario C (table 5.4) is the theoretical case in which the long term maintenance nourishments volumes remain equal to the first maintenance nourishment volumes in reality, while also all return periods remain 5 years. In this case, the coastline position migrates seawards over the years at all nourishment locations.

The development at the 'Zwakke Schakel' locations is different for each different nourishment scenario. Results are presented per location for the three different scenarios in the remaining of this paragraph. In table 5.1 below, the results are summarized.

Nourishment scenario	Scheveningen	Katwijk	Noordwijk
A	Constant	Constant	Constant
B	Constant	Constant	Constant
C	Seawards	Seawards	Seawards

Table 5.1: Coastline development for different nourishment scenarios.

Long term scenario A	Volume (m^3)	Distance from Den Helder (dam)	Width (m)	Cells	Return period (years)
Scheveningen	650,000	9925-10125	2000	10	5
Katwijk	200,000	8575-8800	2250	11	5
Noordwijk	200,000	8075-8325	2500	12	5

Table 5.2: Long term maintenance nourishments as applied in the model in scenario A.

Long term scenario B	Volume (m^3)	Distance from Den Helder (dam)	Width (m)	Cells	Return period (years)
Scheveningen	650,000	9925-10125	2000	10	5
Katwijk	250,000	8575-8800	2250	11	8
Noordwijk	250,000	8075-8325	2500	12	8

Table 5.3: Long term maintenance nourishments as applied in the model in scenario B.

Long term scenario C	Volume (m^3)	Distance from Den Helder (dam)	Width (m)	Cells	Return period (years)
Scheveningen	700,000	9925-10125	2000	10	5
Katwijk	400,000	8575-8800	2250	11	5
Noordwijk	410,000	8075-8325	2500	12	5

Table 5.4: Long term maintenance nourishments as applied in the model in scenario C.

Scheveningen

At the coast of Scheveningen, initially heavy erosion can be observed, after which the reinforcement for the 'Zwakke Schakels' project is applied in 2010 and 2011. After reinforcement, again a decay is found for 4 to 5 years after which a maintenance nourishment of 700,000 m^3 is applied. In figure 5.1, the model result for scenario A with a long term maintenance nourishment volume of 650,000 m^3 and a return period of 5 years is presented. The coastline in this scenario is maintained at a constant position which means that the erosion volume is equally compensated by the nourishment volume of 650,000 m^3. The development is identical for scenario B, in which the long term maintenance nourishment at Katwijk and Noordwijk have a return period of 8 years but the nourishment volume and return period for Scheveningen remains equal. In case of scenario C, the first maintenance nourishment volume of 700,000 m^3 and return period of 5 years are retained on the long term. The figure shows that in this case the coastline in front of Scheveningen will slowly migrate in seaward direction, which indicates that the erosion is overcompensated.

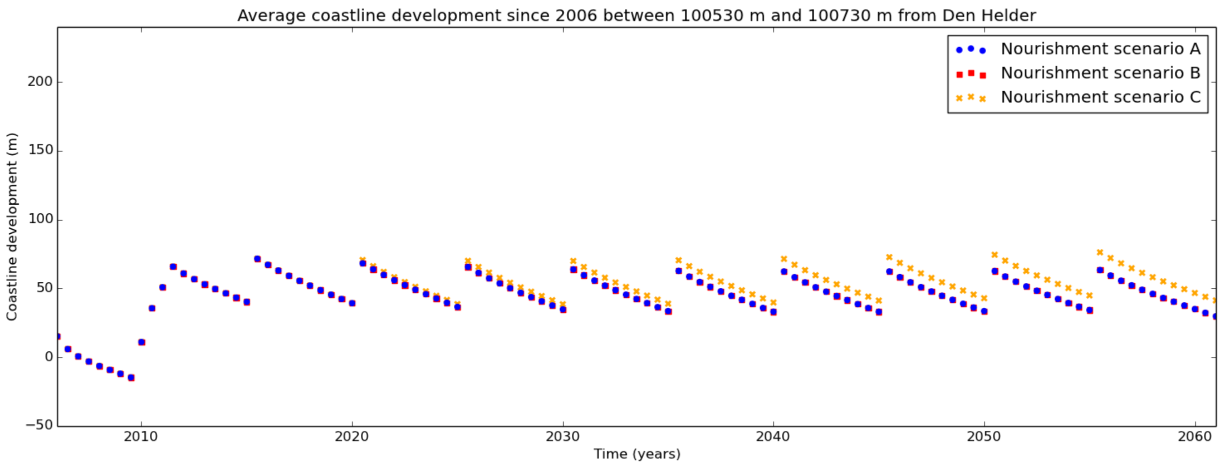

Figure 5.1: Coastline development at Scheveningen for scenarios A, B and C.

Katwijk

In 2014, the reinforcement for the ‘Zwakke Schakels’ project is applied in Katwijk after which at first a maintenance nourishment of 400,000 m^3 is applied in 2019. The long term maintenance nourishments as applied in scenario A have a volume of 200,000 m^3. The coastline position is in this case maintained at a constant level (figure 5.2), which indicates that the erosion at Katwijk is on the long term sufficiently compensated by a nourishment volume of 200,000 m^3. Remarkable is that in this scenario the coastline is maintained at a position landwards from the initial ‘Zwakke Schakel’ coastline. This has to do with the simplifications in nourishment design as well as with the fact that the erosion at Katwijk is not severe. Before reinforcement and on the long term even accretion is found in the model and, at least for the initial years, also in reality. Furthermore, Katwijk lies within the region of influence of the Noordwijk nourishment location. On the long term, maintenance nourishments for safety at Katwijk may not be needed due to these circumstances (see chapter 7). For recreational purposes however, nourishments may be desired. In this research it is chosen to retain the application of maintenance nourishments also on the long term.

For scenario B, the coastline position is also maintained at a position landward of the original reinforcement coastline. In this case, the time over which the coastline position is close to the BKL is even longer, which is unfavourable for recreational purposes. In terms of cost, this scenario will be cheaper since the applied nourishment volume as well as the amount of nourishments is lower over the period of 55 years. With a return period of 8 years and a nourishment volume of 250,000 m^3, a total volume of 750,000 m^3 is saved with respect to scenario A over a maintenance period of 40 years. In this period, the amount of future nourishments decreases from 8 to 5.

In scenario C, the coastline at Katwijk is on the long term maintained with a nourishment volume of 400,000 m^3. The erosion is overcompensated by the large nourishment volume, causing the coastline position to migrate in seaward direction over the years. Concluding, the only solution in which a larger beach is maintained, but still a constant coastline position is maintained, is therefore to apply small nourishments on a frequent timescale.

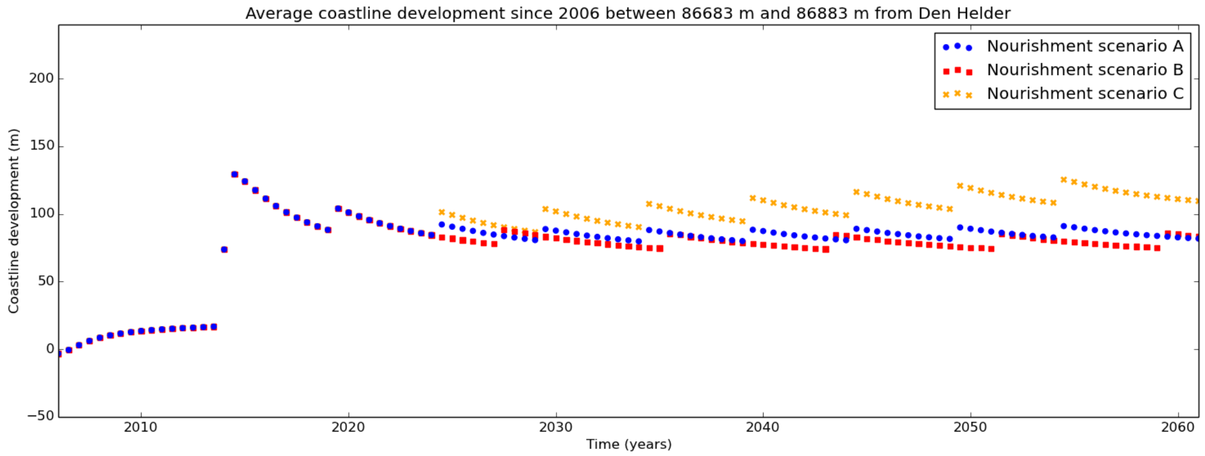

Figure 5.2: Coastline development at Katwijk for scenarios A, B and C.

Noordwijk

In Noordwijk, the situation is similar to the situation in Katwijk. The annual erosion volume in this region is also small, but, in contrast to Katwijk, the coastline position after maintenance is closer to the reinforcement coastline position. Furthermore, the coastline position seems not to stabilise as in the Katwijk case, leading to a situation in which maintenance nourishments are surely needed.

In scenario A, the coastline position is maintained by a long term maintenance nourishment volume of 200,000 m^3 each 5 years (figure 5.3). The same coastline position can be maintained by applying a nourishment of 250,000 m^3 each 8 years. Cost-wise scenario B is again more interesting, while for recreational purposes scenario A is probably preferred. Similar to the case with scenario C at Scheveningen and Katwijk, the coastline position migrates seawards over the years due to overcompensation of the erosion.

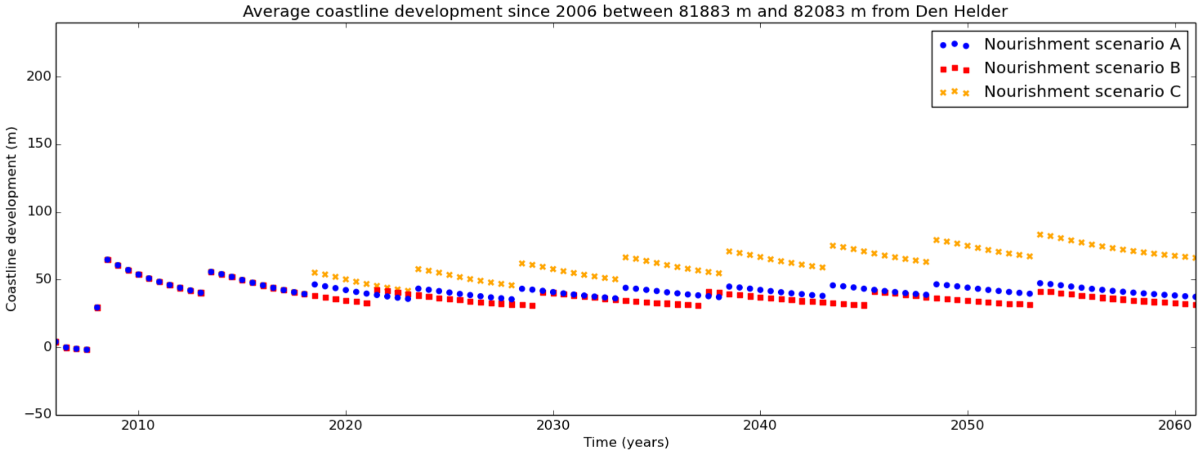

Figure 5.3: Coastline development at Noordwijk for scenarios A, B and C.

5.2. Sediment transport

The first step in determining the effect of the long term application of nourishments on the maintenance of the adjacent coast is to take a look at the effect on longshore sediment transport. Due to the application of nourishments, the coastline orientation changes which on its term causes a change in longshore sediment transport volumes in the area of interest. In the end, this leads to additional accretion and erosion of the coast (see paragraph 2.6). The sediment transport volumes for scenario A are used to visualise the effect of long term nourishment application. The effect with both other nourishment schemes is comparable. All results are presented together with the results from the reference case. In the reference case, only the 'Zwakke Schakel' reinforcement nourishments and the already planned or applied first maintenance nourishments are included.

In the figures, the results are presented for the years 2020, 2030 and 2050 respectively. In order to be able to compare the different results, all presented years are situated at the same moment in the nourishment scheme of scenario A. All results are taken just before the nourishment at Scheveningen, just after the nourishment at Katwijk and 2 years after the nourishment at Noordwijk. The locations of all maintenance nourishments are indicated by the dashed lines. This location in all cases slightly deviates from the location of the 'Zwakke Schakel' reinforcement nourishments (see paragraph 4.5 and Appendix B).

Longshore sediment transport volume

In figure 5.4 the longshore sediment transport volumes along the coast are presented for the year 2020. The minima and maxima close to the edges of the nourishment locations are clearly visible, in line with the theory from paragraph 2.6. Due to the maintenance nourishment at Noordwijk, the maxima and minima are maintained while the extremes flatten out when no maintenance nourishments are applied on the long term. Due to erosion of the nourishments, the coastline orientation goes back to equilibrium.

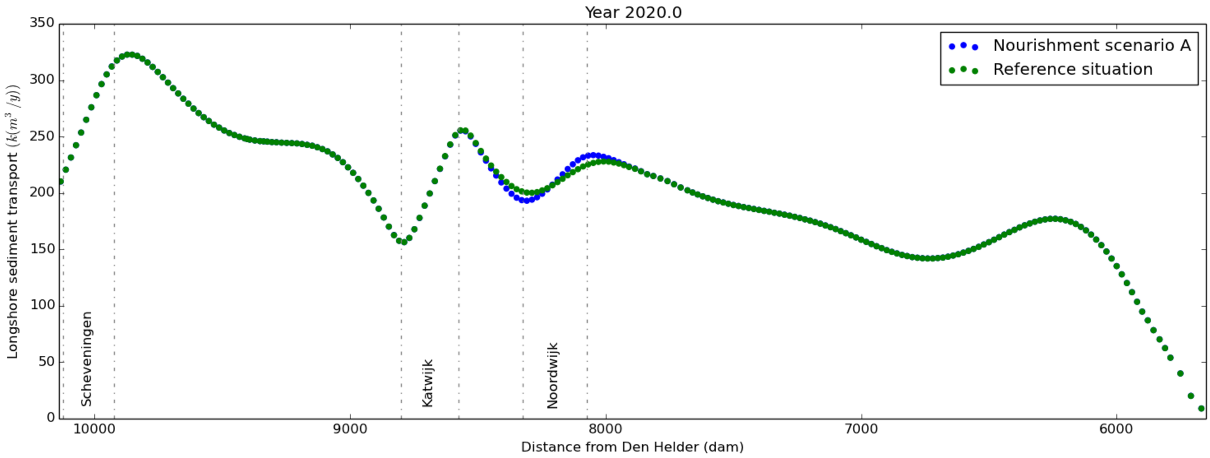

Figure 5.4: Sediment transport volumes in 2020 for scenario A and a reference scenario without maintenance.

If we look at the longshore sediment transport volumes in 2030 and 2050 (figures 5.5 and 5.6), it is clear that the difference between the reference case and the case with long term maintenance has increased. This increase in difference is mainly caused by flattening of the curve in the case without maintenance. On the long term, the transport volumes at the nourishment locations are more or less stable. Every 5 years when a maintenance nourishment is applied, the transport shows the same behaviour which is in line with the stable situation as presented in paragraph 5.1. In 2020 (figure 5.4), which is only 5 years after the large 'Zwakke Schakel' nourishment, the stable situation is not yet reached.

The area over which a difference is present between the long term maintenance and reference case increases due to the fact that the distance over which the nourished sediment is transported increases. In other words, the size of the region of influence increases (paragraph 5.4). In the next section, the development of transport gradients over time is further assessed.

Figure 5.5: Sediment transport volumes in 2030 for scenario A and a reference scenario without maintenance.

Figure 5.6: Sediment transport volumes in 2050 for scenario A and a reference scenario without maintenance.

Longshore sediment transport gradients

Complementary to the figures in the previous section, a significant difference is found in the sediment transport gradients around the nourishment locations. In the computation of the gradients, the effect of sea level rise is included. An additional positive gradient of 5 m^3/m per year is applied (see paragraph 4.4).

In figure 5.7, gradients are presented for the year 2020. Due to application of the maintenance nourishment at Noordwijk, gradients directly at the nourishment location increase in magnitude. Without nourishments, the magnitude slowly tends to go to zero. Close to the edges of the nourishments, where the transport curves reach their minima and maxima, the gradient goes to zero after which the gradient switches sign and becomes negative. The section of erosion at the nourishment locations switches to a section with (additional) accretion.

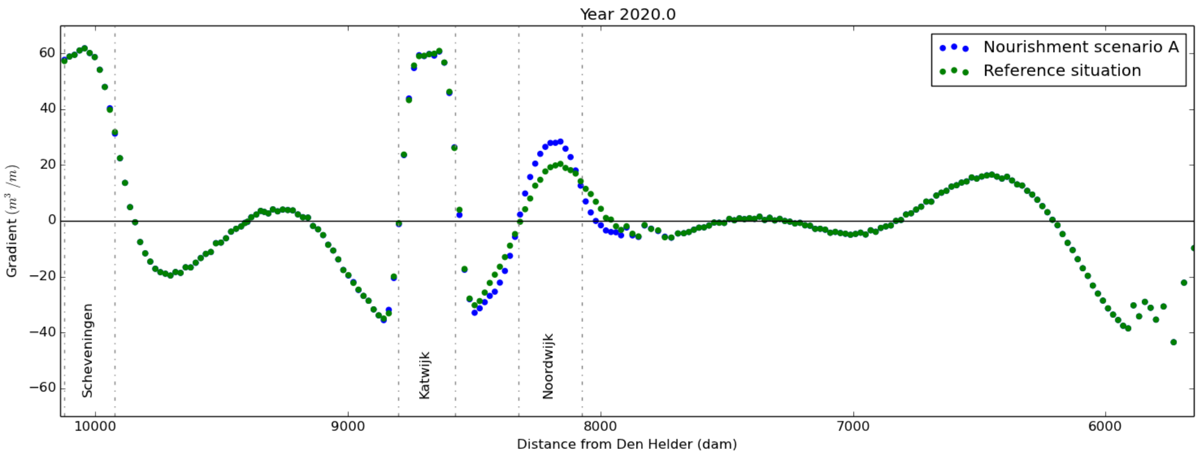

Figure 5.7: Sediment transport gradients in 2020 for scenario A and a reference scenario without maintenance.

In figures 5.8 and 5.9, the gradients are presented for the years 2030 and 2050. Around the nourishment locations, the gradients are at both moments almost equal to each other, in line with the results for the longshore transport volume. Along the adjacent coast an increase in gradient magnitude can again be observed, which is especially clearly visible close to the nourishment locations. In 2020, the gradient reaches its minimum only along a short distance, while in 2030 and 2050 the minimum is reached over a much larger distance. Between Katwijk and Scheveningen, the gradient is almost constant in 2050, in correspondence with the straight blue line in figure 5.6. Northwards from Noordwijk, around km 75, the positive gradient decreases in magnitude over the years and becomes negative, leading to accretion. Further northwards, the gradients tends to go towars zero which implicates an equilibrium situation. Important to note is that in the case without maintenance, the gradients on the long term all tend to go towards zero due to the coastline orientation getting closer to equilibrium.

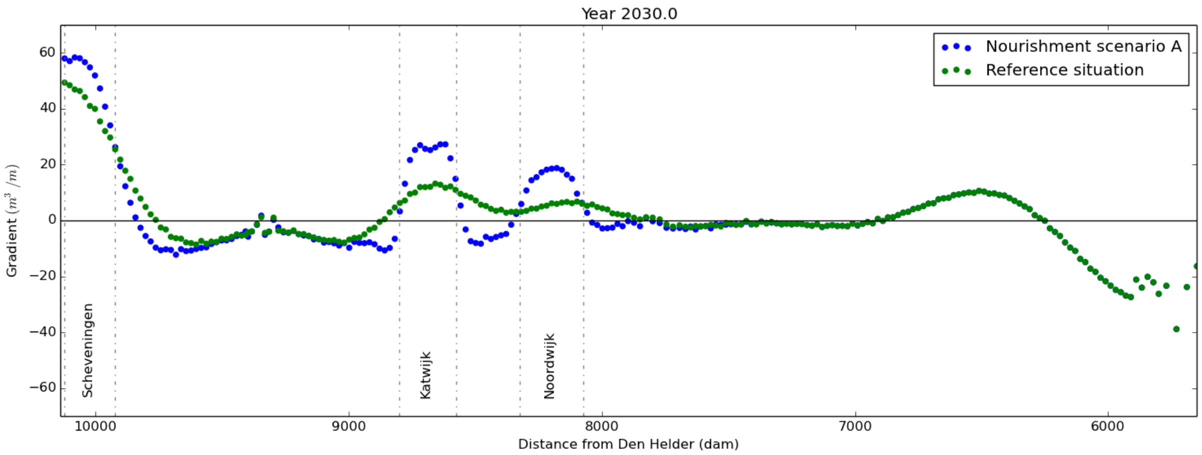

Figure 5.8: Sediment transport gradients in 2030 for scenario A and a reference scenario without maintenance.

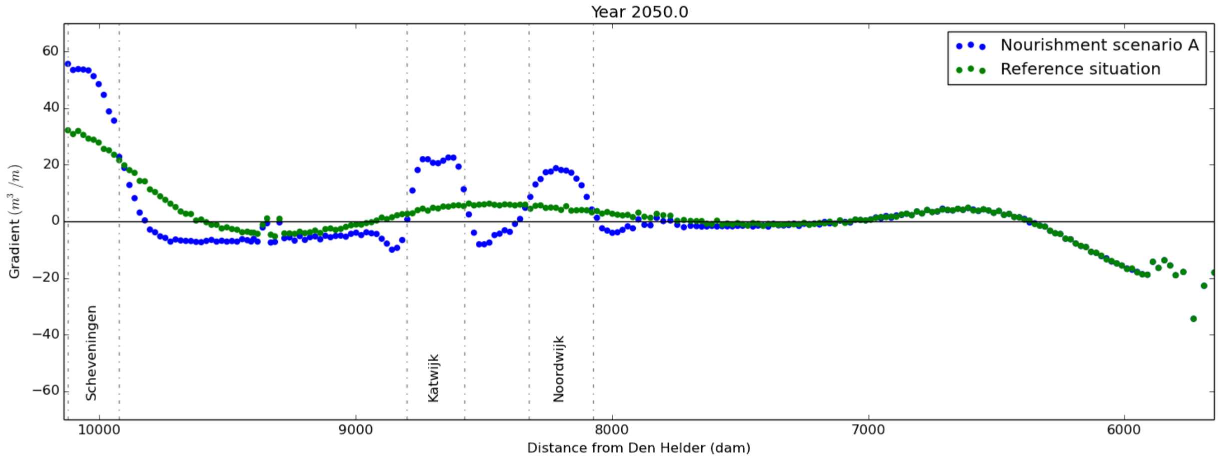

Figure 5.9: Sediment transport gradients in 2050 for scenario A and a reference scenario without maintenance.

5.3. Development of the adjacent coast

For the remaining of this chapter it is also chosen to include only the results from the scenario A. Results on coastline position and coastline development from the other scenarios can be found in Appendix H, together with the results for the reference situation without future maintenance.

Overall development

Variations in longshore sediment transport volume cause the coastline to develop and migrate in either land- or seaward direction. In figures 5.10, 5.11 and 5.12 the coastline development at different moments in time is presented, for both scenario A and the reference situation, relative to the 2006 coastline.

The coastline development corresponds with the sediment transport gradients as presented in the previous paragraph, except for the locations where nourishments are applied. At the nourishment locations accretion is found relative to the reference situation due to the applied nourishment. Close to the nourishment locations, also (additional) accretion can be clearly observed. The relative effect with respect to the reference situation decreases over distance, in 2050 from tens of meters close to the nourishment locations towards less than a meter at a larger distance. Especially north of Scheveningen and south of Katwijk, the accretion volumes are large which is in line with the large negative gradients present in these areas. The source of the large negative gradient is the fact that, also without maintenance nourishments, already relatively large negative gradients are present in these areas. This is also visible in the large accretion volume for the reference situation. Close to IJmuiden at the northern boundary of the area of interest, accretion volumes are large due to the presence of the harbour breakwater. The sediment transport in this area is not affected by the applied nourishments. Southwards of the accretion area near IJmuiden, the coast continuously erodes over the years. However, the gradients show that this erosion is expected to stop on the long term. Also between Scheveningen and Katwijk the coastline is located landward of the 2006 coastline, but due to the influence of the nourishments in combination with autonomous development, the coast migrates seawards on the long term.

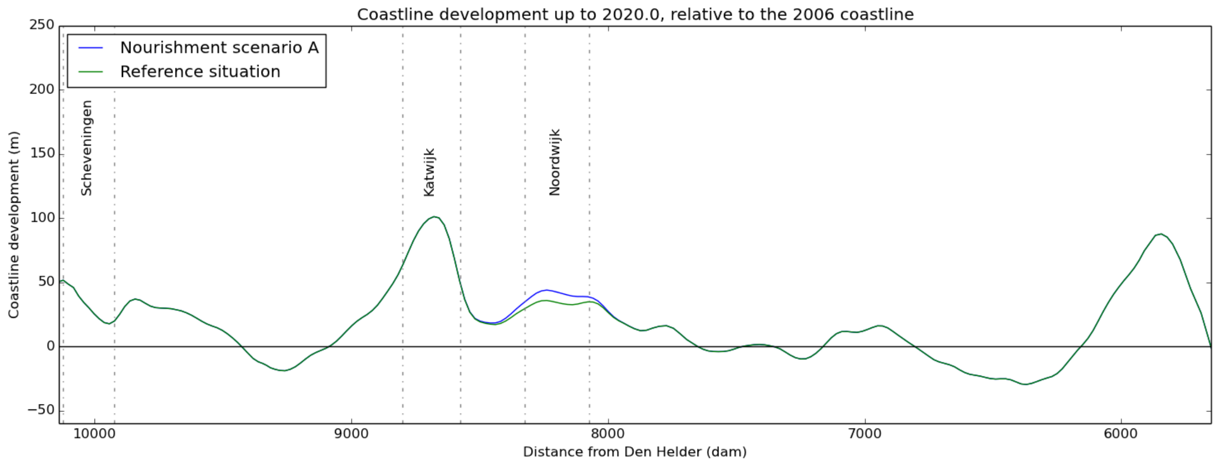

Figure 5.10: Coastline development in 2020 for scenario A, relative to the 2006 coastline.

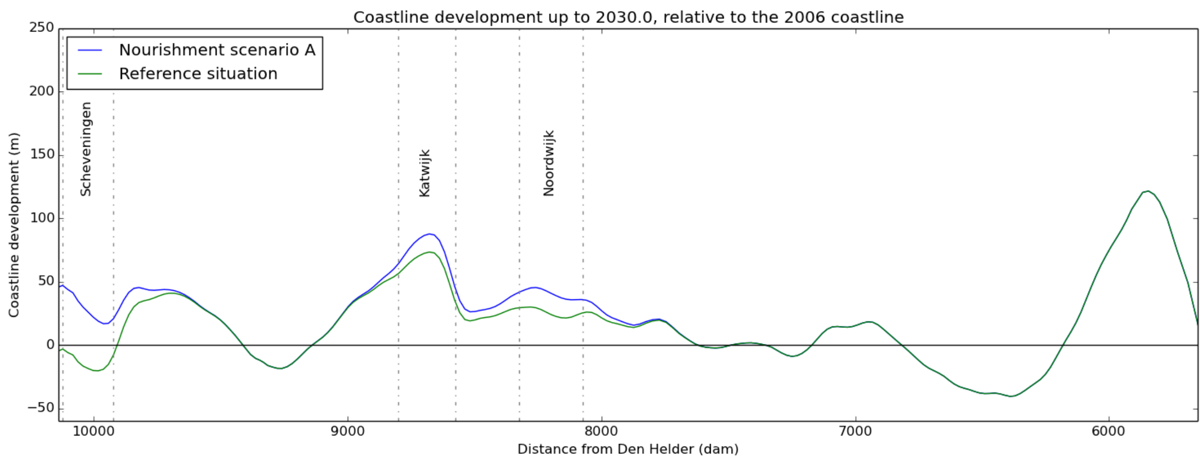

Figure 5.11: Coastline development in 2030 for scenario A, relative to the 2006 coastline.

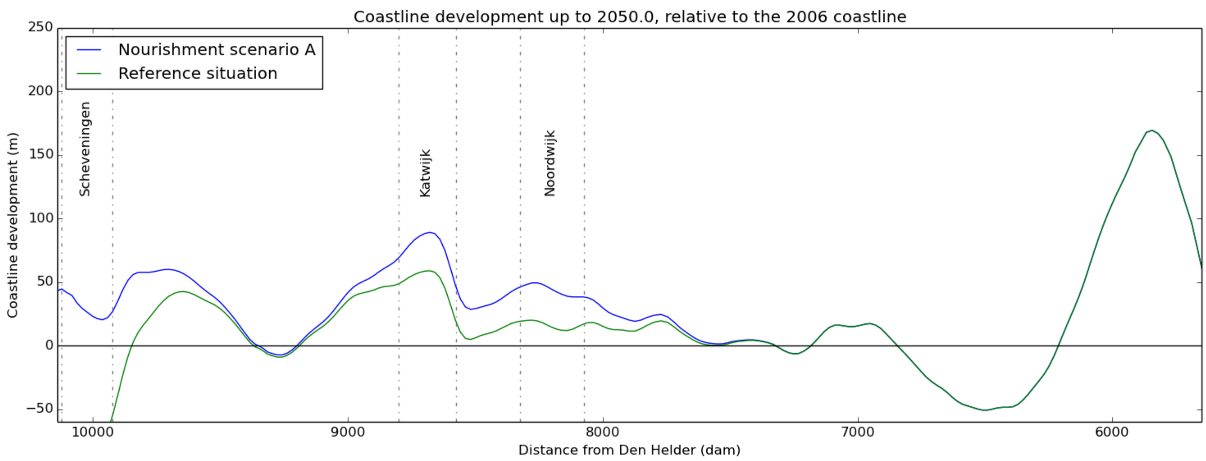

Figure 5.12: Coastline development in 2050 for scenario A, relative to the 2006 coastline.

Coastline position

To create a complete view on the relative coastline position over the years, the results of all years are combined and presented in figure 5.13. A green colour means a seaward coastline position with respect to 2006 (positive), a red colour means that the coastline is located landwards from the 2006 coastline (negative). The dashed line represents a value of zero. Starting in Scheveningen and moving towards the north, the following can be observed.

- Positive coastline position at Scheveningen, maintained by the maintenance nourishments. Erosion is significant and increases with increasing distance from the harbour breakwater.
- Positive and seaward migrating coastline position north of Scheveningen.
- Negative coastline position around km 93, initially migrating landward but from around 2024 onwards migrating in seaward direction. After 2060, a positive coastline position is expected.
- Positive and seaward migrating coastline position south of Katwijk.
- Positive coastline position at Katwijk, maintained by the maintenance nourishments.
- Positive but initially landward migrating coastline position between Katwijk and Noordwijk.
- Positive coastline position at Noordwijk, maintained by the maintenance nourishments.
- Positive and slowly seaward migrating coastline position north of Noordwijk.
- Mainly negative but seaward migrating coastline position around km 75 from Den Helder. After 2060, the coastline position in entire area is expected to become positive.
- Positive and slowly seaward migrating coastline position around km 70 from Den Helder.
- Negative and landward migrating coastline position around km 65 from Den Helder.
- Positive and seaward migrating coastline position near IJmuiden.

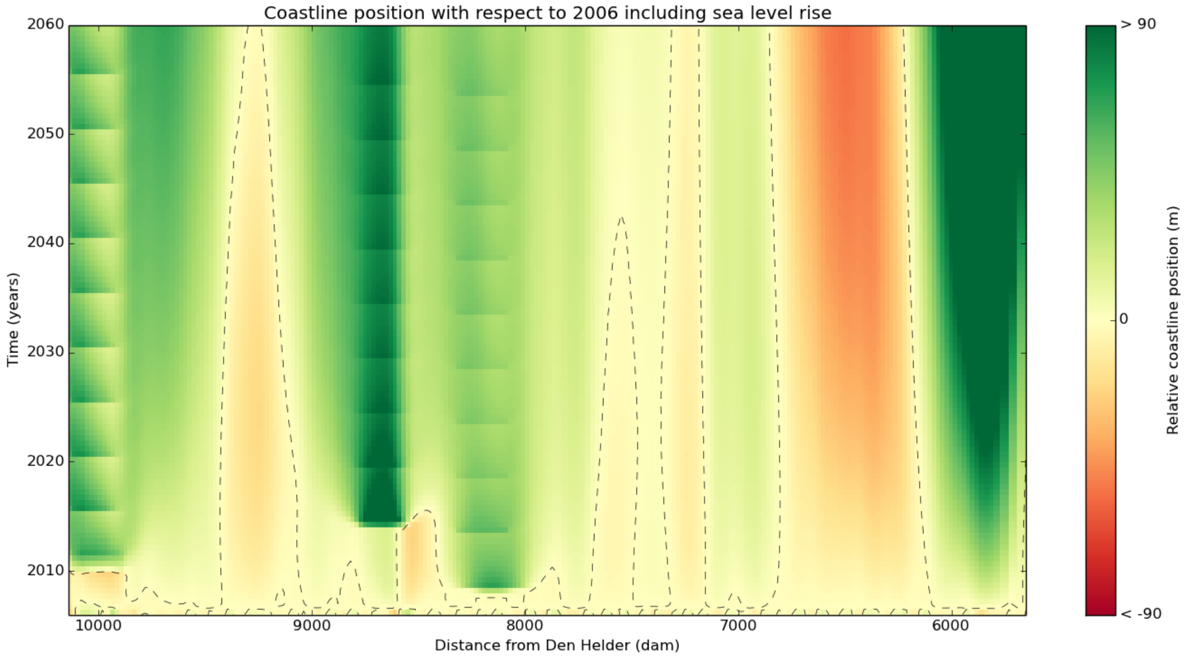

Figure 5.13: Relative coastline position with respect to the 2006 coastline for scenario A.

Especially the areas for which the coastline position is located landward from the 2006 coastline are interesting. In all areas except the area around km 65 from Den Helder, the coastline is migrating seaward on the long term. The question is whether this seaward migration can be attributed to the application of maintenance nourishments. According to the sediment transport gradients in paragraph 5.2, also without maintenance nourishments, seaward migration in these areas can be expected. The maintenance nourishments only accelerate the process of switching from a positive towards a negative gradient. Close to and directly at the nourishment locations, maintenance nourishments are crucial in maintaining the desired coastline position.

Furthermore interesting is that the three areas where a negative coastline position is found (Wassenaar around km 93, Noordwijkerhout around km 75 and Bloemendaal/Zandvoort around km 65) correspond with areas where regularly shoreface nourishments are applied (see Appendix B). The effect of shoreface nourishments in these areas is additionally investigated in Appendix J and K. However, this additional research is not in line with the research objective and therefore the results presented in these appendices are not further addressed.

Coastline development

In figure 5.14, the coastline development over the years is presented, including sea level rise. The red colour means that erosion is found, the green colour means that the coastline is migrating in seaward direction. The figure mainly confirms the conclusions made based on figure 5.13. Around km 93 and km 75, the initial negative development switches into a positive seaward directed development. All nourishment locations continuously suffer from erosion, except for the moments when a nourishment is applied. Next to the conclusions based on the coastline position, some additional conclusions can be made base on the yearly development.

- At the nourishment locations, the area suffering from erosion grows in time, but the magnitude of the erosional development decreases. Both due to flattening of the applied nourishment.
- A change in sign of the trend of coastline development around km 93 in the year 2024.
- The negative development around km 65 decreases in magnitude over time and may become positive on a timescale beyond the time scale of the model.
- The area with erosional development around km 65 slowly migrates southwards, this may be related to the influence of the IJmuiden harbour breakwaters.
- The magnitude of the positive development near IJmuiden decreases over time, but the area with a positive development increases.

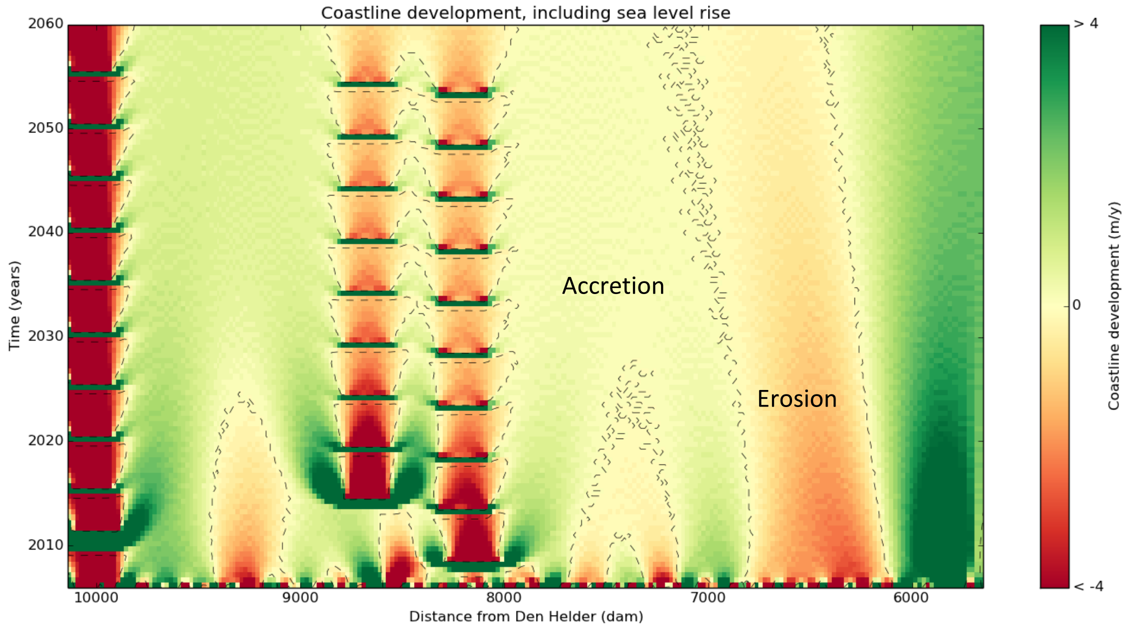

Figure 5.14: Coastline development per year for scenario A.

The coastline development at a certain location within the region of influence of the nourishments follows a more or less linear path over time on the long term. This is already visible in figure 5.14, where on the long term the magnitude of the coastline development seems to be more or less constant. To visualize this linear development, it is chosen to look at the effect north of Noordwijk, over a section of 200 m (see figure 5.15).

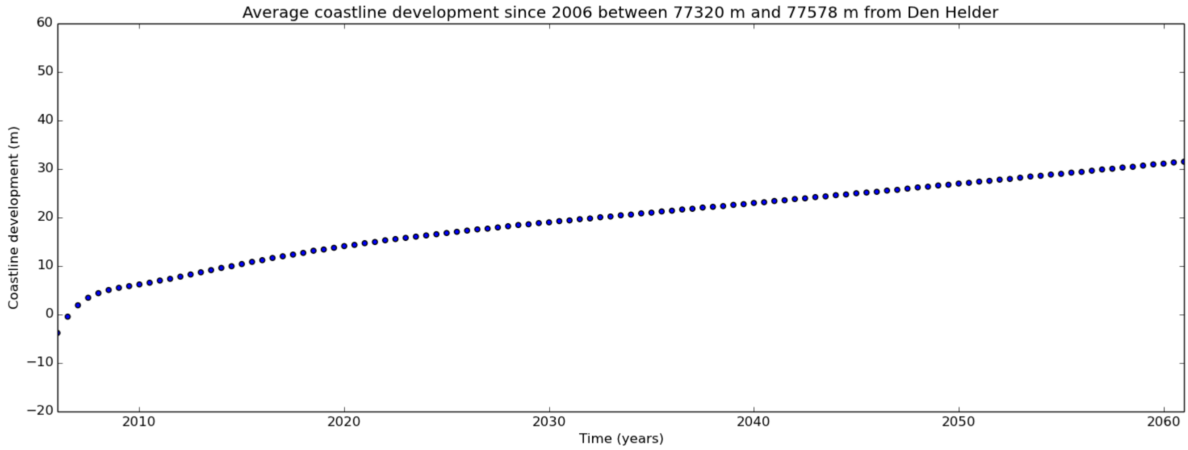

Figure 5.15: Coastline development over time north of Noordwijk for scenario A.

The almost linear development is only possible when the transport gradient over the section is more or less constant over time, which is the case for all locations except locations close to the nourishment locations. On the long term, variations in accretion volumes over a certain section are negligibly low, therefore the coastline orientation of a section remains constant and so do the transport volumes and gradients. Close to the nourishments, the variations in accretion volume are large leading to a nonlinear development. The Unibest model makes this long term linear development possible because only the active part of the coastal profile is migrated seawards and the shoreface is neglected. In reality, the development will probably decrease over time because also the shoreface has to adapt on the long term. Furthermore, the coastline development is expected to decrease on the very long term in both the model and reality, when the coastline position along the adjacent coast exceeds the coastline position at the ‘Zwakke Schakel’ location.

5.4. Region of influence

The region of influence of a (maintenance) nourishment is an important characteristic in assessing the effect of long term maintenance nourishments on the adjacent coast. The region of influence of a certain nourishment is the region in which a positive effect of this nourishment can be found. This positive effect is caused by sediment transported from the nourishment locations towards the adjacent coast. Within the region of influence of a nourishment, the sediment transport volumes and corresponding gradients are affected by the maintenance nourishment application (see paragraph 5.2). Important to note is that still erosion can be present at a location within a region of influence, despite the positive effect of the maintenance nourishment. Whether erosion or accretion is present depends on the balance between the erosion (or accretion) in the reference case and the positive effect caused by the (maintenance) nourishments (see paragraph 5.3).

In order to compute the boundaries of the regions of influence over time, a limit value is needed. This means that the difference between the coastline position in the reference case and the case with long term maintenance needs to be larger than a certain limit value, in order to speak of a significant positive effect. This limit value can be found by looking at the magnitude of the noise present in the model results. It turns out that for a limit value of 10 centimetre or larger, the noise has no significant influence on the computation on the boundaries of the regions of influence. Other possibilities to find a right limit value are to relate the limit value to the yearly coastline development or a value which matches with significant visual perception on the beach. With the yearly coastline development along the adjacent coast generally being much lower than 4 meters per year (see figure 5.14), a positive effect of 10 centimetres already is significant. Therefore, looking at the yearly coastline development, a limit value of 10 centimetres is reasonable. Looking at (personal) visual perception, one can argue that the positive effect should at least be 1 meter in order to be able to observe it clearly. Taking into account all reasonable limit values, it is chosen to represent the boundaries of the region of influence over a bandwidth matching with limit values increasing from 10 centimetres to 1 meter. Logically, the size of the region of influence is smaller for a larger limit value.

Maintenance nourishments

In figure 5.16 the development of the regions of influence for maintenance nourishments at all three ‘Zwakke Schakel’ locations over time is presented for scenario A. In these computations the effect of the large ‘Zwakke Schakel’ reinforcement nourishment is not included. The outer side of the band represents the boundary for a limit value of 0.1 meter, the inner side represents the boundary for a limit value of 1.0 meter. In the figure becomes clear that the regions of influence of the separate nourishment locations are within each other’s range. The northern border of the region of influence of Katwijk (green) lies for instance at all time within the region of influence of Noordwijk. The regions of influence of Scheveningen and Katwijk reach each other between the years 2032 and 2046 according to the model, depending on the size of the limit value. On the long term, in 2060, the entire area from Scheveningen towards a location around 70 kilometre from Den Helder, or 15 kilometre from IJmuiden, is expected to experience a positive effect from the maintenance nourishments. The regions of influence for Katwijk and Noordwijk reach a size of 15 to 24 kilometres, while the size of the region of influence of Scheveningen is only half this size.

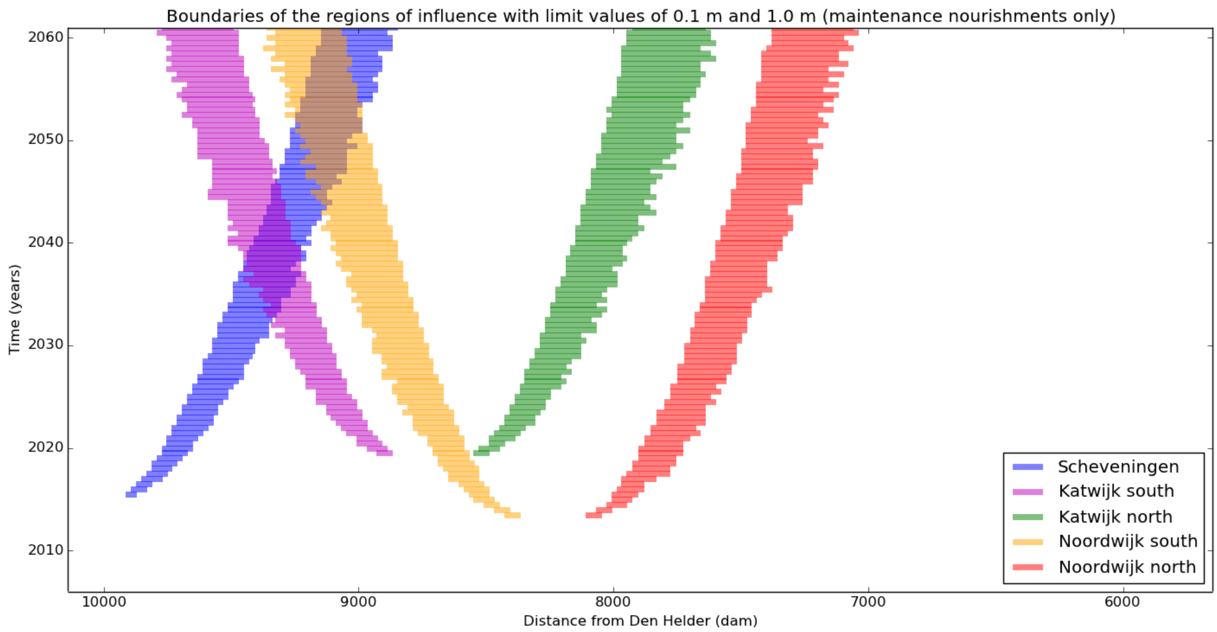

Figure 5.16: Development of the boundaries of the regions of influence of only maintenance nourishments for scenario A.

The development of the region of influence is almost equal for all different nourishments schemes considered (see Appendix H for figures). The influence of different nourishment volumes on the coastline orientation is almost negligible, only for very large deviations from the current schemes, the situation is significantly different. With scenario C, volumes at Katwijk and Noordwijk are almost a factor 2 larger, but the size of the total region of influence over 50 years increases with only 1 km, on a total size of the region of influence in the order of 15 to 24 km. Also for different return periods of the maintenance nourishments, the development of the region of influence does not change significantly. On a longer time scale, changing the return period has the same effect as changing the nourishments volume (see paragraph 5.5).

The speed with which the region of influence grows decreases over time because the effect of nourishments at a larger distance is lower. Changes in coastline orientation close to the nourishment location are larger than changes at a certain distance due to larger accretion volumes close to the nourishment location. The (additional) gradient caused by the nourishments thus decreases over increasing distance. The migration speed of the boundary of influence is slightly larger in northern direction due to the net northward transport. The magnitude of the net sediment transport is however low compared to the magnitude of the two gross transport volumes in northern and southern direction (paragraph 2.8), therefore the difference in migration speed southwards and northwards is small.

If we look at the relative positive effect of the maintenance nourishments within the region of influence, we see the same behaviour with decreasing effect over distance. In figures 5.17 and 5.18, the relative development caused by the maintenance nourishments is presented for the years 2030 and 2050. Both the increasing size of the region of influence as well as the decreasing positive effect over distance are visible in these figures.

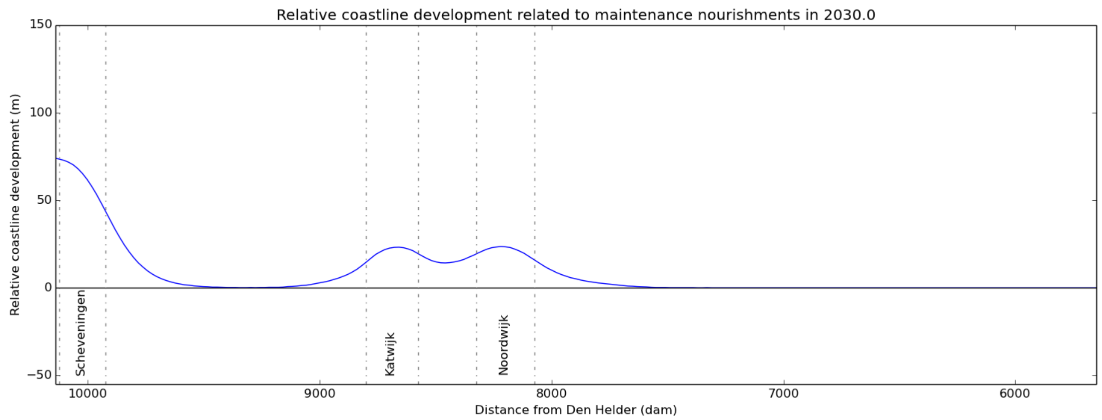

Figure 5.17: Relative coastline development in 2030 related to maintenance nourishments for scenario A.

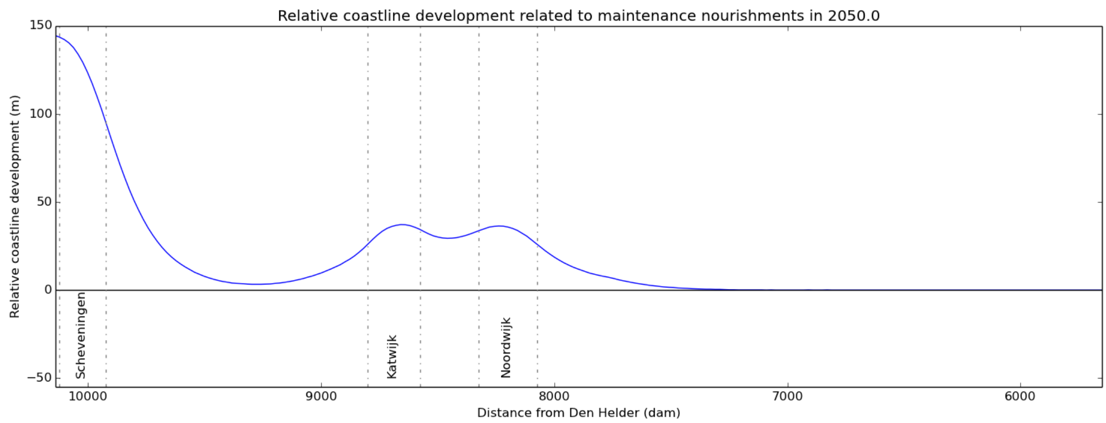

Figure 5.18: Relative coastline development in 2050 related to maintenance nourishments for scenario A.

All nourishments

If also the effect of the large 'Zwakke Schakel' reinforcement nourishments is included in the assessment of the region of influence, different results are obtained (figure 5.19). In this case the regions of influence of Katwijk and Scheveningen reach each other already between the years 2022 and 2030, depending on the limit value. Due to longer timescale over which the nourishment sediment can be transported, the total area of the regions of influence is larger. The addition of the large 'Zwakke Schakel' nourishment also causes the migration speed of the boundary to be larger, especially in the first years when the large reinforcement nourishments are applied.

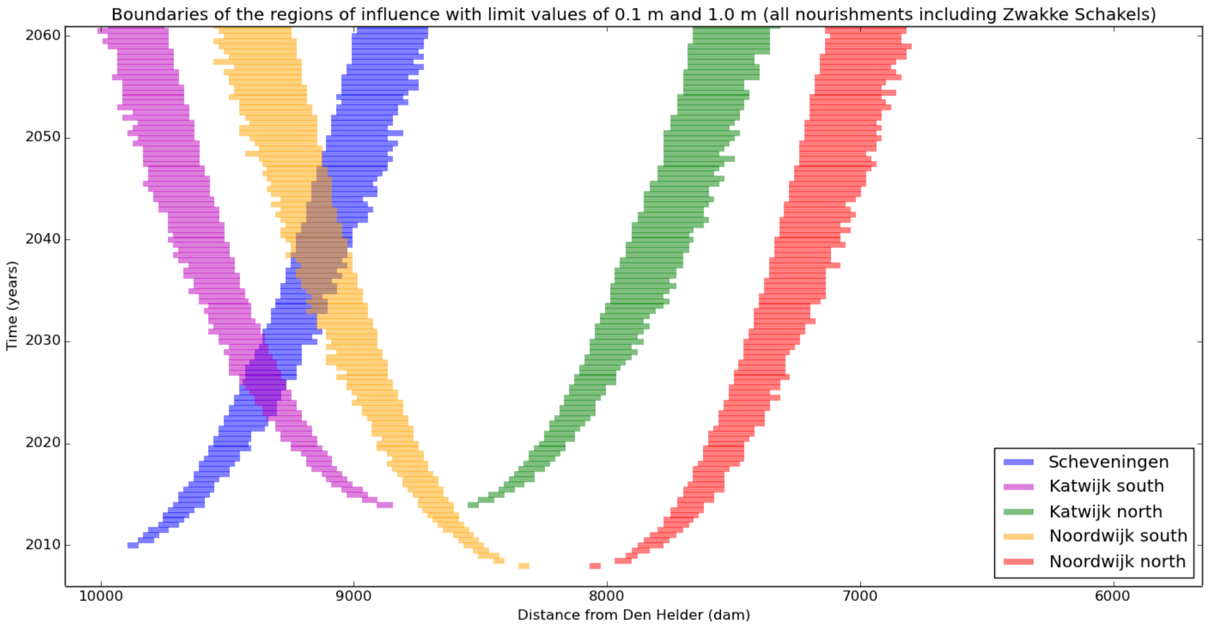

Figure 5.19: Development of the boundaries of the regions of influence of all nourishments for scenario A.

5.5. Sensitivity computations

Nourishment volume

In paragraph 5.4 on the region of influence becomes clear that changing nourishment volumes has no significant influence on the size of the region of influence.Within the region of influence, the relative effect is however significant (see figures 5.17 and 5.18) and varying nourishment volumes changes this relative effect. To assess the effect of changing nourishment volumes within the region of influence, variations are made in nourishment volume by increasing and decreasing the volume of the long term maintenance nourishments in scenario A with +50, +25 and -50 percent over the entire model period. Return periods remain the same, only volumes change.

With the results of the model runs, the ratios between the relative effect for scenario A and the relative effect with varying nourishment volumes are computed. It turns out that the relation between nourishment volume and relative effect can, at least within the range of usual maintenance nourishment volumes, be approximated by a linear relationship. Adding 50% volume has a similar but opposite effect as removing 50% of the nourishment volume, with the effect ratios being 1.5 and 0.5 respectively. When only 25% of the volume is additionally added, the ratio is 1.25.

The directly proportional, linear relationship can be explained by looking at the S-ϕ curve. When close to equilibrium, which is the case for the Holland coast, the relation between coastline orientation and sediment transport volumes (and gradients) is linear. The positive effect of a nourishment causes the coastline orientation along the adjacent coast to change, but this change remains within the linear part of the S-ϕ curve. Only at the boundary of the nourishment, larger variations in coastline orientation can be found, but these variations get smoothened on a time scale much shorter than the mode time scale. The effect of these local large variations is therefore not noticeable in the model results.

Return period

Next to the influence of nourishment volume, the influence of nourishment frequency is also investigated. Initially, all nourishments have a return period of 5 years. To test the influence of the frequency, this return period is reduced to 4 years. Similar to the case with adapted nourishment volumes, the size of the region of influence over time is not affected. When looking into the effect at an arbitrary location within the regions of influence, again a difference is found in the relative effect of the maintenance nourishments. Due to the smaller return period, the coastline position at the nourishment locations is located more seaward, leading to a small increase of the transport gradients. As a result, volumes of erosion and accretion are larger, similar to the case with increased nourishment volume. The same theory can be applied for larger return periods.

5.6. Evaluation model results

The validation of the model (paragraph 4.5) already proved that on the short term, the model is well capable of representing reality. On the long term however, it is much more difficult to judge the model results since no reference is available. The goal of this evaluation is to be able to put a certain value on the long term results of the model and to get a feel for the uncertainty present in these results. In the process towards the model results as presented in the previous chapters, many assumptions are made. Not only in determining the model parameters, but already in the choice to use the Unibest-CL+ model in this research. The consequences of the latter are discussed in chapter 8, this paragraph focusses on the assumptions made during the model setup (chapter 4).

The two most influential parameters on the long term are the active profile height and the effect of sea level rise. Also several other parameters have a significant influence on the transport volumes (see 'Sensitivity analysis' in Appendix F). However, the influence of these parameters on the sediment transport gradients, and resulting erosion and accretion, is low compared to the direct influence of the active profile height and sea level rise on the coastline development. Variations in the wave and sediment transport parameters lead to a change in sediment transport volumes. The resulting effect on the gradients and coastline development is relatively low. In contrast to this low influence, the relation between active profile height and coastline development is linear, while the sea level rise directly determines a significant part of the coastline development. Furthermore, the uncertainty in the values of the active profile height and sea level rise is also larger than the uncertainty in the values for the wave and sediment transport parameters. Together with the large influence, this makes the active profile height and sea level rise the most interesting and questionable parameters.

In order to evaluate the consequences for the model results and determine the possible errors resulting from assumptions made for both parameters, additional model runs are performed with minimum and maximum values for both input parameters. The minimum and maximum values are determined without the use of any statistical formulae. In case of the active height, the values are determined in line with the discussion in the Unibest-CL setup (see paragraph 4.4). The values for sea level rise are based current practice as well as on the values presented in research by Le Bars et al. (2017), DeConto and Pollard (2016) and the Dutch Deltacommissie (2008). Variations in coastal profile slope are based on the input profiles of the Unibest model. The three tables below summarise the relevant parameters of three different cases which are used to evaluate the results. The evaluated parameter in presented in red. In case 1, the assumptions made for the active profile height are evaluated. Case 2 is used to evaluate the results based on different assumptions sea level rise and related coastal profile slope, which significantly influences the effect of sea level rise on coastline development. In the final case, the minima and maxima of case 1 and 2 are combined.

Case	**Active profile height (m)**	**Sea level rise (cm/year)**	**Coastal profile slope (-)**
Minimum case 1	8	1.0	1/50
Maximum case 1	12	1.0	1/50
Minimum case 2	10	0.2	1/50
Maximum case 2	10	1.5	1/60
Minimum case 3	8	0.2	1/50
Maximum case 3	12	1.5	1/60

Table 5.5: Evaluated parameters and corresponding values for three evaluation cases.

Case 1 - Active profile height

The active profile heights determines the amount of coastline development resulting from gradients in sediment transport. For instance, for lower values of the active profile height, more development is found for a constant gradient. As a consequence, the positive effect of the maintenance nourishments on the development of the adjacent coast is strengthened when a smaller active profile height is used. On other hand, a smaller active profile height also strengthens autonomous negative developments. However, due to the application of nourishments, the development in the area of interest is mainly positive and therefore a smaller active profile height leads to a more positive situation. Similarly, the region of influence of a nourishment is larger for smaller active profile heights, since the positive coastline development is strengthened. A summary of the results for the most important characteristics at some important locations along the adjacent coast are presented in table 5.6. The difference between the minimum and maximum case is an indication for the uncertainty present in the model results. The complete figures for the development of the region of influence, coastline development and coastline position can be found in Appendix I.

Active profile height	**Minimum case**	**Original case**	**Maximum case**
Size of the region of influence of Noordwijk on the long term (limit value 0.1 m) [km]	26	23	20
Intersection regions of influence Scheveningen and Katwijk [year]	2029	2032	2037
Positive development around Wassenaar (km 93) [year]	2020	2024	2030
Positive development around Noordwijkerhout (km 75) [year]	2018	2025	Negative
Positive development around Bloemendaal and Zandvoort (km 65) [year]	2060	Negative	Negative
Positive coastline position around Wassenaar [year]	2042	Negative	Negative
Positive coastline position around Noordwijkerhout [year]	2049	Negative	Negative

Table 5.6: Summary of the evaluation results for case 1.

Changes in active height do not significantly influence the nourishment volumes since the active height has no influence on the erosion (and accretion) volumes. The active height only influences the magnitude of coastline development and resulting influence on coastline orientation. Indirectly changes in active height will therefore lead to a change in erosion or accretion volumes, however, these changes are small and have no significant influence on the nourishment volumes needed to preserve the coastline. Important to note is that the influence of active height on coastline development changes the model validation of paragraph 4.5, in which the development trend based on measurements is compared with the development trend based on the model results. The proposed variation in active height with a magnitude of 2 meters cause the development to change with 20%. Taking into account the results of the validation (see Appendix G), the resulting coastline development for varying active profile height will still be close the measurement results.

Case 2 - Sea level rise

As described in paragraph 4.4, sea level rise is taken into account during post-processing of the model results. The assumed sea level rise of 1 centimetre per year is converted to a negative coastline development of 0.5 meter per year, based on the average slope of the coastal profile which is equal to 1/50 for the region between Scheveningen and Noordwijk. The magnitude of the applied negative coastline development is thus determined by the magnitude of sea level rise and the slope of the coastal profile. In both parameters, a relatively high uncertainty is present, which leads to a high uncertainty in the applied effect of sea level rise. In table 5.7, minimum and maximum values of both parameters are presented, based on the setup in paragraph 4.4. In the final row, the resulting coastline development is presented. The maximum case includes an extreme scenario, while the minimum case is in line with the current practice and is probably only valid for the short term.

Parameter	Minimum	Original	Maximum
Sea level rise	0.2 cm/year	1 cm/year	1.5 cm/year
Profile slope	1/50	1/50	1/60
Resulting development	-0.1 m/year	-0.5 m/year	-0.9 m/year

Table 5.7: Minimum and maximum values for sea level rise, profile slope and resulting development.

Also other combinations of sea level rise and profile slope are possible. However, to illustrate the uncertainty, it is chosen to use the two combinations which lead to the largest and smallest resulting coastline development. All other combinations will lead to an intermediate situation. For both relevant combinations, nourishment scenarios are optimized again until a stable coastline position is realised at all nourishment locations (similar to paragraph 5.1). The applied nourishment volumes for both cases are presented in table 5.8. Nourishment volumes at Katwijk and Noordwijk are only 100,000 m^3 for the minimum case. Probably increasing the return period and therewith the nourishment volumes will lead to a more economically justified situation. However, in order to be able to compare the different cases, it is chosen to retain the return period of 5 years. Similar to the original scenarios, the development of regions of influence does not change significantly for the different nourishment volumes (see paragraph 5.4). Table 5.9 presents the most important results of the evaluation on coastline position and coastline development for different imposed effects of sea level rise.

Nourishment	Minimum volume (m^3)	Original volume (m^3)	Maximum volume (m^3)
Scheveningen	570,000	650,000	710,000
Katwijk	100,000	200,000	260,000
Noordwijk	100,000	200,000	260,000

Table 5.8: Nourishment volumes for minimum, original and maximum case of sea level rise.

Active profile height	Minimum case	Original case	Maximum case
Positive development around Wassenaar (km 93) [year]	2019	2024	2032
Positive development around Noordwijkerhout (km 75) [year]	2012	2025	Negative
Positive development around Bloemendaal and Zandvoort (km 65) [year]	2052	Negative	Negative
Positive coastline position around Wassenaar [year]	2040	Negative	Negative
Positive coastline position around Noordwijkerhout [year]	2028	Negative	Negative

Table 5.9: Summary of the evaluation results for case 2.

Important to note is that the magnitude of the sea level rise has no influence on the validation on the model, since the effect of sea level rise is not included in the short term results for model validation. Secondly, important is that the imposed effect of sea level rise is linear, while in reality the effect is exponential. For the long term results (e.g. in 2060), this approach gives no large problems. On the short term however, the influence of sea level rise is overestimated. Finally important to note is that in this research a more shallow slope leads to increased relative erosion due to sea level rise, while on the other hand a shallower slope generally leads to less autonomous erosion. This autonomous effect is however already included in the varying slopes per location in the Unibest model and is not influenced by the assumptions for sea level rise. Further discussion on (the linearity of) the implemented effect of sea level rise can be found in the discussion in chapter 8.

Case 3 - Sea level rise and active profile height

For the final case, the minima and maxima of both sea level rise and active profile height are combined, resulting in a combined maximum case (higher sea level rise and larger active profile height) and a combined minimum case (lower sea level rise and smaller active profile height). The nourishment volumes in these cases are similar to the volumes in case 2, since the addition of varying active profile height has no influence on the nourishment volumes. In table 5.10 the evaluation results for case 3 are summarized.

Active profile height	**Minimum case**	**Original case**	**Maximum case**
Positive development around Wassenaar (km 93) [year]	2017	2024	2045
Positive development around Noordwijkerhout (km 75) [year]	2010	2025	Negative
Positive development around Bloemendaal and Zandvoort (km 65) [year]	2040	Negative	Negative
Positive coastline position around Wassenaar [year]	2032	Negative	Negative
Positive coastline position around Noordwijkerhout [year]	2023	Negative	Negative

Table 5.10: Summary of the evaluation results for case 3.

Conclusion

Conclusions regarding the evaluation can be based on the content of tables 5.6, 5.9 and 5.10, from which two summarizing figures are made (figures 5.20 and 5.21). The figures include the yearly coastline development of the original, intermediate case, the coastline development over time at the most interesting location along the adjacent coast, and the expected relative coastline development in 2050. In blue, the bandwidth of the results is presented, based on the uncertainty computed with evaluation case 3. The figures show that around Wassenaar (figure 5.20), between Scheveningen and Katwijk, a positive development is expected on the long term in all cases. Around Noordwijkerhout (figure 5.21) (north of Noordwijk), the most negative prediction in the bandwidth shows continuous erosion. Looking at the relative coastline position with respect to 2006 both around Wassenaar and Noordwijkerhout, it is not sure whether a positive coastline position can be obtained within the upcoming 40 years. Since the regions of influence of the nourishments do not reach any further than around 70 kilometres from Den Helder, the region north of the regions of influence, with Bloemendaal and Zandvoort, is not included.

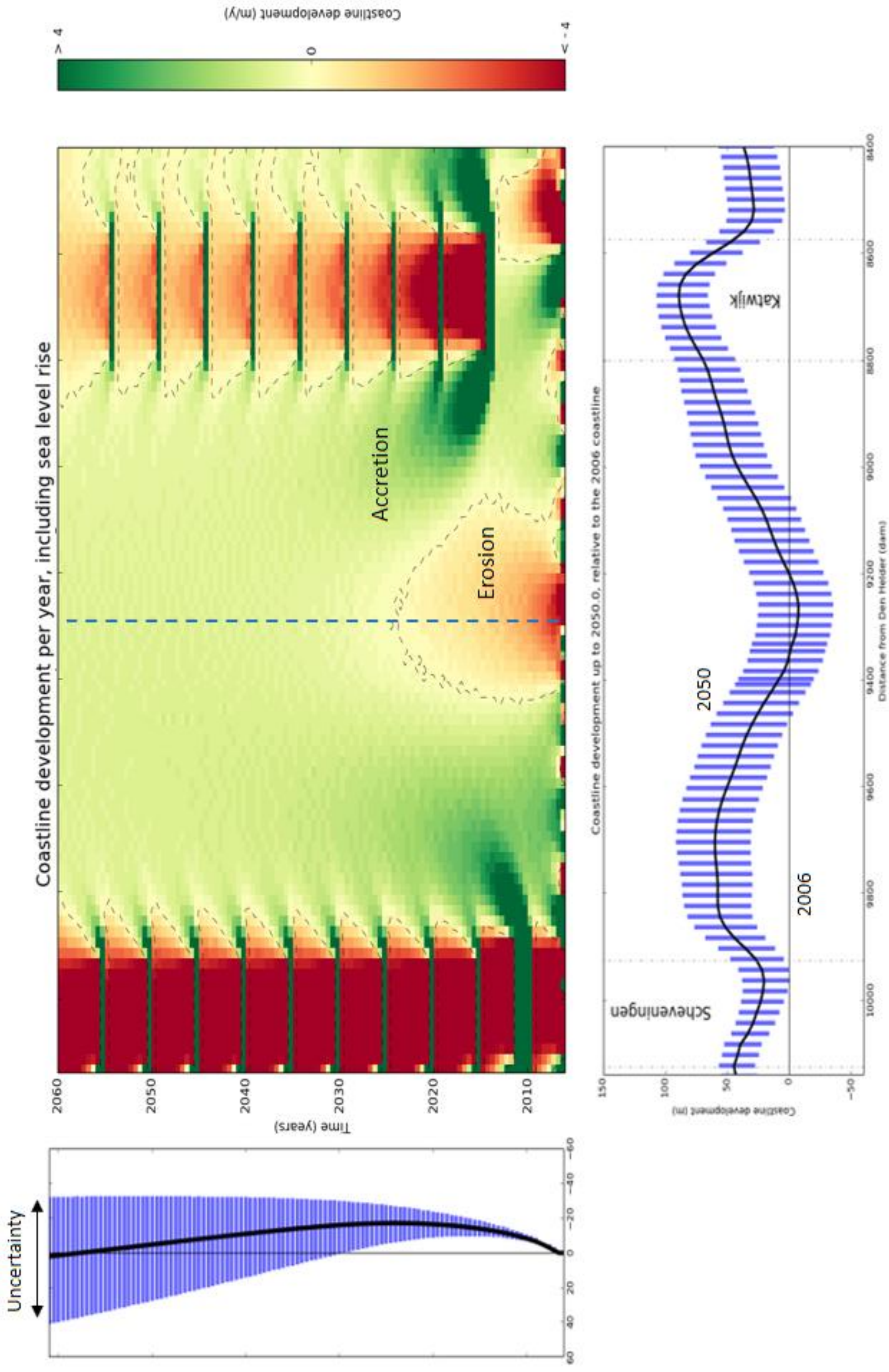

Figure 5.20: Summary of the evaluated model results for the region between Scheveningen and Katwijk.

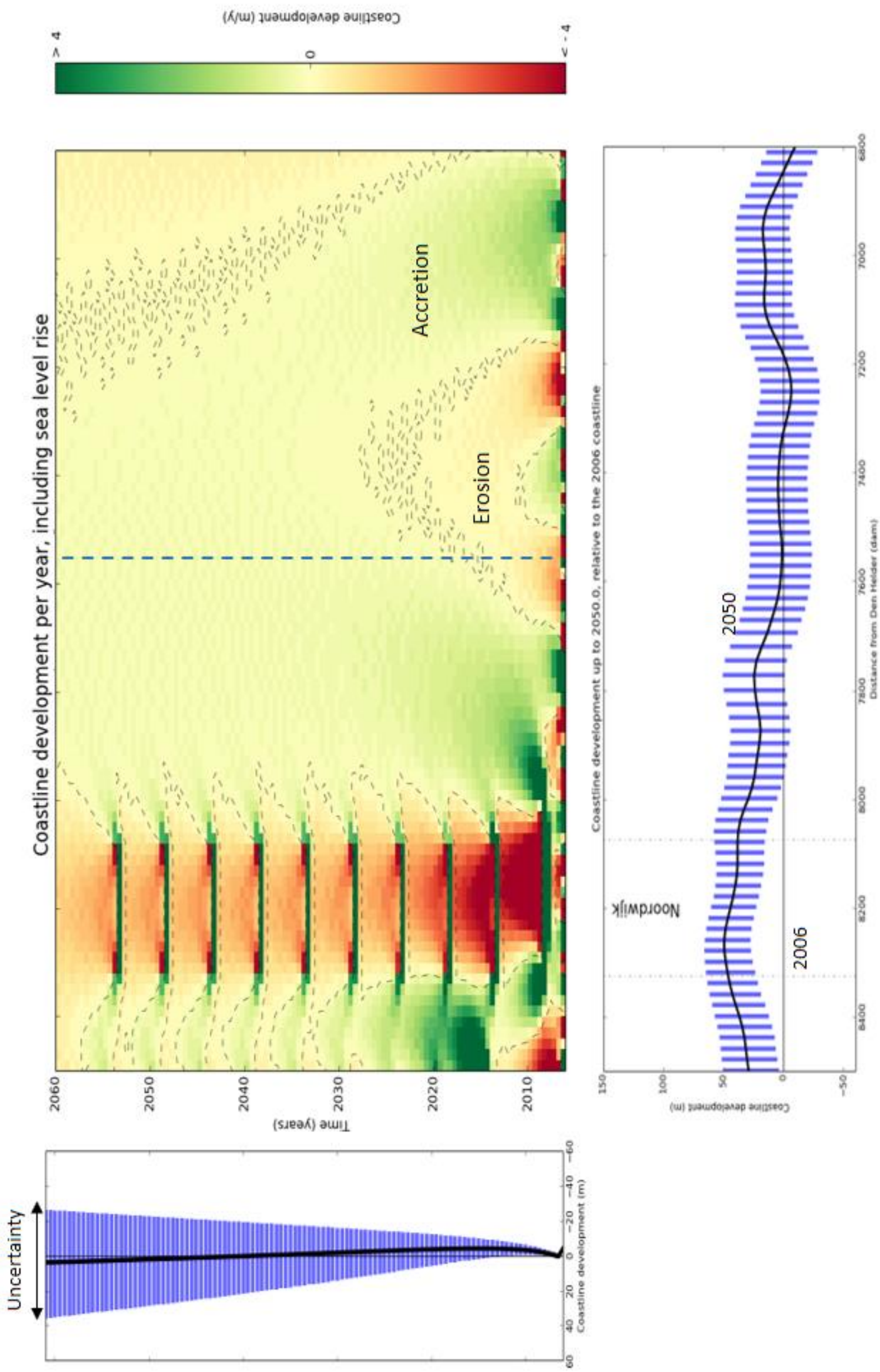

Figure 5.21: Summary of the evaluated model results for the region north of Noordwijk.

6. Conclusion

Conclusions are presented following the research questions as presented in paragraph 1.4, which consist of one main research question and five sub questions. When assigning a certain value to the conclusions, it is important to take into account the assumptions and simplifications made in the process towards these conclusions. The uncertainties which result from the most important assumptions are discussed in paragraph 5.6 ‘Evaluation model results’ and are taken into account in the conclusion. The consequences of several simplifications are discussed in chapter 7 ‘Discussion’.

The conclusions are based on a case study including the coastal stretch between Scheveningen and IJmuiden, with recurring maintenance nourishments at Scheveningen, Katwijk and Noordwijk. The objective of the research is to give an indication on the quantities, spatial scales and time scale of the expected positive effect of the maintenance nourishments on the development of the adjacent coast. Part of this research is done with the help of the Unibest-CL+ model (Deltares, n.d.-b), in combination with the results of yearly measurements along the Dutch coast and a literature review into the history of nourishments and morphology in the research area. As first part of the conclusion, the main research question is answered below.

> *To what extent is the adjacent coast maintained by sediment transported from recurring nourishments at fixed locations along the Holland coast?*

The long term application of maintenance nourishments at the ‘Zwakke Schakel’ locations between Scheveningen and IJmuiden provides a positive trend in coastline development in the region between Scheveningen and Katwijk on the long term (around Wassenaar, 93 km from Den Helder). After initial erosion in this area, positive development is expected in the upcoming decades. North of Noordwijk, the positive effect of long term maintenance reaches towards approximately 10 kilometres northward from Noordwijk. However, it is unsure whether the positive effect is sufficient for providing positive long term development in the region of Noordwijkerhout (around 75 kilometres from Den Helder), given the negative autonomous development and the negative effect of sea level rise.

Due to the initial erosion at some locations, the contribution of the long term maintenance nourishments is not sufficient in acquiring a positive coastline position relative to 2006 within the model time scale up to 2060. Therefore additional (shoreface) nourishments will be needed at Wassenaar and Noordwijkerhout in at least the coming decade to fulfil the requirements of the Dutch coastline preservation policy. On the long term, the application of additional nourishments will not be needed at Wassenaar. North of Noordwijk, around Noordwijkerhout, high uncertainty is present in whether additional nourishments need to be applied on the long term. This uncertainty is amongst other caused by uncertainty in the future rate of sea level rise The coastline development at Bloemendaal and Zandvoort, around 65 kilometres from Den Helder, is not influenced by the sediment transported from the ‘Zwakke Schakel’ maintenance nourishments within the timescale of 55 years. At these locations additional (shoreface) nourishments are surely needed if a positive coastline position needs to be obtained.

a) *How can the local morphology be described?*

The local morphology is characterised by wave dominated longshore transport, with a net sediment volume transported in northern direction. The sediment volumes in the beach and surf zone areas are generally increasing, while the sediment volume present on the shoreface decreases. Only locally, in the region north of the Scheveningen harbour, around Wassenaar, around Bloemendaal and around Zandvoort regular erosion is found. The boundaries of the system play an important role in the sediment transport distribution, with almost no sediment passing the breakwaters in the north near IJmuiden and only part of the sediment passing the breakwaters of the Scheveningen harbour in the south. Next to the dominant longshore sediment transport, offshore migrating bars are found in the surfzone and on the shoreface.

b) *What is the effect of the 'Zwakke Schakel' (maintenance) nourishments on the coastline development of the adjacent coast in the present situation*?

Results of the yearly assessment on measurements in the coastal region show clear changes in trends which can be related to the reinforcement and maintenance nourishments applied at the 'Zwakke Schakel' locations Scheveningen, Noordwijk and Katwijk. At the nourishment locations, the amount of erosion increases significantly in the years after nourishment application, leading to a negative trend in development of the coastline position and the volume being present between +3 and -4.4 m NAP. Along the adjacent coast an increased positive effect is observed, growing in size with around 1 kilometre per 4 years for all nourishments. Positive effects are especially well visible northwards from the nourishment location, the positive effect southwards is more difficult to observe and may be smaller in magnitude.

c) *What is the effect of the recurring maintenance nourishments on the coastline development of the adjacent coast on the long term*?

Long term maintenance of the 'Zwakke Schakel' nourishment locations has a positive effect on the maintenance of the adjacent coast from Scheveningen up to around 10 kilometres northwards from Noordwijk in 2060. For Katwijk and Noordwijk, the size of the region over which a positive effect is expected is around 15 to 24 kilometres. The size of the region of influence of Scheveningen is approximately half this size since, sediment is transported northwards only from Scheveningen. Predicted long term maintenance nourishment volumes at Scheveningen, Katwijk and Noordwijk have a volume of 650,000, 200,000 and 200,000 m^3 per 5 years respectively, given a long term sea level rise predication of 1 centimetre per year on average. At Scheveningen, the erosion volumes are relatively large while at Katwijk and, to a lesser extent, Noordwijk the coastline seems to stabilise at a more or less fixed position on the long term.

Initially, a negative trend in coastline development is observed near Wassenaar, Noordwijkerhout, Bloemendaal and Zandvoort. Partially under influence of the sediment transported from the nourishment locations towards the adjacent coast, this negative trend changes into a positive trend at Wassenaar within the coming decades. Whether a positive development can be expected around Noordwijkerhout is unsure and depends amongst other on the future rate of sea level rise. Bloemendaal and Zandvoort are mainly located outside the region of influence of the nourishments and a positive trend is not expected in this region within the timescale of 55 years.

d) *How is the amount of sediment transported towards the adjacent coast related to nourishment volume and frequency?*

Nourishment volume and frequency have a limited influence on the effect of long term maintenance nourishments along the adjacent coast, at least within the general application range of nourishment volumes and frequencies. The effect on the size of the region of influence is negligible with differences smaller than 1 kilometre over a period of 50 years. Within the region of influence, the influence of volume and frequency is better visible. Increasing nourishment volume or frequency has a, similar, positive effect on the coastline development within the region of influence. The observed positive effect along the adjacent coast is approximately directly proportional with the increase in applied nourishment volume.

e) *What are the consequences of long term maintenance at the 'Zwakke Schakel' locations for the future nourishment programs*?

Next to regular maintenance nourishments at the 'Zwakke Schakel' locations, additional shoreface nourishments at Wassenaar and Noordwijkerhout are needed to strengthen the positive effect of the maintenance nourishments. For Wassenaar, between Scheveningen and Katwijk, this holds for the upcoming decades. Around Noordwijkerhout, additional nourishments may be needed permanently, depending on amongst others the future rate of sea level rise. Beyond the region of influence of the maintenance nourishments, in the region around Bloemendaal and Zandvoort, (shoreface) nourishments are surely needed.

7. Discussion

7.1. Sea level rise

Magnitude of sea level rise

During the evaluation (paragraph 5.6), already the consequences of the assumptions regarding the effect of sea level rise are discussed. In this evaluation, varying magnitudes of sea level rise are applied with values between 0.2 and 1.5 centimetre per year. In general it is concluded that higher sea level rise will simply lead to a more negative situation and lower sea level rise will lead to a more positive future situation.

In the present coastline preservation policy, sea level rise with a magnitude of 0.18 cm per year is included (M. Lazar, personal communication, November 2017), which is close to the magnitude of the smallest sea level rise in the model (0.2 cm per year). The model results including this relatively small sea level rise may give valuable results for the near future, on the long term however larger sea level rise is expected. Therefore it is chosen to use a larger sea level rise in the main model computations. The possible increase of sea level up to even more than 1.5 centimetre per year on average in the upcoming century (Le Bars et al., 2017) justifies the use of a larger sea level rise for a long term research. This choice is supported by the mindset that we have to be aware of the possible risks of extreme sea level rise. On the other hand, it is questionable whether we are able to preserve the Dutch coast on the long term with the current policy. If the sea level rise of the 21st century really amounts up to almost 2 meters, massive nourishment volumes will be needed to compensate this sea level rise up to a depth of -20 meter NAP. Other possibilities in this case are to revise the area over which sea level rise is supposed to be compensated or even pass on to a policy in which land can be reclaimed by the sea. The Unibest model only takes into account the nearshore and therefore sea level rise is also only compensated in this nearshore region (see 'Compensation of sea level rise').

Linearity of sea level rise

Another remark can be made on the linearity of the sea level rise in the model. In reality, the sea level is expected to rise exponentially. Nowadays yearly sea level rise is only in the order of millimetres while the model results include a sea level rise up to 1.5 centimetre per year. On the other hand on the long term, the sea level rise in reality is, following the exponential growth, expected to be larger than 1.5 centimetre per year. As a consequence, real nourishment volumes in the near future are expected to be lower than the nourishment volume model input, while on the long term the nourishment volumes may become larger. In the evaluation (paragraph 5.6), cases with different magnitudes of sea level rise are elaborated. The nourishment volume in the cases with smallest sea level rise are probably more representative for the near future, while the cases with larger sea level rise include more representative nourishment volumes for the long term.

Compensation of sea level rise

An important final note regarding sea level rise has to be made on the fact that sea level rise in the model is only compensated in the active region. With an active height of 10 meters, this active region reaches to a depth of around 5 to 8 meters. Besides the active region, the sea level rise also causes a relative volume loss in the region below -8 m NAP, up to -20 m NAP. Relative volume loss in the deeper part of the coastal profile however probably has to be compensated with shoreface nourishments and will not be compensated by beach nourishments. The possible application of more shoreface nourishments in the future to compensate for sea level rise in deeper water will have some influence on the development of the maintenance nourishments. But since the Unibest model is not capable of modelling the development of shoreface nourishments and since it is questionable if sea level rise in the future will be compensated up to -20 m NAP, this is not included in the research.

7.2. Cross shore transport processes

An important simplification in the Unibest-CL+ model is the fact that cross shore transport processes are neglected. Only longshore transport processes are taken into account, based on equilibrium profiles. The validation in chapter 4 shows that, although cross shore transport processes are not taken into account, real coastline development is well reproduced by the model. Probably this is related to the dominant wave related longshore sediment transport processes along the Holland coast (Bosboom & Stive, 2015). Only in the regions where shoreface nourishments are applied, large differences between the model and reality are found. These differences are related to the absence of cross shore transport and shoreface nourishments in the model. Furthermore the absence of cross shore transport processes is related to the absence of bar migration and the use of equilibrium profiles in the model.

Shoreface nourishments

In the validation in paragraph 4.5, significant differences are found between the model results and real measurements in the regions where shoreface nourishments are applied. This difference is in general not relevant for research results, since the objective of this research is related to the maintenance of the adjacent coast with sediment transported from recurring beach nourishments. Most shoreface nourishments are applied in regions where no beach nourishments are applied and therefore have no significant influence on the sediment transport at the beach nourishment locations. The only exception is the shoreface nourishment which is applied in Rijnland Zuid (2014). The location of this shoreface nourishment corresponds with the location of the 'Zwakke Schakels' Katwijk and Noordijk and will therefore probably have its influence on the development of the beach nourishments at these locations. This influence is not taken into account in this research. Finally, although the effect of shoreface nourishments on the development of the adjacent coast is not related to the research objective, an approximation of this effect is included in appendices J and K.

Cross shore transport and bar migration

According to paragraph 2.7, the sediment budget of the beach and surfzone increase over time, while the shoreface loses sediment. Part of this behaviour may be related to cross shore transport, while also offshore bar migration plays a significant role in the development of the coast. The validation shows however that the absence of bar migration and cross shore transport in the model does not lead to notable errors in coastline development. For the purposes of this research, the use of a model which does not include cross shore transport and bar migration seems to be sufficient.

Equilibrium profiles and Single Line Theory

A small remark can be made on the use of equilibrium profiles in the Unibest model. Due to the presence of amongst others bars, these equilibrium profiles are never present in reality. However, taking into account the timescale of the model which is more than 50 years and the fact that cross shore transport and resulting bar migration cannot be included in the model, the equilibrium profile is the most representative profile for a timescale of more than 50 years. This also complies with the Single Line Theory, which is used for coastline development in the model (see Appendix E). According to this theory, the entire active part of the coastal profile migrates sea- or landwards depending on the gradients in longshore transport. Changes within active region of the coastal profile are not taken into account.

7.3. Aeolian transport and dune growth

As described in paragraph 2.6, a significant relation between (beach) nourishment application, aeolian transport, and dune growth exists. Aeolian transport is related to the maintenance of the Dutch coast, not only for transport across the beach, but also for transport into the dunes, especially since dune growth is part of the dynamic preservation policy. The aeolian transport of sediment across the beach will lead to increase in the positive effect of the recurring beach nourishments on the maintenance of the adjacent coast. The research needed to assess the aeolian transport of sediment from the nourishment location towards the adjacent coast is expected to be an extensive research, which does not fit in the time frame of this research. It is however recommended to perform further research regarding this topic. The effect of recurring beach nourishments is more easy to assess, recommendations for this study are presented in chapter 8.

7.4. Nourishment design

A small remark has to be made on the simplified nourishment design in the Unibest model. The nourishment volume in the model is evenly spread over the relevant area, while in reality nourishment volumes often vary significantly per section and also depend on the available space in the coastal profile. If the goal of this research also included the detailed development of nourishments, the detailed design would be important. Taking into account the time scale and the large spatial scale of the model with respect to a single nourishment, the detailed design of a nourishment is of less relevance when focussing on the effect along the adjacent coast.

7.5. Long term nourishment application at Katwijk and Noordwijk

As described in paragraph 5.1, the long term application of nourishments at Katwijk and, to a lesser extent, Noordwijk is questionable. Looking at especially the model results with relatively low or intermediate sea level rise, it seems as if the coastline will stabilise without nourishment application. Therefore it can be argued that the long term application of nourishments at Katwijk is not realistic, either with a return period of 5 or 8 years. Also the present nourishment program (Rijkswaterstaat, 2016b) shows that no nourishment is planned at Noordwijk up to at least 2020, despite the last maintenance nourishment at Noordwijk being applied in 2013. In figure 7.1, the relative coastline position for a case without long term maintenance at Katwijk is presented. Looking at the area around Katwijk and Noordwijk, between 80 and 90 km from Den Helder, a positive coastline is observed up to 2060, but the reinforcement coastline position at Katwijk is not maintained. In figure 7.2, the yearly coastline development is presented which makes clear that erosion at Katwijk continues up to 2060. In the first years, the magnitude of the yearly erosion decreases but on the long term the yearly erosion volume seems to be constant. Based on both figures it can be concluded that nourishments in the area will surely be needed. Recurring beach nourishments can be used as presented in this research, but another possibility may be a combined application of varying shoreface and beach nourishments at both Katwijk and Noordwijk. This scenario lies outside the scope of this research but research into the possibilities of maintenance with shoreface nourishments at Katwijk and Noordwijk is recommended. In 2014, already an additional shoreface nourishment with a volume of 2,200,000 m^3 is applied at Katwijk and Noordwijk (Rijnland Zuid).

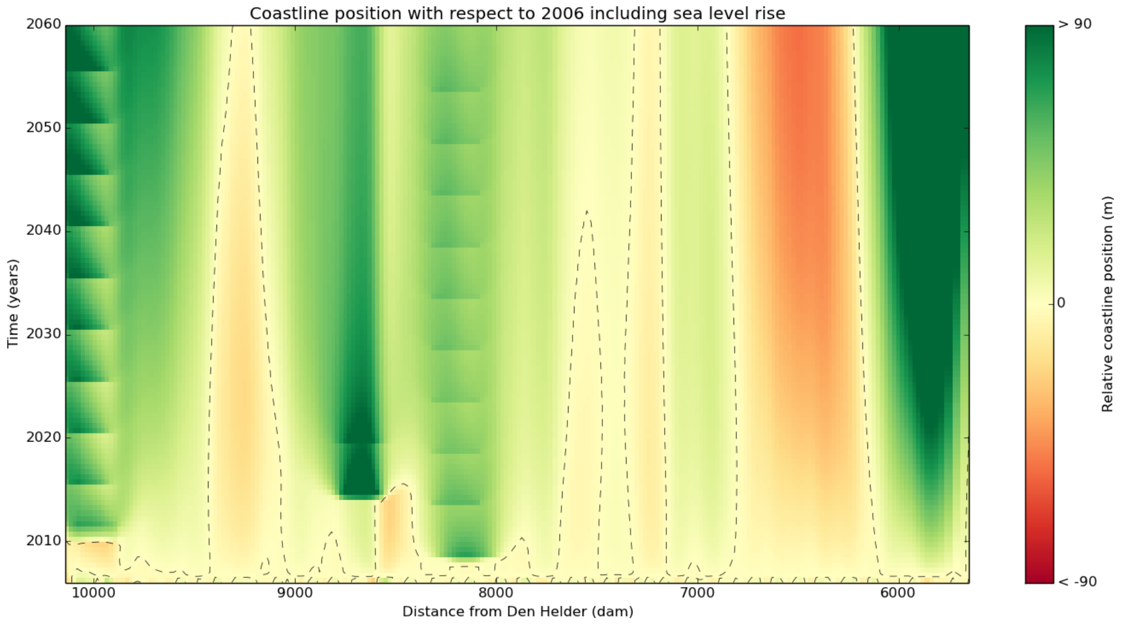

Figure 7.1: Relative coastline position with respect to the 2006 coastline for a situation without long term maintenance at Katwijk.

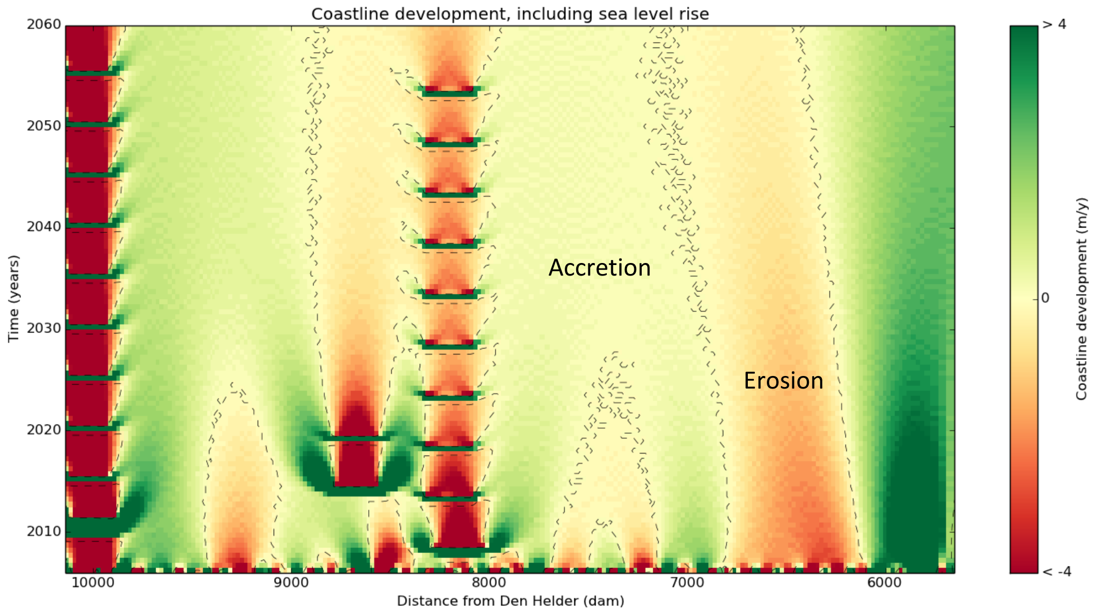

Figure 7.2: Coastline development per year for a situation without long term maintenance at Katwijk.

8. Recommendations

Application of exponential sea level rise in the model

The assumed linearity of sea level rise (see chapter 7) has a significant influence on especially the short term model results. An improvement of the (short term) model results can be achieved if an exponential sea level rise is taken into account. Important to note is that this improvement also has its influence on the complexity of nourishment scenarios, which in that case have to include increasing nourishment volumes over time, in line with the increasing effect of sea level rise.

Research into the design of the ‘Zwakke Schakel’ maintenance nourishments

The nourishments volumes as applied in this research are based on a simplification in nourishments design, in which the applied volume per meter is equal for the entire nourishment area. If more details on the nourishment design are desired, it is recommended to scale down the Unibest model at the nourishment locations. The nourishments volumes from this research can in that case be used as guideline for the volumes needed in long term maintenance of the ‘Zwakke Schakel’ locations.

Research into the long term maintenance of the coastline at Katwijk and Noordwijk

As discussed in chapter 7, the long term application of maintenance nourishments at Noordwijk and especially Katwijk is questionable. At Katwijk, the coastline seems to stabilise on the long term while also the erosion at Noordwijk is relatively low. Instead of the use of beach nourishments, possibly the coastline can also be maintained by the application of shoreface nourishments or a combination of beach and shoreface nourishments. Unfortunately the Unibest-CL+ model is not well capable of modelling the effect of shoreface nourishments. It is recommended to further investigate the long term maintenance of the region around Katwijk and Noordwijk with both beach and shoreface nourishments by using a more extensive model like Delft3D.

Contribution of aeolian transport in the maintenance of the adjacent coast

Aeolian transport contributes directly to the maintenance of the adjacent coast by transporting the sediment across the beach, while it also contributes to the maintenance of the Dutch coast by transporting sediment into the dunes. Investigating the contribution of sediment transported across the beach in the maintenance of the adjacent coast is difficult, since not only aeolian transport determines the sediment volume in the beach area. Therefore small scale measurements and models for aeolian transport are needed in order to quantify this contribution.

In addition to the answer on main research question of this research, investigating the contribution of recurring maintenance nourishments on dune growth along the adjacent coast will be easier. In line with previous research by amongst others Roelse (2002), the development of the dunes can be assessed by analysing the results of the yearly JARKUS measurements. These measurements generally include the first dune row. The amount of measurements present since the application of the ‘Zwakke Schakel’ project is however low. In order to investigate the long term effect it is therefore recommended to perform this research on a later stage when more measurements are available.

Application of the research methodology on other areas

The results of this research are valid for the coastal stretch between Scheveningen and IJmuiden, while similar effects can be expected on other locations along the Holland coast except the region close to the Wadden Sea near Den Helder. The development of almost the entire Holland coast is dominated by wave related longshore sediment transport processes and the wave scenario used in the Unibest model is based on measurements at three locations covering the entire Holland coast. If more knowledge on the influence of long term maintenance at other locations along the Holland coast is needed, the same methodology can be applied. In this case also the effect and maintenance of mega nourishments can be taken into account. Especially the mega nourishment at the Hondsbossche and Pettemer sea defence is interesting, since this nourishment will need regular maintenance (see paragraph 1.6). The Unibest model is well capable of modelling the effect of (maintenance of) this mega nourishment. For more information, reference is made to the recent paper by Tonnon, Huisman, Stam and van Rijn (2018), in which amongst others maintenance volumes of mega nourishments are discussed.

Furthermore, the same methodology can also be applied in the Delta region, where several ‘Zwakke Schakel’ reinforcements are applied. The most relevant areas in this case are the coastal stretch along Zeeuws Vlaanderen and the coastal stretch at the north of Walcheren. Along both stretches however, also shoreface nourishments are applied directly at the ‘Zwakke Schakel’ locations which makes the use of a Unibest model less suitable. The use of a more extensive model like Delft3D will probably give more complete results in this case, but also a Unibest model can be used for some locations with predominantly beach nourishments.

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Appendices

A. Glossary English Dutch

English	Dutch
accretion	aanzanding
aeolian transport	eolisch transport
basal coastline	basiskustlijn (BKL)
breakwater	golfbreker
channel wall	geulwand
coastal foundation	kustfundament
coastal reach	kustvak
coastline preservation	kustlijnzorg
coastline to assess	te toetsen kustlijn (TKL)
cross shore transport	dwarstransport
dynamic preservation	dynamisch handhaven
friction	wrijving
groyne	golfbreker
instantaneous coastline	momentane kustlijn (MKL)
longshore transport	langstransport
nourishment	suppletie
reference coastline	basiskustlijn (BKL)
salinity	zoutgehalte
shoreface	vooroever
tidal channel	getijdengeul
tidal inlet	zeegat
trailing suction hopper dredger (TSHD)	sleephopperzuiger
water board	waterschap

Table A.1: Glossary English Dutch.

B. Nourishments

In table B.1 all relevant nourishments in the area of interest are listed. With the first ‘Zwakke Schakel’ reinforcement applied in 2007, it is chosen to take into account all shoreface nourishments applied or planned in the period from 2000 up to now, based on the lifetime of a shoreface nourishment of 2 to 10 years (paragraph 2.5). With the lifetime of beach nourishments being approximately 5 years, all beach nourishments since 2002 are taken into account. Some nourishment volumes are measured after nourishment execution while others are design values, depending on the available data (Rijkswaterstaat, 2016b; 2016c).

Location	Size (m^3)	Type	Distance from Den Helder (dam)	Date	Program
Bloemendaal	1,002,957	Shoreface	6100-6300	06/2008 – 11/2008	Regular
Zandvoort Noord	1,202,332	Shoreface	6275-6575	11/2004 – 02/2005	Regular
Bloemendaal – Zandvoort	2,400,000	Shoreface	6100-6850	04/2016 – 10/2016	Regular
Zandvoort Zuid	1,001,095	Shoreface	6575-6775	10/2004 – 12/2004	Regular
Zandvoort Zuid	509,913	Shoreface	6775-7075	06/2008 – 09/2008	Regular
Noordwijkerhout	2,645,601	Shoreface	7300-8000	04/2002 – 12/2002	Regular
Noordwijk - Katwijk	1,055,035	Shoreface	8150-8900	03/2006 – 09/2006	Regular
Rijnland Zuid	2,200,000	Shoreface	8000-8850	02/2014 – 08/2014	Regular
Noordwijk	502,812	Beach / Dune	8085-8230	10/2007	Zwakke Schakels
Noordwijk	1,243,217	Beach / Dune	8000-8300	02/2008	Zwakke Schakels
Noordwijk	410,000	Beach	8075-8325	05/2013 – 06/2013	Regular
Katwijk	2,500,000	Beach / Dune	8575-8800	10/2013 – 03/2014	Zwakke Schakels
Katwijk	400,000	Beach	8600-8800	2018/2019	Regular
Wassenaar	2,508,887	Shoreface	9100-9700	02/2002 – 12/2002	Regular
Wassenaar	800,400	Shoreface	8900-9700	05/2006 – 09/2006	Regular
Scheveningen	782,500	Beach	9925-10110	09/2004 – 11/2004	Regular
Scheveningen phase 1	1,363,913	Beach	9900-10150	10/2009 – 03/2010	Zwakke Schakels
Scheveningen phase 2	959,130	Beach	9900-10150	10/2010 – 03/2011	Zwakke Schakels
Scheveningen	700,000	Beach	9925-10125	01/2015 – 02/2015	Regular

Table B.1: Nourishments applied in the area of interest since 2000.

C. Zwakke Schakel reinforcements

The three main locations of interest in this research are Noordwijk, Katwijk and Scheveningen, which all were part of the ‘Zwakke Schakel’ project (paragraph 2.4). At Noordwijk and Katwijk, a ‘seawall within dune’ construction is used to reinforce the coastal zone in order to reach the safety standard, complemented with a beach nourishment to create a new beach profile. In case of Scheveningen, a similar concept is used with a ‘seawall within boulevard’ construction, in which the boulevard takes the place of the dune and covers the seawall.

Noordwijk

In Noordwijk, a ‘seawall within dune’ reinforcement is constructed. The reinforcement reaches from km 80 to km 83 from Den Helder and has a total length of 3 kilometres. As part of the reinforcement, a seawall is constructed with a height varying between +8.50 m NAP and +11.0 m NAP. In front of this seawall a dune is applied over a cross shore distance of 60 meter to 80 meter. The widening of the dune has a magnitude of around 50 m. Near the edges, the dune width decreases from 50 m to 30 m over a distance of 250 meter, after which at both the north and south side of the reinforcement the dunes gradually merge into the existing natural dunes. No seawall is present in these sections. For more details on the reinforcement, see van Rijn (2006). Over the entire area, a nourishment is applied to recreate the beach profile at a location more seaward (see figure C.1). The total sand volume added during the construction in 2007/2008 is 1,746,029 m^3 (see Appendix B)(Rijkswaterstaat, 2016c). In 2012/2013, again 410,000 m^3 of sand was added for maintenance of the coastline.

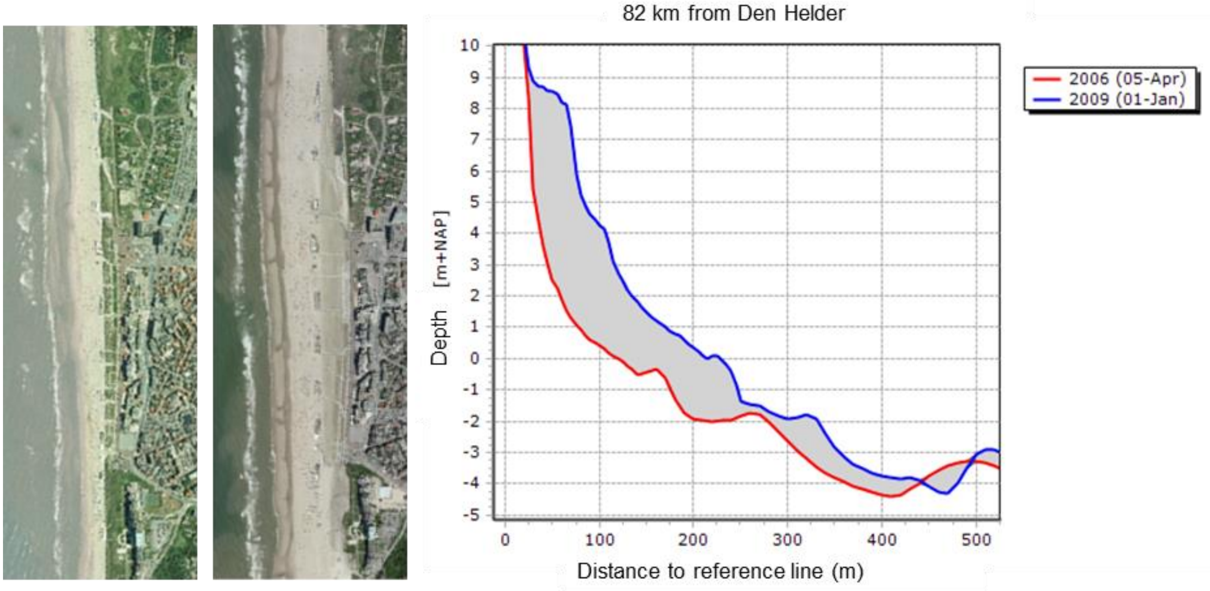

Figure C.1: *Aerial photographs of the nourishment location (left)* (Rijkswaterstaat, n.d.-c) *and the measured coastal profiles (right) before and after reinforcement at Noordwijk* (Rijkswaterstaat, 2016d).

In line with the seaward displacement of the coastline after construction, the BKL in the area is revised in 2012. The changes in BKL vary from 42 m at maximum to 12 m at minimum near the northern boundary (Ministerie van Infrastructuur en Milieu, 2012). The seaward displacement will lead to an increase in the amount of erosion near Noordwijk, and therefore regular nourishments will be needed for maintenance.

Katwijk

Similar to the Noordwijk case, a 'seawall within dune' construction is applied at Katwijk to reinforce the coast over a distance of 1500 meter (Koopal, 2013). At the middle part in front of the city centre, over a distance of 900 meter, the 'seawall within dune' is constructed, the seawall reaches a height of +7.5 m NAP. The dune which is placed on top of this seawall has variable height from +8 m NAP in the centre towards +12 m NAP near the edges. The width of the dune is 120 m meter, from the boulevard up to the dune foot (see figure C.2). On the seaward side of the dunes, a tableland of 30 meters wide is created to accommodate beach restaurants. As a consequence of the seaward extension of the dunes and tableland, the coastline also needs to be migrated seawards in order to remain the same beach profile, leading to a seaward displacement of the coastline of 80 to 100 m (see figure C.3). The seaward displacement of the coastline will lead to an increase in the amount of erosion. Therefore regular nourishments will be needed in this area. Another consequence of the seaward migration is that a new BKL has to be documented. According to the planning, the BKL will be revised in 2017 (Ministerie van Infrastructuur en Milieu, 2012). The nourishment volume used for the project is equal to 2,500,000 m^3, this volume is placed between km 85.75 (on the northern side of the Old Rhine outlet) and km 88 from Den Helder, over a distance of 2250 meter (Rijkswaterstaat, 2016c). For winter 2018/2019, a beach nourishment is planned with a volume of 400,000 m^3 to maintain the coastline (Rijkswaterstaat, 2016b).

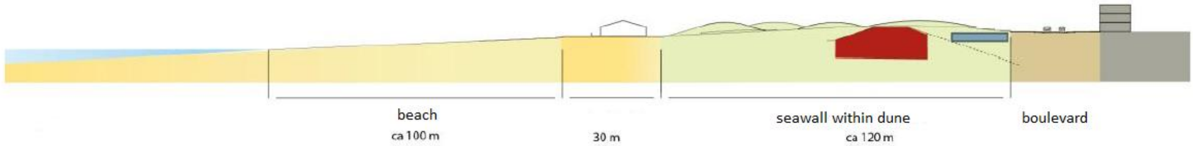

Figure C.2: Cross section of the 'seawall within dune' construction at Katwijk, including the beach profile (Koopal, 2013).

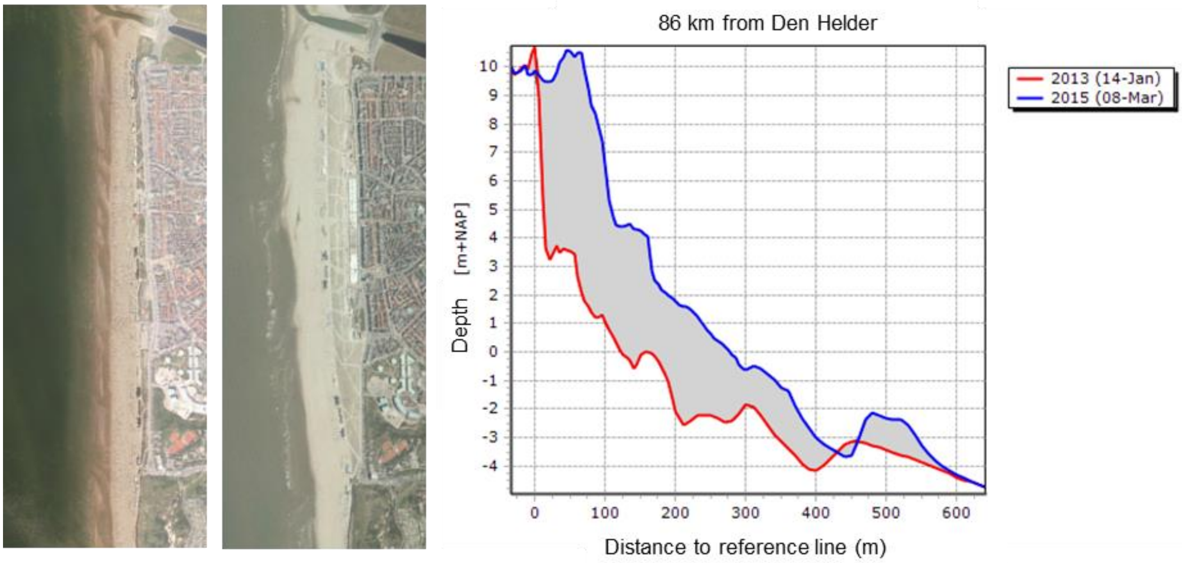

Figure C.3: *Aerial photographs of the nourishment location (left)* (Rijkswaterstaat, n.d.-c) *and the measured coastal profiles (right) before and after reinforcement* (Rijkswaterstaat, 2016d).

Scheveningen

Next to the 'seawall within dune' construction for the Noordwijk and Katwijk case, a 'seawall within boulevard' construction is used for the reinforcement of the coast in front of the city of Scheveningen, complemented by two large beach nourishments (ARCADIS & Alkyon, 2008). The choice for a boulevard instead of a dune is made based on preservation of the spatial quality of the Scheveningen coast, which is a famous destination for beach recreation. On both northern and southern side of the construction, the seawall is replaced by a diaphragm wall, after which the construction merges into the existing coastal defence. The height of the seawall varies from +8.6 m NAP to +12.0 m NAP, with in most cases a height of +10.1 m NAP. The seawall is constructed between the weak spots near km 100.09 and km 100.5, over a distance of 410 meters. Next to the seawall and boulevard, also a reinforcement of the coastal profile is part of the project, with a reduction of wave heights and overtopping near the boulevard as main goal.

In winter 2009/2010 and 2010/2011 two large nourishments are placed with volumes of 1,363,913 m^3 and 959,130 m^3 respectively (Rijkswaterstaat, 2016c). The distance over which the total nourishment is applied is 2000 meters, from km 99.25 to km 101.5. The main idea of the nourishment is to lift the coastal profile uniformly between +4.5 and -5 m NAP. Over the cross shore, this is a distance of approximately 500 to 600 meters. Since it is difficult to place the nourishment in the surfzone, it is however chosen to supply most of the sand to the beach and let nature create the uniformly lifted equilibrium profile. Part of the nourished sand volume is used for a tableland of 75 meters wide at +4.5 m NAP in front of the boulevard, this tableland provides space for beach restaurants. As a consequence of the reinforcement, the coastline migrates 70 to 90 m seawards (see figure C.5), leading to an increase in the amount of erosion. Also, similar to the Katwijk case, the BKL will be revised in this region in 2017 (Ministerie van Infrastructuur en Milieu, 2012). In 2015, the first maintenance nourishment was applied, with a volume of 700,000 m^3 (Rijkswaterstaat, 2016c).

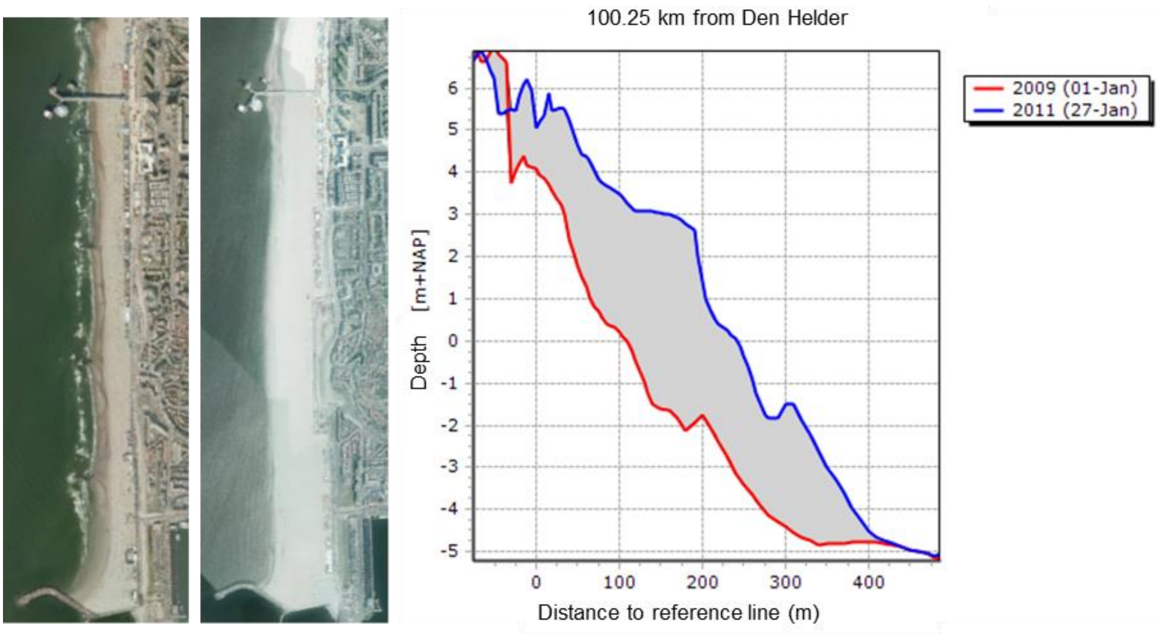

Figure C.4: *Aerial photographs of the nourishment location (left)* (Rijkswaterstaat, n.d.-c) *and the measured coastal profiles (right) before and after reinforcement* (Rijkswaterstaat, 2016d).

D. Volume measurements

In chapter 3 the results of the yearly measurements are discussed with the help of figures on the coastline development. The same type of figures can be made with a beach and surfzone volume as variable. It is chosen to use the general output volume of the yearly assessments as variable, the sediment volume present between +3 and -4.4 m NAP (figure D.1). In figures D.2 to D.5 the development of the volume in this zone is presented for the three 'Zwakke Schakel' nourishment locations and the entire area of interest. The development of the beach volume is similar to development of the coastline, no significant differences can be found. In all figures, the same positive effect along the adjacent coast can be observed, while the erosional trend becomes visible three years after nourishment application.

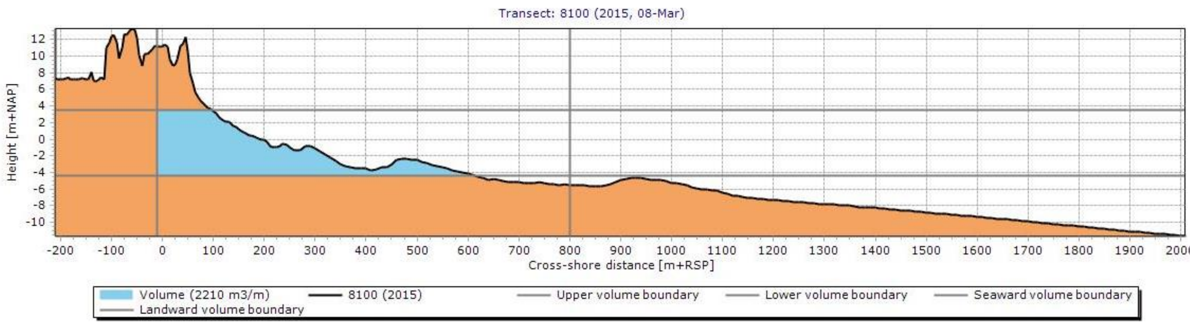

Figure D.1: Example of the MKL volume near Noordwijk (km 81) (Rijkswaterstaat, 2016d).

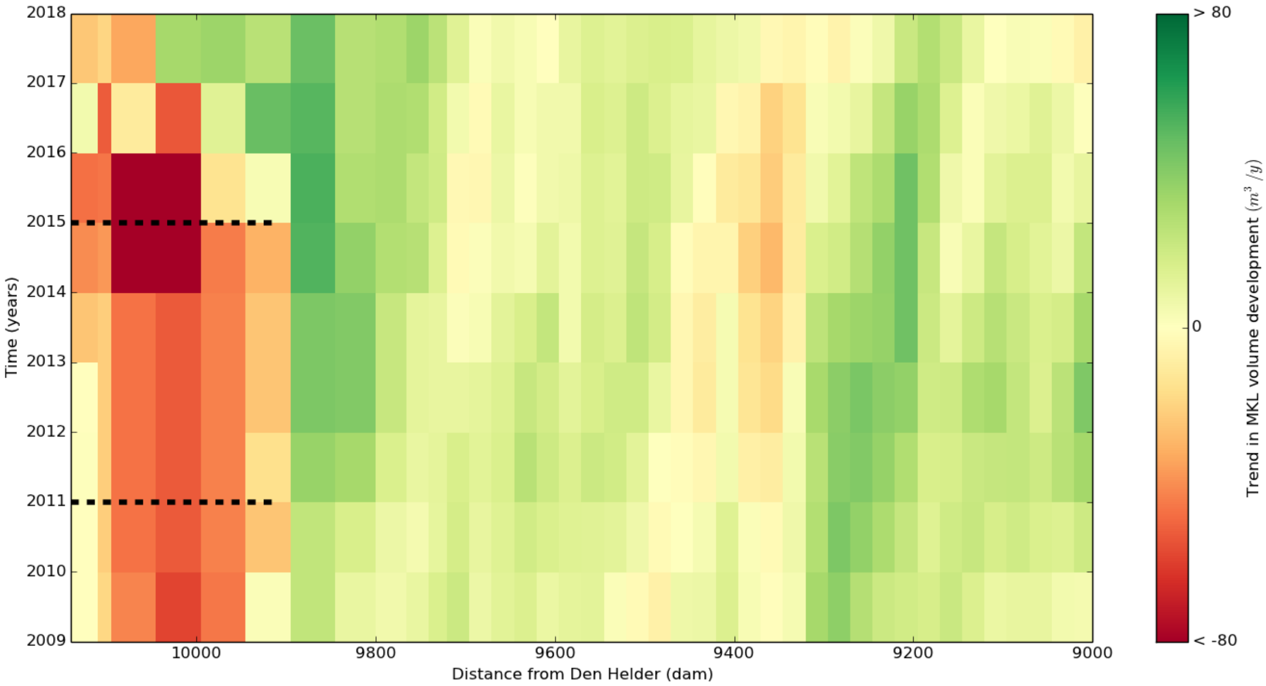

Figure D.2: *Trends in volume development around Scheveningen.*

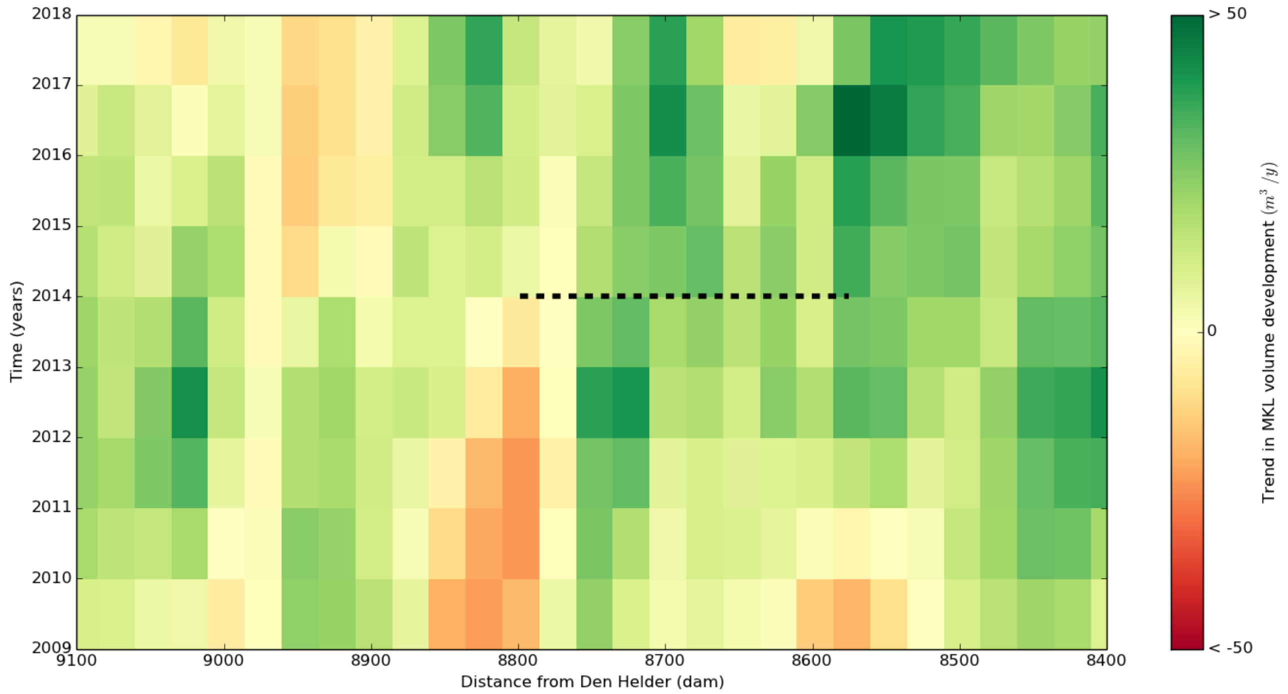

Figure D.3: *Trends in volume development around Katwijk.*

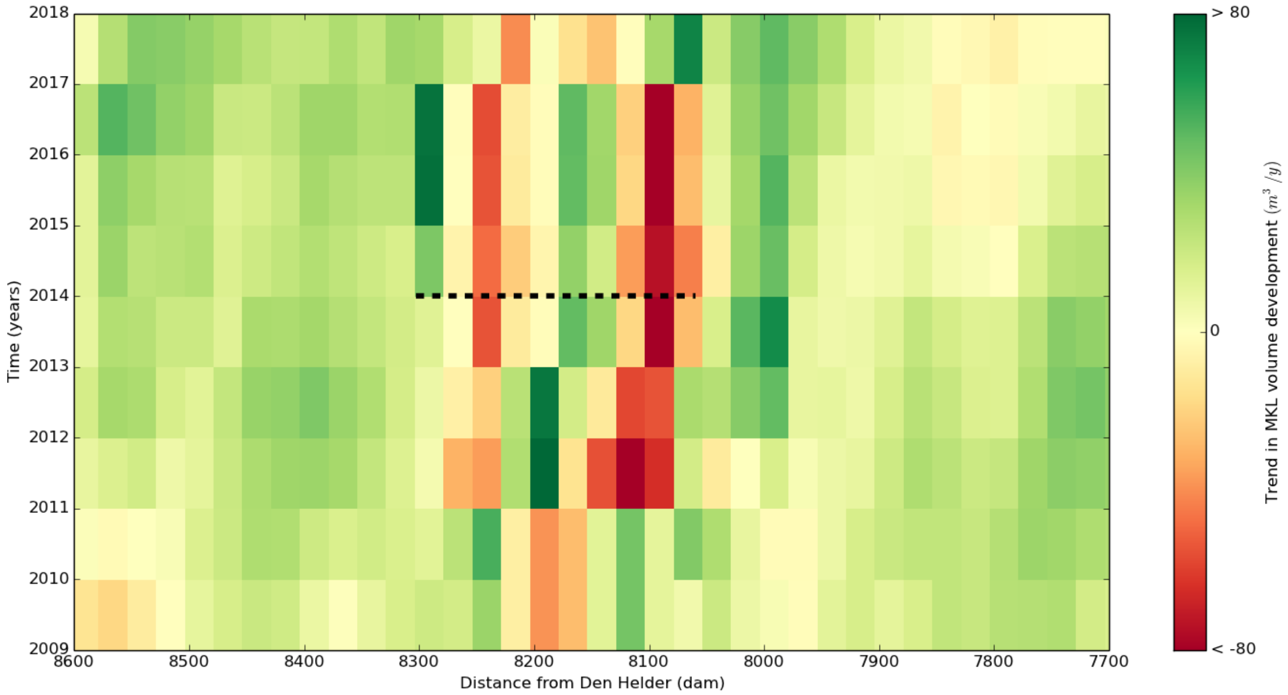

Figure D.4: *Trends in volume development around Noordwijk.*

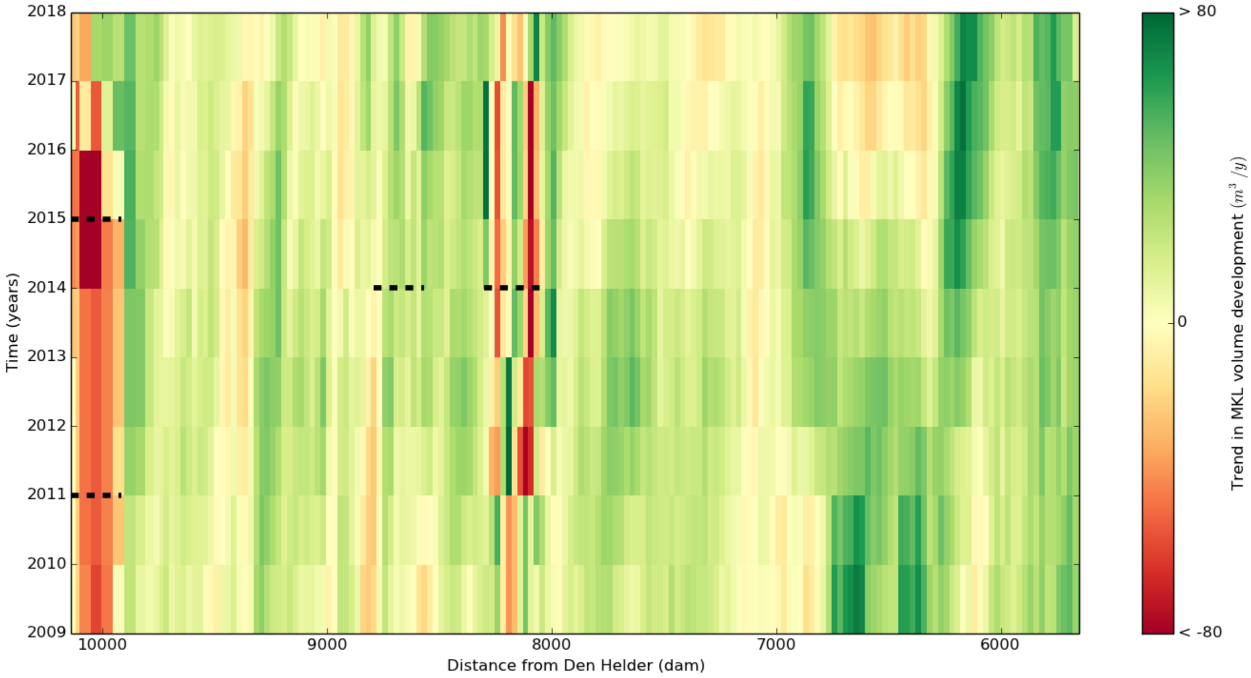

Figure D.5: Trends in volume development for the entire area of interest.

E. Model theory

Understanding the theoretical background of the research is essential when you want to understand what you actually are doing. In this appendix, the results of a literature review on the theoretical background of the Unibest-CL+ model are presented.

Single line theory

The single line theory by Pelnard-Considère (1956) is used to model coastline evolution and can be described with a continuity equation and an equation of motion, when combined leading to a diffusion equation. Initial conditions and boundary conditions are generally needed to solve the diffusion equation. The starting point for the derivation for the single line theory is the continuity equation, with x in longshore direction and y in cross shore (normal) direction (Bosboom & Stive, 2015; Deltares, 2011).

$$h_p \frac{\partial y}{\partial t} + \frac{\partial Q_s}{\partial x} + q_b = 0 \qquad [1]$$

$with$:

Q_s $total\ longshore\ transport\ (m^3/s)$

y $coastline\ position\ (m)$

h_p $active\ profile\ height\ (m)$

q_b $sediment\ source\ or\ sink\ (m^3/m/s)$

The active profile height can be seen as the height over which erosion or sedimentation takes place, typically from deeper water up to a small distance above the waterline, depending on the largest wave height. To compute the horizontal displacement of the entire coastal profile, the active profile height is used. For example, with an volume surplus of 40 m^3/m and an active profile height of 10 m, the entire coastal profile and therewith the coastline position moves horizontally over a distance of 4 m (accretion) according to the single line theory.

To find a diffusion equation which describes the single line theory, first the equation of motion has to be set up for the total longshore transport. When the total longshore transport is described as function of coastline orientation θ with the help of a Taylor sequence, neglecting second order terms and higher, the following equation is obtained.

$$Q_s(\theta) = Q_{\delta 0} + \theta\left(\frac{\partial Q_s}{\delta \theta}\right)_{\theta=0} \qquad [2]$$

With $Q_{\delta 0}$ equal to the longshore transport for a coastline orientation parallel to the x-axis and θ defined as angle with respect to the x-axis. For small changes in angle, $\theta = tan(\theta) = dy/dx$, and with assuming $-dQ_s/d\theta = s_l$, equation 2 can be rewritten as follows.

$$Q_s(\theta) = Q_{\delta 0} - s_l \frac{dy}{dx} \qquad [3]$$

$with$:

$Q_s(\theta)$ $total\ longshore\ transport\ (m^3/s)$

$Q_{s\delta}$ $longshore\ transport\ along\ a\ straight\ coastline\ parallel\ to\ the\ x-axis\ (m^3/s)$

s_l $variation\ in\ sediment\ transport\ as\ function\ of\ coastline\ orientation\ (m^3/s)$

θ $coastline\ orientation\ with\ respect\ to\ the\ x-axis$

When substituting the equation of motion into the continuity equation and assuming constant $Q_{s\delta}$ and constant s_l (equation of motion), and assuming zero source or sink q_b (continuity equation), the diffusion equation for the single line theory can be made (equation 4).

$$\frac{\partial y}{\partial t} = \frac{s_l}{h_p}\frac{\partial^2 y}{\partial x^2} \qquad [4]$$

This diffusion equation can be solved analytically when two boundary conditions and one initial condition are known. In the Unibest model, a numerical approach is used in which s_l is not assumed to be constant and the sources or sinks can be included. Also Q_s may vary over time when the wave climate varies over time. The sediment transport is computed for a number of coast angles, which can be visualised in an Q_s-θ curve (generally known as S-ϕ curve) and is used when numerically solving the continuity equation and the equation of motion.

Wave propagation and breaking

Sediment transport is strongly related to wave propagation and breaking, especially along the Holland coast were sediment transport is dominated by wave related processes (Bosboom & Stive, 2015). In the Unibest model, three main equations are used, an equation for wave energy balance, an equation for wave set-up and Snell's law (Deltares, 2011). Altogether, this theory is used in the transformation of wave data from offshore to nearshore conditions.

Wave energy balance

The equation for the wave energy balance consists of three parts, representing the change in wave energy in x-direction, dissipation due to wave breaking and dissipation due to bottom friction. Important to note is that this is a 1D equation, valid in shore normal direction.

$$\frac{d}{dx}\left(c_g \cos(\varphi)\frac{E}{\omega_r}\right) + \frac{D_b}{\omega_r} + \frac{D_f}{\omega_r} = 0 \qquad [5]$$

$with$:

c_g $wave\ group\ velocity\ (m/s)$

φ $angle\ of\ incidince\ of\ the\ wave$

E $wave\ energy: E = \frac{1}{8}\rho g\, H_{rms}^2\ (kg/s^2\ or\ J/m^2)$

ω_r $relative\ wave\ peak\ frequency: \omega_r = \omega - k\sin(\alpha)\, V\ (s^{-1})$

V $alongshore\ flow\ velocity\ (m/s)$

k $wave\ number, according\ to\ the\ dispersion\ relation: \omega_r^2 = gk\tanh(kd)\ (m^1)$

D_b $energy\ dissipation\ due\ to\ wave\ breaking\ (m/s)$

D_f $energy\ dissipation\ due\ to\ bottom\ friction\ (m/s)$

The equations for energy dissipation are especially relevant due to the fact that the main parameters of these equations have to be specified by the Unibest model user. For the energy dissipation due to wave breaking, the relation is as follows. This relation was first presented in Battjes and Janssen (1978).

$$D_b = \frac{1}{4}\rho\alpha_c Q_b\left(\frac{\omega_r}{2\pi}\right)H_m^2 \qquad [6]$$

$with$:

α_c $coefficient\ for\ wave\ breaking\ (-)$

Q_b $local\ fraction\ of\ breaking\ waves\ (-)$

H_m $depth\ limited\ wave\ height: H_m = \frac{0.88}{k}\tanh(\frac{\gamma kd}{0.88})\ (m)$

γ $coefficient\ for\ wave\ breaking\ (-)$

In the Unibest-LT model, both α_c and γ have to be defined. In the equation for the depth limited wave height H_m, γ is used to allow for the effect of different beach slopes and wave steepness. In shallow water, this equation equals $H_m = \gamma d$, with d being the water depth (Battjes & Janssen, 1978). Battjes and Stive (1985) performed further calibration of the wave breaking dissipation model and suggested values for the two coefficients. Given $\alpha_c = 1$, which is a good value for a good working model (Battjes & Janssen, 1978), the value for γ varies between 0.60 and 0.83. Since the two coefficients are physically related to each other, it is allowed to pin α_c on one specific value and search for an appropriate value for γ (Battjes & Stive, 1985).

Energy dissipation due to bottom friction is, next to wave related parameters, defined by a coefficient for bottom friction f_w. This coefficient has to be specified in the Unibest model and features in the dissipation equation as follows.

$$D_f = \frac{1}{8}\rho f_w \pi^{\frac{1}{2}} \left[\frac{\omega_r H_{rms}}{\sinh(kd)}\right]^3 \quad [7]$$

Snell's law

Snell's law is used for the refraction of waves when approaching the shore. Under influence of changing depth, the velocity of the waves c decreases according to the equation $c = \sqrt{gd}$. Snell's law relates the angle of incidence φ and the wave velocity c at two points along a wave ray as follows.

$$\frac{\sin(\varphi_2)}{c_2} = \frac{\sin(\varphi_1)}{c_1} \quad [8]$$

This law also holds for deep water, which means that the ratios above are also equal to $\frac{\sin(\varphi_0)}{c_0}$. Important to note is that the law only holds for parallel depth contours, which is the case in the simplified situation of the Unibest model where the depth contours are parallel for each cell. The angles of incidence which are computed with this law are used in the below described wave set-up equation as well as in the earlier described wave energy equations.

Wave set-up

Wave set-up is directly related to radiation stress, which is equal to the momentum flow in propagating waves. When during wave propagation the flow of momentum and therefore the radiation stress changes, a force is needed according to Newton's second law. The radiation stress consists of several components, in case of gradients leading to a force in x-direction and a force in y-direction. These forces are responsible for water level set-up in the surf zone, water level set-down in the shoaling zone and longshore currents in case of oblique waves. Set-up and set-down (x-direction) are discussed in this paragraph, while the longshore current (y-direction) is discussed in the next paragraph. Wave forces are generally only present in the nearshore region, as the forces depend on changes in wave energy E, wave angle of incidence φ and wave (group) velocity (within parameter n).

Wave set-up and set-down is related to the S_{xx} component of the radiation stress in case of an alongshore uniform coast. The subscript 'xx' in S_{xx} means that we are talking about the transport of x-momentum in x-direction. For each cell in the Unibest model, an alongshore uniform coast is assumed, which makes S_{xx} the only relevant component of the radiation stress for wave set-up and set-down. The force which is responsible for wave set-up and set-down, is equal to the gradient in x-direction, $-\frac{dS_{xx}}{dx} = F_x$. The radiation stress component in this equation can be described as follows (equation 9).

$$S_{xx} = \left[n(1 + cos^2\varphi) - \frac{1}{2} \right] E \qquad [9]$$

$with$:

n $\quad ratio\ between\ wave\ group\ velocity\ and\ wave\ velocity$: $n = \frac{1}{2} + \frac{kd}{\sinh(kd)}$

When looking in x-direction, S_{xx} initially will increase in the shoaling zone due to the increase in wave height and therefore wave energy. As a consequence, a force in opposite (offshore) direction will develop. This force then has to be compensated to create force balance; a pressure gradient is needed, provided by a set down of the water level. This pressure gradient results in an onshore directed force which compensates the wave force. Similarly, in the surf zone S_{xx} decreases due to the breaking of waves leading to an onshore directed wave force F_x. A water level set-up then needs to be provided to create a pressure gradient resulting in a compensating offshore directed force. The wave set-down and set-up phenomena are important for the depth-related sediment transport in longshore direction (Bosboom & Stive, 2015; Deltares, 2011).

Longshore current

The longshore momentum equation is the most important equation in describing the distribution and origin of the longshore current. The equation can be split into three separate parts, involving radiation stress (waves), tidal surface slope and friction respectively. Wind is not directly included in the research and the Unibest model, but can be related to the applied wave climate.

$$\frac{d}{dx} S_{xy} + \rho g d \frac{dh_0}{dy} + \rho \frac{g}{C^2} V |V_{tot}| = 0 \qquad [10]$$

$with$:

S_{yx} $\quad radiation\ stress\ component$

dh_0/dy $\quad longshore\ tidal\ surface\ slope$

C $\quad Chézy\ friction\ coefficient$: $C = 18 \log\left(\frac{12d}{k}\right)\ (m^{1/2}/s)$

V $\quad longshore\ flow\ velocity\ (m/s)$

V_{tot} $\quad instantaneous\ flow\ velocity\ (m/s)$

The S_{yx} component of the radiations stress, the transport of y-momentum in x-direction, (see previous paragraph), is responsible for the longshore current and can be described as follows. In this equation, φ is equal to angle of incidence of the waves, n to the ratio between wave group velocity and phase velocity and E to wave energy. Again only S_{yx} is responsible for the force in longshore direction, $-\frac{dS_{yx}}{dx} = F_y$, as a consequence of the alongshore uniform coast.

$$S_{yx} = E\, n \cos\varphi \sin\varphi \qquad [11]$$

Similar to wave set-up and set-down, a change in S_{yx} can occur when moving with the flow in x-direction. This change is generated by change in wave energy, velocity and angle of incidence. The consequence is a force in y-direction. However, in this case the wave force cannot be compensated by a pressure gradient as no set-up or set-down in y-direction can be developed along an infinite uniform coast. A pressure gradient resulting from the difference in tidal surface elevation in longshore direction can be present, as the tide propagates along the coast (on a much larger scale than waves). When the force due to the gradient in radiation stress and the force due to the tidal pressure gradient are combined, generally a third force is needed to create a force balance. This force is supplied by bed shear stresses which are present when a longshore current develops. This longshore current can reach velocities of 1 m/s and is responsible for the longshore sediment transport, which is an important part of the research and in particular of the Unibest model (Bosboom & Stive, 2015; Deltares, 2011).

Sediment transport and coastline development

The interaction between sediment transport and hydrodynamics is very complex and still relatively poorly understood. This leads to a situation in which many different (empirical) formulae are present, giving different sediment transport quantities for the same situation. The basics of sediment transport and coastline development are already discussed in the literature study (paragraph 2.6), in this paragraph the focus is the underlying formulae and assumptions.

Van Rijn 2004 sediment transport formula

In the 'Holland Coast' Unibest model, it is chosen to use the Van Rijn 2004 sediment transport formula. Different parameters which have to be specified within the model for this formula are presented in Appendix F on the model setup. An important characteristic of this transport formula is that the bed-load transport in case of sand is related to velocity to the power 2.5. This power is an important point of discussion in the world of sediment transport formulae and varies significantly betweem different sediment transport formulae. For suspended transport in the coastal zone, the most important aspect is that this transport is strongly related to the relative wave height. Furthermore also the grain size diameter and current velocities play a significant role. For more details on the van Rijn 2004 formula, reference is made to the papers by van Rijn (2007a; 2007b).

Sediment transport and coastline angle

After computation of the sediment transport for all relevant coast angles, a (continuous) $Q_s - \theta$ curve (also known as S-ϕ curve) is constructed in which the sediment transport is presented as function of the coast angle. Important in this relation is the equilibrium angle, which is the coast angle perpendicular to the wave angle of incidence, for which the sediment transport is zero. Depending on whether the present coast angle is smaller or larger than the equilibrium angle, sediment transport is positive or negative. Positive and negative values are associated with the direction of the sediment transport. The sediment transport as function of the coast angle can be described with the following formula.

$$Q_s^a = c_1 \theta_r e^{-(c_2 \theta_r)^2} \quad [12]$$

In this formula, θ_r is the relative coast angle, which is difference between the present coast angle and the equilibrium coast angle. When the sediment transport is computed for all relevant coast angles, the coefficients $c_{1,2}$ are determined with the method of the least squares to fit the function to the computed points.

Numerical solutions

In the Unibest-LT model, three main equations have to be solved numerically in cross shore direction; the wave energy equation, wave set-up equation and the equation for the longshore current. These equations are solved on a non-equidistant grid which can be specified by the user of the model. For instance, at locations with large bottom changes, a smaller grid size can be chosen. In the end, three non-linear equations with three unknowns remain, wave energy E, water level elevation η and velocity V. Within the model, the three equations are linearized and iteratively solved until a solution for the non-linear equations is found. The boundary values for the three unknowns are taken from the boundary conditions specified in the model (wind, wave, tide and current scenario) (Deltares, 2011).

The coastline equations (see Single Line Theory) are numerically solved within the Unibest-CL model. Along the coastline (x-direction) a staggered grid is defined, with the alongshore sediment transport Q_s computed at the one point and the coastline position y defined at the other point. If specified, the function for alongshore sediment transport may be multiplied with a multiplication factor β, depending on the application of groynes or revetments. For more details on the numerical solutions of the coastline equations, reference is made to the Unibest manual (Deltares, 2011).

F. Unibest-LT setup

The original ‘Holland Coast’ model is used in several other studies and has proven its value (Huisman & Luijendijk, 2010; Tonnon et al., 2012). However, the information on the background of the chosen Unibest-LT input parameters is limited. Therefore it is chosen to check all input parameters, partly with the help of the model theory as elaborated in Appendix E. In the end, all the chosen Unibest-LT input parameters except the bottom friction coefficient are equal to the original ‘Holland Coast’ input parameters.

Cross shore profile

In the original ‘Holland Coast’ model, profiles computed by averaging measurements from multiple years are used in order to reach a situation close to the equilibrium profile. Unibest-CL is designed with the assumption that the cross shore profile is in equilibrium, therefore it is chosen to use the present equilibrium profiles. However, it is important to also take a look at sediment transport for non-equilibrium profiles in order to be see the differences in transport for the of different kind of profiles.

To investigate the difference in results between the use of the different profiles, profiles derived from 2007 JARKUS measurements are implemented in the model and corresponding sediment transport is computed. The comparison is made with profiles which are located close to each other, taking into account the real measurement spacing distance of 250 m. For instance, for Scheveningen the JARKUS profile of at 100,250 m is used to compare with the equilibrium profile in the model at approximately 101,137 m from Den Helder. Three locations are tested, a location at the Scheveningen Zwakke Schakel (km 100.25), a location at the Katwijk Zwakke Schakel (km 87.5) and a location at the Noordwijk Zwakke Schakel (km 82). The cross shore length is equal for both assessed profiles used at each location, therefore the difference in profile height with respect to sea level is the only parameter which changes.

The main difference which can be observed is that the transport generally takes place at a location further away from the coastline due to the presence of banks in the non-equilibrium case. Only at Scheveningen, the main transport is concentrated closer to the coast in the non-equilibrium case as a consequence of the presence of a bank very close to the coastline. At the banks, depth is reduced (with respect to the equilibrium profile) causing larger amounts of sediment transport. In all three cases the total annual longshore transport volume at the given coastline orientation increases when using the non-equilibrium profile. Again, this can be related to the presence of shallow bank areas.

Next to the cross shore profile itself, three additional parameters have to be specified, the dynamic boundary, the truncation boundary and the grid size. The dynamic boundary is defined as the location until which longshore sediment transport rates are computed and therefore the location until which the coast is rotated as a consequence of gradients in sediment transport. The truncation boundary is the location until which the sediment transport is taken into account for the total sediment transport. For instance in case of a rocky part of the coastal profile, it is possible to neglect the sediment transport but take into account the wave propagation at this rocky stretch. For all cross shore profiles, the grid size is set on 10 m, while the dynamic- and truncation boundary are defined at the seaward end of the profile. The seaward end of the profile is generally at a depth of 5 to 6 meters and a cross shore distance of 400 to 900 meters. The boundaries are defined at the seaward end of the profile because we are dealing with a sandy profile with limited depth at the seaward end, where sediment transport cannot be neglected. Extending the profiles further seaward is not needed since the SWAN model (see ‘Wave scenario’) is better capable of modelling wave propagation and most of the sediment transport takes place in shallow water. Only during extreme conditions, significant sediment transport volumes may be present at depths larger than -6 m NAP. Furthermore, recent research proved that the Unibest model gives the most valuable results when only the nearshore region rotates and deeper parts of the profile are excluded (see Tonnon et al., 2018).

Wave scenario

The wave scenario used in this research is the same wave scenario as used in the original Holland Coast model (Huisman & Luijendijk, 2010). For the composition of the wave scenario, 26 years of wave data is used from the period between 1979 and 2005. It is assumed those 26 years of wave data are representative for the present situation, which seems, taking the long period into account, a valid assumption.

The offshore wave climates are obtained at three locations in front of the Holland coast, at the Europlatform (EUR), IJmuiden Munitiestortplaats (YM6) and the Eierlandse Gat (ELD), see figure F.1. The starting point of the composition of the wave scenario are the wave conditions at YM6. For each wave condition in the YM6 climate the corresponding wave heights in the ELD and EUR climate were obtained, which means the wave characteristics which were measured simultaneously with the YM6 condition. In the end, an offshore wave field is obtained with an equal number of wave conditions per location and with equal probability of occurrence for each simultaneous wave condition. Wave height, wave period and wave angle vary locally for each simultaneous wave condition. The wave heights and probability of occurrence for the three wave climates are presented in the wave roses in figure F.2 (Huisman & Luijendijk, 2010).

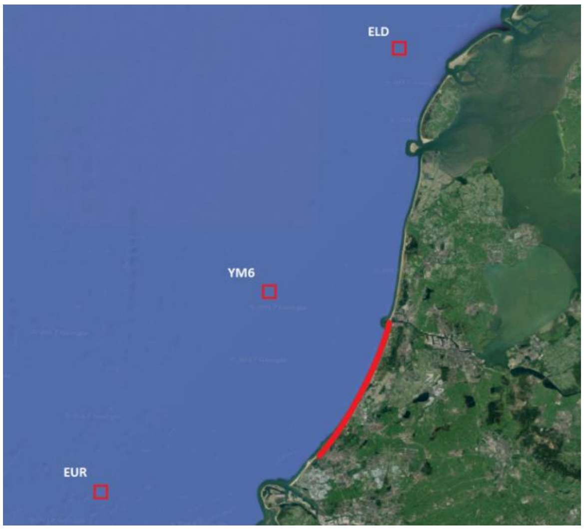

Figure F.1: Locations of measurements stations from which wave data is used.

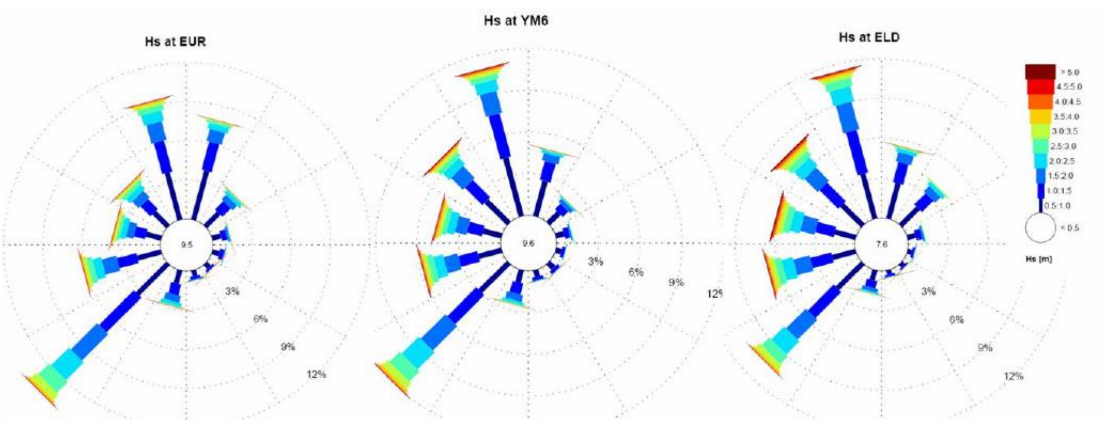

Figure F.2: Wave roses at the three measurement locations (Huisman & Luijendijk, 2010).

The three wave climates obtained in the previous steps were imposed at the boundaries of a SWAN model for the Holland coast, in which the nearshore wave conditions were computed for all defined locations in the UNIBEST model. These nearshore wave conditions include 269 conditions and are the base input of the Unibest-LT model, in which the longshore sediment transport is computed. The resulting average wave direction is around west, leading to a net transport in northern direction, which is both in line with literature (see paragraph 2.7). The bathymetry used in the SWAN model was composed out of a combination of 2003 and mainly 2004 measurement data. With the model starting in 2006, it is assumed that the bathymetry used in the SWAN model is still valid.

Tide

In addition to the wave scenario, it is possible to include tidal currents and surface elevation in the model. Tide is however not included in the model as transport caused by waves (and resulting currents) is dominant over transport caused by the tide along the Holland coast (Bosboom & Stive, 2015).

Wave parameters

Unibest-LT has a built in wave model to simulate the propagation of waves from the nearshore towards the coast, including breaking, refraction and shoaling (see Appendix E). In the LT-model, four parameters have to be specified for this wave model. Two coefficients for wave breaking , α and β, a coefficient for bottom friction f_w and the bottom roughness k_b.

Parameter	**Value**
Coefficient for wave breaking γ	0.8
Coefficient for wave breaking α	1.0
Coefficient for bottom friction f_w	0.01
Value of bottom roughness k_b	0.1 m

Table F.1: Wave parameters as applied in the Unibest-LT model.

The coefficient for wave breaking γ is depending on amongst others the bottom slope, which is highly variable, even within the research area. On average, the coefficient of wave breaking is approximately equal to 0.8 (Bosboom & Stive, 2015), which is also within the range presented by Battjes and Stive (Battjes & Stive, Calibration and Verification of a Dissipation Model for Random Breaking Waves, 1985). The value of 0.8 will be used in the model and is also the value present in the original model configuration. The coefficient for wave breaking α is in the order of 1.0 according to the Unibest manual. The values of both coefficients are in line with the literature review as presented in Appendix E.

The evaluation of the coefficient for bottom friction can be found in paragraph 4.2. In the original model, a value of 0.0 was used for the bottom friction coefficient, while in this research the advised value of 0.1 is applied. For the bottom roughness k_b, the Unibest manual advises a value of 0.1 meter, equal to the value used in the original Holland Coast model. This value is used in the computation of the Chézy coefficient, which plays an important role in the equation for the longshore current distribution (see Appendix E).

Sediment transport parameters

In order to compute the longshore sediment transport, a certain amount of sediment transport parameters have to be specified in the model (table F.2). Which parameters have to be specified depends on the choice in transport formula. In the model the van Rijn 2004 sediment transport formula is used (van Rijn L. , 2007a; 2007b). Research by Huisman & Luijendijk (2010) makes clear that the van Rijn 2004 formula is best suitable in the Holland Coast model, in favour of for instance the Bijker formula. For more information on the van Rijn 2004 transport formulations, see Appendix E.

Parameter	Value
D_{10}	120 µm
D_{50}	200 µm
D_{90}	300 µm
D_{SS}	160 µm
Sediment density	2650 kg/m^3
Seawater density	1025 kg/m^3
Porosity	0.4
Temperature	15 ºC
Salinity	$30 \cdot 10^3$ ppm
Current related suspended transport factor	1
Current related bedload transport factor	1
Wave related suspended transport factor	1
Wave related bedload transport factor	1

Table F.2: Sediment transport parameters as applied in the Unibest-LT model.

Salinity

The salinity of the water along the Holland coast is on average between 28-30 g/l (Rijksoverheid, 2017), which is roughly around $30 \cdot 10^3$ ppm. Salinity increases when the cross shore distance increases. Close to the shore, the salinity is lower due to the fresh water inflow of the Rhine and the Meuse near Rotterdam, the Rhine ROFI (Region Of Freshwater Influence) (Joppe, 1986). In the model, the salinity value is set on $30 \cdot 10^3$ ppm, which is in line with the data. Sensitivity computations are done with a salinity of $35 \cdot 10^3$ ppm, which is a general salinity value for the open ocean.

Seawater temperature

The temperature of the North Sea water has risen over the past decades. In comparison with the large oceans, the North Sea adapts faster to changes in air temperature due to its shallowness. As a consequence of this shallowness and the highly varying air temperatures around the seasons, sea water temperatures in winter and summer are significantly different. In winter, the average temperature lies around 5 degrees Celsius, while in summer the temperature may rise up to 20 degrees Celsius (Bosboom & Stive, 2015; Pietrzak, 2016). On average, the sea water temperature of the North Sea is around 12 degrees Celsius (Stewart, 2008). This value may however increase in the upcoming decades under in fluence of climate change. Due to the high variability of temperature, it is difficult to pick the right mean seawater temperature. In the initial Unibest model, a value of 15 degrees Celsius is used and with the timescale of the model of 55 years, it is chosen to retain this seawater temperature.

Grain size diameter

In order to choose the right value for the grain size diameter parameters, D10, D50 and D90, three studies are used. In the first large research by TAW (1984), every 2 kilometres, five measurements were done in the dunes, both at the toe, at the top and on the landward side. For each location, the D50, the ratio between D90 and D10 and the standard deviations of both values are computed. From these values, all grain size characteristics can be computed. For the second TAW research (Glim, 1985), hundreds of measurements were done in the period between 1976 and 1982 in the Wadden sea area and along the Holland coast. Only the measurements done at 70 kilometres from den Helder lie within the research area. Before and after a storm, measurements were done around NAP, on the seaward side of the dune and on top of the dune. The third research by Terwindt (1969) consists of measurements done at three locations in front of the Katwijk coast. Important is that in case of this research, the measurements are done in the surfzone and foreshore, and not in the dune. The surfzone is the main area of interest for this research and also the most relevant for the Unibest model.

In the original model, the following grain size characteristics are used based on the measurements along the Holland Coast.

D10 (µm)	D50 (µm)	D90 (µm)	D50 suspended (µm)
120	200	300	160

Table F.3: Grain size diameters as applied in the Unibest-LT model.

According to the TAW studies (1984, 1985), the average D50 in the research area is around 10% larger than the values used in the model, while according to the research of Terwindt (1962) the D50 is around 10% smaller than 200 µm. Taking the outcome of all three studies into account, the choice for a D50 of 200 µm is reasonable. The TAW studies (1984, 1985) also elaborate on the D10 and D90. The average ratio between D90 and D10 is around 2 (TAW, 1984). The D90 and D10 around 70 kilometres from Den Helder are estimated on around 10% larger values than the model values (Glim, 1985). Both studies however concentrated on the dune area, which is of minor importance for this research. It is therefore chosen to retain the values for D10 and D90.

With the diameter of suspended sediment particles generally being smaller than diameter of sediment in the bed, it is chosen to also retain the D50 for suspended sediment of 160 µm. The sensitivity of the model for different values of all grain size characteristics is tested in the sensitivity analysis.

Seawater and sediment density

Most of the sandy beaches across the world consist of quartz sand, which has a density of 2650 kg/m^3. Also for the European waters, where the Dutch part of the North Sea belongs to, this is the case. The seawater density is set on 1025 kg/m^3. In general, the sea and ocean water density lies around 1027 kg/m^3 (Stewart, 2008), however, the relatively low salinity of the Dutch coastal waters (see salinity) and high temperature (see temperature) justify the use of a lower seawater density.

Porosity

The final relevant parameter in the sediment transport formula of van Rijn is the porosity, a common used value for porosity is 0.4, which is also used in this research (Bosboom & Stive, 2015).

Sensitivity analysis

In the sensitivity analysis, the sensitivity of the model for small changes in parameters is checked in order to test the performance of the Unibest-LT model after model setup. If large, unexpected, deviations occur, it may be an indication that the setup of the model is not correct. To test the sensitivity, the longshore sediment transport volume is computed at a certain cross shore profile for two different values of the same parameter. Background information on the different (test) values can be found in the first part of this Appendix, on the Unibest-LT setup.

Parameter	Original value	Test value	Original transport (k(m_3/y))	Test transport (k(m^3/y))	Deviation
Wave coefficient γ	0.8	0.6	197.373	173.406	12.1%
Friction coefficient f_w	0.0	0.01	197.373	186.526	5.5%
Bottom roughness k_b	0.1	0.05	197.373	266.116	34.8%
Salinity	30.0	35.0	197.373	199.647	1.2%
Seawater temperature	15.0	12.0	197.373	216.938	9.9%
D10	120.0	130.0	197.373	192.767	2.3%
D50	200.0	180.0	197.373	230.619	16.8%
D90	300.0	320.0	197.373	198.857	0.8%
D50 (suspended)	160.0	180.0	197.373	197.372	0.0%
Seawater density	1025.0	1027.0	197.373	197.373	0.0%
Sediment density	2650.0	2700.0	197.373	186.247	5.6%

Table F.4: Results of the sensitivity analysis.

Wave coefficient γ

In case of smaller wave coefficient for wave breaking, the wave will break earlier, which causes the transport to take place further offshore. At larger depth, influence of most other parameters is still smaller, leading to a weaker longshore current and less longshore transport. Concluding, the model behaves well regarding changes in wave coefficient γ. It is chosen to not assess the sensitivity of the model for the coefficient α, since γ and α are related (see Appendix E).

Friction coefficient f_w

Due to the presence of friction in case of a value of 0.01, dissipation due to friction increases. As a consequence the remaining wave energy decreases, leading to a decrease in gradients of the radiation stress and a decrease in longshore transport. The model results for different friction coefficients is already assessed in the model setup (paragraph 4.2).

Bottom roughness k_b

When bottom roughness decreases, the Chézy coefficient increases, leading to larger longshore flow velocities (see Appendix E). As a consequence, the longshore transport volume increases significantly as expected.

Salinity

Increased salinity causes an increase in seawater density, which in the end is responsible for a (small) increase in longshore transport volume. The behaviour of the model corresponds with the expectations.

Seawater temperature

Decreasing seawater temperature increases the sediment transport volume as a consequence of the higher seawater density. The influence of changing seawater temperature with 3 degrees Celsius, from 15 to 12, is significant and discussion on the right value for the seawater density is possible. In the model setup (paragraph 4.2) it is chosen to use a value of 15 degrees Celsius.

Grain size diameter

Varying the grain size diameter has the expected effect on the local net transport volume. Decreasing the D50 with 10% causes a significant increase in transport. Furthermore, when varying D10 and D90, the slope of the grain size distribution curve will change. Decreasing the slope (increasing D10) will cause the sediment to be more narrowly graded, while increasing the slope (increasing D90) causes the sediment to be more widely graded. When sediment is more widely graded, the transport is expected to increase because effects of for instance sheltering are less. For more narrowly graded the same reasoning, but then vice versa, can be applied. The influence of varying D10 and D90 is significantly smaller than the influence of varying D50. Varying the D50 of the suspended sediment has no significant influence on the net longshore transport volume.

Seawater and sediment density

It turns out that changing the seawater density has no influence on the model results, which indicates that seawater density is computed from the seawater density and salinity and the parameter ‘seawater density’ is not used in the model. Increasing sediment density leads to a decrease in longshore sediment transport volume according to the expectations. To transport heavier sediment, a larger force is needed, and therefore less sediment can be transported with the same forces.

G. Validation coastline development

In paragraph 4.5 the Unibest-CL model is validated with the help of the results of yearly assessments. In the yearly assessment of the measurement results, the predicted trend in coastline development for the upcoming year is presented. For the years 2011 to 2018, these predicted trends are compared with the predicted coastline development based on the results of the Unibest model. In figures G.1 to G.7 the graphs for all years are presented. Both trends are based on at least 3 years of (fictional) measurements. If possible, the amount of measurements used to compute the trend increases up to maximum 10 measurements. The first fictional model measurement is set on the year 2008, after application of the first 'Zwakke Schakel' nourishment, at Noordwijk. The dashed lines in the figures represent the boundaries of the most recent applied nourishment at a certain location.

In figure G.1 the predicted trend for the new situation at Noordwijk is taken into account, since from 2011 onwards sufficient measurements are available to make a trend based on the coastline after the application of the 'Zwakke Schakel' nourishment. For the nourishment at Scheveningen (2009/2010), the amount of measurements available is not sufficient to compute a trend. Nevertheless, the positive influence along the adjacent coast north of Scheveningen can, both in the measurements as well as in the model, already be observed. The predicted model trend is much less variable over the area. In the Unibest model, the nourishment design is simplified and variations in sediment transport are only present on a large scale. As a consequence, the small scale variations are not present in the model results. Remarkable is that the model trend underestimates the coastline development around km 75 and km 65, which may have to do with the influence of shoreface nourishments which are applied between after 2002 in almost the entire region north of Noordwijk. The same holds for km 86 and km 93, where the difference is partly related to the shoreface nourishments at Noordwijk-Katwijk and Wassenaar respectively (see Appendix B).

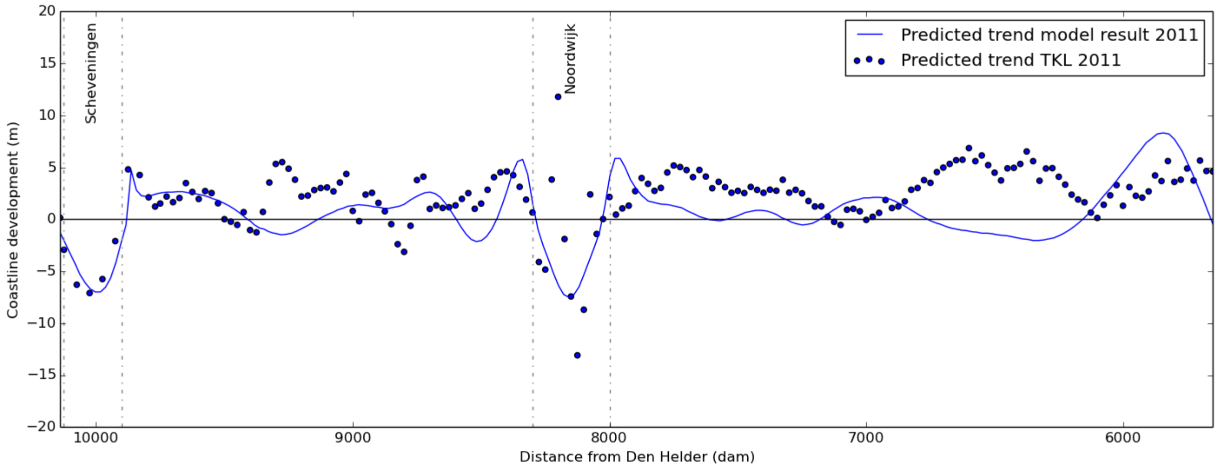

Figure G.1: Predicted model trend and measurement trend for 2011.

The trends for 2012 and 2013 (figure G.2 and G.3) are mainly similar to the 2011 trends from figure G.1. The positive development close to Scheveningen increases in magnitude due to the positive influence of the nourishment application at Scheveningen. In 2012 and 2013, more measurements including this positive influence are available, leading to an increase in the trend.

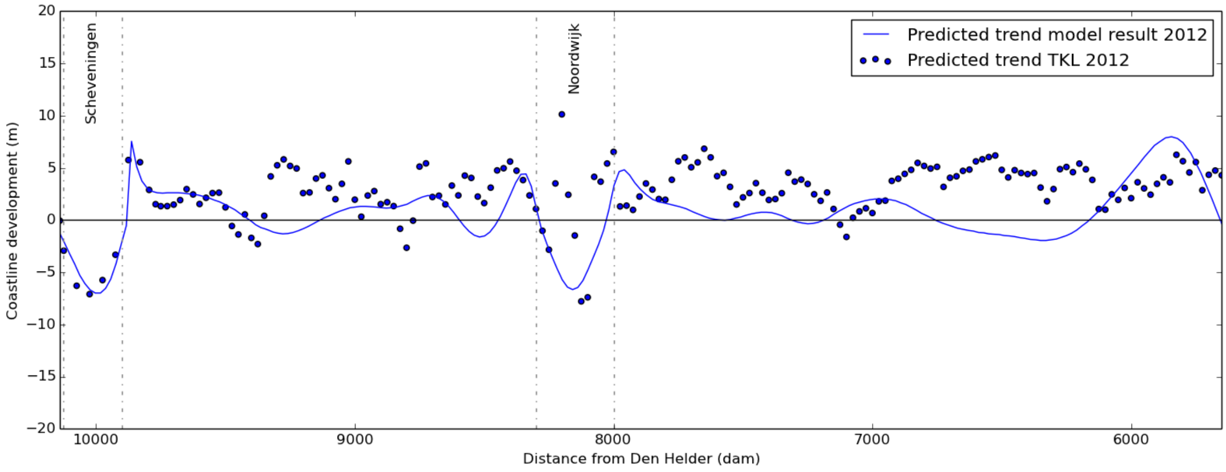

Figure G.2: Predicted model trend and measurement trend for 2012.

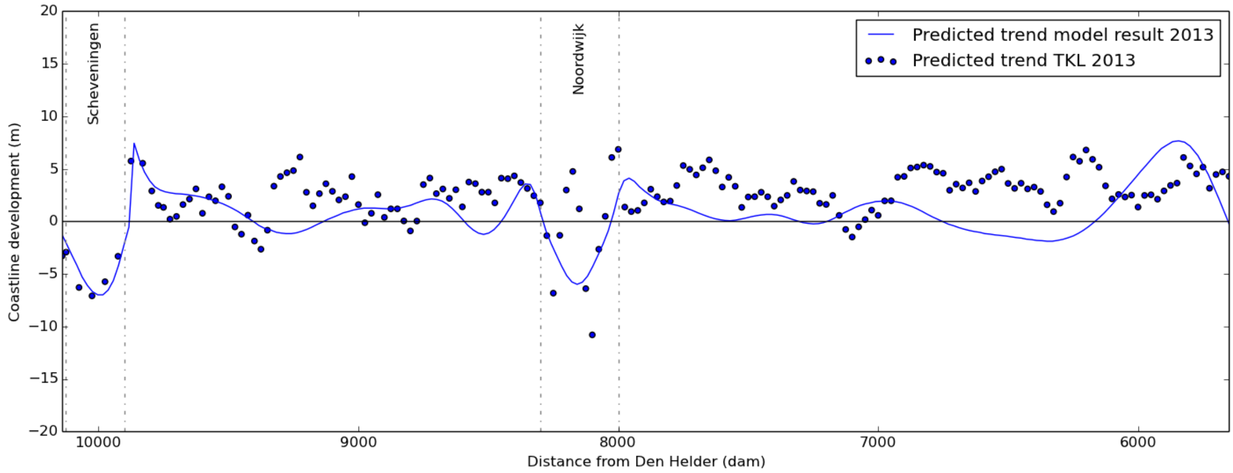

Figure G.3: Predicted model trend and measurement trend for 2013.

The predicted trends for 2014 (figure G.4) contains the (fictional) measurements at Scheveningen after ‘Zwakke Schakel’ nourishment application. Remarkable is the very large predicted local erosion of around -18 meters per year. Neglecting this extreme erosion prediction, the model trend around Scheveningen is in the same order of magnitude as the measurement trend. The Unibest model is not capable of modelling the highly variable erosion pattern but instead computes a more average trend of erosion. Furthermore remarkable are the new positive peaks around km 68 and km 62 in the model trend. These positive peaks are probably related to the shoreface nourishments applied in 2008 at Bloemendaal and Zandvoort. Due to nourishment application at Noordwijk in 2013, the predicted trends at this location are based on measurements done before 2013. The new trend is used from 2017 onwards.

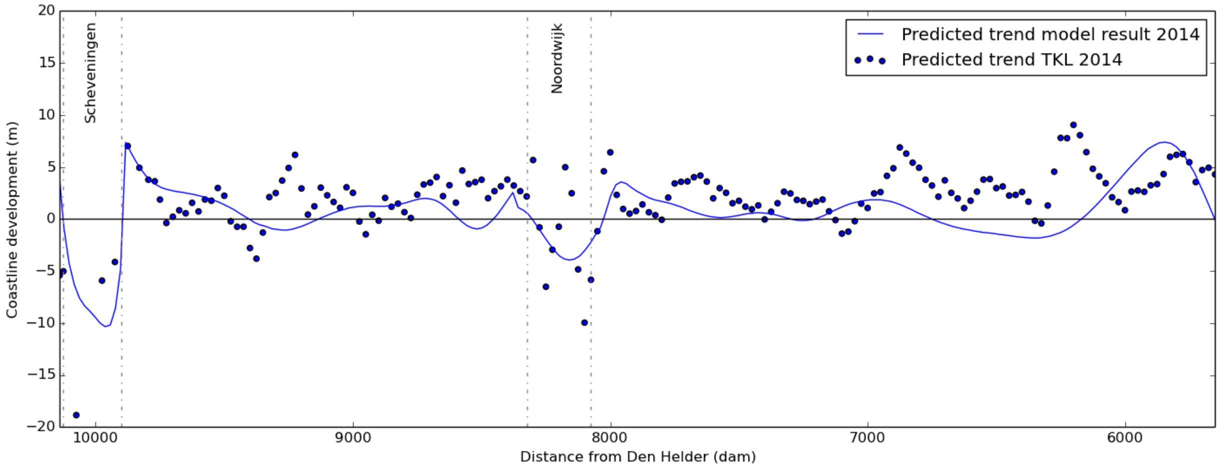

Figure G.4: Predicted model trend and measurement trend for 2014.

With respect to the predicted trend for 2014, only around Katwijk significant changes are found in 2015 (figure G.5). The adjacent coast around Katwijk experiences a positive influence of the application of the large ‘Zwakke Schakel’ nourishment, leading to a (more) positive trend with respect to earlier years.

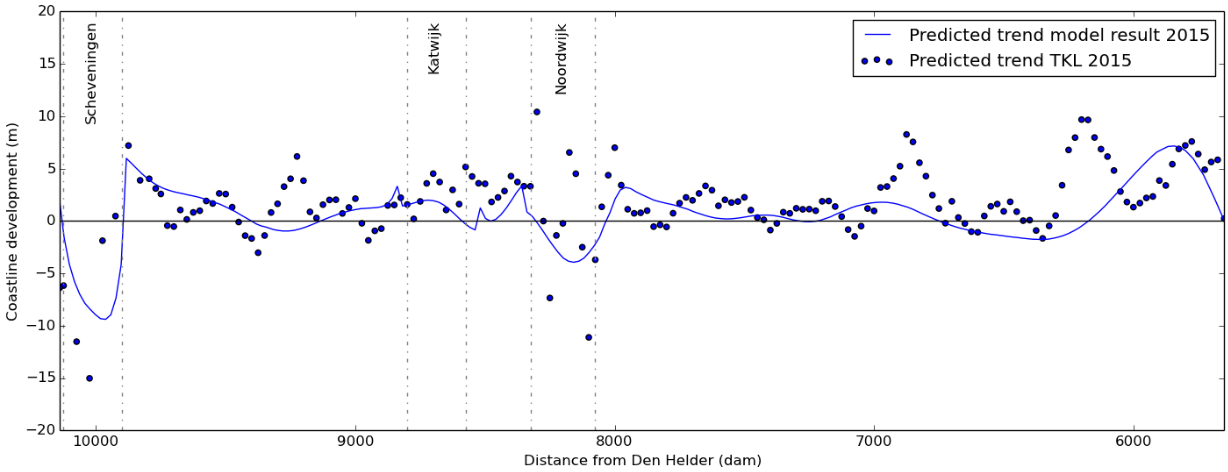

Figure G.5: Predicted model trend and measurement trend for 2015.

In figure G.6 and G.7 the predicted trends for 2016 and 2017 are presented. At Scheveningen and Katwijk, trends based on measurements before nourishment application are used, due the which the results are still more or less similar to the results of 2015 and 2014. An important increasing positive development is found between Katwijk and Noordwijk in both trends, which is caused by the effect of the ('Zwakke Schakel') nourishments applied at Katwijk and Noordwijk. North of Noordwijk, especially for 2017, the model trend is significantly lower than the measurement trend. This difference may be related to the difference in nourishment design in application in the model with respect to reality.

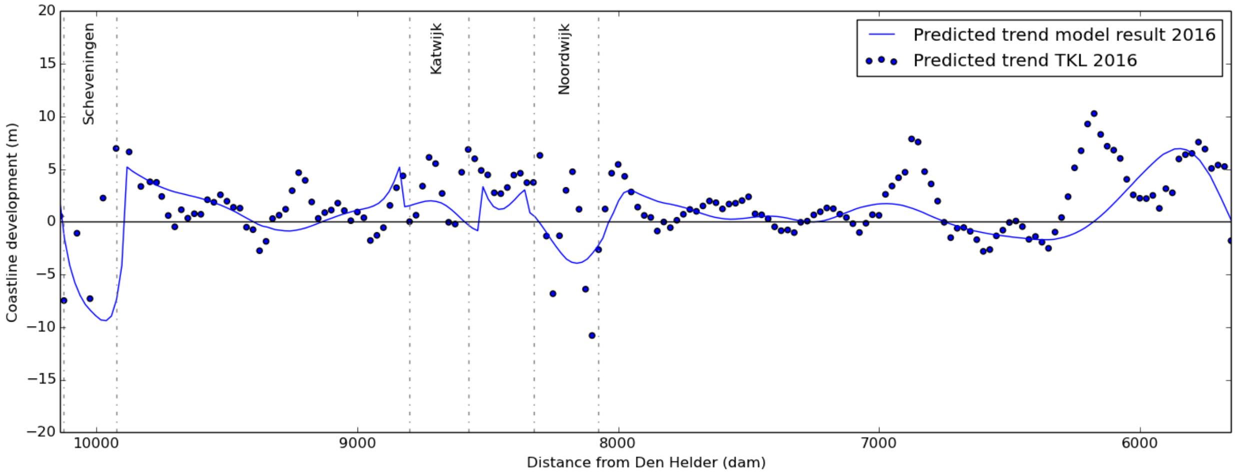

Figure G.6: Predicted model trend and measurement trend for 2016.

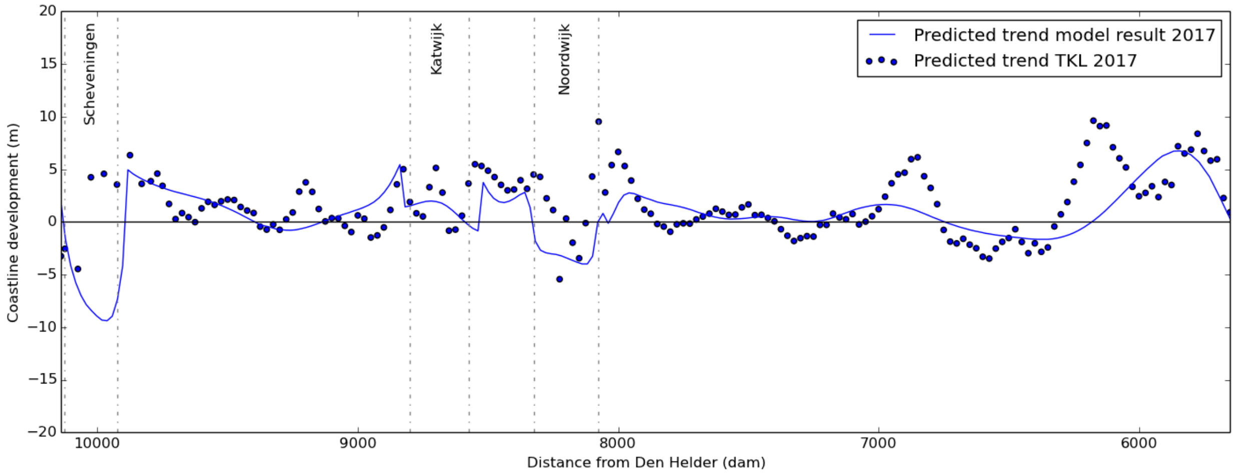

Figure G.7: Predicted model trend and measurement trend for 2017.

In figure G.10 the model results and predicted trend for 2018 are presented. This figure is also discussed in the validation of the Unibest-CL model (paragraph 4.5).

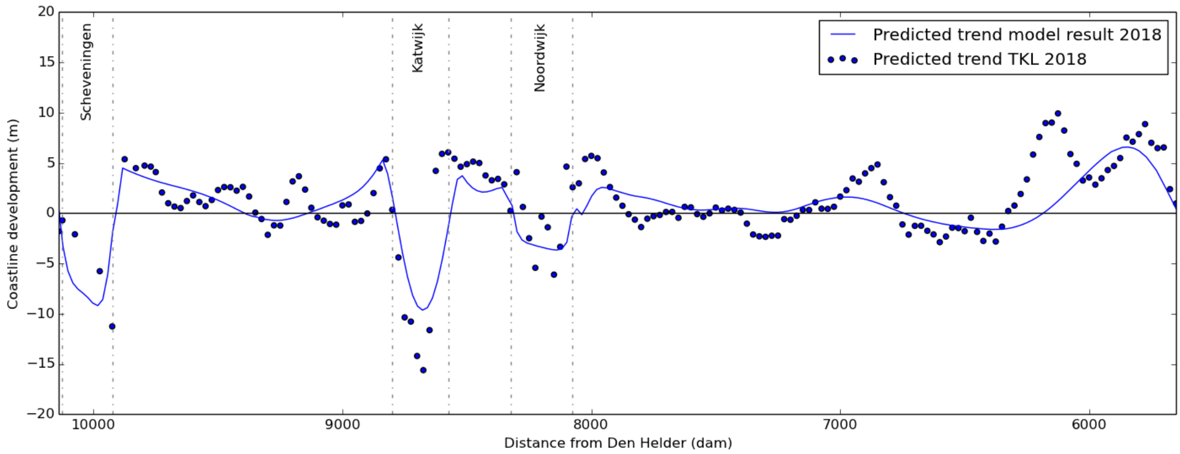

Figure G.8: Predicted model trend and measurement trend for 2018.

Conclusion

Overall the model results and the predicted trend show similar behaviour for all years, the main differences can be summarized as follows.

- Differences in coastline development along the adjacent coast, probably related to the effect of shoreface nourishments in reality. Mainly around Bloemendaal and Zandvoort this difference is clearly visible and in correspondence with shoreface nourishment application.
- Other differences in coastline development are probably mainly related to the simplifications made in the Unibest model, causing the model trend to be much smoother than the measurement trend. Amongst others natural bar migration will have its influence on the measurement trend, while this process is not included in the model. Also the simplified nourishments design leads to a more smooth result for the model trend at the nourishment locations.

H. Additional model results

In figure H.1 to figure H.8, model results are presented for nourishments scenarios B and C, and a reference situation without long term maintenance. It is chosen to only include the figures on coastline position, coastline development and the region of influence since these figures are most illustrative. Figures on overall development and sediment transport for scenarios B and C are almost identical to the figures for scenario A.

The coastline position and coastline development for scenario B show similar results than for scenario A, since in both case the erosion volume is evenly compensated by the maintenance nourishments. The main difference is found in the coastline development (figure H.2) at Katwijk and Noordwijk, due to the increase of the return period from 5 to 8 years.

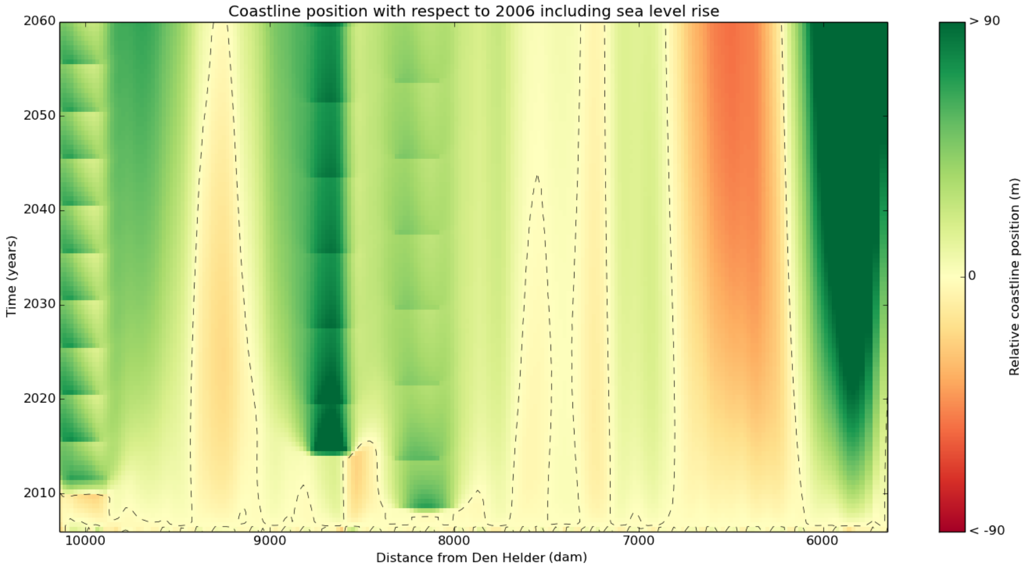

Figure H.1: Relative coastline position with respect to the 2006 coastline for scenario B.

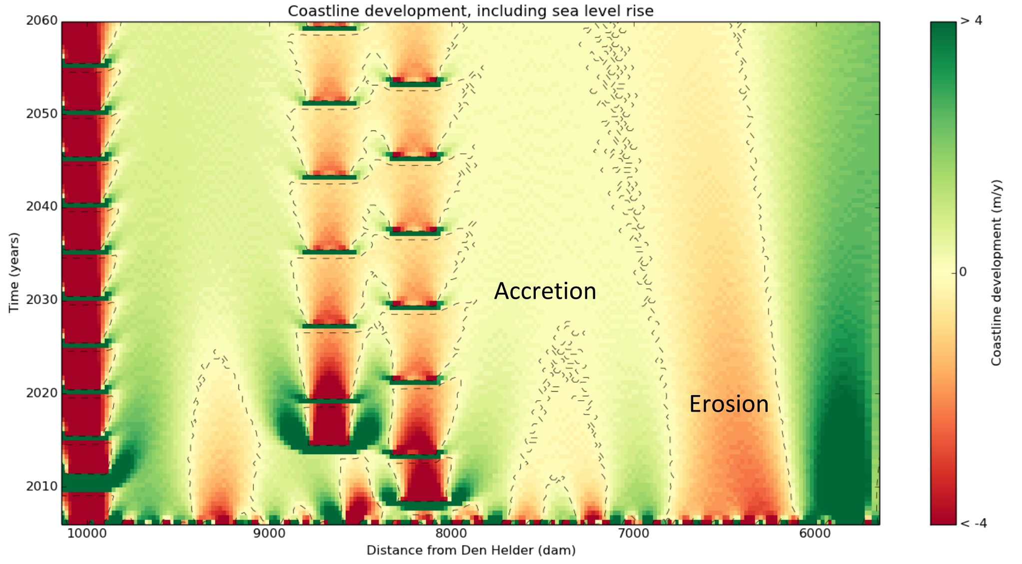

Figure H.2: Coastline development per year for scenario B.

The development of the region of influence (of maintenance nourishments only) for scenario B is as expected almost identical to the development for scenario A (paragraph 5.4). In both scenarios the erosion volumes are evenly compensated by the maintenance nourishments, therefore the coastline orientation and resulting sediment transport (gradients) area around the maintenance nourishments are almost equal for both cases.

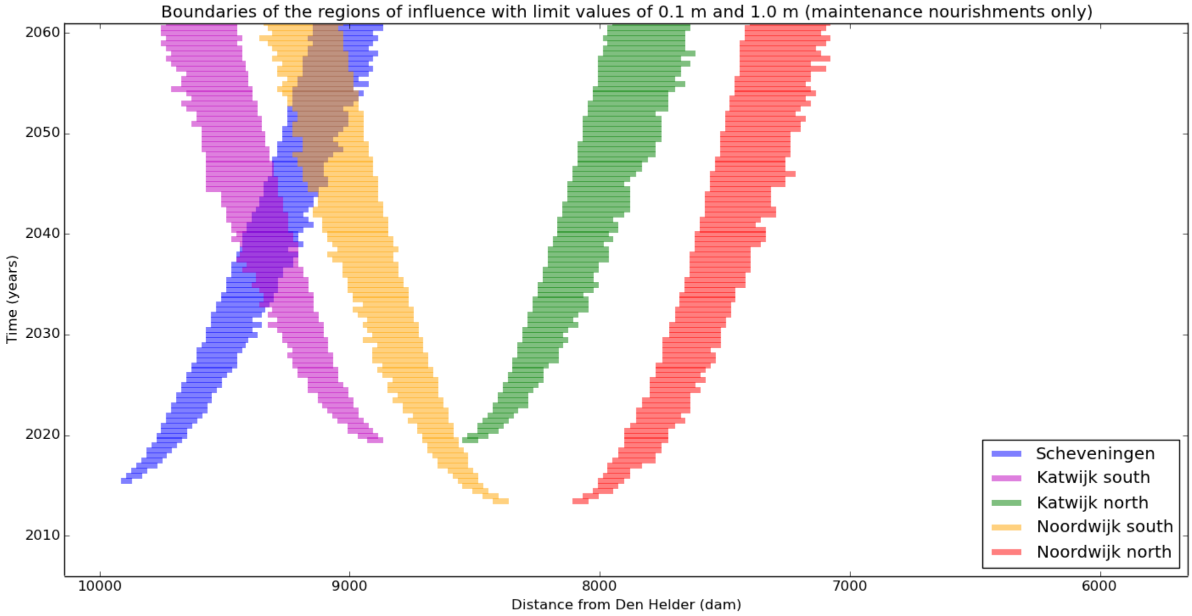

Figure H.3: Development of the region of influence for maintenance nourishments of scenario B.

In figure H.4 and H.5 the results for scenario C are presented, in which the volumes of the recently applied maintenance nourishments are maintained on the long term. In this case the coastline migrates seaward at all nourishment locations. Next to the difference at the nourishment locations, the main difference is found for the coastline position (figure H.4) at the locations with an initial negative coastline position. Due to the overcompensation of the erosion at the nourishment locations, more sediment is transported towards the adjacent coast. As a consequence, the process towards a positive coastline position at Wassenaar (km 93) and Noordwijkerhout (km 75) is accelerated.

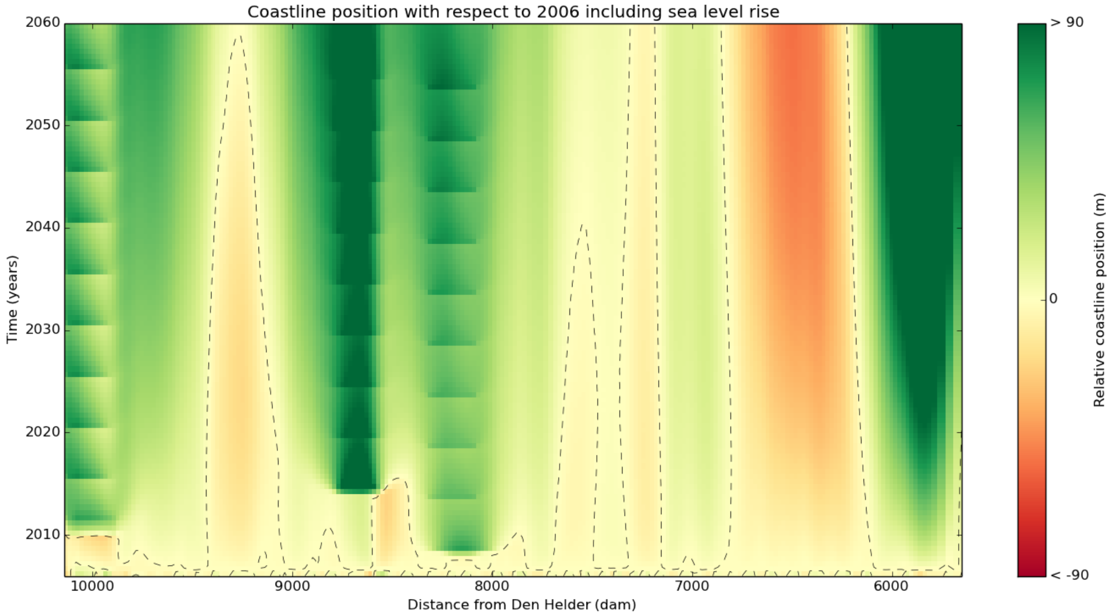

Figure H.4: Relative coastline position with respect to the 2006 coastline for scenario C.

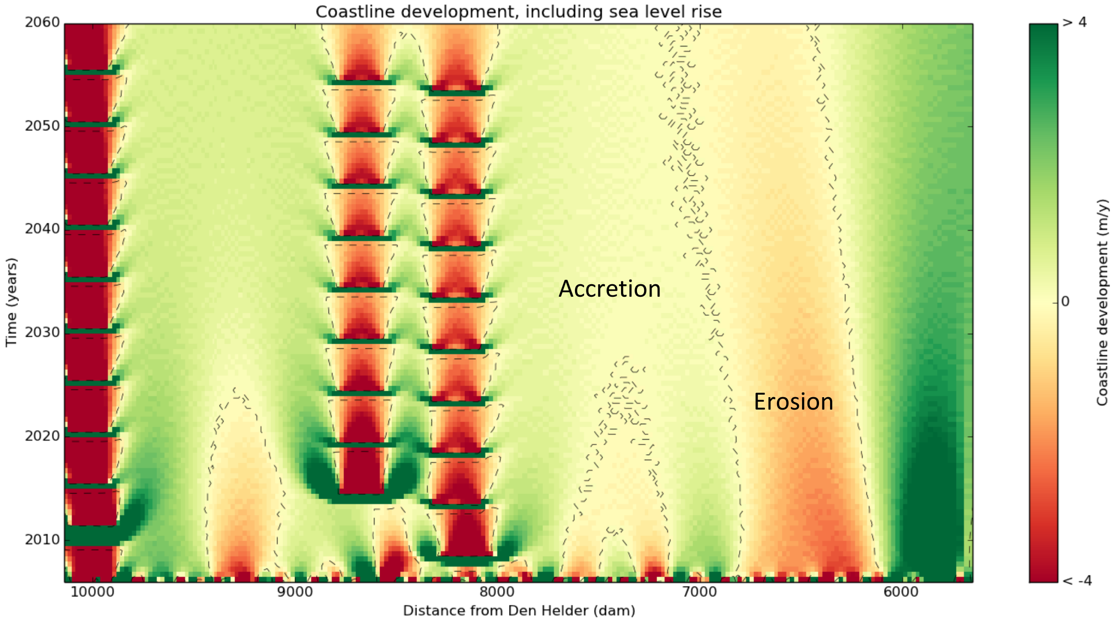

Figure H.5: Coastline development per year for scenario C.

The development of the regions of influence for scenario C is slightly different than for both other scenarios. Due to overcompensation of the erosion at the 'Zwakke Schakel' locations, the effect of nourishments on the transport gradients is larger, leading to an increase in size of the region of influence. However, with respect to the scale of the region of influence of around 15 to 24 kilometres, the difference of 1 kilometre in 2060 is almost negligible.

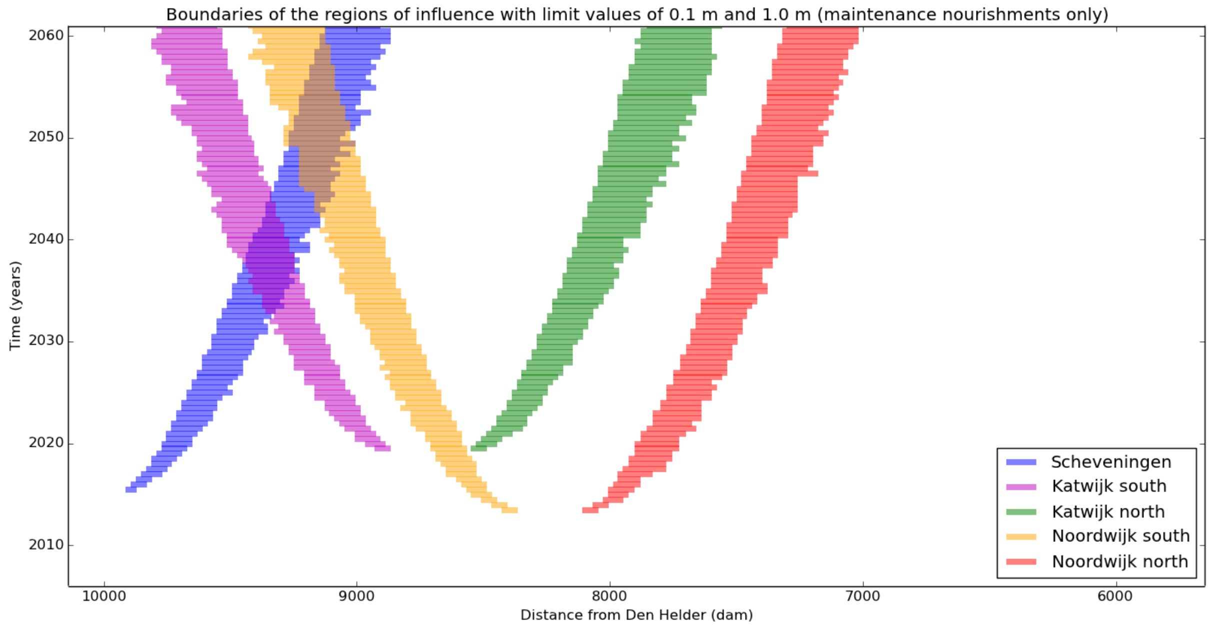

Figure H.6: Development of the region of influence for maintenance nourishments of scenario C.

The results for the reference case show that the area of erosion increases around the nourishment locations on the long term. The magnitude of the erosion however decreases over time because the situation on the long term is closer to the equilibrium situation (figure H.8). Around Katwijk and Noordwijk, the positive coastline position is at almost all locations maintained on the long term (figure H.7). The erosion in this area however also continues, so a negative coastline position is expected on the long term. Discussion on the maintenance of the nourishment locations at Noordwijk and Katwijk can be found in chapter 7. Figures H.7 and H.8 both make clear that long term application of nourishments in the area between Scheveningen and IJmuiden will surely be needed in order to maintain the desired coastline position at the 'Zwakke Schakel' locations.

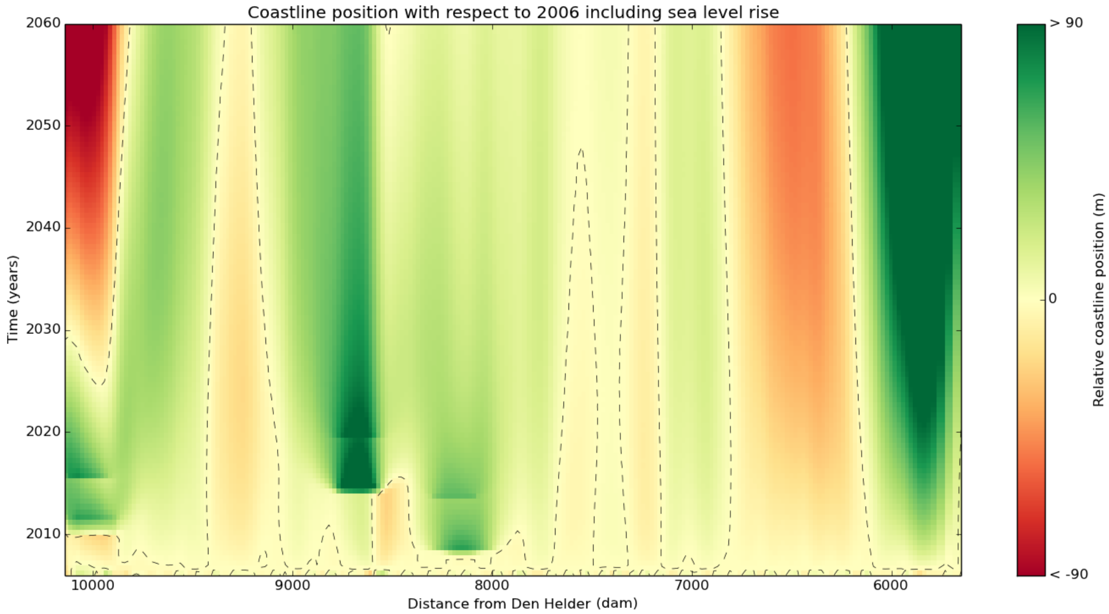

Figure H.7: Relative coastline position with respect to the 2006 coastline for the reference situation.

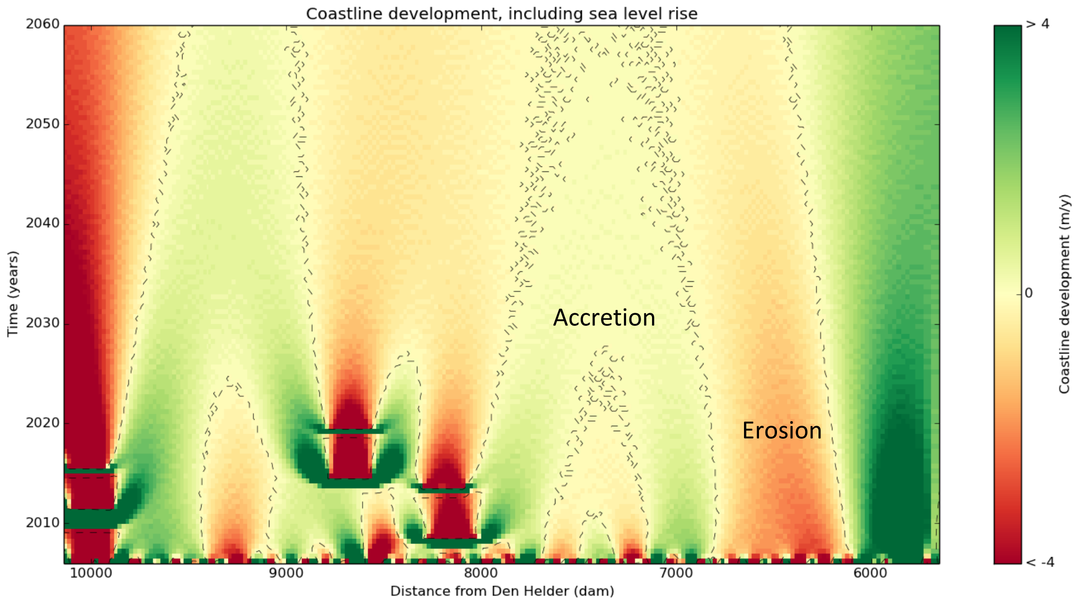

Figure H.8: Coastline development per year for the reference situation.

I. Evaluation model results

The figures presented in this appendix are complementary to the results of the evaluation as presented in paragraph 5.6. Figures for coastline development and figures presenting the relative coastline position are included for all cases. In table I.1 below, the characteristics of all cases are presented. The values in red are values which are changed with respect of the original situation. In case 1 therefore the influence of assumptions regarding the active profile height is investigated . Case 2 is used to investigate the consequences of the assumptions for sea level rise and case 3 includes a combined minimum and maximum scenario.

Case	Active profile height (m)	Sea level rise (cm/year)	Coastal profile slope (-)
Minimum case 1	8	1.0	1/50
Maximum case 1	12	1.0	1/50
Minimum case 2	10	0.2	1/50
Maximum case 2	10	1.5	1/60
Minimum case 3	8	0.2	1/50
Maximum case 3	12	1.5	1/60

Table I.1: Evaluated parameters and corresponding values for three evaluation cases.

Case 1 - Active profile height

In figure I.1 the development of the regions of influence are presented for active profile heights from 8 to 12 meter. On the long term, the uncertainty in active profile height leads to differences of around 3 kilometres for each boundary, on a total size varying between 20 and 26 kilometres. The variability in the moment of closure of the area between Scheveningen and Katwijk is 7 years, with the intersection expected to occur between 2029 and 2037. The limit value in for the region of influence in this case is set on 0.1 meter (see paragraph 5.4).

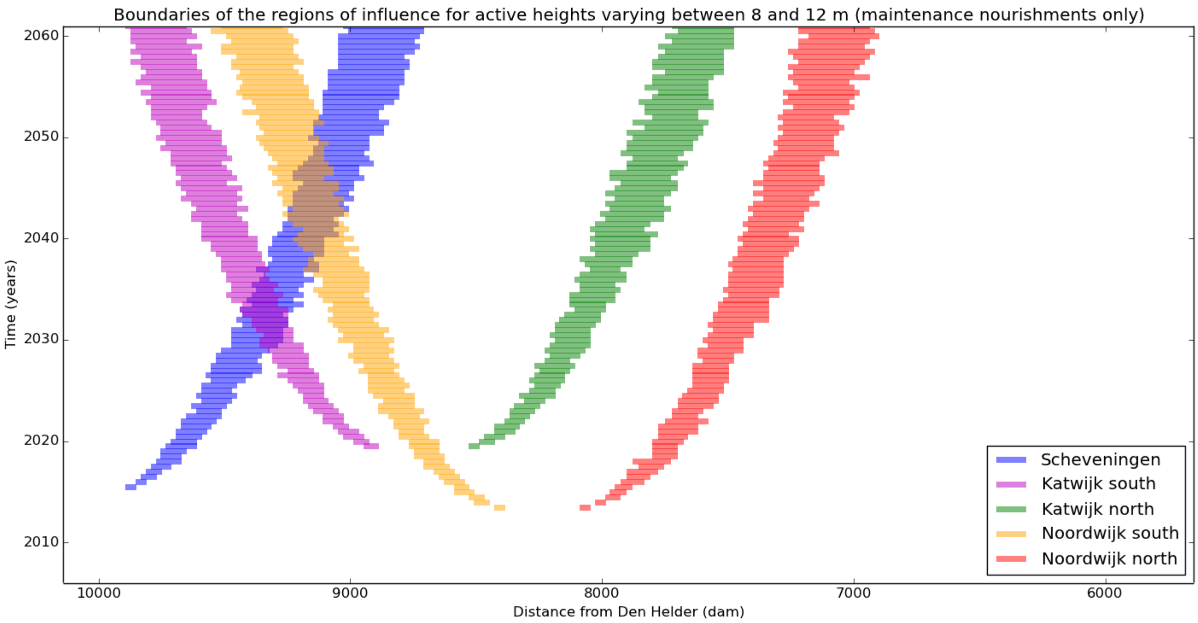

Figure I.1: Development of the boundaries of the regions of influence of only maintenance nourishments different values of the active profile height and a limit value of 0.1 meter.

Additionally, the effect of varying active profile heights on the development of the adjacent coast can be assessed by looking at the yearly coastline development. Generally, the development of the adjacent coast is more positive in case of a smaller active profile height (figure I.2). With an active profile height of 8 meter, positive development around Wassenaar (km 93) is already expected in 2020, while with an active profile height of 12 meter positive development is found from 2030 onwards. North of Noordwijk, the development is on the long term clearly more negative in case of an active profile height of 12 meters. Apparently the positive effect of the long term maintenance at Katwijk and Noordwijk is in this case not sufficient for providing a positive development in the region of Noordwijkerhout on the long term.

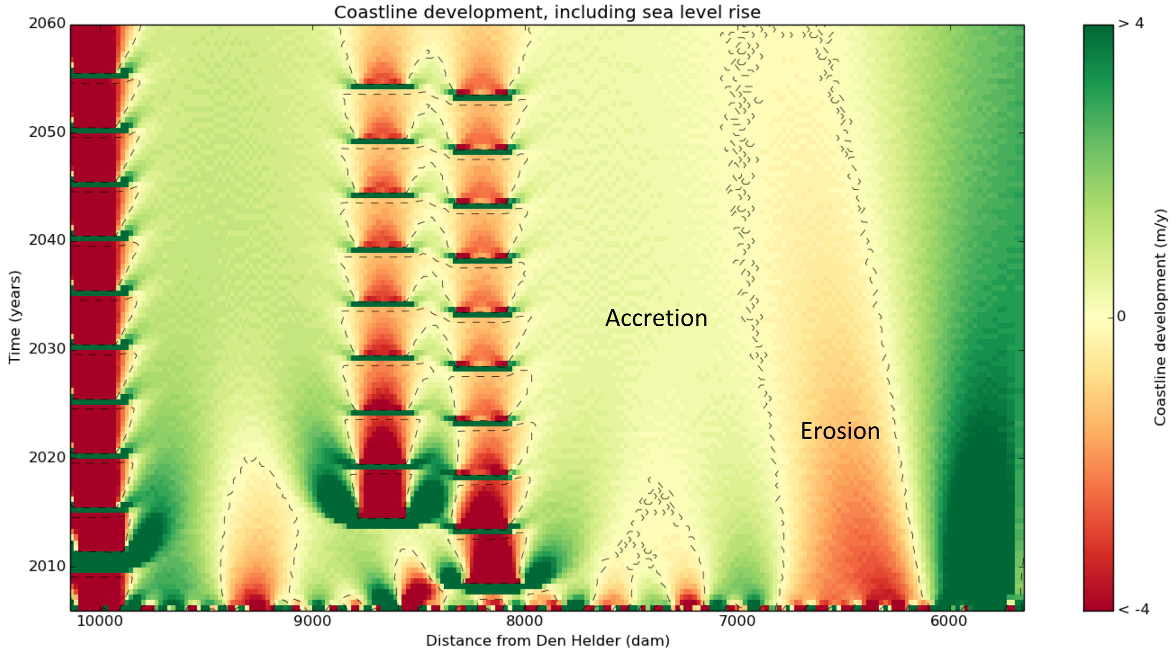

Figure I.2: Coastline development per year for minimum case 1 with smaller active profile height.

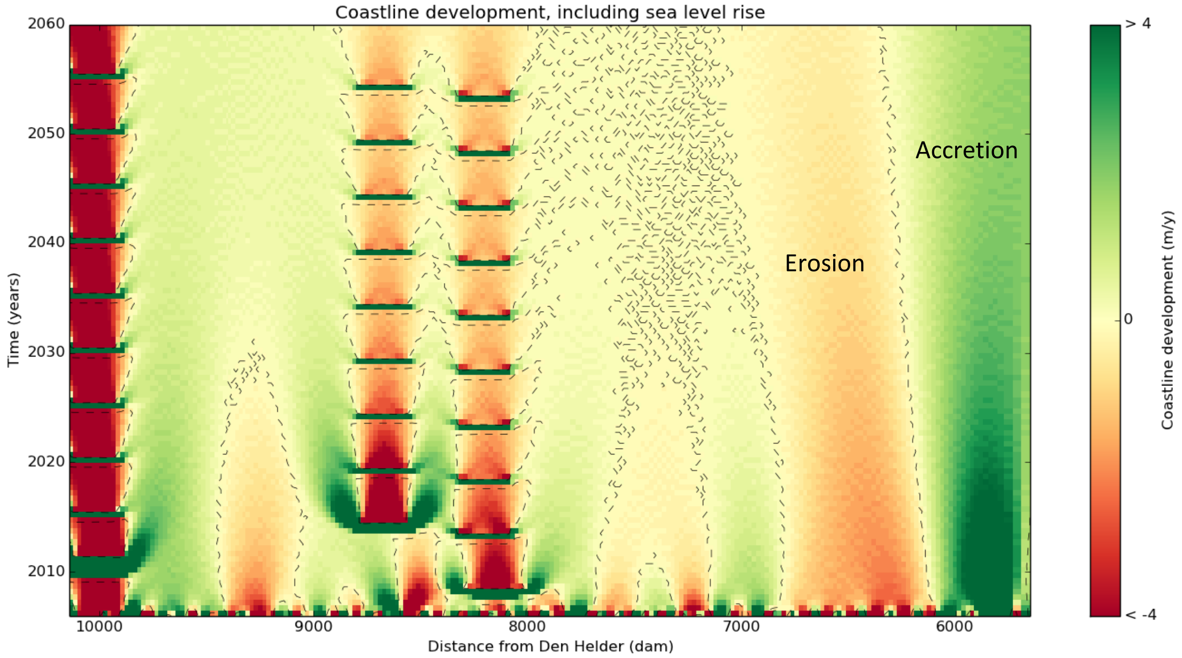

Figure I.3: Coastline development per year for maximum case 1 with larger active profile height.

The results for the relative coastline position are in line with the development results. Around Wassenaar and Noordwijkerhout, positive coastline positions are already expected between 2040 and 2050 in case of an active profile height of 8 meters (figure I.4). In the original case, no positive coastline position was found in these regions within the model timescale. On the other hand, a more negative result is found with an active profile height of 12 meters (figure I.5). Due to the positive development on the long term, the coastline position at Wassenaar is also in the maximum case moving towards a positive position. North of Noordwijk, this is however not the case due to the negative development which is expected on the long term.

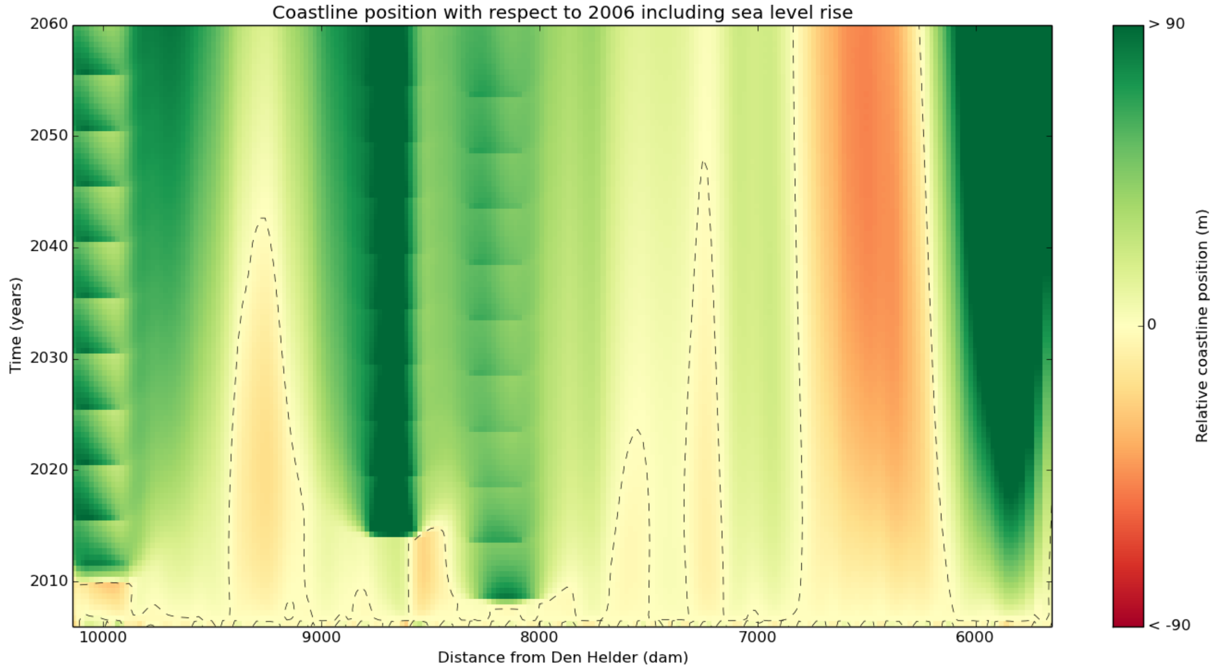

Figure I.4: Relative coastline position with respect to the 2006 coastline for minimum case 1 with smaller active profile height.

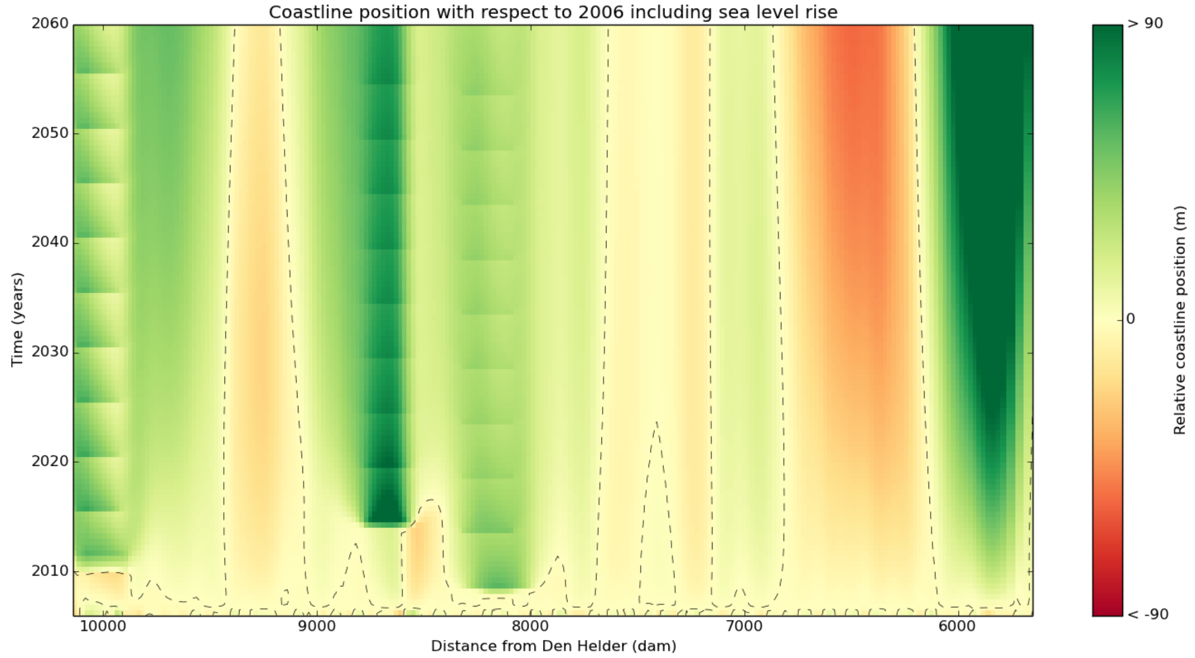

Figure I.5: Relative coastline position with respect to the 2006 coastline for maximum case 1 with larger active profile height.

Case 2 - Sea level rise

Figure I.6 visualises the yearly coastline development for the minimum case, in which the effect of sea level rise is equal to -0.1 m/year. This effect of sea level rise is especially interesting for the short term results, since it is in line with current practice. Figure I.7 visualises the maximum case with an additional negative coastline development of -0.9 m/year. North of Noordwijk, mainly positive development is found on the long term for low sea level rise, while mainly negative development is found with high sea level rise. Around Wassenaar (km 93), the variable effect of sea level rise has its influence on the moment for which negative development turns into positive development. Between both cases, a difference of 10 years is found.

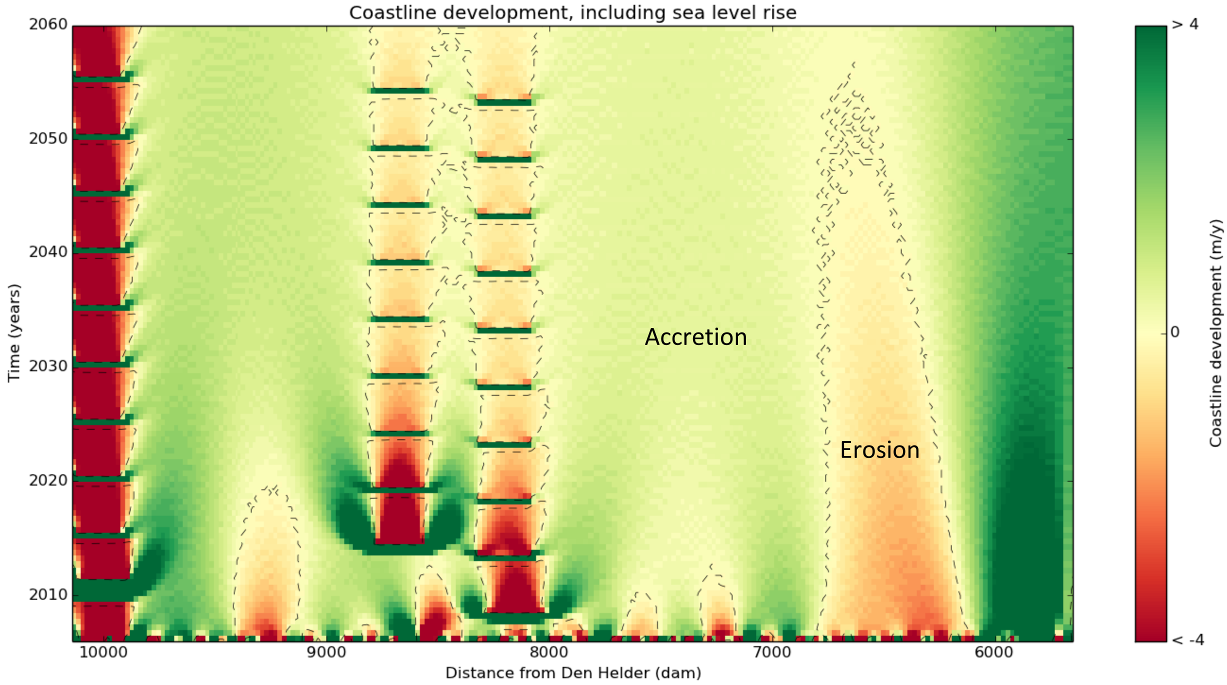

Figure I.6: Coastline development per year for minimum case 2 with a smaller effect of sea level rise.

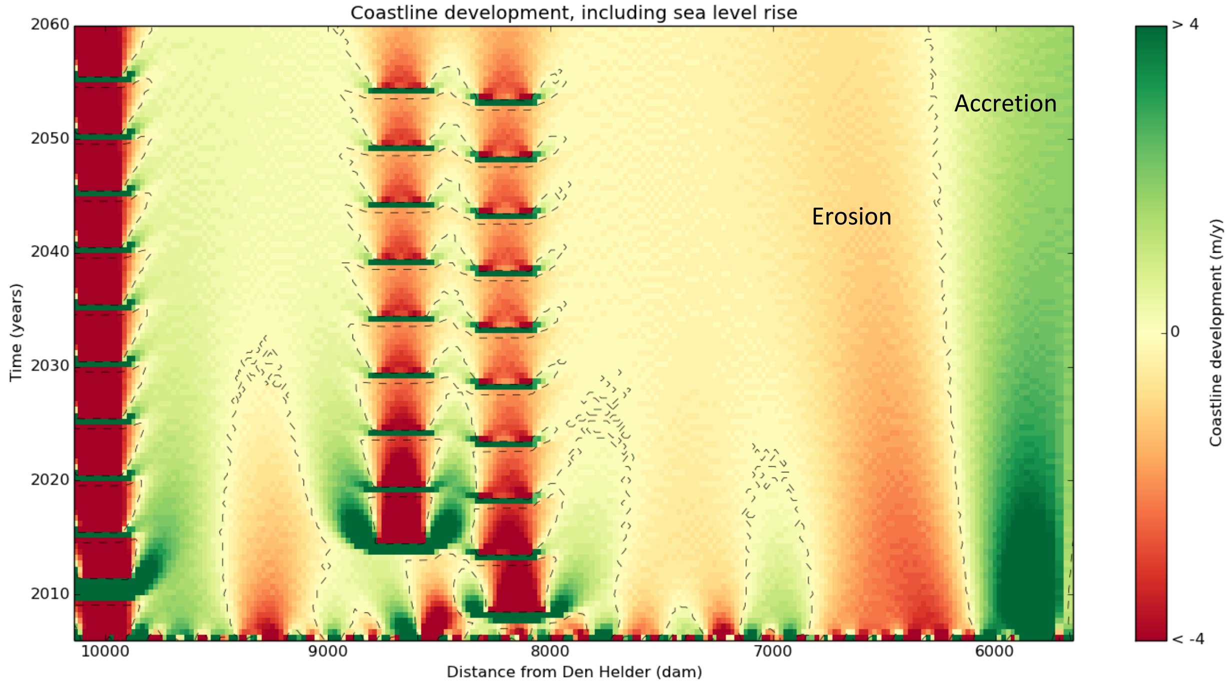

Figure I.7: Coastline development per year for maximum case 2 with a larger effect of sea level rise.

A much more positive result is found for the coastline position in case of smaller sea level rise. Around Wassenaar and Noordwijkerhout, positive coastline positions are found within the model time scale (figure I.8). For an increased effect of sea level rise, a negative coastline position is found for almost the entire area of interest except around the nourishment locations. Around Wassenaar however, a positive coastline position is expected on the long term. The region around Noordwijkerhout cannot be maintained by the sediment transported from the recurring maintenance nourishments according to these model results.

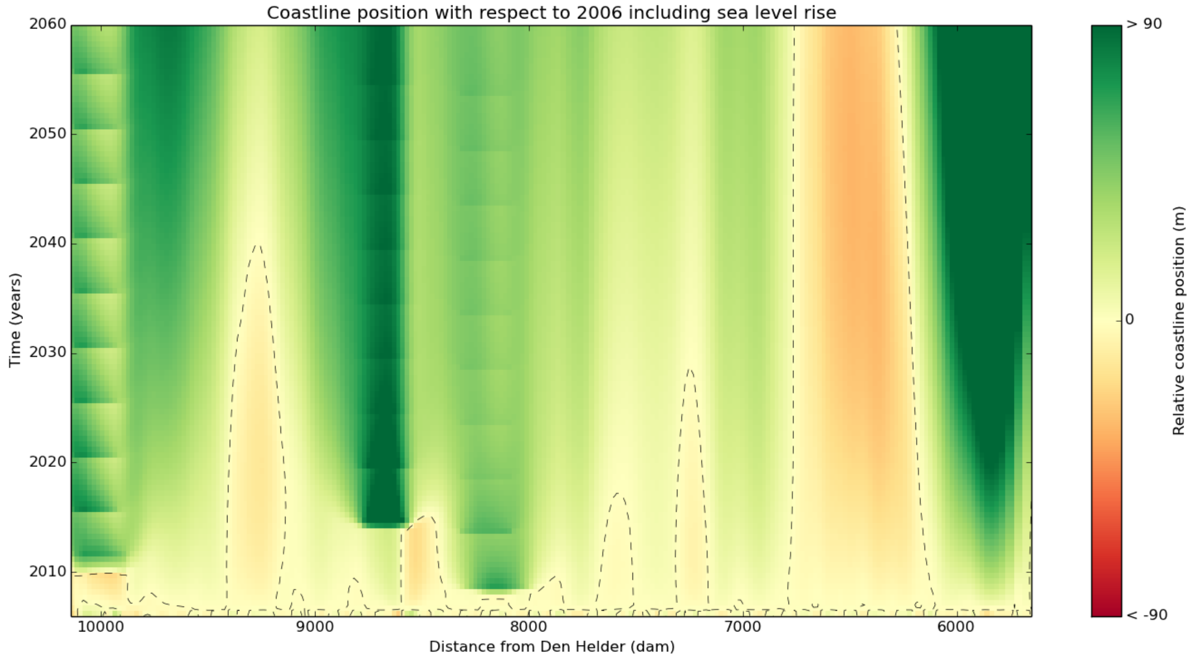

Figure I.8: Relative coastline position with respect to the 2006 coastline for minimum case 2 with a smaller effect of sea level rise.

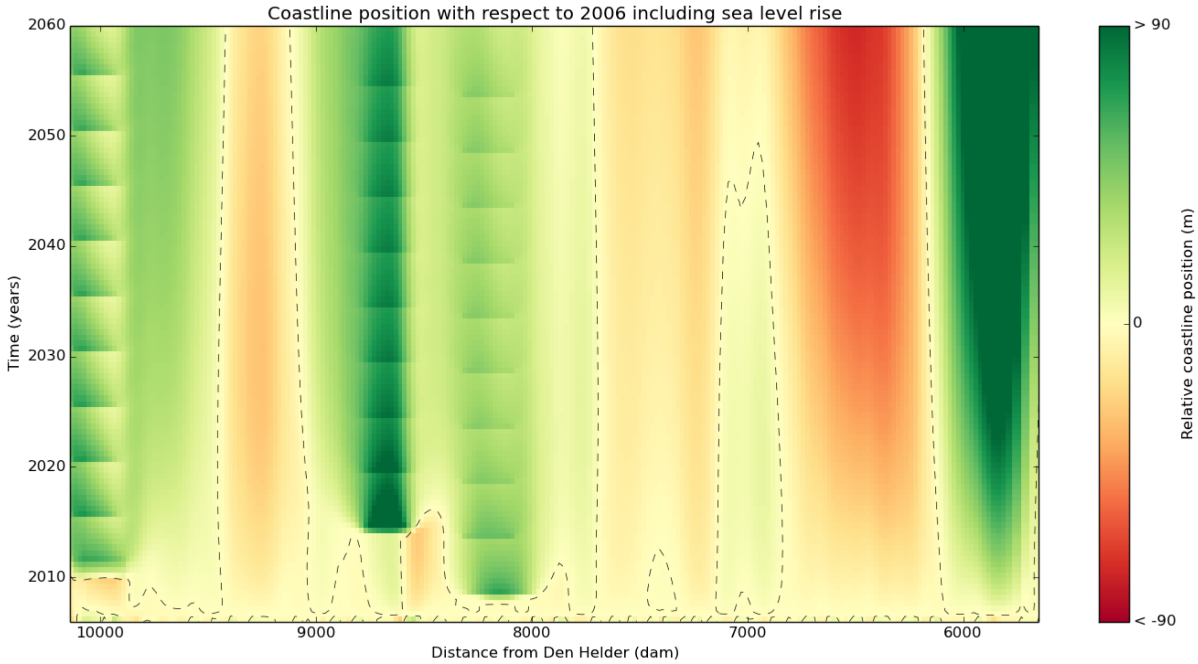

Figure I.9: Relative coastline position with respect to the 2006 coastline for maximum case 2 with a larger effect of sea level rise.

Case 3 - Sea level rise and active profile height

Looking at the yearly coastline development, a very large difference between the minimum and maximum case can be observed. Where the minimum case shows positive coastline development already from 2017 onwards, the maximum case shows only positive coastline development around Wassenaar at the end of the model time scale. The development in this case is around zero between the years 2040 and 2060. Taking into account both case, high uncertainty is present in whether to expect a positive development or not around Noordwijkerhout on the long term.

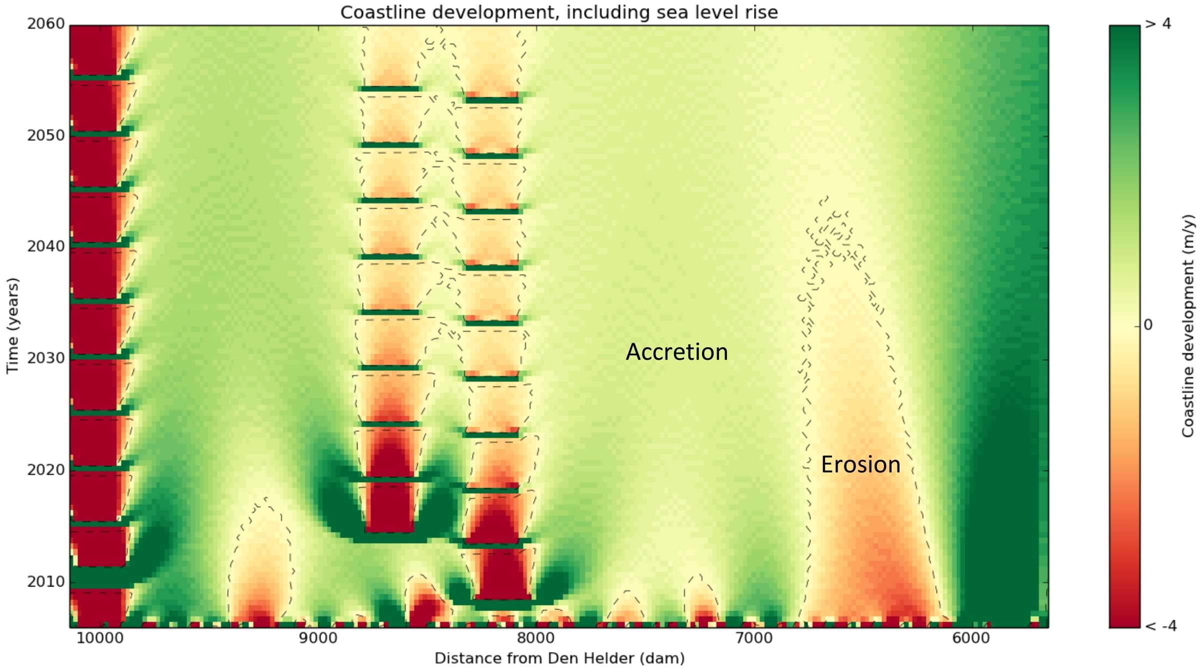

Figure I.10: Coastline development per year for minimum case 3 with smaller active profile height and a smaller effect of sea level rise.

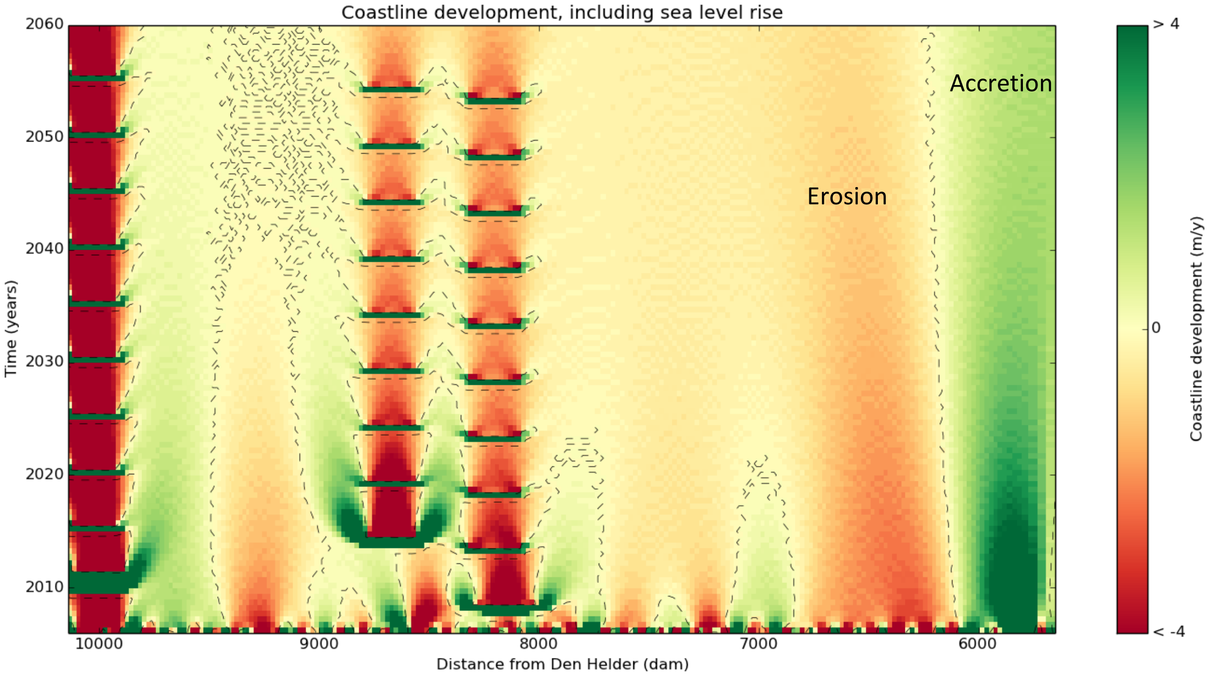

Figure I.11: Coastline development per year for maximum case 3 with larger active profile height and a larger effect of sea level rise.

The difference in coastline development between the minimum and maximum case becomes also clear in the coastline position over time (figure I.12 and I.13). In the positive situation the entire coastline within the regions of influence is expected to be located seawards from the 2006 coastline from around 2032 onwards. In the maximum case, a positive coastline position is only observed close to the nourishment locations. North of Noordwijk, the situation even becomes worse over time despite the regular application of maintenance nourishments.

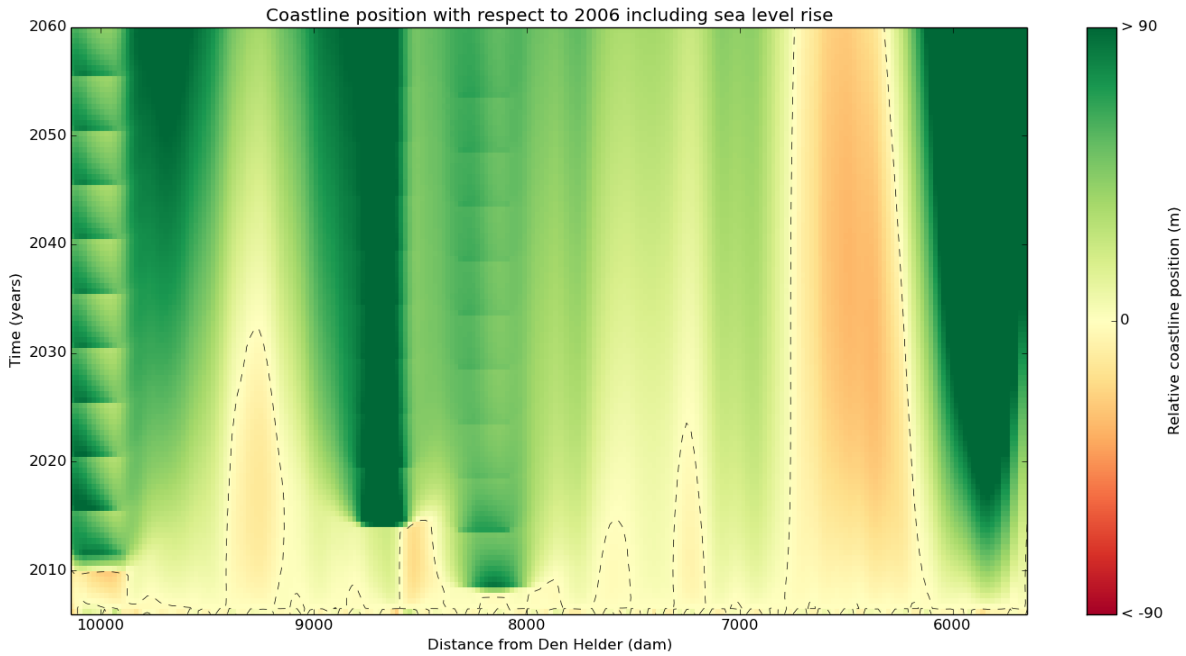

Figure I.12: Relative coastline position with respect to the 2006 coastline for minimum case 3 with smaller active profile height and a smaller effect of sea level rise.

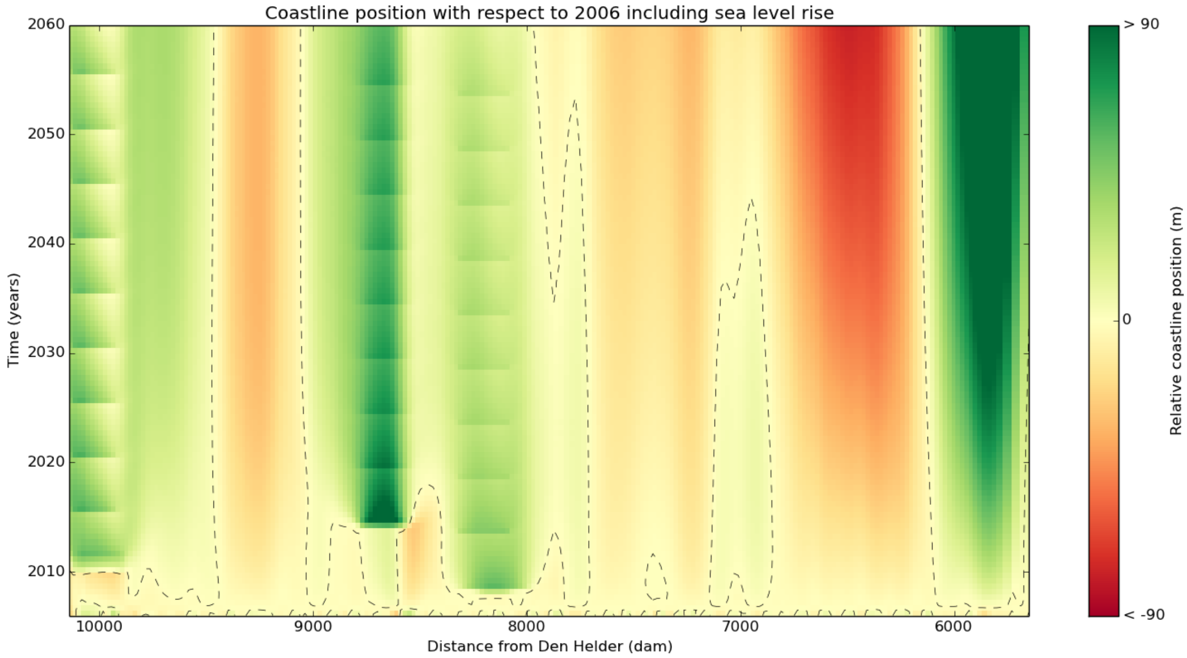

Figure I.13: Relative coastline position with respect to the 2006 coastline for maximum case 3 with larger active profile height and a larger effect of sea level rise.

J. Model setup shoreface nourishments

Important to note is that investigating the effect of shoreface nourishments is not in line with the problem description, objective and research questions of this thesis. Therefore the effect of shoreface nourishments is only discussed in appendices J (setup) and K (results). The results of this additional research are not used to answer the research questions, but only used to give an additional impression on the possible contribution of shoreface nourishments on the maintenance of the coast in the area of interest.

In the model validation (paragraph 4.5) becomes clear that shoreface nourishments probably have a significant influence on the coastline development. Additionally, in the model results in paragraph 5.3, it becomes clear that the coastline in the upcoming decades cannot be maintained by only the ‘Zwakke Schakel’ maintenance nourishments. In reality, additional shoreface nourishments already are applied in the area of interest. Over the past decades, shoreface nourishments are applied in Wassenaar (km 92), Noordwijkerhout (km 75) and Bloemendaal/Zandvoort (km 60 to 70). These areas correspond to the erosional spots in the model results. Furthermore, also at Katwijk and Noordwijk, additional shoreface nourishments are applied.

However, the shoreface nourishments are mostly applied outside the area which is covered by the Unibest model and the Unibest model does not take into account cross shore sediment transport, which is an important process in the development of shoreface nourishments. In reality, some sediment from the shoreface nourishments will however end up in the surf zone and beach area and therefore contribute to a positive coastline development. According to previous research on the effectiveness of shoreface nourishments with respect to coastline development, around 20 to 35% of the shoreface nourishment volume in the region of Katwijk and Noordwijk contributes directly to the coastline development during the shoreface nourishment lifetime (Witteveen+Bos, 2006a; 2006b). The area over which this contribution is measured is comparable with the considered area in the Unibest model, which on average reaches a depth of 5 to 6 meter.

Table J.1 shows all applied shoreface nourishments in the period between 2006 and 2017. The effect of these nourishments on the coastline development is additionally investigated with the Unibest model. In figure 5.13 and 5.14 of the model results, it is clearly visible that Wassenaar, Noordwijkerhout and Bloemendaal-Zandvoort are the weak spots in the region, despite the recurring nourishments at the ‘Zwakke Schakel’ locations. At these locations, regularly shoreface nourishments were applied in the past decades which should be taken into account in the model. It is chosen to include only nourishments applied since 2006 in the model, although the lifetime of a shoreface nourishment may be up to 10 years (paragraph 2.5). The effect of nourishments applied in the period before 2006 may however already partly be present in the equilibrium profiles used in the model. As a consequence, shoreface nourishments around Noordwijkerhout are not included while clearly negative development is found at this location. Nevertheless, this exclusion is in line with the current practice, since one is cautious with applying nourishments in the region of Noordwijkerhout, because sand waves are present in this area (Kuijper et al., 2015).

Location	Size (m^3)	Type	Distance from den Helder (dam)	Date	Program
Bloemendaal	1,002,957	Shoreface	6100-6300	06/2008 – 11/2008	Regular
Bloemendaal - Zandvoort	2,400,000	Shoreface	6100-6850	04/2016 – 10/2016	Regular
Zandvoort Zuid	509,913	Shoreface	6775-7075	06/2008 – 09/2008	Regular
Noordwijk - Katwijk	1,055,035	Shoreface	8150-8900	03/2006 – 09/2006	Regular
Rijnland Zuid (Noordwijk - Katwijk)	2,200,000	Shoreface	8000-8850	02/2014 – 08/2014	Regular
Wassenaar	800,400	Shoreface	8900-9700	05/2006 – 09/2006	Regular

Table J.1: Shoreface nourishments applied in the area of interest from 2006 onwards.

In table J.2, the effect of shoreface nourishments on coastline development over the years is presented. A value of 15% means that 15% of the original nourishment volume contributes to the sediment volume present in the surf zone and beach area. The values in these table are schematized for use in the Unibest model. A continuous sediment source is added to the relevant location, such that volume percentages of table J.2 are present at the beach at the given years. In reality, more fluctuations in the effect over the years are present and slightly different results are found for different alongshore and cross shore locations. The timescale over which the shoreface nourishments affect the coastline development is set on 7 years, taking into account the variable lifetime of shoreface nourishments and the results from previous research. Half a year past the 7 years, a new shoreface nourishment is applied in the model, which sets the return period of the nourishments on 7.5 years. This return period is in correspondence with the real return period of the shoreface nourishments at Bloemendaal and Zandvoort. Note that at Bloemendaal and Zandvoort, alternating nourishment locations are used in line with the different locations as presented in table J.1.

Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
0%	15%	17.5%	20%	22.5%	25%	27.5%	30%

Table J.2: Percentage of the volume of shoreface nourishments which is present in the nearshore.

Furthermore important for the model implementation is that part of the sediment which is added as source is transported towards the adjacent coast. Therefore, in order to reach a volume percentage of 30% in year 7, more than 30% of the original nourishment volume needs to be added as source. The larger the nourishment volume per meter, the larger the source (in percentage), because the erosion volume increases for increasing absolute nourishment volume.

The values in the table are based on research done on shoreface nourishments at Noordwijk, Katwijk and Wassenaar. For the region around Bloemendaal-Zandvoort, no research is done into the effect of shoreface nourishments. However, for the region around Bergen, which is located northwards from Bloemendaal-Zandvoort, the effect is comparable to the effect in Noordwijk and Katwijk. Therefore it is assumed that also the effect of shoreface nourishments at Bloemendaal-Zandvoort is similar to this effect.

K. Model results shoreface nourishments

With the modelled return period of the shoreface nourishments being equal to 7.5 years (Appendix J), it is chosen to present the model results for the years 2023 and 2053. In this case two comparable results are generated, with the same moment in time relative to the shoreface nourishment scheme. First the effect of the shoreface nourishments on sediment transport (gradients) is presented, after which the development of the coastline is assessed.

Longshore sediment transport volume

In figures K.1 and K.2 becomes clear that the influence of the shoreface nourishments on the longshore sediment transport volumes in the nearshore is low. The influence of the shoreface nourishments on the coastline orientation is relatively low, because only small amount of sediment reach the beach at a certain moment in time. With beach nourishments, large amounts of sediment reach the beach during application, leading to large changes in coastline orientation. Remarkable are the points of reflection around km 68 and km 60 in the case with shoreface nourishments. This behaviour is directly caused by the (small amount of) sediment transported from the shoreface nourishment towards the beach, which is the continuous source in the model. This small amount of sediment leads to a small change in coastline orientation, causing an abrupt change in sediment transport volume. The points of reflection are, to a lesser extent due to the smaller nourishment size, also visible around the shoreface nourishment at Wassenaar.

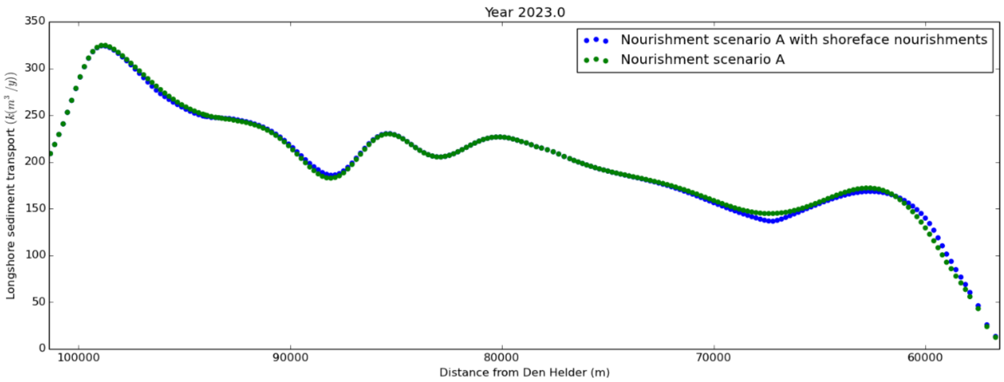

Figure K.1: Longshore sediment transport volumes in 2023 for nourishment scenario A, with and without shoreface nourishments.

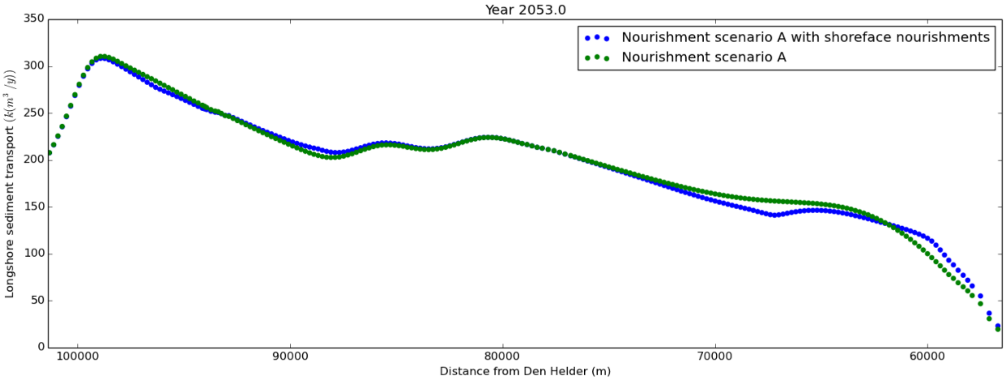

Figure K.2: Longshore sediment transport volumes in 2053 for nourishment scenario A, with and without shoreface nourishments.

Longshore sediment transport gradient

The influence of the shoreface nourishments on the sediment transport is better visible when looking at the sediment transport gradients. On the long term it is clearly visible that the gradient is affected by the shoreface nourishments. Along the stretch where the shoreface nourishment contributes to the sediment volume in the nearshore, the gradient becomes more positive. Leading to either additional erosion or a decrease in accretion. In case of a decrease in accretion, the application of shoreface nourishments is questionable. In that case, a positive development is also expected without the application of shoreface nourishments. Whether the effect of the shoreface nourishment is positive in the end, depends on the sediment which contributes to the development of the coastline via cross shore transport. This effect is not included in the graphs below, only longshore transport gradients are presented. The decision on whether to apply a shoreface nourishment or not is not included in this part of the research, which focusses on the long term contribution of shoreface nourishments assuming a fixed return period of 7.5 years.

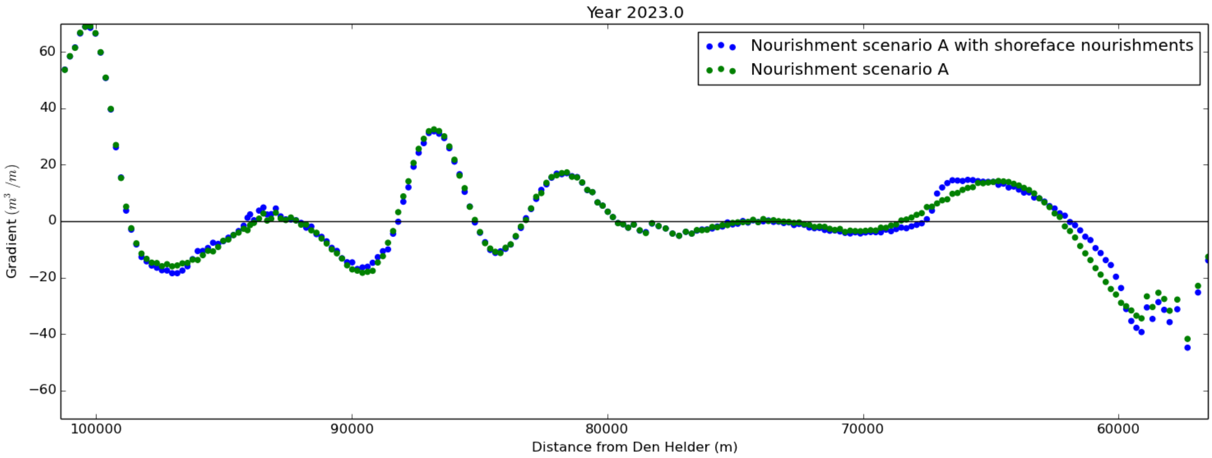

Figure K.3: Longshore sediment transport gradients in 2023 for nourishment scenario A, with and without shoreface nourishments.

Figure K.4: Longshore sediment transport gradients in 2053 for nourishment scenario A, with and without shoreface nourishments.

Overall development

Looking at the overall development, it is clear that shoreface nourishments in general have a positive contribution to the development of the coastline. The process of migrating from a negative coastline position towards a positive coastline position is accelerated at Wassenaar (km 93), while the negative trend in coastline development at Bloemendaal and Zandvoort (km 65) even turned into a positive trend. When assigning a certain value to these results, it is important to take all assumptions which are made during model setup into account (see Appendix J).

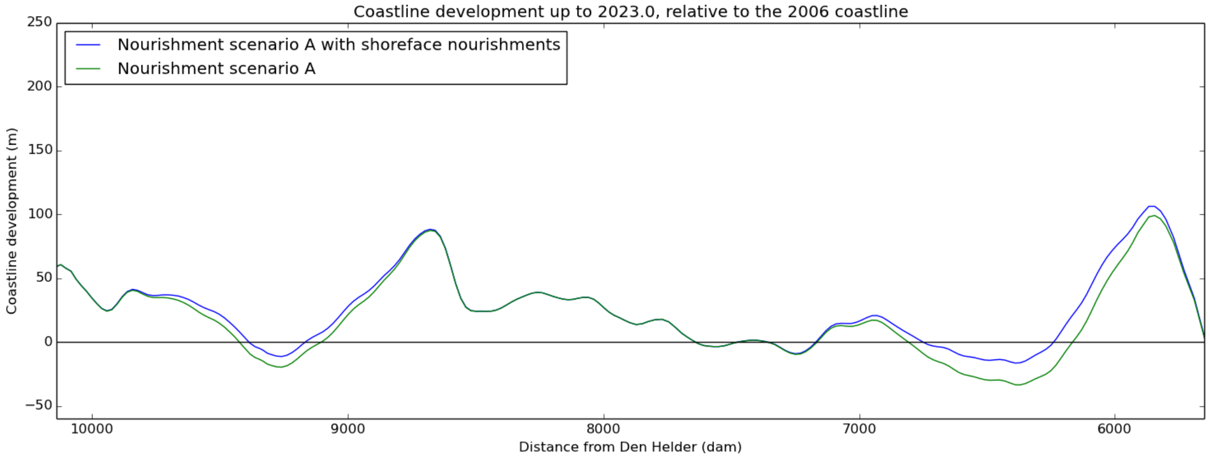

Figure K.5: Coastline development in 2023 for scenario A, with and without shoreface nourishments, relative to the 2006 coastline.

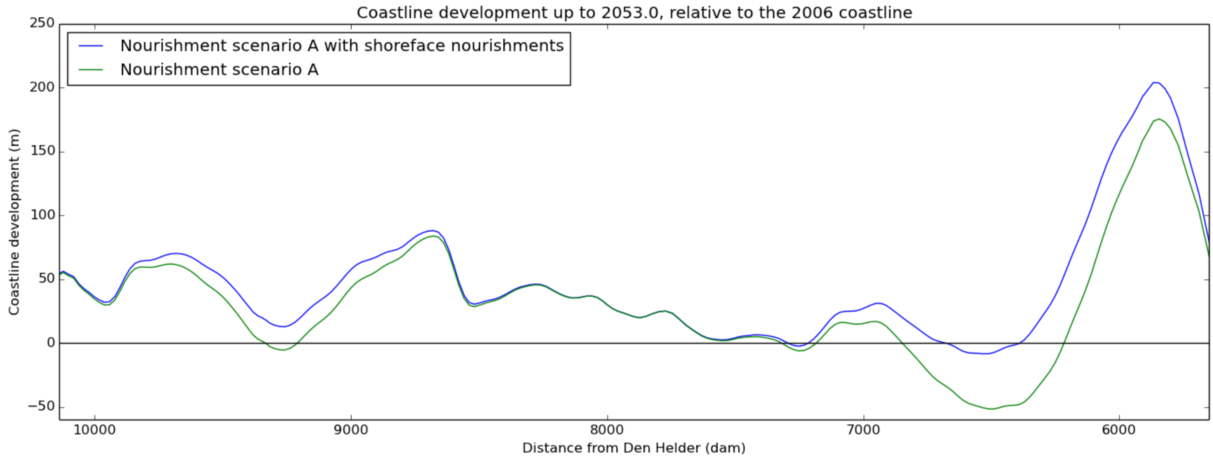

Figure K.6: Coastline development in 2053 for scenario A, with and without shoreface nourishments, relative to the 2006 coastline.

Coastline development and coastline position

Looking at coastline development and the coastline position over time, the shoreface nourishments clearly improve the situation. The relative coastline position at Wassenaar becomes positive in 2040 and the area with a negative coastline position around Bloemendaal and Zandvoort decreases in size over the years and moves landwards, opposite to the situation without shoreface nourishments. Clearly, the effect is best visible in the first year after nourishment application, when the negative development switches to positive development (figure K.8). This behaviour is directly caused by the assumptions made for implementation of the effect of shoreface nourishments in the model (Appendix J). In the six years thereafter, the contribution of the shoreface nourishments is initially not sufficient to compensate the autonomous negative development. On the long term however, positive development can be observed at all locations except for the 'Zwakke Schakel' nourishment locations. In 2060, the magnitude of the negative relative coastline position has a magnitude of around 20 meters. Without the effect of shoreface nourishments, the coastline is located around 2 to 3 times further landwards with respect to the 2006 coastline. Although not implemented in the model, the application of shoreface nourishments in the region of Noordwijkerhout (km 75) may provide a positive coastline position in this region within the model time scale, similar to the Wassenaar case. Again important to note is that the shoreface nourishments have a significant influence on the state of the coast in the area of interest, but do not significantly influence the sediment transport quantities around the maintenance nourishment locations. Therefore these results are irrelevant for the main objective of this research and are not used when answering the research questions.

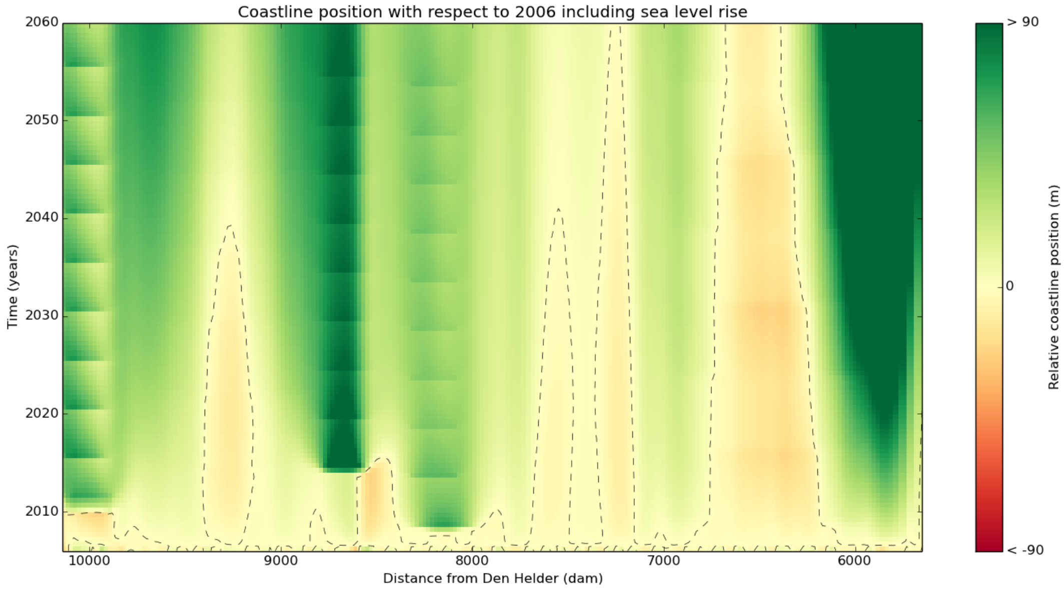

Figure K.7: Relative coastline position with respect to the 2006 coastline for scenario A, including the effect of shoreface nourishments.

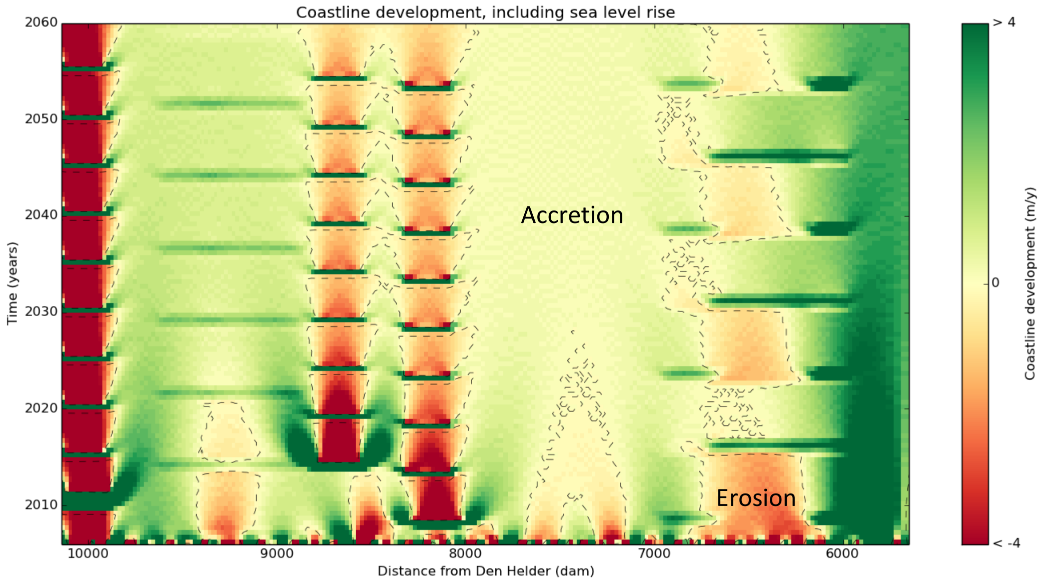

Figure K.8: Coastline development per year with scenario A, including the effect of shoreface nourishments.