Master of Science Thesis

Morphological behaviour of shoreface nourishments along the Dutch coast

Data analysis of historical shoreface nourishments for a better understanding and design

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TU Delft Delft University of Technology

Interreg North Sea Region Building with Nature European Regional Development Fund EUROPEAN UNION

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Deltares Enabling Delta Life

Front cover:

A view on the coast at Zandvoort. In this picture, breaking waves on a sandbar are well shown. (Source: https://beeldbank.rws.nl *, Rijkswaterstaat)*

Morphological behaviour of shoreface nourishments along the Dutch coast

Data analysis of historical shoreface nourishments for a better understanding and design

By

R.J. (Rolf) Bruins

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“Education is the most powerful weapon, which you can use to change the world”

Nelson Mandela

Preface

This thesis report concludes the Master of Science program in Civil Engineering at Delft University of Technology, the Netherlands. The topic of this graduation thesis is the morphological behaviour of shoreface nourishments. The thesis is carried out at Rijkswaterstaat and Deltares.

I would like to thank all my supervisors for the opportunity to work with them on the interesting topic of this thesis. Thanks to Quirijn Lodder for the opportunity he gave me to perform this thesis on my own way at Rijkswaterstaat. I appreciate the freedom he gave me to find the best path to approach this thesis, but also the support and chances he gave me. I would like to thank Dirk-Jan Walstra and Ad van der Spek for the supervision and feedback they gave to improve the research more deeply and their advices from their experience at Deltares. I would like to thank Bram van Prooijen for his valuable feedback on my report and the nice talks we had about the process of graduating and I would like to thank Marcel Stive for his valuable and constructive feedback during meetings. Apart from my supervisors, I would like to thank my colleagues and fellow students at Rijkswaterstaat and Deltares for their nice talks, lunches and coffee breaks, which were pleasant and gave me a good impression of the companies. In addition, I especially would like to thank Warner Bruins, Bertjan Bosselaar, Gert-Jaap Koppenol, Rinse Wilmink and Bas Quirijns for their valuable feedback on this report.

I would like to say thanks to my parents, for the opportunity they gave me to study and for their encouragements and support during my study. In addition, I would like to say thanks to my family and friends for their support during my study. Last, but certainly not least, special thanks to my wife for her support and trust in me during my study and especially this thesis.

R.J. (Rolf) Bruins

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Summary

Relative sea level rise occurs in The Netherlands, because of sea level rise, subsidence of land and erosion along the coast. This leads to a higher risk of coastal flooding and threatens activities in the coastal zone. To counteract this problem, the Dutch ministry of infrastructure and environment created a policy aiming at compensating the relative sea level rise and maintaining the functions of the beach and dunes. One of the measures of this policy is adding sand in the coastal profile: sand nourishments.

The shoreface nourishment is one type of sand nourishments. Sand is nourished on the shoreface, under water, between typically -5 m and -8 m NAP. The observed morphological behaviour of shoreface nourishments is divers. In this thesis, the behaviour of historical shoreface nourishments is analysed. The morphological behaviour and factors that might influence this behaviour are compared to identify factors that steer the morphological behaviour. The results of this comparison are validated and finally, conclusions are drawn about the behaviour and the design of shoreface nourishments.

This research revealed two different types of migration for shoreface nourishments along the Dutch coast. The first type has a negligible alongshore migration and an on- or offshore directed cross-shore migration. This type occurs mainly at locations where there is no influence of coastal structures (such as groynes) and outer deltas of tidal inlets. The second type has an onshore and alongshore directed migration. This type occurs mainly southward of outer deltas of the Wadden Sea. For the situation with dominant cross-shore original bar behaviour, the sand bars and shoreface nourishments migrate to the zone of decay. In this zone, sandbars and shoreface nourishments dissipate. The development of a bar-trough system occurs if the natural bar behaviour is cross-shore dominated. For situations with dominant alongshore migration of sandbars, the formation of troughs almost never occurs. In addition, a higher crest results in a deeper trough.

Shoreface nourishments generally have a positive effect on the sediment volume in the coastal profile. After execution of the shoreface nourishment, the sediment volume increases. In subsequent years, the sediment volume remains constant or slightly decreases. Between the year before execution and the last year of occurrence of the shoreface nourishment, a net positive volume trend exists. At locations with cross-shore migration, the sediment volume will increase onshore of the shoreface nourishment. At locations with alongshore migration, it seems that the salient effect induces an increase of sediments onshore of the shoreface nourishment.

The last part of this thesis focusses on improving the decision making process in designing a shoreface nourishment. This thesis shows that execution of new shoreface nourishments depends on 1) the natural behaviour of the bar system, 2) the position of the zone of decay (in case of dominant cross-shore bar behaviour) and 3) the position of the outer bar. The shoreface nourishments should be executed in the zone between -5 m and -8 m NAP and offshore of the outer bar, this is in line with common design rules for shoreface nourishments. In addition, the shoreface nourishment should be applied in front of the erosion location and at the zone of decay or offshore of this zone.

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Acronyms

AD	=	Year of the Lord (Anno Domini)
AM	=	Ameland
BCL	=	Reference CoastLine (in Dutch BKL: Basis KustLijn)
BP	=	Before Present
DELF	=	Delfland
HW	=	High Water
JARKUS	=	Yearly coastal survey (JAaRlijkse KUStmeting)
MCL	=	Present CoastLine (in Dutch MKL: Momentane KustLijn)
MCM	=	Million Cubic Meters
MHWL	=	Mean High Water Level
MLW	=	Mean Low Water
MLWL	=	Mean Low Water Level
MSL	=	Mean Sea Level
NAP	=	Amsterdam Ordnance Datum (Normaal Amsterdams Pijl)
NH	=	Noord-Holland
NW	=	NorthWest
RD	=	Basis for the designation of coordinates in The Netherlands (RijksDriehoek)
RSP	=	Reference line for the cross-shore migration from the coast (RijksStrandPaal)
RIJN	=	Rijnland
VLIE	=	Vlieland
SLR	=	Sea Level Rise
SW	=	SouthWest
TEX	=	Texel

Symbols

α	=	Bed slope	[°]
θ	=	Angle of wave incidence	[°]
ξ	=	Irribarren number	[-]
ρ_w	=	Density of water	[kg/m^3]
A_{KF}	=	Area of Coastal Foundation	[m^2]
A_{WDS}	=	Area of The WaddenSea	[m^2]
A_{WS}	=	Area of The Western Scheldt	[m^2]
C	=	Wave velocity	[m/s]
E	=	Mean wave energy per unit horizontal area	[J/m^2]
g	=	Acceleration by gravity	[m/s^2]
H	=	Wave height	[m]
h_{xb}	=	Water depth above the crest of a sandbar	[m]
K_r	=	Refraction coefficient	[-]
L_0	=	Wave length at deep-water	[m]
T_r	=	Bar cycle period	[year]
V_{sand}	=	Volume of sand in a specified area	[m^3]

1. Introduction

1.1 Background

Sea level rise, lack of natural input of sediments and human interventions (such as building groynes, breakwaters and closure dams) are big issues in coastal zone management. This causes gradual structural erosion along the Dutch coast. On longer timescales, erosion leads to a higher risk of coastal flooding and threatens fresh water extraction, beach recreation and buildings on and behind the dunes (Lodder, et al., 2015). Since the 1990s, the Dutch ministry of infrastructure and environment created a policy aiming at compensating the sediment losses and maintaining the functions of the beach and dunes (Rijkswaterstaat, 1990). There are two ways to perform this policy:

- **Hard measures**: Measures like dikes and dams. In history, these measures were used on a wide scale.
- **Soft measures**: These are measures like sand nourishments in the coastal profile and are applied more and more in recent decennia.

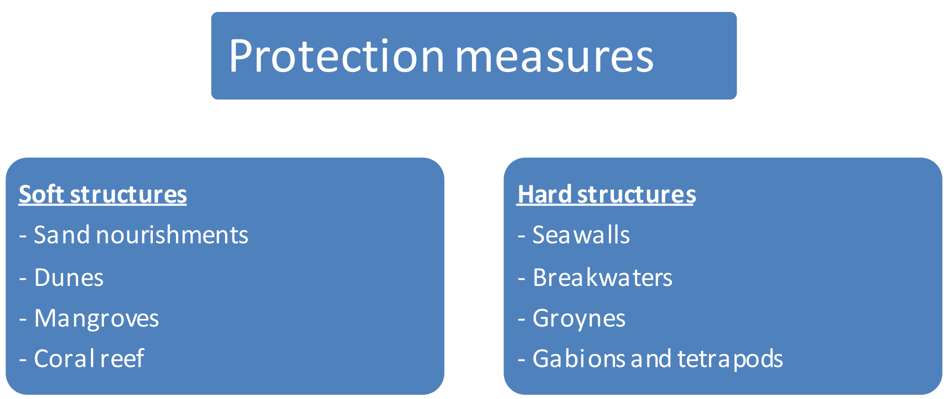


Figure 1: Protection measures to maintain the coastal zone and its functions.

In history, hard measures were used a lot, but because they disturb the natural character of the coast, soft measures are applied more last decennia. Nourishing the coast with sand is one of the most used soft measures in the Netherlands, because of the flat coastal profile and the natural wave climate that spreads out the sand along the coast (Rijkswaterstaat, 1990). The sediments are placed at different positions in the cross-shore profile of the coast. The four nourishments types, which are used the most, are beach nourishments, shoreface nourishments, channel nourishments and mega nourishments (Van der Spek, et al., 2013).

In recent years, much knowledge is developed for all these nourishment types. However especially for shoreface nourishments many unknowns remain, concerning their behaviour and effectiveness. Shoreface nourishments are applied on a wide scale, but it is not always clear how effective they are and how the sediments behave and develop in time.

In the past, different studies with shoreface nourishments have been performed by Bougdanou (2007), Lodder, et al. (2015), Spanhoff (2005), Mulder, et al. (1994), Van Leeuwen, et al. (2006), Halbertsma (1997), Spanhoff, et al. (2006), Van Duin, et al. (2004), Kroon, et al. (1994), Grunnet, et al. (2005) and Ojeda, et al. (2008). The behaviour of the shoreface nourishments is different in these studies, sometimes shoreface nourishments migrate towards the coast, but other shoreface nourishments remain at their position. The conclusion was that further research into the causes of the observed differences is needed to be able to draw better conclusions about the behaviour of shoreface nourishments in general and the driving processes behind this behaviour (Lodder, et al., 2015).

1.2 Problem description

In recent decennia, shoreface nourishments are applied on a wide scale, not only in The Netherlands, but also in other European countries (Hanson, et al., 2002) and the United States (Trembanis, et al., 1998). The experiences with shoreface nourishments in The Netherlands are positive, the sediment volume in the coastal zone is increasing, but it is still unclear why shoreface nourishments behave as they do (De Sonneville, et al., 2012). The behaviour of shoreface nourishments is different per location (Lodder, et al., 2015):

- Migration to the coast (see Figure 2)
- Migration along the coast (see Figure 3)
- Negligible migration, the shoreface nourishment remains at its execution position.

The driving forces behind the different behaviour of shoreface nourishments are not known yet. In addition, the impact of shoreface nourishments is diverse (De Sonneville, et al., 2012). De Sonneville, et al. (2012) compared five shoreface nourishments and a diverse reaction in migration of bar systems is visible.

The gaps in our understanding about the behaviour and impact are mentioned by Spanhoff, et al. (2006):

"The effect of a shoreface nourishment is so far not sufficiently understood and predictable"

"Morphological changes and the responsible processes are hard to describe"

and by De Sonneville, et al. (2012):

"Where does the sand, that is lost from the shoreface nourishments, go to?"

These problems are not only an issue for The Netherlands, but also for other countries along the North Sea. In the recently formed 'Building with Nature-programme' for the North Sea, the urgency for more knowledge about shoreface nourishments is mentioned (Interreg_NSR, 2016).

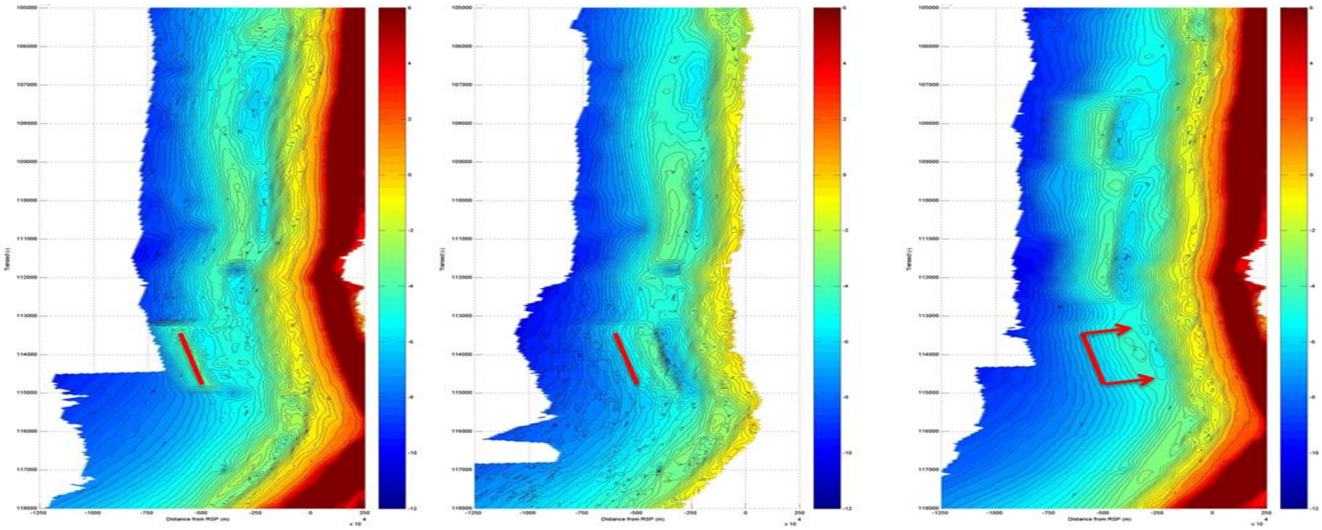


Figure 2: Migration towards the coast of the shoreface nourishment at Ter Heijde from 1998 until 2003. Left figure: 1998, middle figure: 2000 and right figure: 2003. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m. (Note: See the new nourishment in the north in the right figure, which seems to interact with the old one).

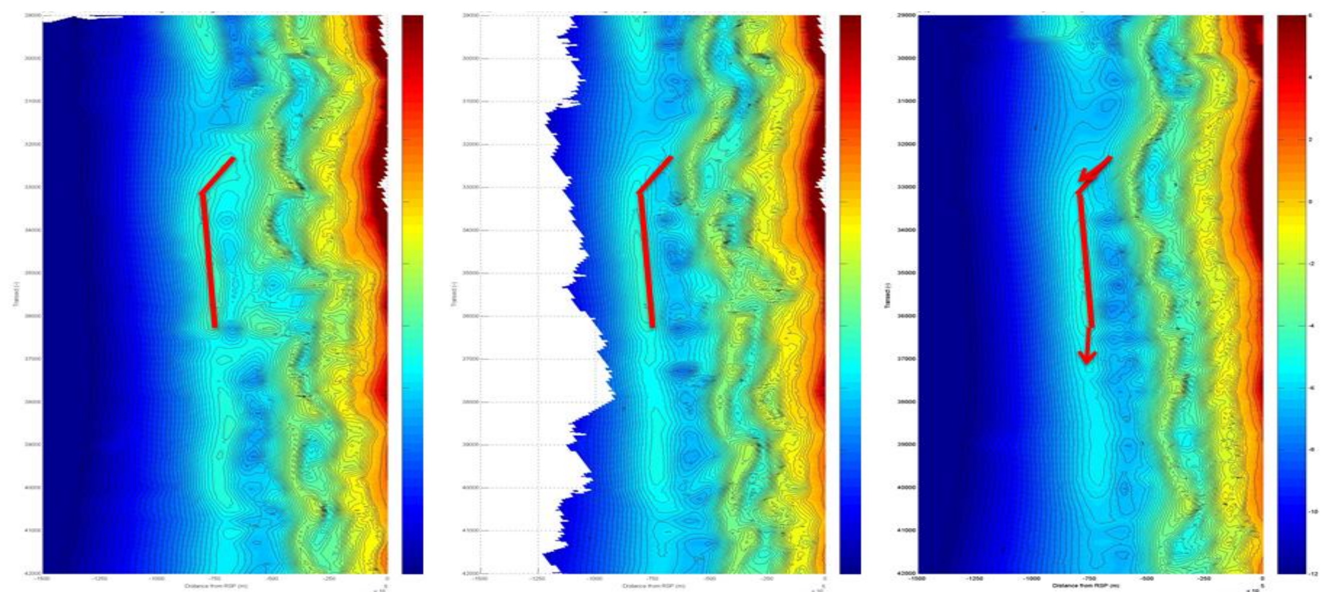


Figure 3: Migration along the coast of the shoreface nourishment at Bergen from 2006 until 2009. Left figure: 2006, middle figure: 2007 and right figure: 2009. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

1.3 Objective

The objective of this thesis is to get more insight in the morphological behaviour of shoreface nourishments. With this better insight, guidelines are formulated for the application of future shoreface nourishments. The main objective of this thesis is described by:

"To draw conclusions about the morphological behaviour of shoreface nourishments and provide guidelines for the design of future shoreface nourishments."

Besides this main objective, other sub-objectives in this thesis are the analysis of the overall behaviour of different shoreface nourishments, identification of the main processes and drawing generic conclusions for this behaviour that are valid for all shoreface nourishments along the Dutch coast.

1.4 Scope

The scope of this thesis includes only the shoreface nourishments along the Dutch coast and the bar systems at the location of the shoreface nourishments. In recent years, many of these nourishments have been executed. Data since 1965 until today is used to analyse the bar system and data since 1998 until today is used to analyse the shoreface nourishments.

1.5 Research questions

Originating from the objective in section 1.3, one main- and three sub-research questions are formulated. The main research question of this thesis is:

"What are the driving factors for the morphological behaviour of shoreface nourishments?"

To find the answer on this main research question, three sub-questions are drafted. To get a better insight in the behaviour of shoreface nourishments, the first sub-question is about the morphological behaviour of shoreface nourishment. In this question, different processes that might have an influence on the behaviour are analysed.

1) What is the morphological behaviour of shoreface nourishments and what are the drafted parameters?
    a) What are the different directions of migration of shoreface nourishments?
    b) How does the sediment volume in the coastal profile change, because of execution of shoreface nourishments?
    c) What is the behaviour of the original bar system?
    d) Are there surrounding structures that might influence the behaviour?
    e) What are the dimensions of the shoreface nourishments in terms of:
        i) Length
        ii) Volume
        iii) Depth of the crest

In the next sub-question, answers found on the previous sub-question are compared and further research into the differences in morphological behaviour is performed. This sub-question supports the process of finding a pattern between the behaviour of shoreface nourishments and driving processes.

2) Is it possible to define indicators for the morphological behaviour of shoreface nourishments in terms of:
   a) Depth of the crest?
   b) Volume per running meter coast?
   c) Length of the shoreface nourishment?
   d) Behaviour of the original bar system?
   e) Surrounding coastal structures?

To draft future recommendations and guidelines, the last sub-question is about drawing conclusions about the optimal design of shoreface nourishments.

3) What is the optimal generic design to apply a shoreface nourishment?
   a) What is the optimal position for a shoreface nourishment in terms of distances from the erosion hotspot?
   b) What are the optimal design parameters for a shoreface nourishment?

1.6 Approach and outline

In Figure 4, the outline for this thesis is shown. First, a literature research about theory is performed. Next, the analysis method is determined. Then, the data analysis that contains the major part of this thesis is performed to get more insight into the behaviour and parameters. At the end of the data analysis, the results are compared to find patterns and correlations that might describe the morphological behaviour. These patterns and correlations are validated and finally, conclusions and recommendations are given.

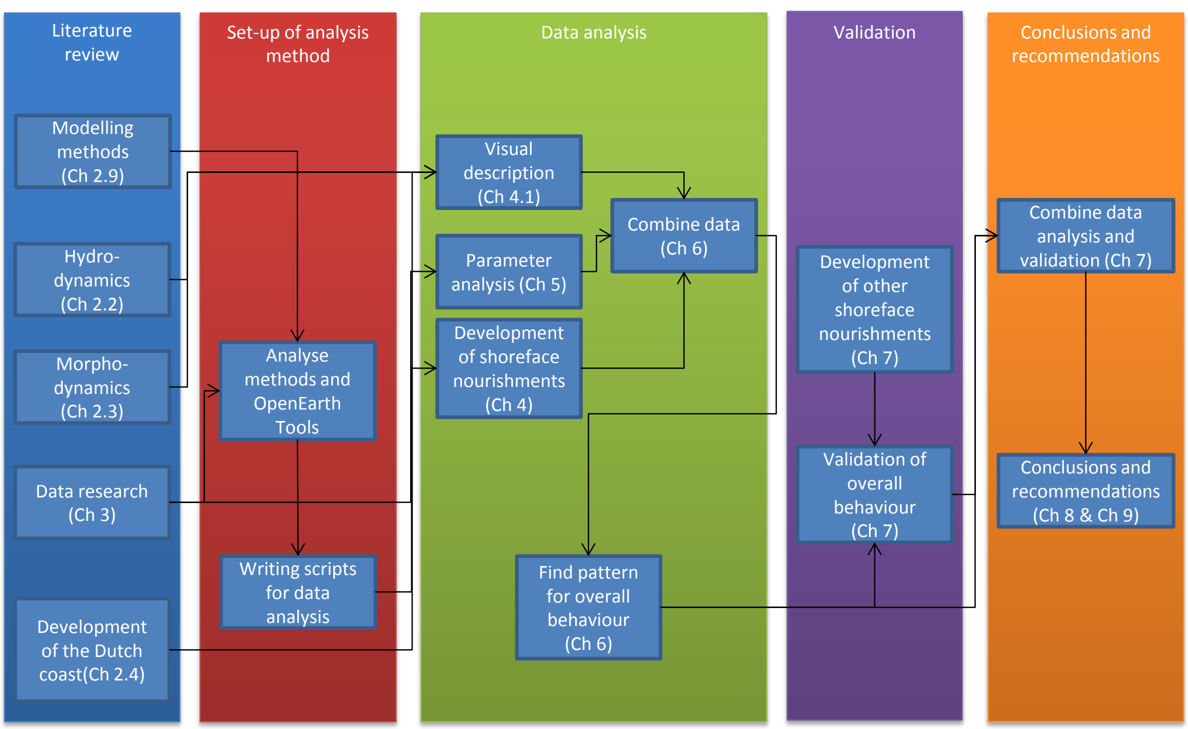


Figure 4: Outline for thesis approach. This research study follows the steps in this scheme.

2. Theory

In this chapter, results are presented for the literature study performed to gain information and knowledge about the subject. First, a short introduction is given to understand coastal terminology. Next, hydrodynamic and morphological processes that might influence the behaviour of shoreface nourishments are described. After that, the evolution of the Dutch coast and the policy of the government are explained. Then, the morphological behaviour of shoreface nourishments, studied in previous reports, is described and finally, a short description of the available data is given.

2.1 Coastal terminology

In this thesis, a broad spectrum of coastal terminology is used to describe areas in and around the coastal zone, see Figure 5. The terms that are used most in this thesis are explained in this section (based on (Department_of_the_army, 1984)).

The coastal zone is the area where land and sea interact with each other. It is the part of the land affected by its proximity to the sea and the part of the sea affected by its proximity to the land. The region of the coastal zone that lies underneath the Mean Low Water Level (MLWL) is called the shoreface zone. In this zone, nourishments that are the main objective in this research are executed. The foreshore zone is the part of the beach that is affected by the sea. During Mean High Water Level (MHWL), this area is drowned and during MLWL, this area is dry. The other part of the beach is called the backshore. The zone in between the beach and the hinterland is called the dunes. These natural hills of sand are water-retaining objects that protect the hinterland.

Coastal erosion is erosion of the coast due to negative gradients in sediment transport. Erosion occurs mainly during heavy conditions like strong winds, high waves, high tides and storm surge conditions. Coastal erosion leads on long-term to coastline retreat (Russell, 1992). This means that the coastline is developing towards the land and the beaches are getting narrower.

In the shoreface zone, different sandbars are present. A bar is a submerged shore parallel sand body, which is built up in the breaker zone, due to breaking waves and cross-shore currents. The amount of bars in the shoreface zone is different for every location. Along the Dutch coast, this varies from zero to three bars.

In this thesis, the terms 'position' and 'location' are used a lot. For a consistent use and a clear meaning of this terms, in Figure 6 the difference is shown. The location determines the alongshore variability and the position determines the cross-shore variability.

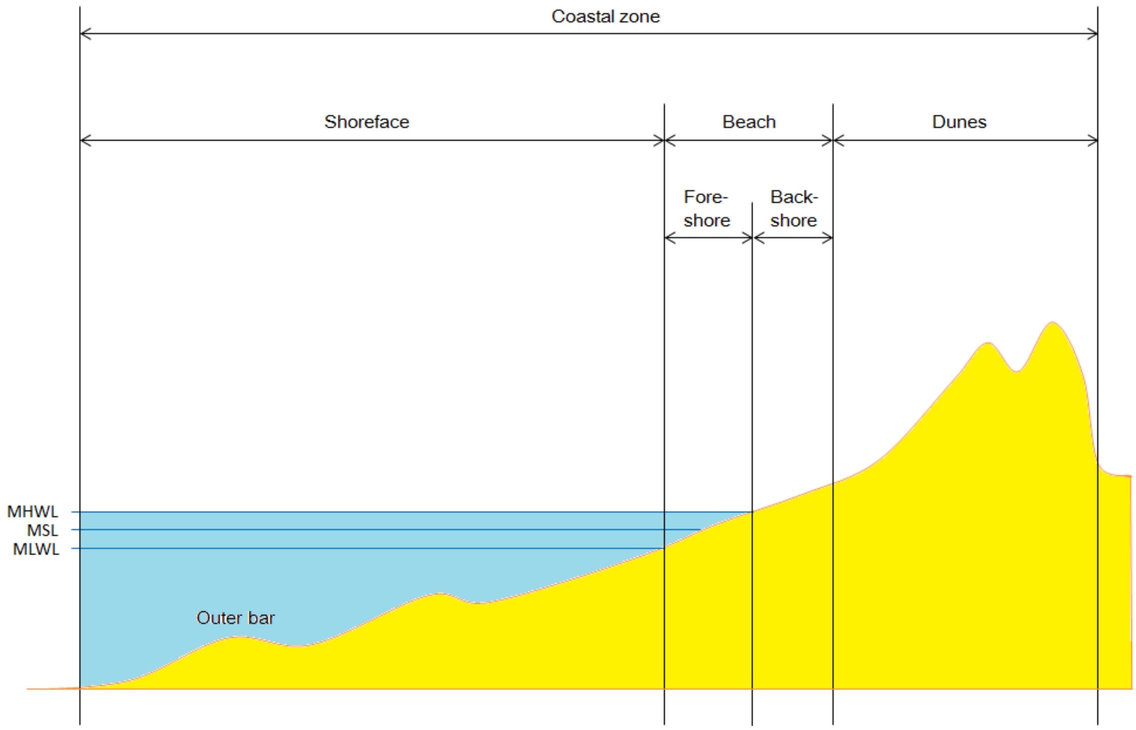


Figure 5: Coastal profile with an illustration of used terms for this thesis. In this figure, two bars are present.

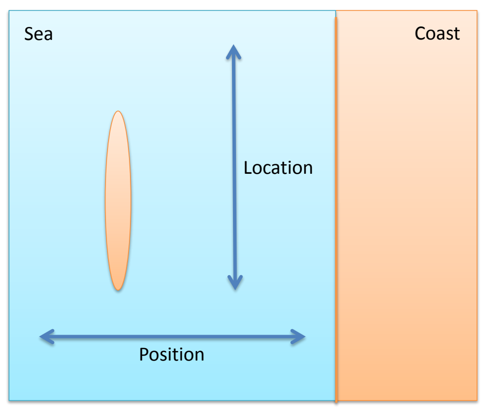


Figure 6: Definition of 'position' and 'location'.

2.2 Hydrodynamics

Hydrodynamics are contributing to morphological changes at the Dutch coast. It is necessary to gain more insight about the wave characteristics at the Dutch coast.

2.2.1 Wave characteristics

The wave direction that occurs most often at the coastline of The Netherlands is south-west. Twenty-three per cent of the time, waves are coming in from this direction. Waves from the west have an expectation of sixteen per cent and from the north-west twelve per cent. During storm, wave conditions are different. The dominant wave direction during storm is west or north-west (Roskam, 1988). Because of the long fetch over the North Sea, waves from the north are in general higher than waves from the west (Pot, 2011).

2.3 Morphodynamics

The feedback between the hydrodynamics and the change in morphology is called morphodynamics. Many morphodynamic processes affect the change in morphology, such as tide, waves and currents (Wright, et al., 1984). In this section bar behaviour and sediment transport in cross- and alongshore direction are discussed.

2.3.1 Cross-shore processes

As waves enter the coastal zone, they start to shoal and break and the shape of the waves becomes asymmetrical, pitched-forward, with steep front faces. This phenomenon induces high onshore velocities and pushes the sandbar onshore. During storms, the high intensity of breaking waves induces a high offshore-directed current, called 'undertow', that carries sediment offshore and results in an offshore-directed sandbar migration (Hoefel, et al., 2003). The magnitude of both on- and offshore directed bar migration determines the overall behaviour of sandbars. Bars migrate onshore during calm conditions, but offshore during storm conditions (Walstra, 2016).

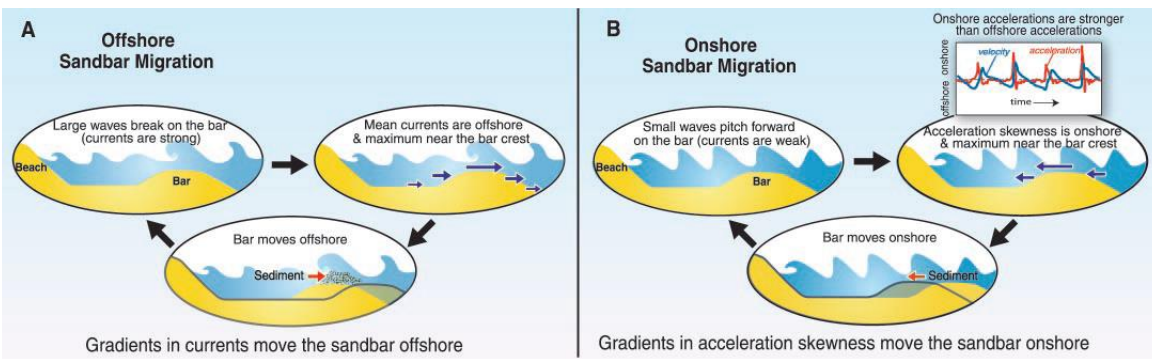


Figure 7: Driving processes that steer sandbar migration. In the left figure, the process for offshore migration is given and in the right figure, the process for onshore migration. (Hoefel, et al., 2003)

2.3.2 Bar behaviour

Along most parts of the Holland coast, a barred system is present. This means that in the near shore zone one or more sandbars can be found. A sandbar can be characterized as an area where the elevation of the bed level is higher than the average bed level. More bars can be distinguished. For example an intertidal bar closest to the beach, an inner bar and an outer bar. In between these bars, often a trough occurs (Pot, 2011). A trough is the opposite of a bar, i.e. an area where the elevation is lower than the average bed level.

Bars are not static, they migrate in time. They often have a multi-annual lifetime, during which they behave in a cyclic way. Bars have a strong alongshore uniformity and an offshore-directed migration (Walstra, 2016). The bar system can be described with a cyclic pattern. This cyclic pattern passes through three stages. In the first stage the bar is generated in the inner near shore zone, the bar remains for some time in this zone. In the second phase, the bar is migrating from the inner near shore zone to the outer near shore zone and is growing (Ruessink, et al., 1994). This offshore-directed migration follows from the gradient in onshore-directed migration during calm conditions and offshore directed bar migration during storm conditions. In general, the net migration of sandbars is offshore-directed (Walstra, 2016). In the third and last phase, the bar is decaying and disappearing in the outer near shore zone (Ruessink, et al., 1994). The position where the bar is decaying is called the zone of decay (Spanhoff, et al. (2006) call it the 'graveyard' of the bar system). Due to the decay of the outer bar, the net offshore migration of next inner bar is stimulated, which is perpetuating the cyclic system (Walstra, 2016).

The bar cycle period (T_r) is not consistent for all locations. This differs from one year until fifteen year (Shand, et al., 1999). In Figure 8, the definition for T_r (in the figure called return period) is given. T_r is the duration between two successive bar decay events (Walstra, 2016).

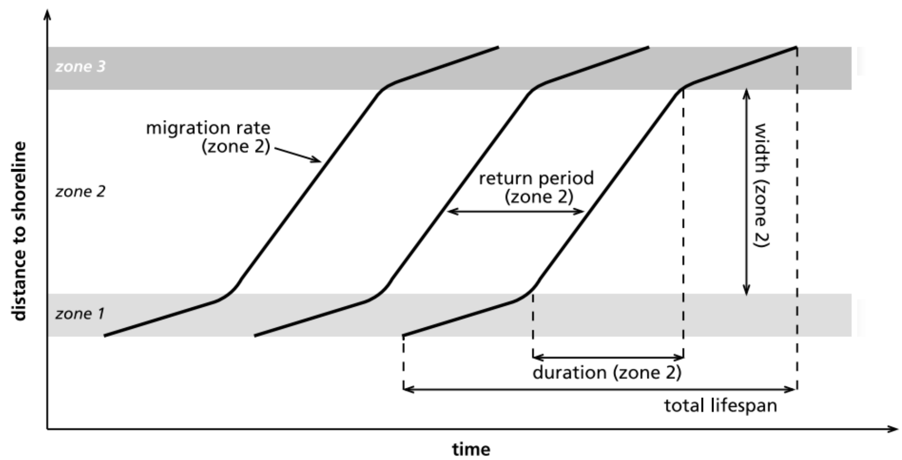


Figure 8: Definition of bar cycle period. In this figure, the bar cycle period is given by the return period. (Grunnet, et al., 2003)

The bar slope of the shoreface causes the different T_r. With a steeper slope, the offshore-directed sandbar gains faster depth (h_{xb}) than a flat slope for the same cross-shore distance, see Figure 9. This higher h_{xb} reduces the wave breaking and the offshore migration rate, which leads to a higher cycle period. (Walstra, 2016).

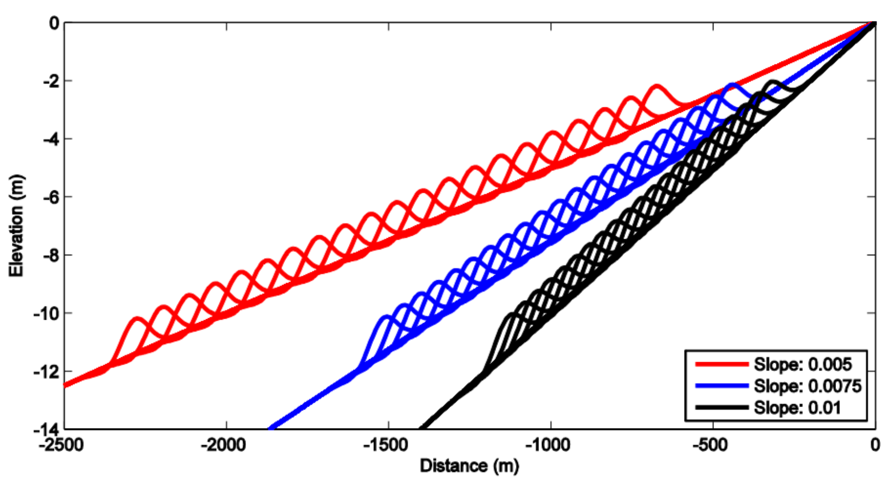


Figure 9: Representation of different slopes. For the same cross-shore distance, the black profile gains a higher h_xb than the red profile. This higher h_xb reduces the wave breaking and reduces the offshore migration rate. (Walstra, 2016)

2.4 Holocene evolution of Dutch coast

The present Dutch coastline is divided in three subsystems, which differ with respect to the dominance of particular physical processes. The three subsystems are the Delta Coast in the south, The Wadden Coast in the north and in between the Holland Coast (Giardino, A., et al., 2010), see Figure 10. The shape of the Dutch coastline is inherited from the older Pleistocene morphology, but is strongly modified by Holocene coastal processes (Beets, et al., 1992).

Figure 10: Map of The Netherlands, including the three sub-regions of the Dutch coast: Delta Coast, Holland Coast and Wadden Coast (Mulder, et al., 2010)

Between 9000 and 8000 BP (Before Present), the shoreline was forced to recede rapidly due to a high rate of relative sea level rise. After 7000 BP, this relative sea level rise decelerated and, due to an on-going sediment supply in the estuaries, outran the creation of accommodation space (Baeteman, et al., 1999). Consequently, the beach barriers (shown in Figure 11) started to stabilize and the tidal basins and inlets started to silt up (Beets, et al., 2000).

Around 5000 BP, a change in barrier movement from transgressive to regressive occurred. In the period between 4000 and 2000 BP, a strong deceleration of the rate of sea level rise occurred. This resulted in the development of peat cushions behind the beach barriers. At the same time erosion of the headlands occurred. These processes were the main events in the development of the Holland Coast up to the Middle Ages (Beets, et al., 1992). In the Middle Ages, major flood-disasters appeared. This was caused by subsidence of peat layers (because of excavating and drainage) and a decreased natural sediment supply. In the 14th century, the Water Boards were founded, because of the major flood-disasters. These

Water Boards, and later on Rijkswaterstaat (founded in 1798), were leading the construction and maintenance of new dikes and the existing dunes to avoid new floods. However, the on-going process of erosion was never stopped in this time (Berendsen, H.J.A., et al., 1984).

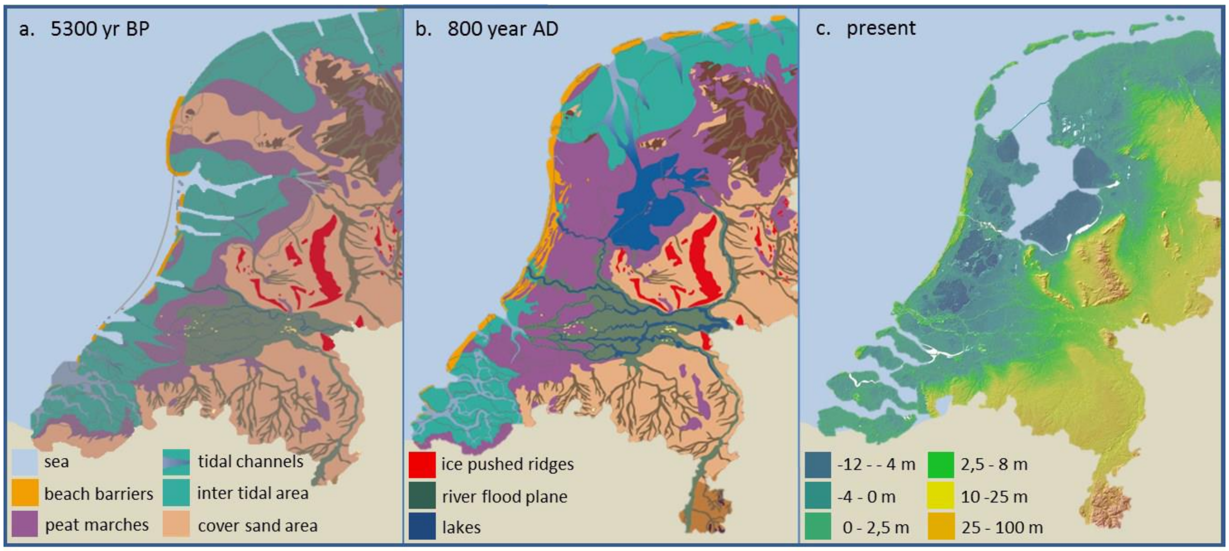


Figure 11: The evolution of the Dutch coast for different periods in history. The left figure shows the transgressive coast around 5300 BP. In the figure in the middle, the inlets are silted up. In the right figure, is the present situation given. (Pot, 2011)

2.5 Dutch policy on coastal zone management

After the flood-disaster in 1953, the Dutch national government decided to change the policy on coastal zone management. They introduced the 'Delta project'. The main goals in this new policy were the closing of major sea-arms and the reinforcement of the dikes and dunes. The new safety standard for floods was set on once in 10.000 years. This meant that the dikes and dunes could withstand a water level that exists once per 10.000 years. After this project, the flood defence system was strong enough to withstand high water levels and waves. However, the reinforcement of dikes and dams did not stop the natural process of structural erosion. (Rijkswaterstaat, 1990)

Structural erosion before the 1990s and a structural rise of the sea level (SLR) did force the government to counteract these problems. They made four alternatives with different measures for the dune system (Rijkswaterstaat, 1990):

- **Retreat**: the acceptance of coastal erosion. Only measures to counteract erosion in coastal zones where safety of the hinterland is in danger.
- **Selective preservation**: not only measures at locations where the safety is in danger, but also at locations where significant interests in the dunes or behind the dikes exist.
- **Dynamic preservation**: the whole coastline is preserved on the actual position.
- **Offshore**: eroding hotspots and weak parts of the coastal defence are counteracted with measures to accrete these locations.

Safety against flooding on the long-term, i.e. counteract the gradual structural erosion, and preservation of the dune system for the expansion of the society were important factors to select the policy of Dynamic Preservation (Rijkswaterstaat, 1990). Preserving the coastline was the most important measure of this new policy. To define this coastline, the concept of the MCL (Present CoastLine, in Dutch MKL: Momentane KustLijn) was developed. (Hillen, R., et al., 1991)

The concept of MCL is showed in Figure 12. The calculation is based on the Mean Low Water (MLW) line in a given cross-shore profile. After the dune foot is set on a fixed position, the area of the calculation zone is determined. This area is the yellow zone in Figure 12 and contains the volume of sediments in the box with a vertical boundary of two times H and a horizontal boundary between the dune foot and the crossing of the sand line with the lower limit. The calculation of the MCL is:

$$MCL = \frac{A}{2*H} - C$$

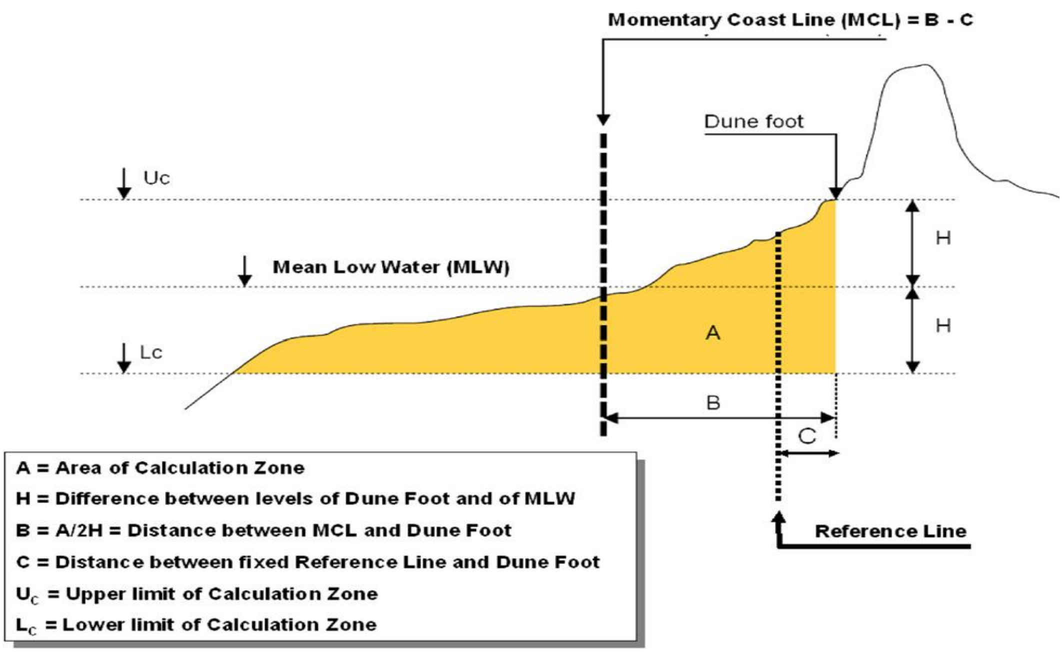


Figure 12: Definition of the MCL. The MCL is calculated by dividing the area of the calculation zone (A) by two times the height H and subtract the distance between the fixed reference line and dune foot of it. When the MCL is further onshore than the BCL, accretion of sand is needed. (TAW, 2002)

2.6 Sediment volume

As said in section 2.4, the Dutch coast is divided in three zones: Delta Coast, Holland Coast and Wadden Coast. The surface area of these zones is defined by the term 'Kustfundament'. This Kustfundament, see Figure 13, is defined in the Nota Ruimte from 2006 (Ministerie_van_VROM, 2006). The offshore boundary is defined as the -20 m NAP line and the onshore boundary is at the inner dune (i.e. the dune system is taken into account in the Kustfundament). The Wadden Sea and the Western Scheldt are not taken into account in the Kustfundament. The area of the Kustfundament, the Wadden Sea and the Western Scheldt multiplied by the amount of SLR results in the needed volume of sand (V_{sand}) to counteract erosion along the entire Dutch coast (Gawehn, 2014):

$$V_{sand} = (A_{KF} + A_{WS} + A_{WDS}) * SLR$$

In which:

$$A_{KF} = Surface\ area\ Kustfundament$$

$$A_{WS} = Surface\ area\ Western\ Scheldt$$

$$A_{WDS} = Surface\ area\ Wadden\ Sea$$

Figure 13: The Kustfundament along the Dutch coast. The area is displayed by the zone with the yellow lines. (Ministerie_van_VROM, 2006)

From the 1990s, the government started to intensify sand nourishments. Because of the negative sediment budget along the Dutch coast, due to SLR and erosion, a total of five to seven mcm (million cubic meters) of sand was nourished to the beaches each year. This happened mainly as beach nourishments at locations where the calculated MCL exceeded the BCL. In the year 2000, the area of interest was extended with the lower shoreface and the higher dunes. The new borders were around -20 m NAP and the inner dune. It turned out that there was still erosion on the lower shoreface, see Figure 14, and that there were more losses of sand than expected due to subsidence and loss of sand from the Holland Coast to the Wadden Sea and Western Scheldt. To counteract these negative effects and the negative sediment budget, the amount of nourishment volume was extended to 12 mcm and the focus was moved from beach nourishments to shoreface nourishments (Van der Spek, A.J.F., et al., 2015).

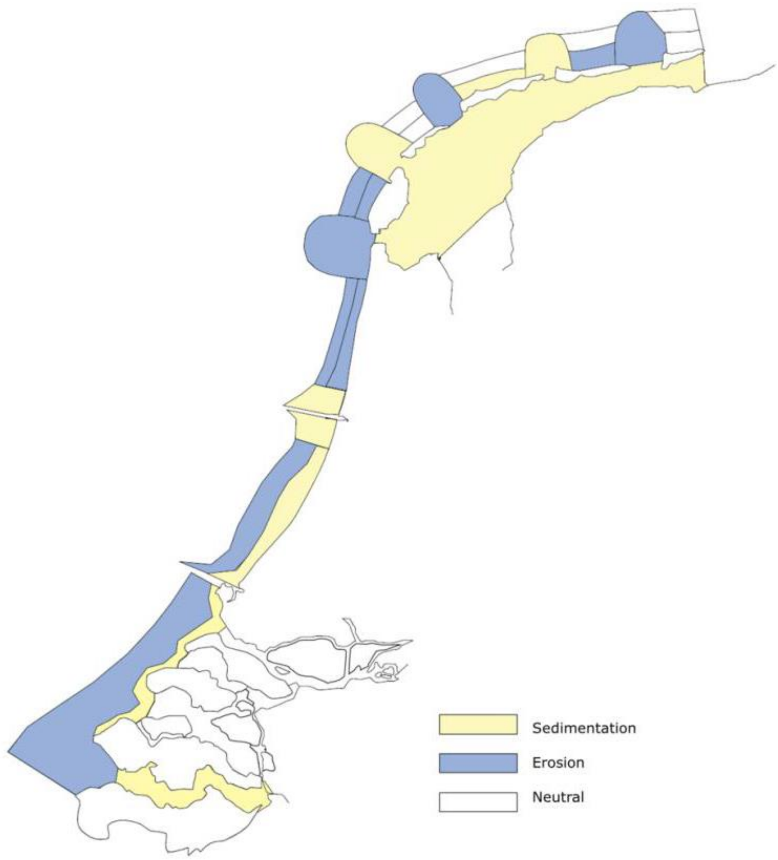


Figure 14: Sediment budget 1965-1995. In this figure, sedimentation occurs in the yellow zones and erosion occurs in the blue zones. (Min.V&W, 2000)

2.7 Different types of nourishing

There are different types of nourishing the coastal zone, depending on where the sediment is placed in the cross-shore profile. In these days, four major types of nourishments are mainly used in coastal areas (Van der Spek, et al., 2013):

a) Beach or dune nourishment, see Figure 15a.
   - The sand is placed between MLW and the dunes.
b) Shoreface nourishment, see Figure 15b.
   - The sand is placed between -8 m and -5 m NAP.
c) Mega nourishment, see Figure 15c.
   - A large amount of sand is placed along the coast.
d) Channel nourishment
   - The sand is placed against the slope of a tidal channel.

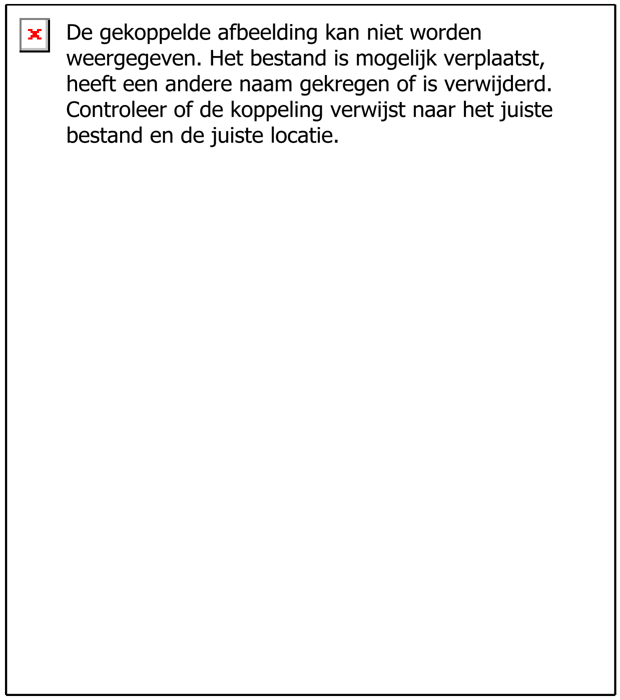


Figure 15: Types of nourishment. The first figure is a beach nourishment; the sand is placed at the beach. The second figure is a shoreface nourishment; the sand is placed between -8 m and -5 m NAP. The third figure is a mega nourishment; the sand motor is a good example of this type. (Stive, et al., 2013)

In the beginning of nourishing, the sand was mainly placed at the beaches and the dunes. This was directly visible for the public and the MCL developed directly towards the sea (i.e. there was no time lag between nourishing and further retreat). From 2005 on, shoreface nourishments were used more and more (Spanhoff, et al., 2006). The benefit of shoreface nourishments is that the implementation costs are lower. It can be applied in a wider range of conditions than beach nourishments, without hindering the recreational public on the beach. The disadvantages of the shoreface nourishment are the monitoring costs (Hamm, et al., 2002). Besides that, a time lag occurs between the performance of the nourishment and transgression of the coastline (Spanhoff, et al., 2006). Beach nourishments are needed at locations with an urgent and immediately need to counteract the erosion or if shoreface nourishments are not sufficiently effective. (Min.V&W, 2000).

2.8 Morphological behaviour of a shoreface nourishment

2.8.1 Design

The primary goal of shoreface nourishments is to counteract the structural erosion during a period of five years. The execution area of the nourishment is between -5 m and -8 m NAP. When a smooth profile occurs, it is just against the -5 m NAP depth contour. In case bars exist, the nourishment is placed against the offshore side of the outer bar. The grain size diameter of sediments is in the order of 250 µm. This must be comparable the native material at the coast. If this is not possible, coarser sediments are used for the nourishments. Dimensions of shoreface nourishments are in the order of kilometres in alongshore direction and in the order of 250 m in cross-shore direction. The volume is around 400 m^3/m. The shoreface nourishment has often a flat crest and at the offshore side, the slope is around 1:10. (Spanhoff, et al., 2006)

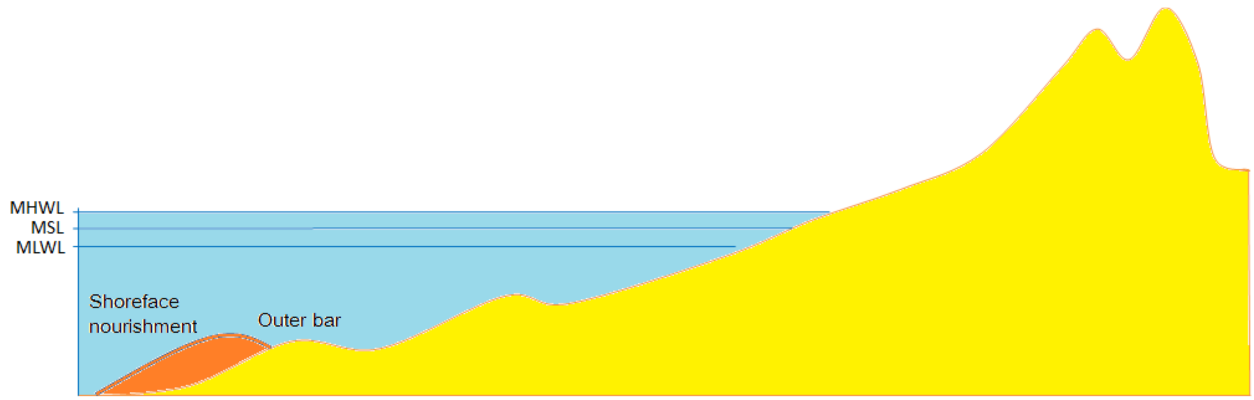


Figure 16: Typical profile of a shoreface nourishment. The shoreface nourishment is placed offshore of the outer bar.

2.8.2 Behaviour

Spanhoff, et al. (2006) describe the behaviour of a few shoreface nourishments along the Holland Coast. The behaviour is described in different phases. This description gives a first insight in the behaviour of shoreface nourishments and is the starting point for this research in shoreface nourishments.

Bar formation and lack of offshore losses

After the shoreface nourishment is executed, it quickly turns into a normal bar. Because the nourishment has an unnatural shape (a steep offshore flank and a flat crest), nature tries to reshape the shoreface nourishment, into a bar with a shape and volumes per meter that are comparable to the bars in the original system. The first years after the execution, most shoreface nourishments migrate slowly towards the coast. Due to a larger (onshore directed) transport of sediments at the crest than at the bottom, the crest of the nourishment is pushed onshore and upward. Behind the crest of the new formed bar, at the onshore side, a trough is formed.

Shift of nourishment and natural bar

The new bar and trough migrate onshore. Due to the formation of an extra bar, the bar system tries to restore itself into the original state. To counteract an extra bar in the system, the original bars migrate onshore. A new bar cannot originate at the coast and the sediments are pushed towards the coast.

Volume redistribution

To analyse the possible effect of the shoreface nourishment, the newly formed bar acts either as a breaker bar or feeder bar. According to Van Duin, et al. (2004), the process of dissipated wave energy influences the new bar. The incoming waves partly break at the nourishment. Because the waves break earlier than in the neighbour parts, a difference in alongshore sediment transport occurs. This effect is called the *salient effect*. This reduces the littoral drift locally and the sediments are trapped in the lee-side (at the onshore side) of the shoreface nourishment, see Figure 17.

Van Duin, et al. (2004) based the hydrodynamic and morphodynamic effects of shoreface nourishments on the effects of a breakwater and summarized the effects as:

*"**Alongshore effect:** large waves break at the shoreface nourishment causing a calmer wave climate behind the shoreface nourishment area (wave filter) and a reduction of the alongshore current and, hence, the transport capacity. The shoreface nourishment acts as a blockade resulting in:*

- *A decrease of the alongshore transport;*
- *Up drift sedimentation;*
- *Down drift erosion.*

***Cross-shore effect:** Large waves will break at the offshore side of the shoreface nourishment; remaining shoaling waves generate onshore transport due to wave asymmetry over the nourishment area; the smaller waves in the lee-side generate less stirring of the sediment and the wave-induced return flow (cross-shore currents) reduces. This results in:*

- *An increase of the onshore sediment transport;*
- *A reduction of the offshore sediment transport."*

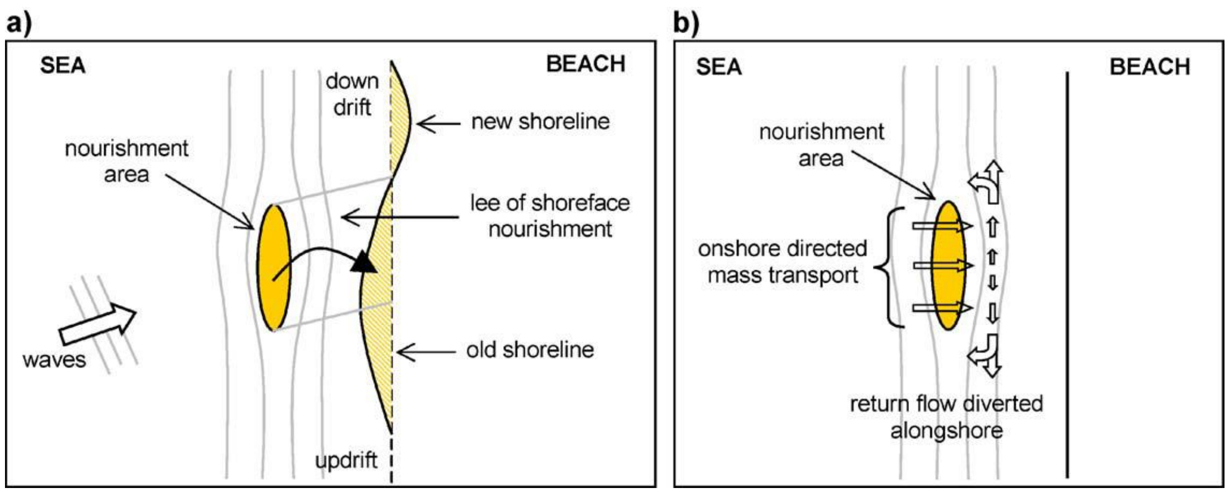


Figure 17: Expected effects by Van Duin (2004) because of the execution of a shoreface nourishment.

2.9 Morphological data

Depth surveys are used to reproduce the state of the coast and the development of the bathymetry. Since 1843, different depth surveys are applied for the Dutch coast and the government decided to determine the position of the coastline. These surveys tell a lot about the development and state of the Dutch coastal zone and with these surveys, management decisions are made. (Pot, 2011)

The most valuable surveys to reproduce the bathymetry is the JARKUS survey (Yearly coastal survey, in Dutch: JAaRlijkse KUStmetingen) and the vaklodingen. Both of these surveys measure the depth in the coastal zone. The difference between the two surveys is the frequency of measuring and the distance between the surveys. The JARKUS data is measured every year and is executed every 250 m, the vaklodingen are measured once every three years and are executed every 1000 m (see Figure 18).

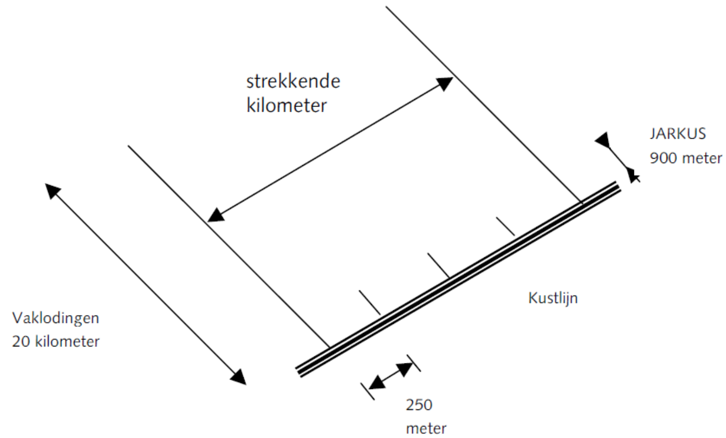


Figure 18: Visualisation of the differences between JARKUS and vakloding. The JARKUS survey is performed each year with a distance of 250m and the vaklodingen are performed every three year with a distance of 1000m. (Wiegmann, 2002)

2.9.1 JARKUS survey

For the analysis of shoreface nourishments in this thesis, the JARKUS survey is used. Shoreface nourishments tend to have a lifetime of five years (Van der Spek, A.J.F., et al., 2015) and a length in the order of kilometres (Spanhoff, et al., 2006). Due to the frequency in time and the distance of 250 m between transects, the JARKUS survey gives the best results to analyse the development of the coast and shoreface nourishments. The JARKUS survey is performed at fixed locations, which makes it easy to compare every year. These locations are given in the RD-coordinates (RijksDriehoekcoordinaten). The fixed reference in the horizontal plane is the RSP-line (Rijks StrandPalen-lijn) and for vertical plane the NAP (Normaal Amsterdams Peil) is used (Pot, 2011).

The data of the JARKUS survey can be analysed with self-written Matlab scripts or with MorphAn. Matlab is a numerical computing environment and in this thesis, it is used for plotting of functions and data. MorphAn is a special software program developed by Deltares. It is developed to analyse the sandy coasts in The Netherlands. The program is made to analyse the JARKUS survey and to determine the current beach state.

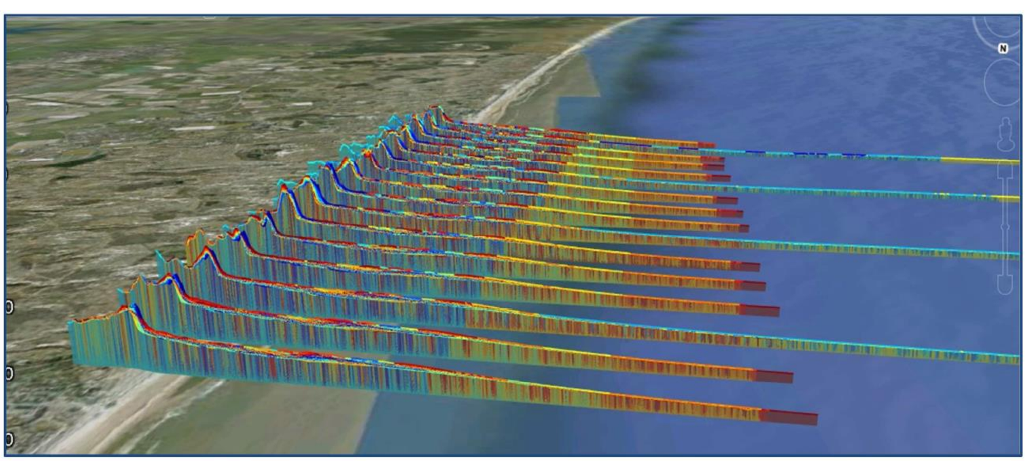


Figure 19: Sixteen JARKUS transects are shown that give a good representation of the bathymetry. (Pot, 2011)

3. Data selection

In this study, the data from the JARKUS survey is analysed. First, a visual description is given for shoreface nourishments based on the JARKUS survey. This is performed for better understanding of the behaviour of specific shoreface nourishments.

3.1 Shoreface nourishments in the Netherlands

The Dutch coast is divided in different coastal sections (in Dutch called Kustvakken). There are seventeen coastal sections in The Netherlands, see Figure 20.

Figure 20: Coastal sections in The Netherlands. This figure shows the seventeen coastal sections in which the Dutch coastline is divided. In this study, the sections Ameland, Vlieland, Texel, Noord-Holland, Rijnland and Delfland are inside the scope. (Vuik, et al., 2012)

Shoreface nourishments are not executed in all coastal sections. In the nourishment database from Rijkswaterstaat, the shoreface nourishments are registered. In Table 1 is shown how many shoreface nourishments are performed in each coastal section. Only shoreface nourishments that are usable for this thesis are taken into account. For some shoreface nourishments there is no data, because the JARKUS survey is not good enough. Others are recently executed and there is not sufficient data to analyse the morphological behaviour.

Table 1: Amount of shoreface nourishments in every coastal section. In this table is shown that shoreface nourishments are executed in Ameland, Vlieland, Texel, Noord-Holland, Rijnland, Delfland and Walcheren.

Coastal section	Number	Amount of nourishments
Rottumerplaat/-oog	01	-
Schiermonnikoog	02	-
Ameland	03	3
Terschelling	04	-
Vlieland	05	3
Texel	06	7
Noord-Holland	07	13
Rijnland	08	4
Delfland	09	7
Maasvlakte	10	-
Voorne	11	-
Goeree	12	-
Schouwen	13	-
Oosterschelde	14	-
Noord-Beveland	15	-
Walcheren	16	1
Zeeuws Vlaanderen	17	-

Most shoreface nourishments are performed along the Holland Coast. Some are performed along the Wadden Coast and one along the Delta Coast. In Appendix A, all shoreface nourishments are given per coastal section. This gives a clear insight in the area of execution (given with the first and last JARKUS transect), year of execution and length of the shoreface nourishments.

3.2 Selection of shoreface nourishments

A selection of shoreface nourishments is made for the data analysis. In total, 38 shoreface nourishments are available for the data analysis. The selection is performed based on different coastal sections, years of execution and length of the shoreface nourishments. First, a distinction between different coastal sections is made. In addition, a distinction is made between the execution areas inside the coastal section. To avoid that all the selected shoreface nourishments are at the same location, the selection has a distinction in JARKUS transects. Finally, the years of execution and lengths are included to gain the best selection for this study. The selected shoreface nourishments for the data analysis, 20 in total, are shown in Table 2 and Figure 21.

Table 2: Selected shoreface nourishments for data analysis. The shoreface nourishments are arranged per coastal section and for every coastal section, they are arranged on year of execution. The numbers in the first column are used further in this thesis and they represent the shoreface nourishments.

	Shoreface nourishment	Year	First JARKUS transect	Last JARKUS transect	Length [m]	Total volume [m^3]	Mean Volume [m^3/m]
1	Am – Midden	1998	13	21	7000	2.030.510	290
2	Vlie – Oost	2009	47	50	3000	1.780.870	594
3	Tex – De Koog	2002	17	23	6000	4.593.493	766
4	Tex – Eierland	2004	25.2	27.8	2600	2.401.361	924
5	Tex – Zuidwest	2007	9	13.5	4500	2.000.970	445
6	Tex – Eierlandse Dam	2009	26	28.8	2800	1.304.348	466
7	NH – Bergen aan Zee	2000	32.25	34.25	2000	994.000	497
8	NH – Callantsoog	2001	14.01	11.08	2930	1.499.940	512
9	NH – Camperduin	2002	26.5	30	3500	1.972.272	564
10	NH – Callantsoog-Zwanenwater	2003	10	16	6000	2.315.360	386
11	NH – Bergen	2005	31.5	36.2	4700	1.306.114	278
12	NH – Callantsoog-Zwanenwater	2006	10	15.2	5200	1.651.965	318
13	NH – Den Helder-Julianadorp	2009	7	10	3000	1.301.565	434
14	NH – Egmond-Bergen	2010	31	40	9000	1.713.913	190
15	Rijn – Noordwijkerhout	2002	73	80	7000	2.645.601	378
16	Rijn – Zandvoort Zuid en Noord	2004	62.75	67.75	5000	2.203.427	441
17	Delf – Ter Heijde	1997	113.15	114.85	1700	882.605	519
18	Delf – Kijkduin-Ter Heijde	2001	107.4	112.5	5100	2.970.879	583
19	Delf – Monster	2005	108.6	113	4400	882.056	200
20	Delf – Kijkduin-Ter Heijde	2011	111.76	113.94	2180	2.000.000	917

Figure 21: Overview of selected shoreface nourishments. When two or more shoreface nourishments are executed at the same location, the first one executed in time is the one closest to the coast. The second one is represented by the next one in row and so on. I.e. the shoreface nourishments are alongshore on the exact location, but cross-shore they are based on their execution phase and not the cross-shore distance to the coast. (Source of map: google.com)

4. Morphological behaviour

In this chapter, the morphological behaviour of the selected shoreface nourishments is analysed. This gives an answer on the first sub-question of this thesis. Further on in this thesis, in chapter six, the morphological behaviour is compared with variable parameters, found in chapter five, to find correlations and patterns.

To understand the behaviour as best as possible, this analysis is divided in two parts. First a visual description of selected shoreface nourishments is given. After this visual description, data of the shoreface nourishments is analysed in detail. The migration of the shoreface nourishments is given for the cross- and alongshore direction and volume trends for different shoreface nourishments are determined.

4.1 Visual description

In this section, a visual description is given for the selected shoreface nourishments. For the visual description a figure with two situations is given. The left figure is the first year shown in which the shoreface nourishment is visible in the data. This is usually the first year after execution. For example, the shoreface nourishment at Ameland is executed in 1998, but in the data visible since 1999. The right figure shows the last year for which the shoreface nourishment is visible in the data. After this year, the shoreface nourishment is disappeared or a new shoreface nourishment is executed.

The shoreface nourishments are analysed on their migration. Different directions of migration occur. In cross-shore direction, the shoreface nourishment can migrate off- and onshore and in alongshore direction the shoreface nourishment can migrate to the north or south. In addition, the formation of troughs and the deformation of the shoreface nourishment are taken into account.

Besides the behaviour of the shoreface nourishment, the behaviour of the bar system is analysed. This is done for the situation before and after the execution of the shoreface nourishment. In this situation the migration direction and amount of sandbars is analysed. In addition, the area around the shoreface nourishment is examined on the occurrence of earlier executed nourishments or the presence of structures, such as a groynes or breakwaters.

4.1.1 Visual description per shoreface nourishment

Ameland – Midden – 1998

In the first years, the shoreface nourishment at Ameland Midden migrates slowly offshore. In the middle of the nourishment, this is clearly visible. The northern tip migrates southward and the southern tip migrates northward. The shape slowly changes from a coastward bulging line into an offshore bulging line. The formation of a trough occurs fast and the existing bars get in one line with the shoreface nourishment. After seven years, the shoreface nourishment disappears.

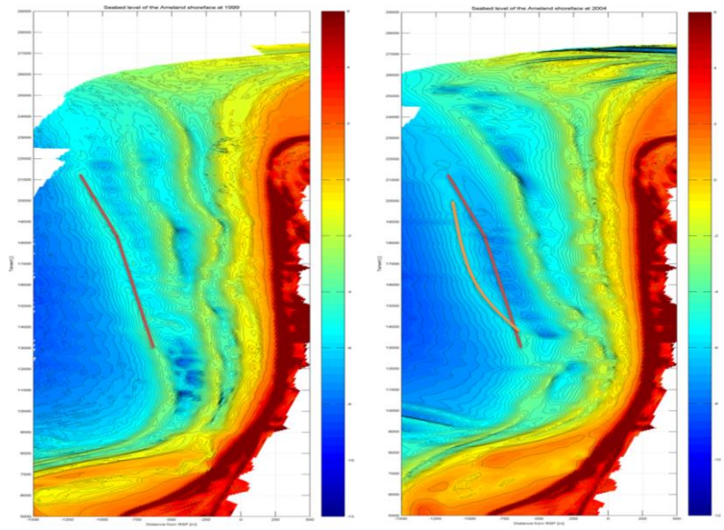


Figure 22: Migration Ameland - Midden from 1999 until 2004. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Vlieland – Oost – 2009

This shoreface nourishment is difficult to analyse, because the shoreface nourishment is executed in a gully. Most of the sediments remain in the gully. In the nourishment database, this is marked as shoreface nourishment (the reason why it is in this selection), but with the figures, another conclusion is found. This is most likely a channel nourishment and not a shoreface nourishment. This has influence on the behaviour and the analysis performed in this thesis. A detailed migration cannot be performed for this nourishment.

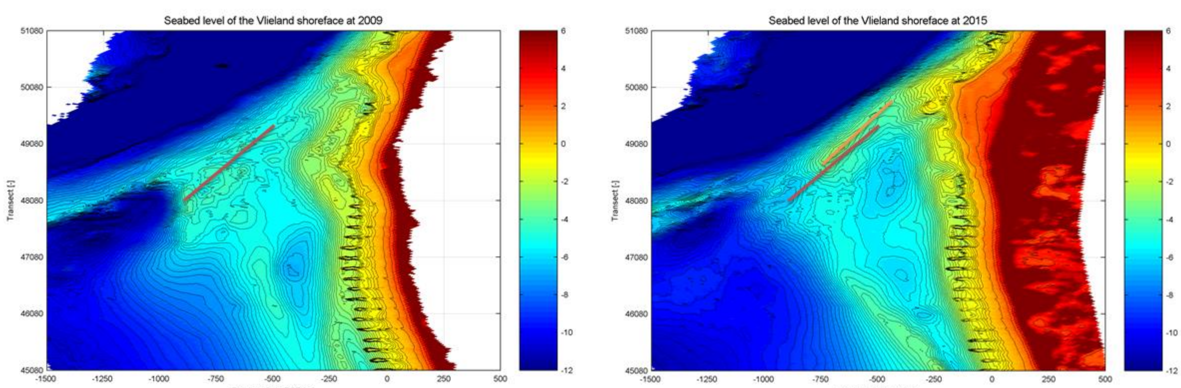


Figure 23: Migration Vlieland - Oost from 2009 until 2015. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Texel – De Koog – 2002

The shoreface nourishment migrates slightly towards the coast. The shape of the nourishment changes and it might be possible that this happens because of a measuring pole that exists in the middle of the shoreface nourishment (Schrijvershof, 2016). In addition, a deep trough onshore of the shoreface nourishment develops. The original bar is pushed towards the coast by the new nourishment. After five years, the following shoreface nourishment is executed at exactly the same position. The old one merges into the new one.

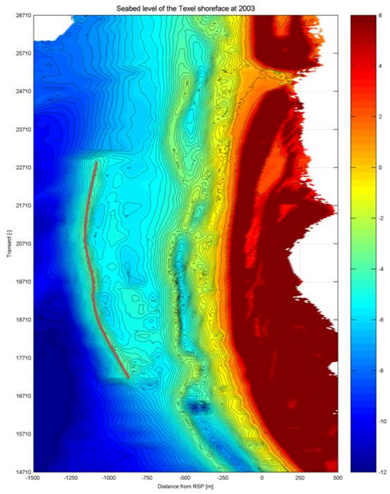


Figure 24: Migration Texel - De Koog from 2003 until 2006. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Texel – Eierland – 2004

After execution, the shoreface nourishment migrates fast towards the coast. There is not a clear through visible along the entire nourishment, but at the tips, small troughs are formed. The nourishment even migrates along the coast. After three years, the nourishment interacts with the original bar. The original bar migrates towards the sea and connects with the nourishment. When they merge into one bar, the bar migrates towards and along the coast.

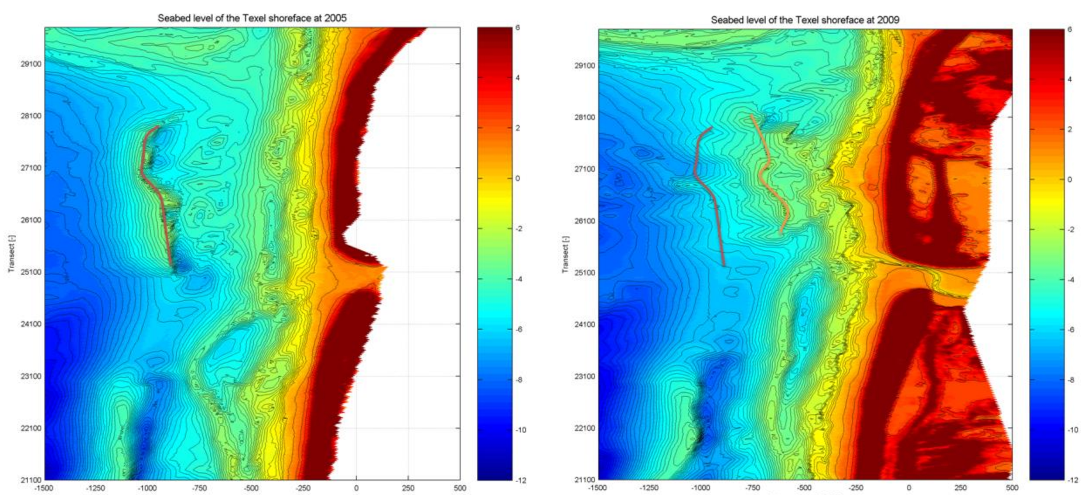


Figure 25: Migration Texel - Eierland from 2005 until 2009. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Texel – Zuidwest – 2007

The shoreface nourishment interacts directly with the older nourishment that is placed three years earlier at the northern side. This nourishment migrates slightly towards the coast. At the side of the earlier established shoreface nourishment, fast migration occurs, but in the middle, the nourishment remains exactly at the same position. At the other side, the nourishment merges with the coast.

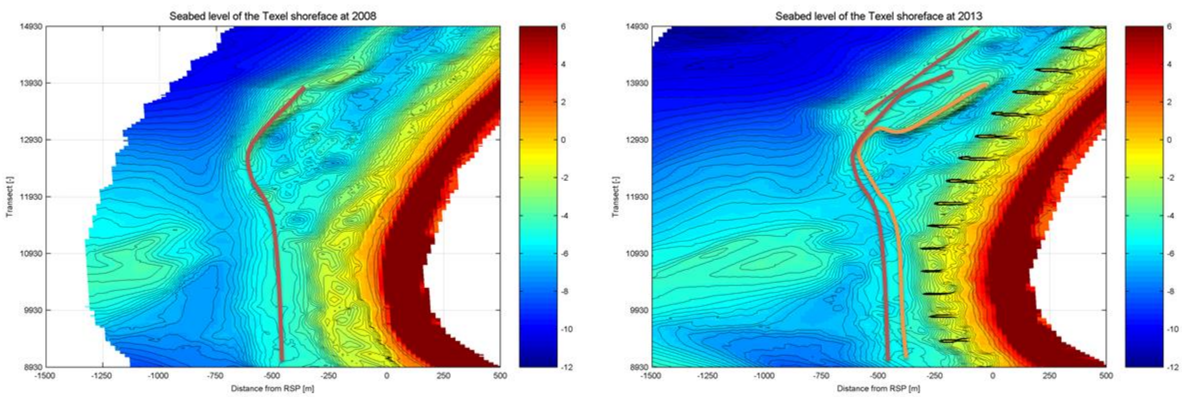


Figure 26: Migration Texel - Zuidwest from 2008 until 2013. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m. The new red line in the right figure represents a new shoreface nourishment.

Texel – Eierlandse Dam – 2009

This shoreface nourishment is the second one at this location. The shoreface nourishment is placed against the slope of the shoreface. The nourishment migrates towards and along the coast. There is not a clear interaction with the original bar system and no trough develops.

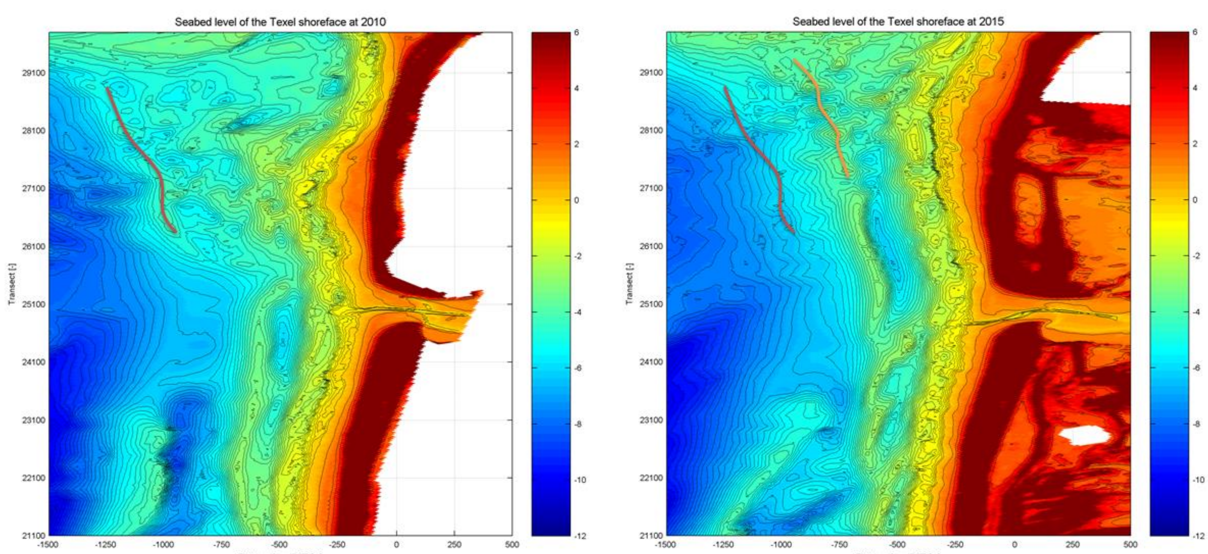


Figure 27: Migration Texel - Eierlandse Dam from 2010 until 2015. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Noord-Holland – Bergen aan Zee – 2000

This one is executed on the outer bar of the original system. This shoreface nourishment does not migrate at all. It remains all the time at the same position. When new nourishments, up- and downstream, are executed, they interact, but not that much. The original bar system is influenced by the shoreface nourishment. The inner bar breaks up and migrates slowly towards the coast.

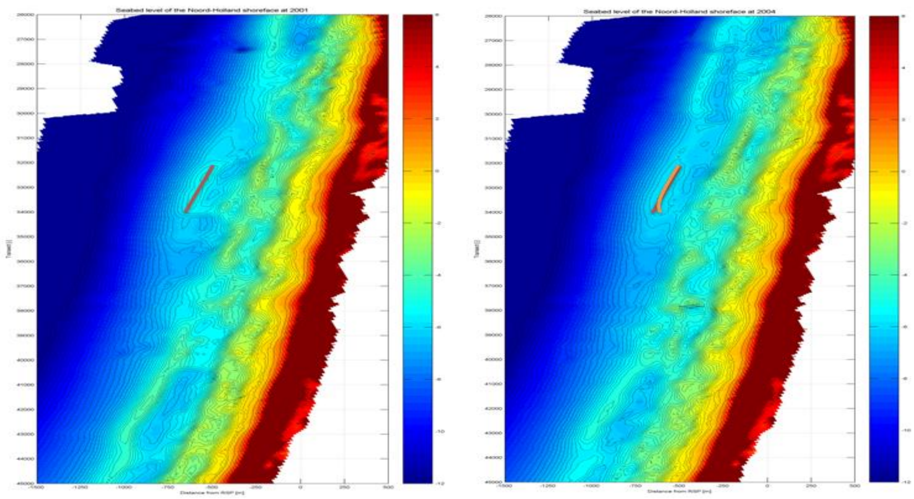


Figure 28: Migration Noord-Holland – Bergen aan Zee from 2001 until 2004. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Noord-Holland – Callantsoog – 2001

This shoreface nourishment is the first one in a row of shoreface nourishments at this location. This first one is executed against the outer bar, which causes a disturbance of the original bar system. The nourishment migrates slowly towards the coast and a bit towards the north. After four years, the next shoreface nourishment is executed and the old and new one merge into each other.

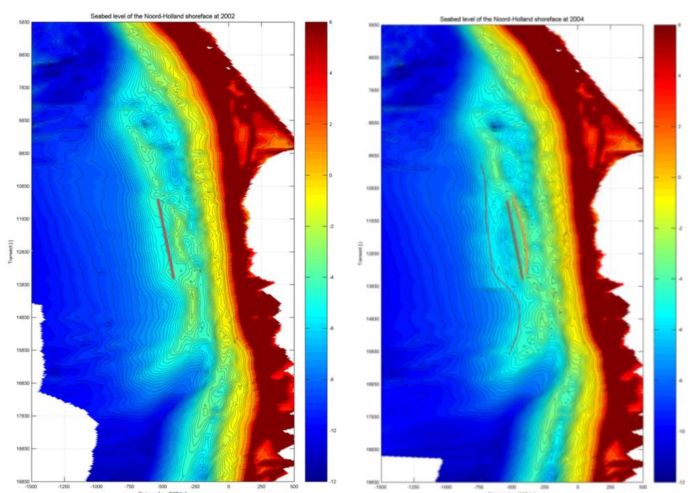


Figure 29: Migration Noord-Holland - Callantsoog from 2002 until 2004. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m. The new red line in the right figure represents a new shoreface nourishment.

Noord-Holland – Camperduin – 2002

This shoreface nourishment is stable. It remains on the same position for the next 6 years. When the new shoreface nourishment is executed, the old and new one merge into each other. The bar system gets stable after execution and at the onshore side a deep trough develops.

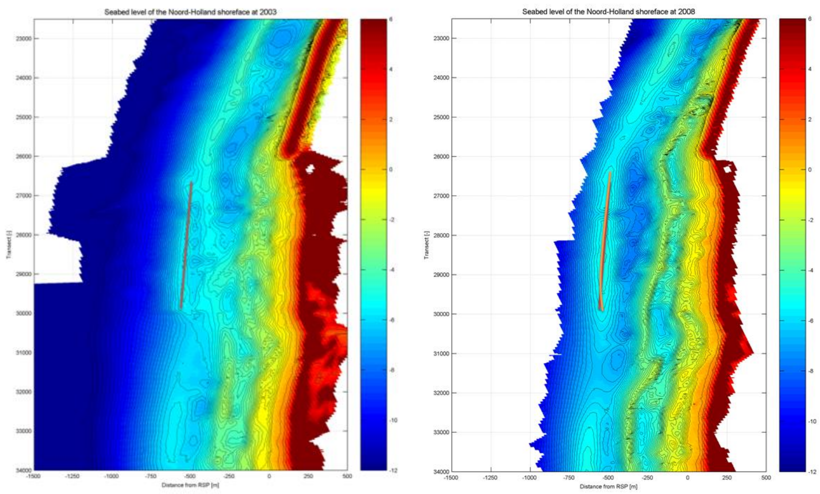


Figure 30: Migration Noord-Holland Camperduin from 2003 until 2008. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Noord-Holland – Callantsoog-Zwanenwater – 2003

The shoreface nourishment is executed after a shoreface nourishment two years earlier. The first two years, the shoreface nourishment is stable, but in the third year, the nourishment migrates towards the coast. The original bar merges completely into the nourishment. After four years a new shoreface nourishment is executed, which pushes the sediments partly towards the coast and partly merges into the new one.

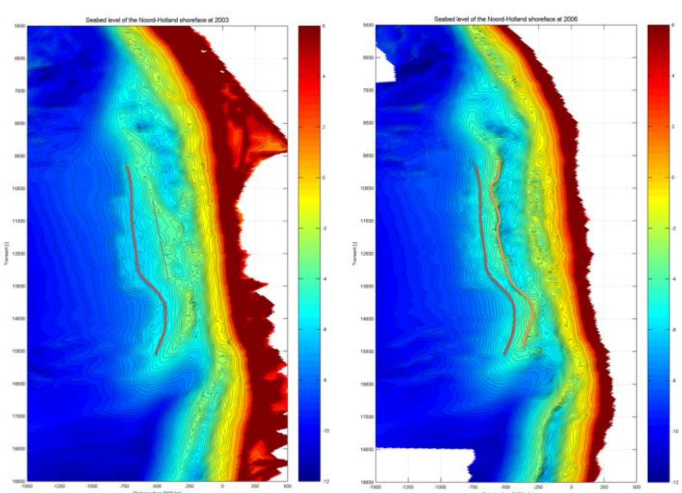


Figure 31: Migration Noord-Holland - Callantsoog-Zwanenwater from 2003 until 2006. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Noord-Holland – Bergen – 2005

The shoreface nourishment at Bergen from 2005 is executed with a slight curve. The northern tip of the nourishment migrates fast towards the south. The southern tip migrates a bit towards the south. The curves, originating from the execution, disappear and change into a straight line. The position that is reached in the first year after execution is immediately the final position. In 2011, the new shoreface nourishment is executed and the one from 2005 disappears.

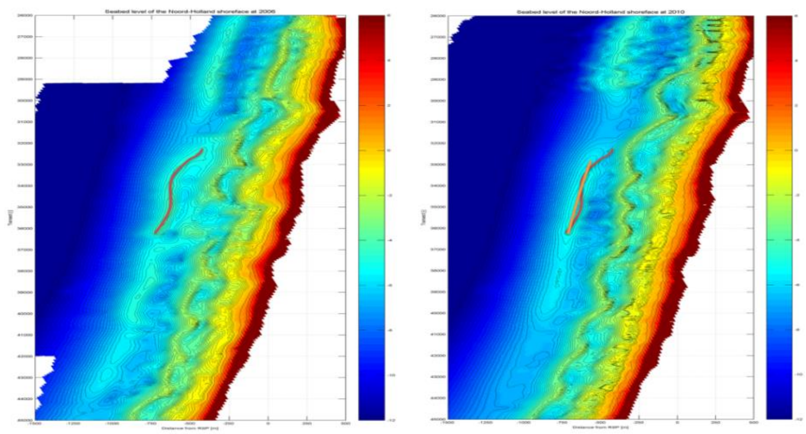


Figure 32: Migration Noord-Holland - Bergen from 2006 until 2010. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Noord-Holland – Callantsoog-Zwanenwater – 2006

This shoreface nourishment is executed close against the outer bar (which originates from earlier shoreface nourishments). The curvy shape is the same in the years after execution. The nourishment migrates towards the coast and northward. After four years, a new shoreface nourishment is executed on the exact same position. A trough does not develop.

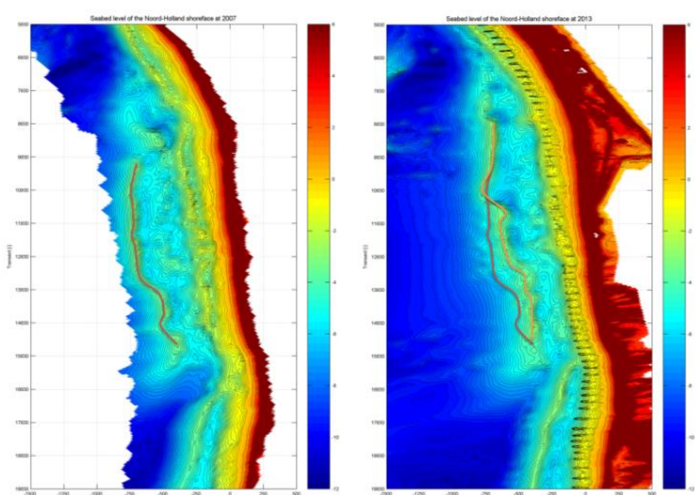


Figure 33: Migration Noord-Holland - Callantsoog from 2007 until 2013. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Noord-Holland – Den Helder-Julianadorp – 2009

There is a rapid interaction with the existing bar system (which is under influence of older shoreface nourishments). The shoreface nourishment is executed at the seaside of the outer bar, but merges in two years into the bar. The years after, the nourishment migrates towards the coast and towards the north. When a new shoreface nourishment, southward of the 2009 one, is executed, the bar system is disrupted and the old shoreface nourishment migrates further towards the coast.

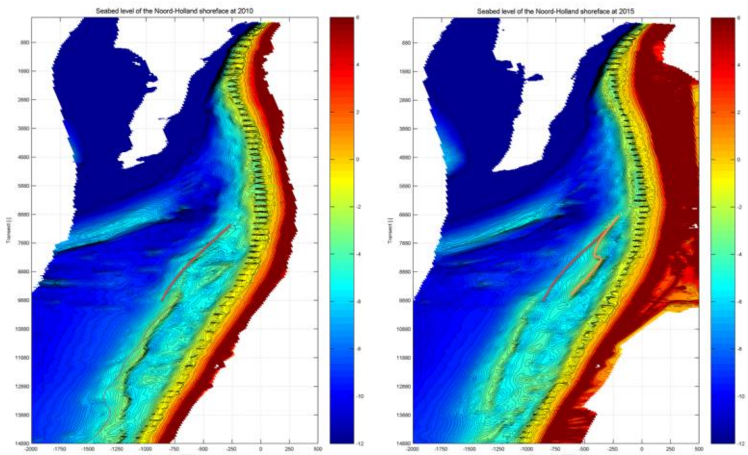


Figure 34: Migration Noord-Holland - Den Helder-Julianadorp from 2010 until 2015. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Noord-Holland – Egmond-Bergen – 2010

The shoreface nourishment is executed in two parts: the northern and southern part. A deep trough is formed onshore of the shoreface nourishment. The migration of the shoreface nourishment is negligible. Even the original bar system does not change at all. Just as the two earlier shoreface nourishments executed in this area.

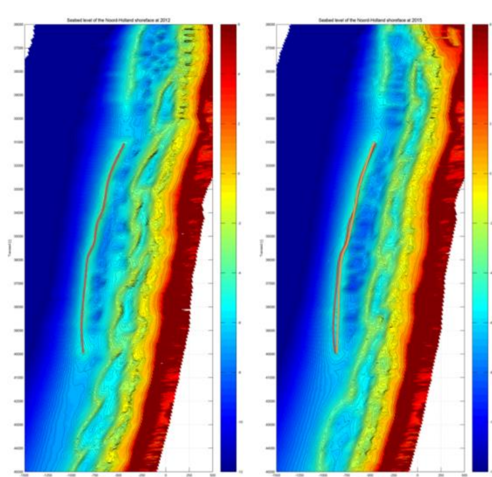


Figure 35: Migration Noord-Holland - Egmond-Bergen from 2012 until 2015. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Rijnland – Noordwijkerhout – 2002a

A deep trough is formed onshore of the shoreface nourishment. In the first years, the original bar system is disrupted, but after five years, the original system recovers. The nourishment migrates a little bit towards the coast. It is difficult to measure the exact migration of this shoreface nourishment, because some data is missing. This has consequences for the analysis further on in this research.

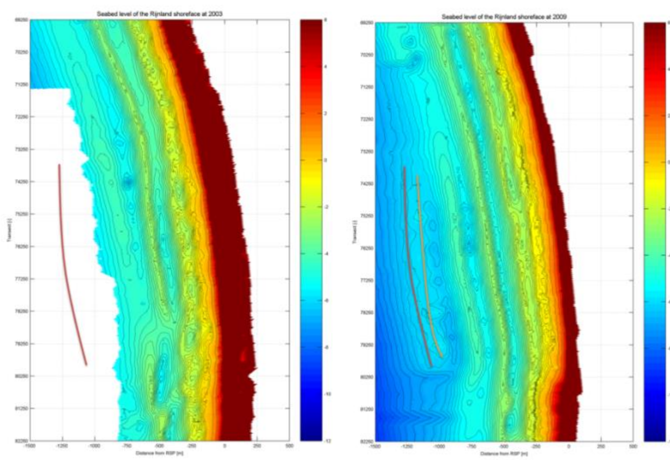


Figure 36: Migration Rijnland - Noordwijkerhout from 2003 until 2009. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Rijnland – Zandvoort Zuid and Noord – 2004

The shoreface nourishment migrates fast towards the coast. A deep trough is formed that develops from the south end of the shoreface nourishment towards the north. The bar system is in the first two year stable. After these years the shoreface nourishment disappears slightly and the bar system regains its offshore migration.

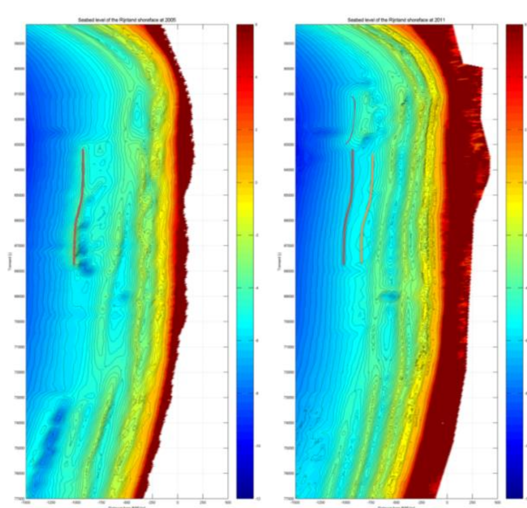


Figure 37: Migration Rijnland - Zandvoort from 2005 until 2011. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m. The new red line in the right figure represents a new shoreface nourishment.

Delfland – Ter Heijde – 1997

After execution, strong onshore migration occurs. A trough is formed at the onshore side of the nourishment. After five years, a new shoreface nourishment is performed downstream, northward, of the existing one. There is a little interaction between the two. The entrance of the Rotterdam harbour influences nourishments in this area.

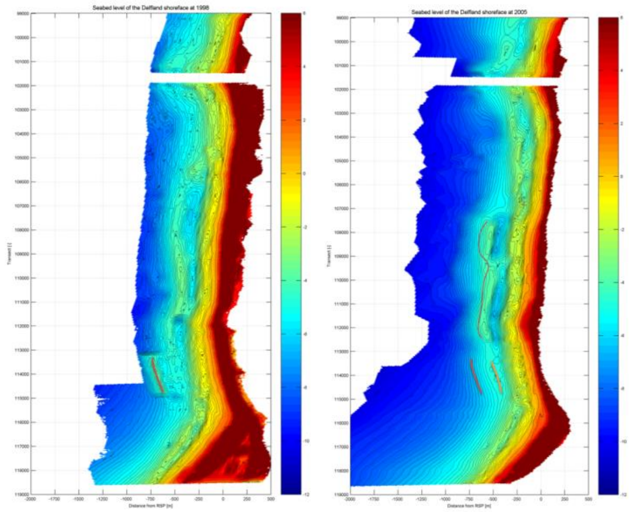


Figure 38: Migration Delfland - Ter Heijde from 1998 until 2005. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m. The new red line in the right figure represents a new shoreface nourishment.

Delfland – Kijkduin-Ter Heijde – 2001

This one is not executed in a straight line, but in two parts. The two parts both migrate towards the coast. Troughs are formed, but at the middle (were the north and south part are linked) no trough develops. After five years, a new shoreface nourishment is executed.

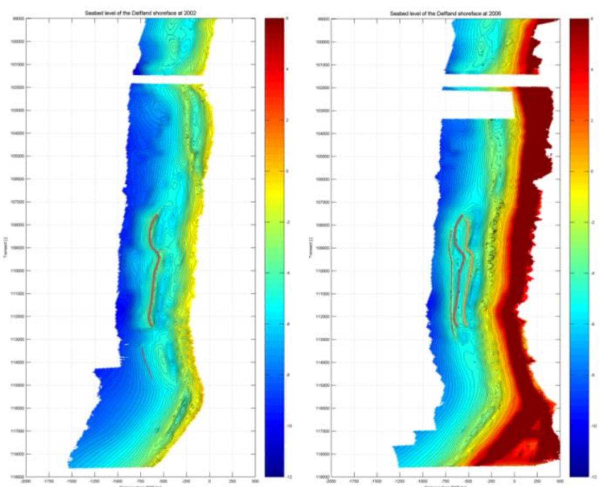


Figure 39: Migration Delfland - Kijkduin-Ter Heijde from 2002 until 2006. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m. The new red line in the right figure represents a new shoreface nourishment.

Delfland – Monster – 2005

This shoreface nourishment is executed after another one. A small trough develops and migrates slightly towards the coast. After seven years, the sand motor is executed and disrupts the system.

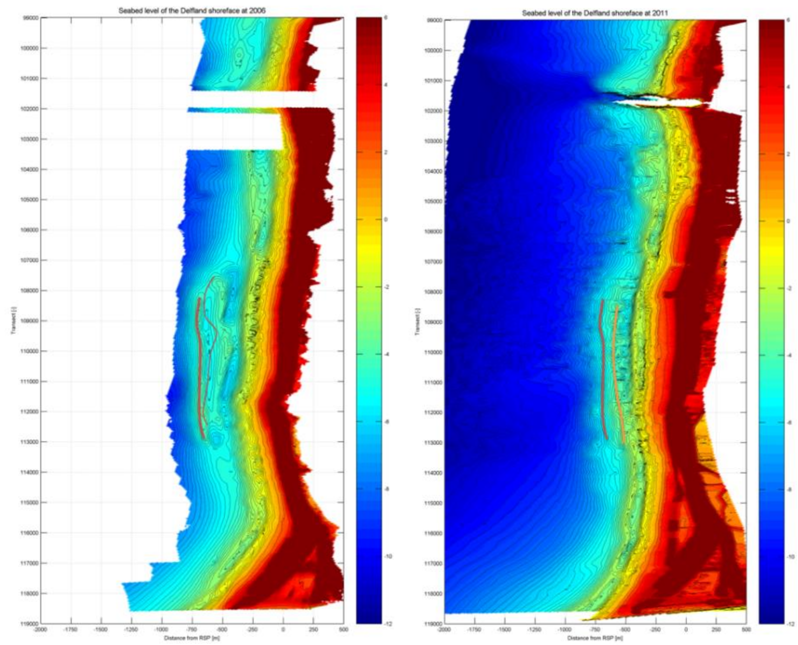


Figure 40: Migration Delfland - Monster from 2006 until 2011. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m. The thin red line in the left figure represents an older shoreface nourishment.

Delfland – Kijkduin-Ter Heijde – 2011

This shoreface nourishment is executed southward of the sand motor and in the leeside of the Rotterdam harbour. The overall migration is towards the coast. A small trough is formed at the southern end of the nourishment. Due to the sand motor the bar system in this region changes and it is difficult to draw conclusions about the influence of the shoreface nourishment on the bar system.

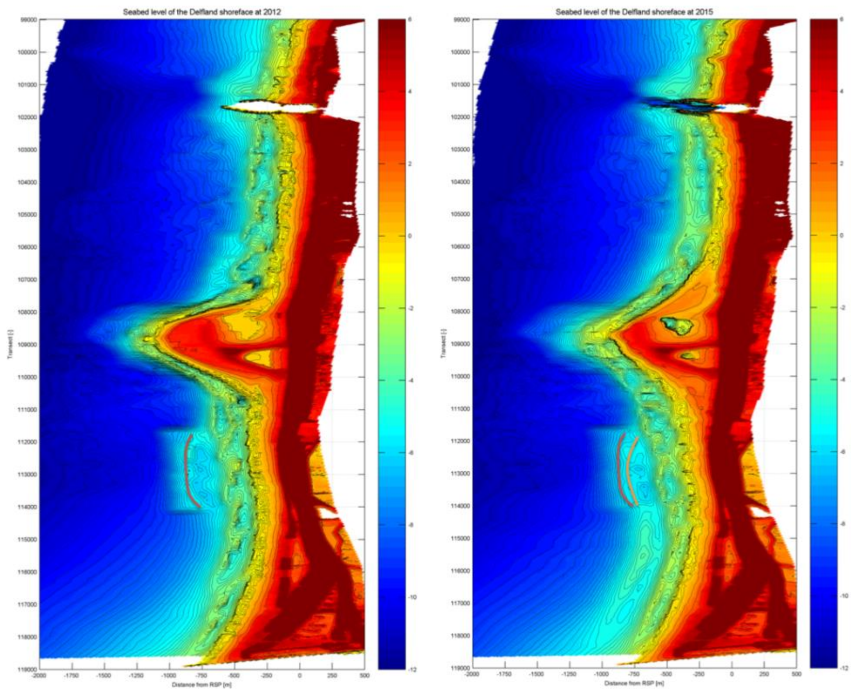


Figure 41: Migration Delfland - Kijkduin-Ter Heijde from 2012 until 2015. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

4.1.2 Overview behaviour shoreface nourishments and bar systems

In this section, an overview is given for the selected shoreface nourishments and their behaviour. This analysis is performed based on the visual description given in the previous section. The bar system is analysed in the years before and after the execution of the shoreface nourishments. After this analysis, the systems before and after are compared. The reaction of the bar system is important for the understanding of the analysis further in this research and the future design of shoreface nourishments. Important morphological phenomenon's are:

- Bar behaviour before and after the execution of the shoreface nourishment
- Migration direction and number of bars
- Development of the shoreface nourishment
- Formation of a trough
- Influence of earlier nourishments at the same location
- Influence of surrounding coastal structures and environment.

In Table 3, on the next page, an overview is given.

Table 3: Behaviour of shoreface nourishments and sandbars. In this table different aspects of the bar system and shoreface nourishment are given. The values and categorisation are based on the visual description.

	Shoreface nourishment	Life-time [years]	Exis-ting bars	Trough formed	Migration bar before nourishment	Migration bar after nourishment	Migration nourishment	Earlier nourish-ment	Influencing structures or environment
1	Am – Midden	6	3	Yes	Offshore	Stable	Offshore	No	No
2	Vlie – Oost	Not possi-ble	1	No	Offshore	Stable	Alongshore	Yes	No
3	Tex – De Koog	4	1	Yes	Offshore	Onshore	Stable	No	No
4	Tex – Eierland	5	2	Partially	Alongshore	Onshore	Onshore and Alongshore	No	Outer deltas Wadden Sea
5	Tex – Zuidwest	5	1	Yes	Offshore	Onshore	Onshore	Yes	No
6	Tex – Eierlandse Dam	6	1	No	Alongshore	Onshore	Onshore and Alongshore	Yes	Outer deltas Wadden Sea
7	NH – Bergen aan Zee	4	2	Yes	Offshore	Stable	Stable	No	No
8	NH – Callantsoog	3	1	No	Alongshore	Onshore	Onshore and Alongshore	No	Outer deltas Wadden Sea
9	NH – Camperduin	6	2	Yes	Offshore	Stable	Stable	No	No
10	NH – Callantsoog-Zwanenwater	3	1	Partially	Alongshore	Onshore	Onshore and Alongshore	Yes	Outer deltas Wadden Sea
11	NH – Bergen	5	2	Yes	Offshore	Stable	Alongshore and alongshore	Yes	No
12	NH – Callantsoog-Zwanenwater	7	2	No	Alongshore	Onshore	Onshore and Alongshore	Yes	Outer deltas Wadden Sea
13	NH – Den Helder-Julianadorp	6	1	No	Alongshore	Onshore	Onshore and Alongshore	Yes	Outer deltas Wadden Sea
14	NH – Egmond-Bergen	Not possi-ble	2	Yes	Offshore	Stable	Stable	Yes	No
15	Rijn – Noordwijker-hout	7	3	Yes	Offshore	Stable	Onshore	No	No
16	Rijn – Zandvoort Zuid en Noord	7	3	Yes	Offshore	Stable	Onshore	No	No
17	Delf – Ter Heijde	8	0	n/a	n/a	Bar disappeared	Onshore	No	Rotterdam Harbour
18	Delf – Kijkduin-Ter Heijde	5	1	Yes	Offshore	Bar disappeared	Onshore	No	Rotterdam Harbour
19	Delf – Monster	6	2	Yes	Offshore	Onshore	Onshore	No	Rotterdam Harbour
20	Delf – Kijkduin-Ter Heijde	Not possi-ble	1	Yes	Bar system disturbed by sand motor	Bar system disturbed by sand motor	Onshore	Yes	Rotterdam Harbour & Sand Motor

4.2 Migration in detail

In this section, the detailed migration of the shoreface nourishments is determined. This is performed for cross- and alongshore migration. Finally, an overview is given for the different detailed migrations. In chapter six, this is compared with variable parameters to find an answer on the research question of this thesis.

4.2.1 Cross-shore migration

To determine the exact migration of shoreface nourishments in cross-shore direction, the JARKUS transects are analysed as described in the method below. There are more options to do this. For the visual description, the migration was determined by the development of the crest of the shoreface nourishment. For the detailed migration, a better description is needed, because the shape of the shoreface nourishment changes in time. In the first year, the shoreface nourishment has a clear profile with the crest in the middle, but after a few years a trough is formed and the crest is no longer a good representation for the position of the shoreface nourishment. In this case, the centroid is a better value that illustrates the mean of the shoreface nourishment. This is illustrated in Figure 42. In the next section, the method to determine the centroid is explained.

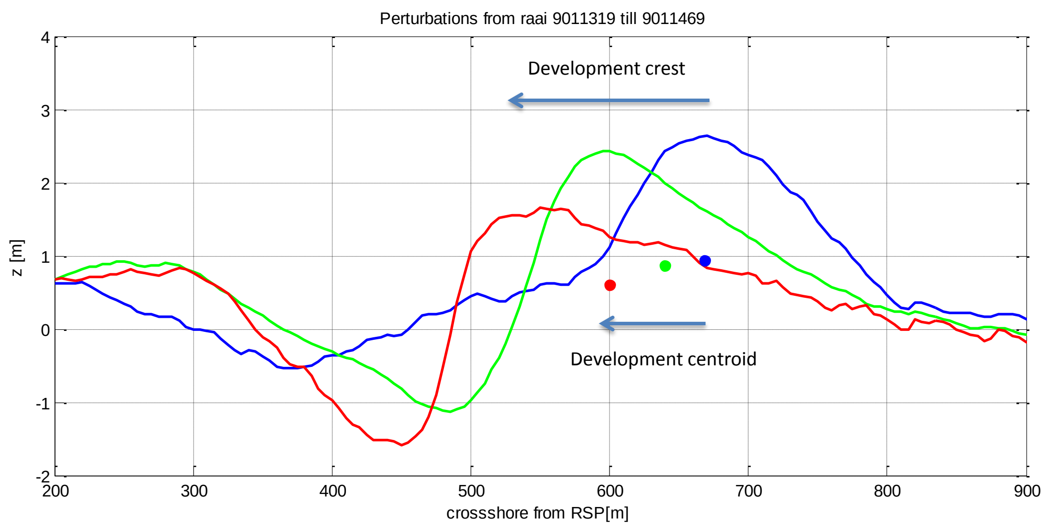


Figure 42: Difference between migration crest and centroid. For the visual behaviour, the crest is taken into account. For the detailed cross-shore migration, the migration of the centroid is determined. This centroid is a better value for the mean shoreface nourishment than the crest.

Method

The first step in this method is making a mean profile. The JARKUS transects at the location of the shoreface nourishment are averaged in space. This results in a mean cross-shore profile for the shoreface nourishment. Then these mean profiles are determined for twenty years, before the first shoreface nourishment is executed, and averaged over these twenty years. This results in a mean profile in space (the area of the shoreface nourishment) and time (twenty years). See Figure 43.

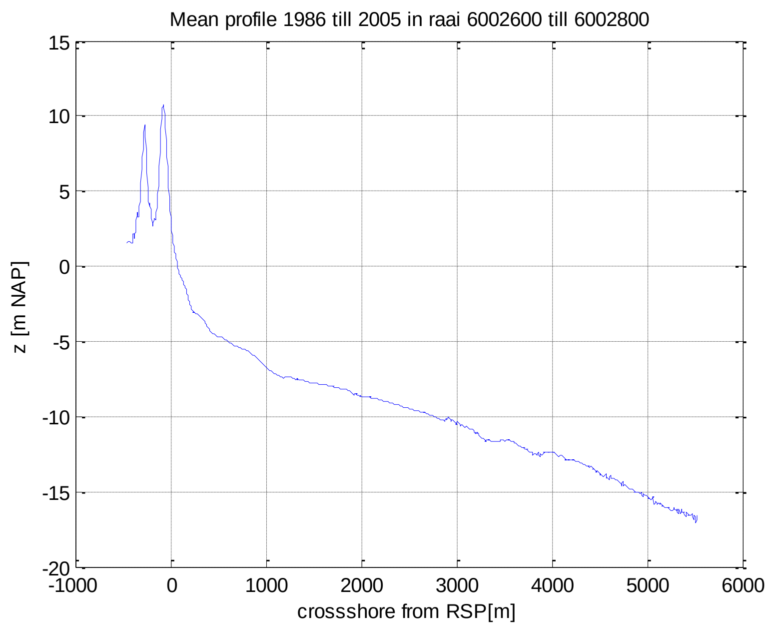


Figure 43: Example of a mean cross-shore profile. First, the mean profile is determined for the JARKUS transects at the shoreface nourishment. This is done for 20 years before the first shoreface nourishment and averaged over these 20 years. The result is a cross-shore profile averaged in space and time.

The next step is to determine the mean profiles of the years of interest. These profiles are averaged over space and the mean profile for twenty years is subtracted. This results in perturbations that represent the migrating bars and shoreface nourishment. On the position of the shoreface nourishment, often a large hump is visible. In Figure 42 this is shown. The next step is to determine the centroid of the nourishment humps. The points, which are above the threshold level of 0.3 m, are selected to determine the centroid of the area under these points. This threshold level is chosen because then the small perturbations around 0.0 m are excluded. Figure 44 is an example of the determination of the area and the centroid.

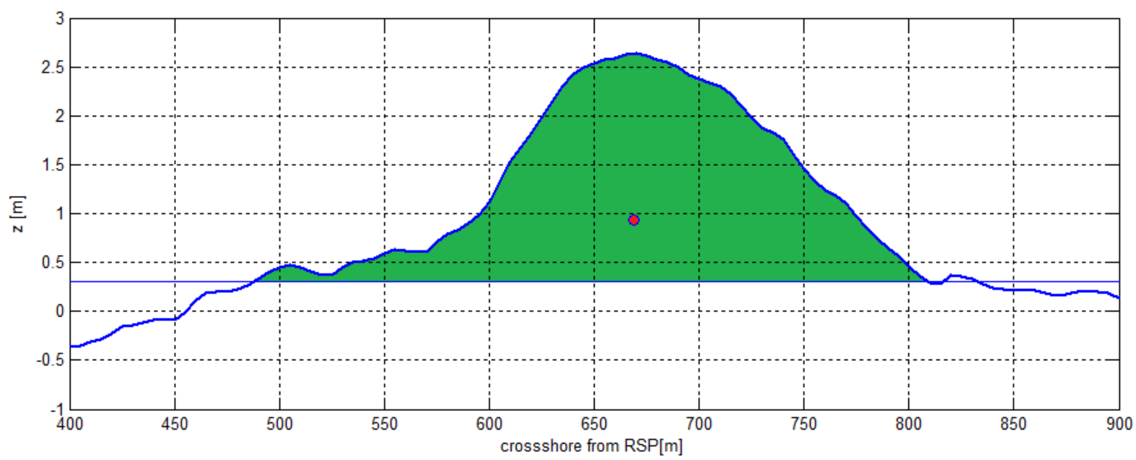


Figure 44: Selected area (green zone) to determine the centroid (red dot) of this area. The threshold value is set on 0.3 m. The values above this threshold value are taken into account to determine the centroid.

The following step is to transform the centroids into a mean cross-shore migration of the shoreface nourishment. By looking at the distance (in meters) between the centroids of two successive years, the migration is determined. This is executed for each year and a summation results in a cumulative migration. The mean migration each year is determined by plotting a straight line through the cumulative line with the lowest error. This is shown in Figure 45. The slope is equal to the mean migrations each year in cross-shore direction.

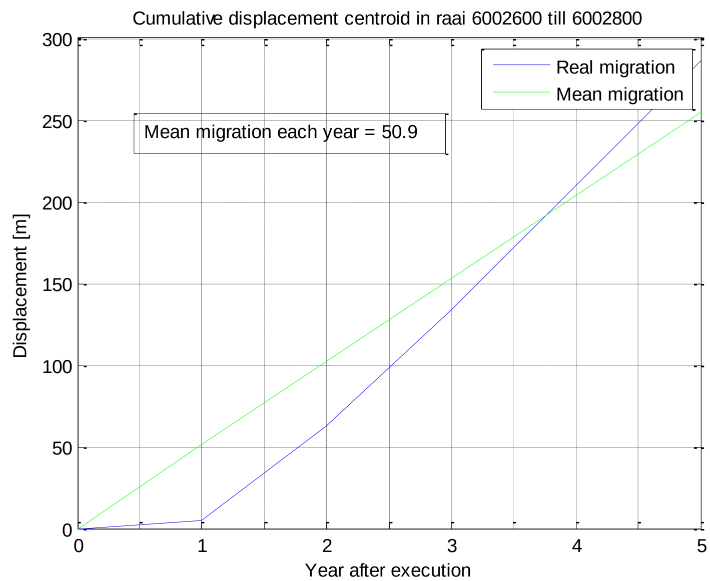


Figure 45: Example of the migration of a centroid each year. The blue line represents the real migration. The green line represents the mean migration. The mean migration for this example is 50.9 m/y.

The cross-shore migration is measured with the explained method for the shoreface nourishments and the values are given in Table 4. In Appendix B, the figures are given for all the shoreface nourishments.

4.2.2 Alongshore migration

The alongshore migration is difficult to describe, because the JARKUS transects are cross-shore measured and not alongshore. Measuring the alongshore migration is not possible like it was done for the cross-shore component.

Method

To measure the alongshore migration, the migration of the tips of the shoreface nourishments is taken into account. It is assumed that the shoreface nourishment is a straight line in between the two tips and the mean alongshore migration is determined based on these tips. When for example the upstream tip migrates 100 m downstream and the downstream tip migrates 200 m downstream, the mean alongshore migration of the shoreface nourishment is 150 m downstream.

There are cases where the alongshore length reduces (i.e. the upstream tip migrates downstream and the downstream tip migrates upstream). For these cases, it is assumed that the alongshore component for migration is zero meters, i.e. the shoreface nourishment migrates not in alongshore direction.

The explained method is applied for the shoreface nourishments. In Table 4 the alongshore components are given. In Appendix C, the results are given for the shoreface nourishments with alongshore migration.

4.2.3 Overall migration

Now that the cross- and alongshore migration is known, the overall migration of all shoreface nourishments is known. These migrations are given in Table 4, Figure 47 and Figure 48. In Table 4, the migration is given in cross- and alongshore direction, in overall direction and the angle between the migration direction and the coast. The combination between the overall migration and the angle results in the best representation for the migration of the shoreface nourishments. The angle of migration is given relative to the coastal orientation (see left frame of Figure 46).

Table 4: Overall migration of shoreface nourishments. A negative migration means a migration upstream (i.e. towards the south along the Holland Coast and towards the west along the Wadden islands) or offshore and a positive migration means a migration downstream (i.e. towards the north along the Holland Coast and towards the east along the Wadden islands) or onshore. For case 2 and 15, it is not possible to determine the migration (see visual description in section 4.1).

	Shoreface nourishment	Cross-shore migration [m/y]	Alongshore migration [m/y]	Overall migration [m/y]	Angle of overall migration with coast [°]
1	Am – Midden	-153.4	0.0	153.4	270.0
2	Vlie – Oost	n/a	n/a	n/a	n/a
3	Tex – De Koog	2.2	0.0	2.2	90.0
4	Tex – Eierland	78.7	141.7	162.1	29.0
5	Tex – Zuidwest	6.5	0.0	6.5	90.0
6	Tex – Eierlandse Dam	50.9	138.2	147.3	20.2
7	NH – Bergen aan Zee	5.1	0.0	5.1	90.0
8	NH – Callantsoog	38.8	130.0	135.7	16.6
9	NH – Camperduin	-2.9	0.0	2.9	270.0
10	NH – Callantsoog-Zwanenwater	9.5	53.6	54.4	10.0
11	NH – Bergen	-24.1	-118.3	120.8	191.5
12	NH – Callantsoog-Zwanenwater	2.8	93.4	93.5	1.7
13	NH – Den Helder-Julianadorp	25.8	23.1	34.6	48.2
14	NH – Egmond-Bergen	-2.3	0.0	2.3	270.0
15	Rijn – Noordwijkerhout	n/a	n/a	n/a	n/a
16	Rijn – Zandvoort Zuid en Noord	22.5	0.0	22.5	90.0
17	Delf – Ter Heijde	21.7	0.0	21.7	90.0
18	Delf – Kijkduin-Ter Heijde	5.5	0.0	5.5	90.0
19	Delf – Monster	4.0	0.0	4.0	90.0
20	Delf – Kijkduin-Ter Heijde	8.5	0.0	8.5	90.0

The results from Table 4 are visually presented in Figure 48. This figure provides a good representation of the overall migration (red arrows). It is possible to cluster the shoreface nourishments in different groups, based on their migration. In clusters, distinction is made in on- and offshore migration and up- and downstream migration (see right frame in Figure 46).

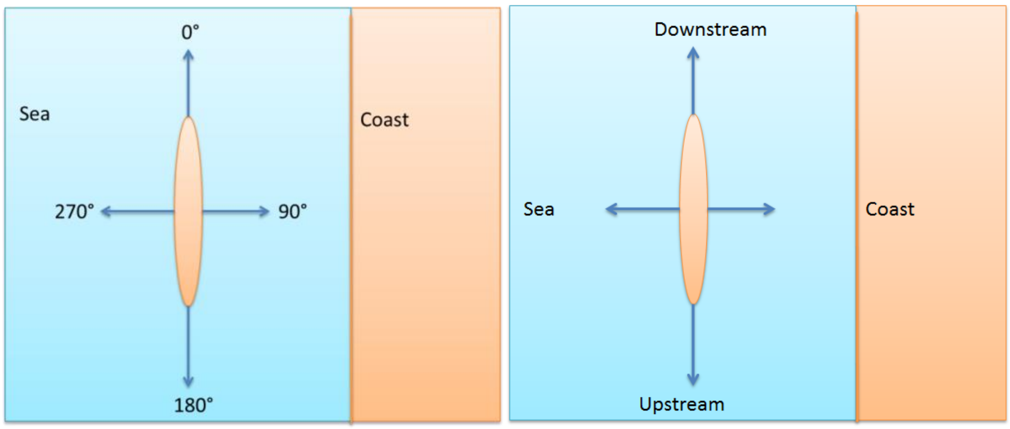


Figure 46: Frames with angle and direction of the migration of shoreface nourishment. The angles are based on the coastal orientation. E.g., shoreface nourishments with only a cross-shore migration onshore have an angle of migration of 90°. The terms 'Upstream' and 'Downstream' are based on the net sediment transport along the Dutch coast, from southwest (Zeeland) to northeast (Schiermonnikoog). E.g. for a shoreface nourishment at Noord-Holland, which migrates towards the north, the alongshore migration is downstream.

The cross-shore migration (given in meters per year) is plotted against the alongshore migration (in meters per year) in Figure 47. In this figure, clusters are made to group the different shoreface nourishments. These clusters can be used in further research.

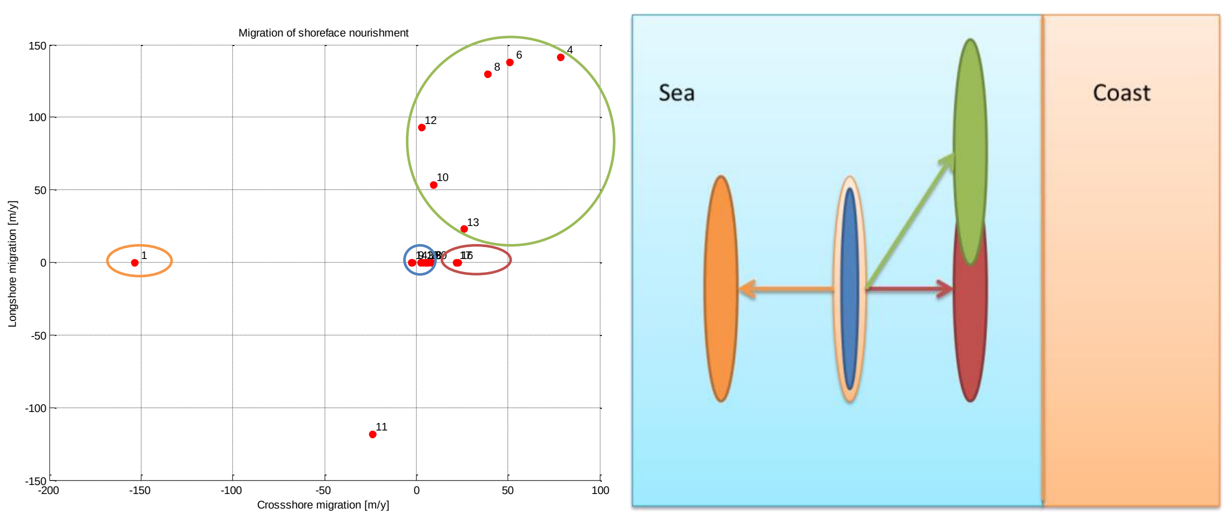


Figure 47: Left: Cross- and alongshore migration of shoreface nourishments. The shoreface nourishment at Bergen (number 11) can be classified in the orange cluster. For further information, see the section about the orange cluster further on in this chapter. Right: Migration of clusters. The original shoreface nourishment is coloured the same as the coast. The blue cluster remains on the same position of the original shoreface nourishment and overlaps in this figure the original shoreface nourishment.

Figure 48: Visual migration of the shoreface nourishments along the Dutch coast. In this figure, the shoreface nourishments from the selection are shown with their migration given by the red arrow and the colour based on the cluster. When two or more shoreface nourishments are executed at the same location, the first one executed in time is the one closest to the coast. The second one is represented by the next one in row and so on. I.e. the shoreface nourishments are alongshore on the exact location, but cross-shore they are based on their execution phase and not the cross-shore distance to the coast. (Source of map: google.com)

4.2.4 Migration per cluster

For every cluster, it is possible to give the cross- and alongshore (only for the green cluster) migration with the methods used earlier. In the next sections, every cluster is described separately and the different representations of the migration are given. This detailed migration of the different clusters gives a better insight in the overall behaviour of shoreface nourishments and supports the way to find an answer on the research questions.

Blue cluster - Stable

The blue cluster exists of shoreface nourishments that remain on the same position. A good example for this group is the shoreface nourishment at Camperduin from 2002. The nourishment is executed in 2002 and remains on the same position for the next seven years, until the next shoreface nourishment is executed. This means that the cross- and alongshore migration of the shoreface nourishment is negligible. In Figure 49, this is represented by the centroids (the colored dots), which remain almost exactly on the same position (around 800 m + RSP). In Figure 50, the cumulative migration of the centroid is given. For this example, the calculated mean migration is -2.9 meters a year. In comparison with the migration of other shoreface nourishments, this value is negligible.

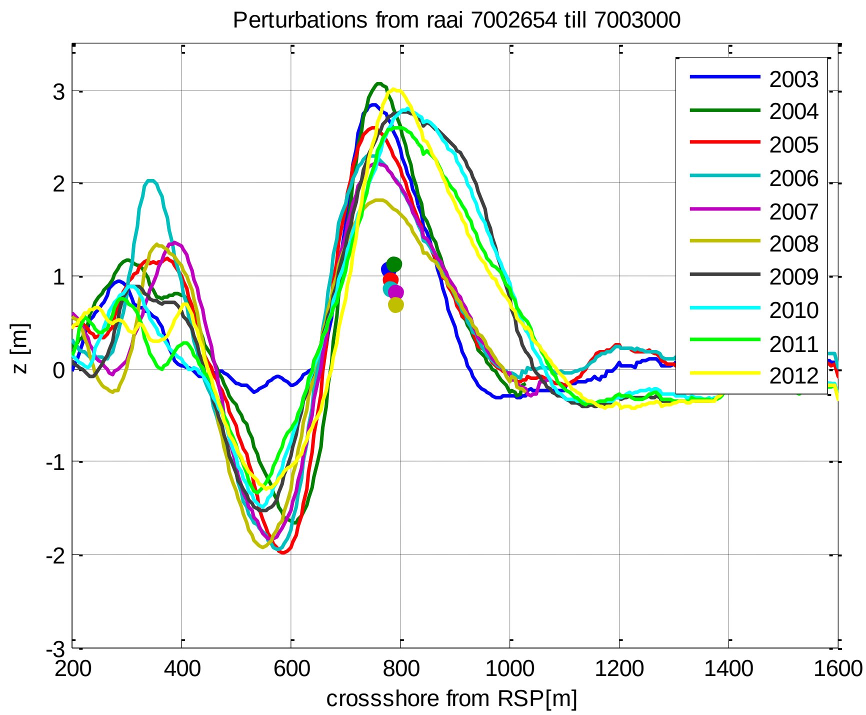


Figure 49: Perturbations of the blue cluster. The centroids remain on the same position (around 800m +RSP). This means that the shoreface nourishment remains in cross-shore direction on the same position.

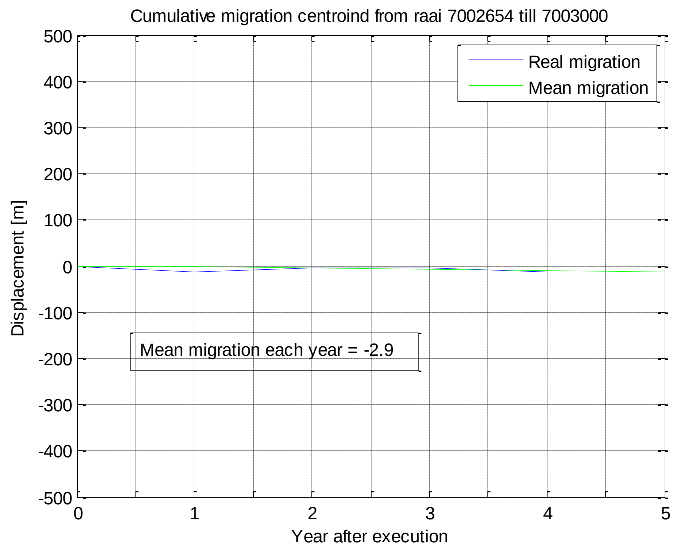


Figure 50: Cross-shore migration of centroid blue cluster. The blue line represents the real migration. The green line represents the mean migration.

Red cluster – Onshore migration

The red cluster has a strong cross-shore migration towards the coast, but the alongshore migration is negligible. A good example for this cluster is the shoreface nourishment at Ter Heijde from 1997. This nourishment has a strong onshore migration and at the same time the alongshore migration is negligible. In Figure 51, this strong onshore migration is represented by the centroids that are developing onshore. (In addition: this figure shows a good example of the development of a system with a crest and a trough.)

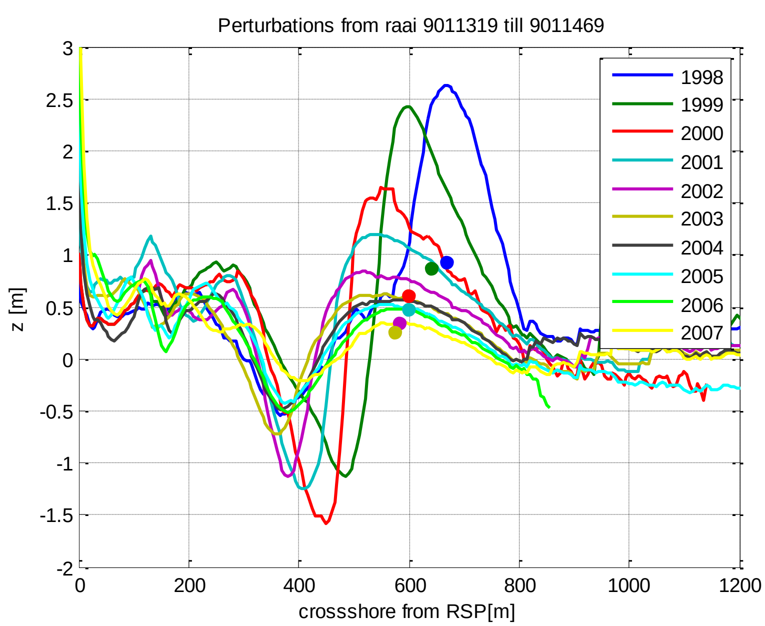


Figure 51: Perturbations of the red cluster. In this example is clearly visible that the centroids are migrating onshore. I.e. the shoreface nourishment is migrating towards the coast.

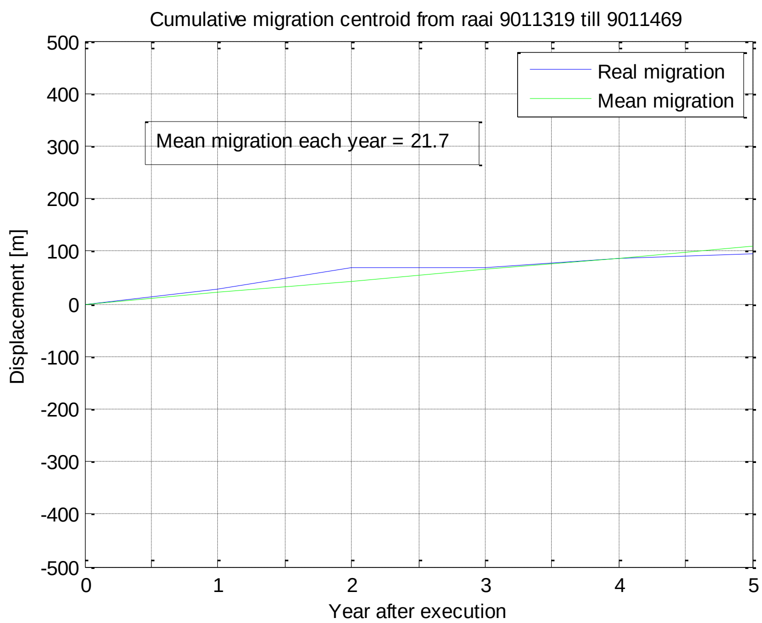


Figure 52: Cross-shore migration centroid red cluster. The blue line represents the real migration. The green line represents the mean migration.

Green cluster – Onshore and alongshore migration

The migration of the green cluster is onshore and along the coast, in downstream, northward, direction. An example of this group is the shoreface nourishment at Eierland from 2004. In Figure 53 and Figure 54, a clear constant onshore migration of 78.7 meters a year is given. In Figure 55, the alongshore migration of 141.7 meters a year is represented.

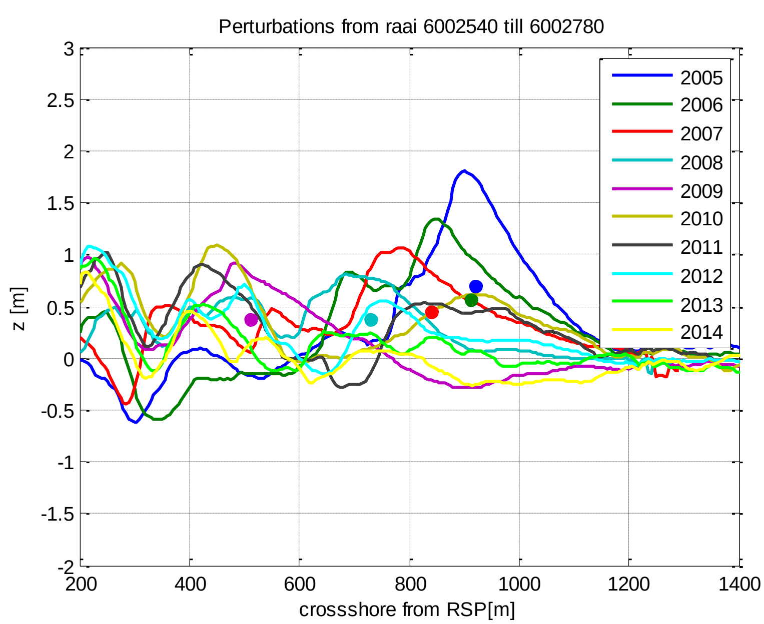


Figure 53: Perturbations of the green cluster. In this example is clearly visible that the centroids are migrating onshore. I.e. the shoreface nourishment is migrating towards the coast.

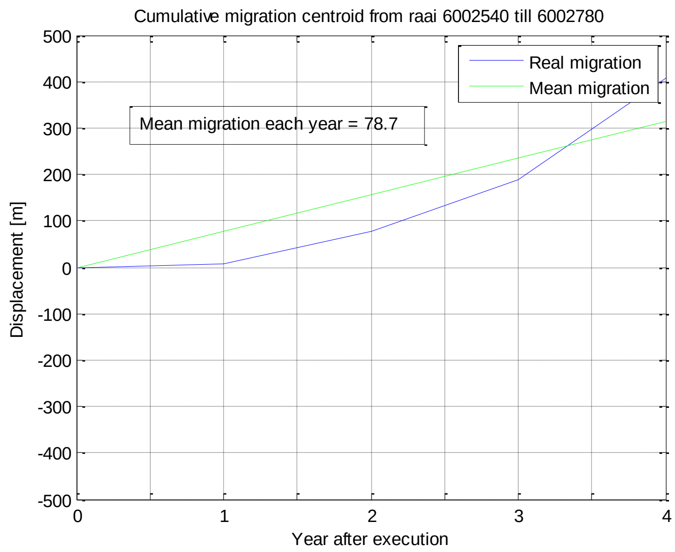


Figure 54: Cross-shore migration centroid green cluster. The blue line represents the real migration. The green line represents the mean migration.

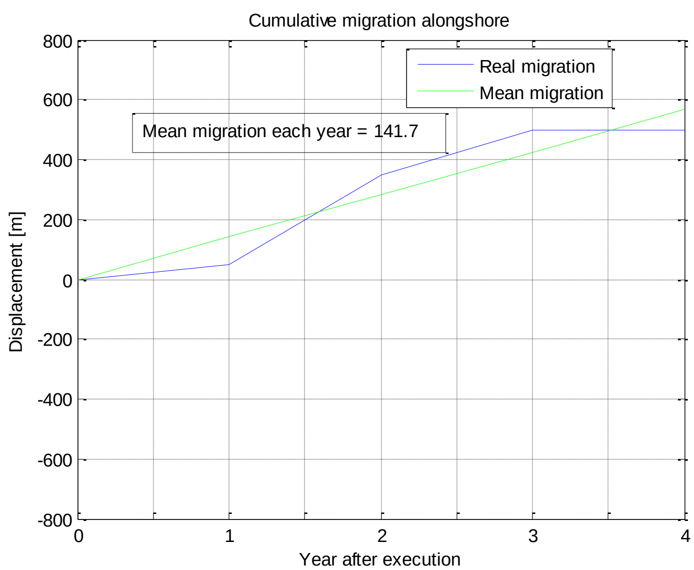


Figure 55: Alongshore migration green cluster. The blue line represents the real migration. The green line represents the mean migration.

Orange cluster – Offshore migration

The last one is the orange cluster. This cluster has an offshore-directed cross-shore component and the alongshore component is negligible. Actually, the shoreface nourishment at Ameland is the only case in this cluster, but a further look into detail shows that the shoreface nourishment at Bergen (2005) might be placed in this group. This shoreface nourishment has a clear offshore-directed migration and in alongshore direction it remains at its location. Because of the definition of alongshore migration in this study, it looks like the shoreface nourishment migrates upstream, towards the south. This happens because the northern tip is executed with a slight curve and this tip disappears in the first year. When only focussing on the main part of the shoreface nourishment, it has no alongshore component.

In the next figures, the shoreface nourishment of Ameland is given as an example for this cluster with a strong offshore (negative) migration of 153.4 meters a year.

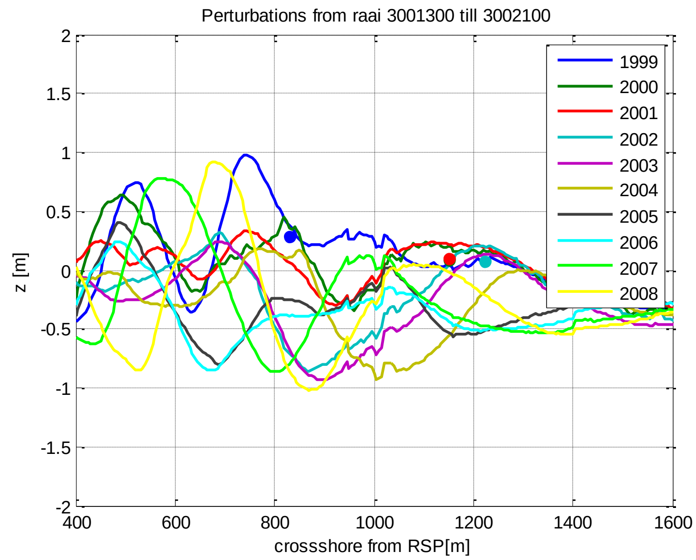


Figure 56: Perturbations for the orange cluster. In this example is clearly visible that the centroids are migrating offshore. I.e. the shoreface nourishment is migrating towards the sea.

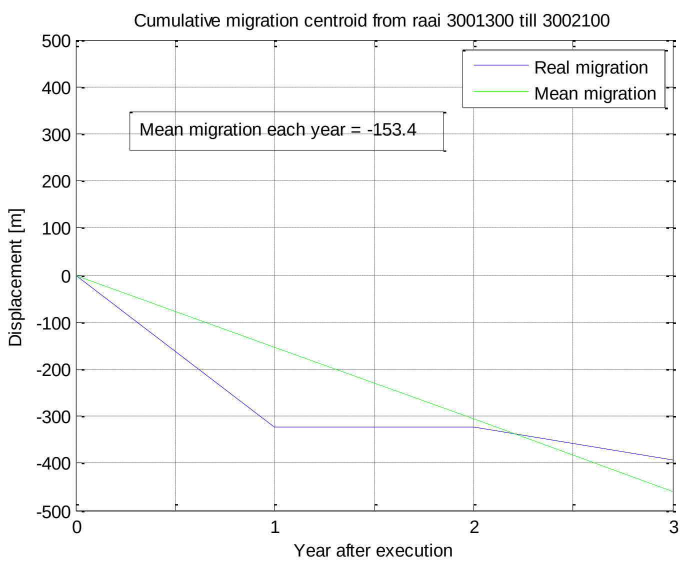


Figure 57: Cross-shore migration centroid orange cluster. The blue line represents the real migration. The green line represents the mean migration.

4.3 Volume trends

Due to the execution of nourishments, sediment volumes in the cross-shore profiles are changing. One of the goals of shoreface nourishments is to get more sediment in the system. Despite the focus in this thesis is on the migration of the shoreface nourishments, this section provides additional information on the volume trends for the shoreface nourishments. This gives a better insight in the erosion or sedimentation due to shoreface nourishments and tells something about the morphological behaviour of shoreface nourishments.

4.3.1 Method

The mean profiles for the years of interest, determined for the detailed cross-shore migration, are used to calculate the volume trends, i.e. the volume trends are determined for a mean profile which is representative for the whole shoreface nourishment. The JARKUS transects at the shoreface nourishment are averaged over space and one representative cross-shore profile is produced for which the volumes are calculated. Next, this mean profile is cross-shore divided in different bins of 200 m, see Figure 58, with a lower limit of -10 m NAP. For every bin, the volume is calculated per year. This results in volume trends for more years. With these volume trends, the effect of the shoreface nourishment on the sediment volume development is determined.

The lower limit and the land- and seaward limit are different per shoreface nourishment, because in some cases the data records stop at a certain point (e.g. at 110 m for the Ter Heijde case, as the land surveys are not included for some years). For this reason, only the volume trends of shoreface nourishments are compared. The axes of the trend figures have the same range (2000 m^3/m).

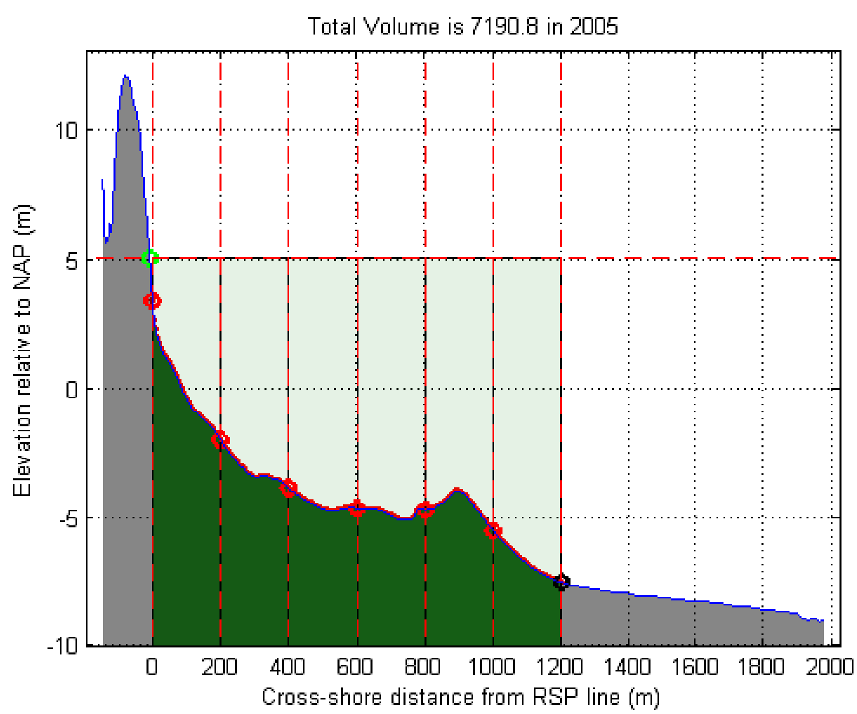


Figure 58: Different bins for the mean cross-shore profile. The volume in these bins is calculated for the years of interest and results in a volume trend.

4.3.2 Volume trends for clusters of shoreface nourishments

In this section, the volume trends for the different clusters are calculated. The volume trends for every bin and the total volume in the cross-shore profile are determined. In Appendix D, the results for all shoreface nourishments are given. The first four figures in this appendix show the total volume trends per cluster. The volume of the year before execution is set on zero. This provides a good comparison between the trends of the different shoreface nourishments per cluster. In the next sections, the characteristic shoreface nourishment for every cluster is featured.

Blue cluster - Stable

This cluster contains the shoreface nourishments that remain stationary. In the volume trends, this is visible. The volume in bin 800-1000 m is increased after execution and remains the same in the subsequent years. The volume in bin 600-800 m increases as well after execution, but decreases in the subsequent years due to the formation of a trough. Trough formation is also the reason why the volume in bin 400-600 m decreases. The volume in bin 000-200 m slightly increases in the years after execution. The total volume in the cross-shore profile increases in the first year of execution of the shoreface nourishment, but decreases in the next years. This indicates that sediments are migrating slightly along- or offshore, outside the range of this cross-shore profile.

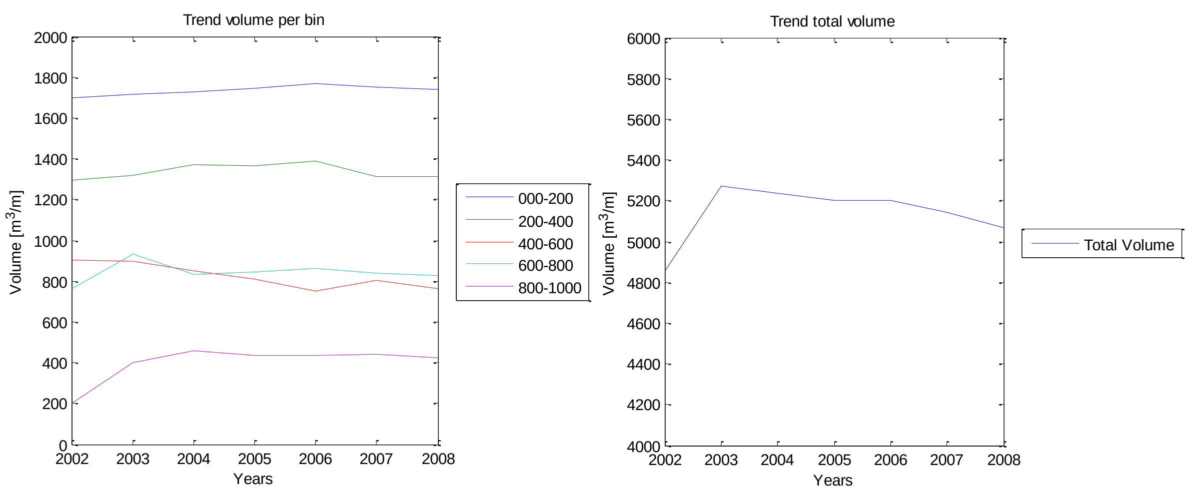


Figure 59: Volume trends for the cross-shore profile at Camperduin, executed around 750 m, from 2002 until 2008. In the left figure, the volume trends per bin are given and in the right one the trend of the total volume (sum of all bins).

Red cluster – Onshore migration

The shoreface nourishments in this cluster migrate onshore. For the shoreface nourishment at Ter Heijde, the landward boundary is set on 110 m +RSP and the seaward boundary at 800 m +RSP, as for some years the data records reach only until these boundaries.

The trend of the total volume is almost the same as encountered for the shoreface nourishment at Camperduin, because both do not have a dominant alongshore component and the sediment remains in the profile (only a small part migrates along- or offshore). The volume in bin 600-800 m increases in the first year and decreases during the next years, because the shoreface nourishment migrates onshore. The volume in bin 400-600 m increases in the first year, but decreases in the second year because of the trough and again increases in the subsequent years, because the trough migrates onshore. The onshore migrating trough declares the decrease after three years in bin 200-400 m.

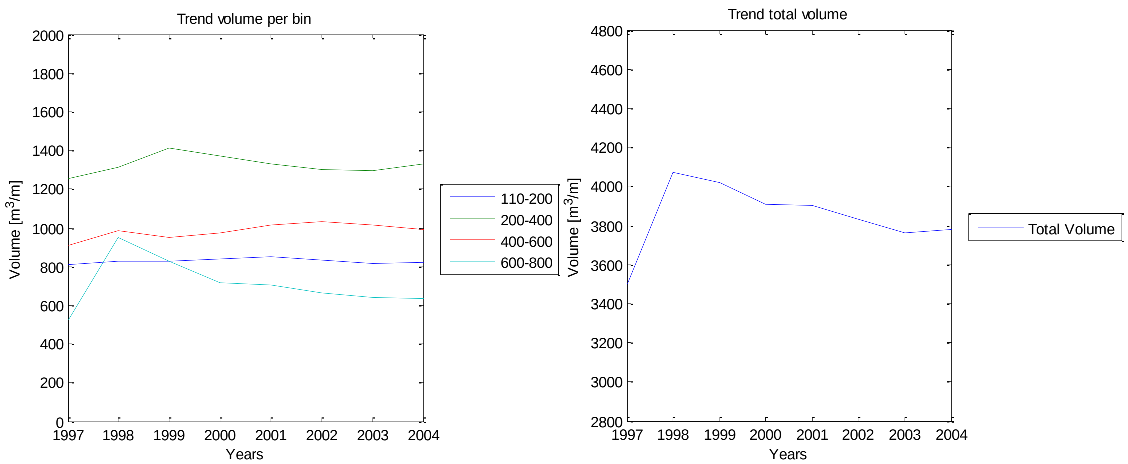


Figure 60: Volume trends for the cross-shore profile at Ter Heijde, executed around 700 m, from 1997 until 2004. In the left figure, the volume trends per bin are given and in the right one the trend of the total volume (sum of all bins).

Green cluster – Onshore and alongshore migration

Shoreface nourishments in the green cluster migrate on- and alongshore. For Eierland 2004 the volume trends are given. Based on the migration, the trend for the total volume would decrease after execution, because the sediment migrates alongshore, i.e. outside the boundaries of the cross-shore profile. However, the trend for the total volume is clearly constant after execution. In the visual description is mentioned that the shoreface nourishment migrates alongshore, i.e. sediments migrate outside the northern boundary. Now that the volume trend is constant, this means that sediment is entering the southern boundary at the same rate. This suggests that the salient effect, mentioned by Van Duin, et al. (2004), exists onshore of the shoreface nourishment.

For the area 800-1200 m, the trend increases in the year of execution and decreases (until the original volume) in the subsequent years. The volume for the area 200-600 m increases slowly after the shoreface nourishment is executed, because of sediments from the shoreface nourishment and the salient effect, and after five years, the volume at the beach (bin 000-200 m) increases.

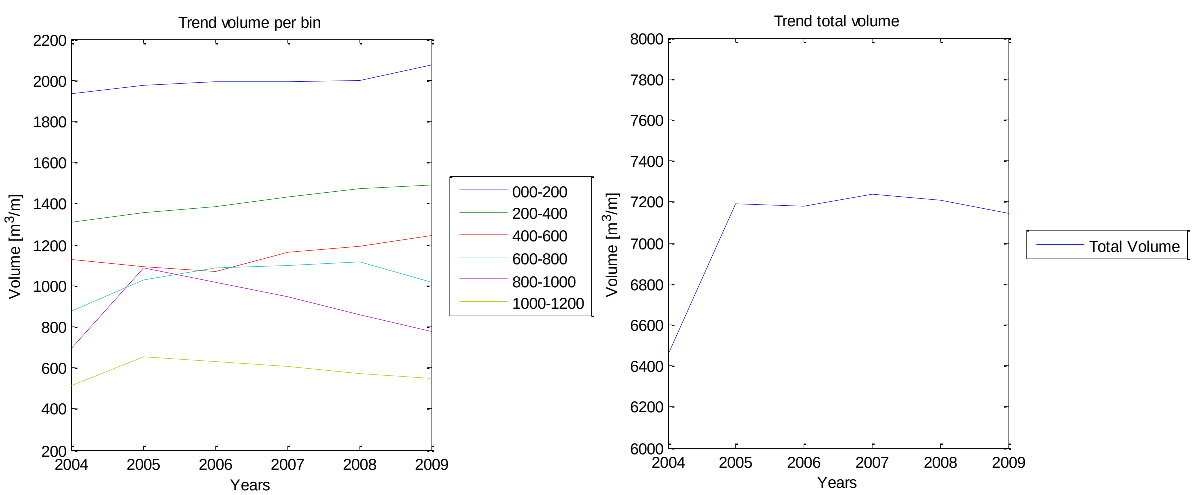


Figure 61: Volume trends for the cross-shore profile at Eierland, executed around 900 m, from 2004 until 2009. In the left figure, the volume trends per bin are given and in the right one the trend of the total volume (sum of all bins).

Orange cluster – Offshore migration

This cluster contains the shoreface nourishments that migrate offshore, like the one at Ameland. The volume trends for these shoreface nourishments are different from the previous ones. The trend of the total volume is not as expected. In the first three years, nothing special occurs, but after the third year, the total volume decreases, i.e. erosion might occur in the profile, but this might happen also because of land subsidence in the area of Ameland. The volume in the area 000-600 m remains virtually constant after execution; this corresponds with the offshore migration of the shoreface nourishment. As a result, this means that the influence of the shoreface nourishment is negligible for the area of 000-600 m. In the area of the execution of the shoreface nourishment (600-1200 m), for the first year the trend increases, but in the subsequent years decreases. This mainly happens because the trough is formed and migrated offshore. Because of land subsidence in this area, robust conclusions about the volume development are not possible based on these volume trends.

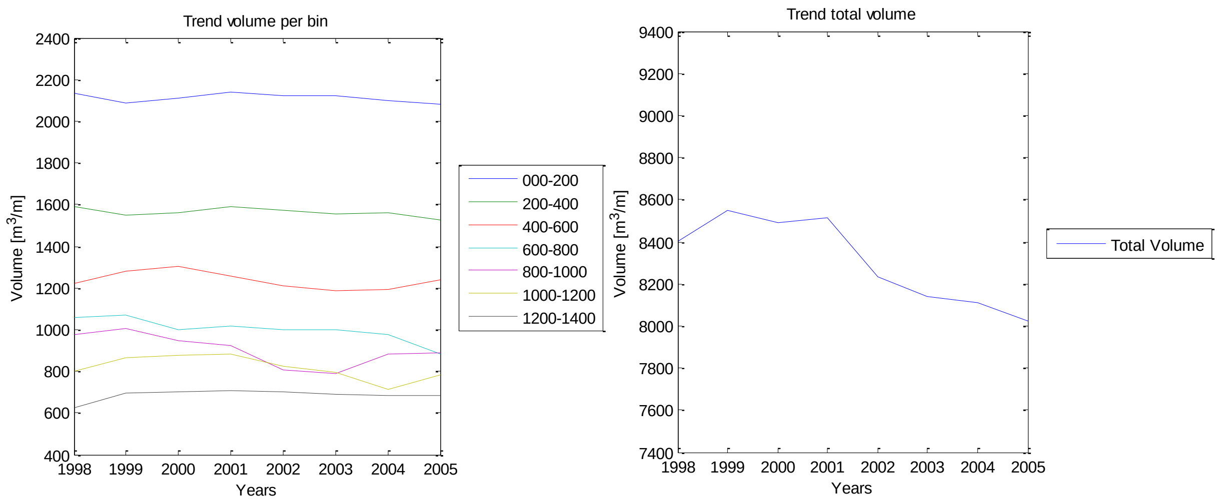


Figure 62: Volume trends for the cross-shore profile at Ameland, executed around 800 m, from 1998 until 2005. In the left figure, the volume trends per bin are given and in the right one the trend of the total volume (sum of all bins).

4.4 Conclusions

In this chapter, the migrations and volume trends of the shoreface nourishments are determined. In chapter six, the migration and volume trends are used for the research on driving processes behind the morphological behaviour of shoreface nourishments.

For the shoreface nourishments a difference in migration is found, grouped in four clusters by their cross-shore and alongshore component. In the regions influenced by outer deltas of the Wadden Sea, an onshore and downstream migration is found. For shoreface nourishments along the Holland coast, cross-shore migration is found but the alongshore migration is negligible. For most shoreface nourishments, an increase of sediment volume is found. Only for the shoreface nourishment at Ameland Midden a negative volume trend is found, but because of land subsidence in this area, it is hard to conclude that erosion still occurs for this cluster.

5. Parameter analysis

In the previous chapter, the development of shoreface nourishments is described. More detail about the different parameters of the bar system, shoreface nourishments and hydrodynamics is given in this chapter. With the results in this chapter, the first sub-research question of this thesis, stated in section 1.7, can be answered.

5.1 Original bar system

The visual analysis shows that shoreface nourishments influence the original bar system. Based on this visual analysis, the assumption is made that the behaviour of the shoreface nourishment depends on one or more properties of the original bar system. In this section, further research into different aspects of the original bar system follows.

5.1.1 Cross-shore bar cycle

As Walstra (2016) mentions in his work (see section 2.3.3), there is a difference in bar cycle period along the Dutch coast. In this section, T_r is determined with the definition stated in the theory (see section 2.3.3). The JARKUS transects are analysed with the software program MorphAn. T_r is determined at the location of shoreface nourishments. As an example, the determination of T_r for the bar system at Zandvoort is drawn from Figure 63. In 1993 (red line) the first year of the bar cycle period is given. After four years, in 1997 (blue line), the same bar state is present as in 1993. Based on this data, the bar cycle period is four years.

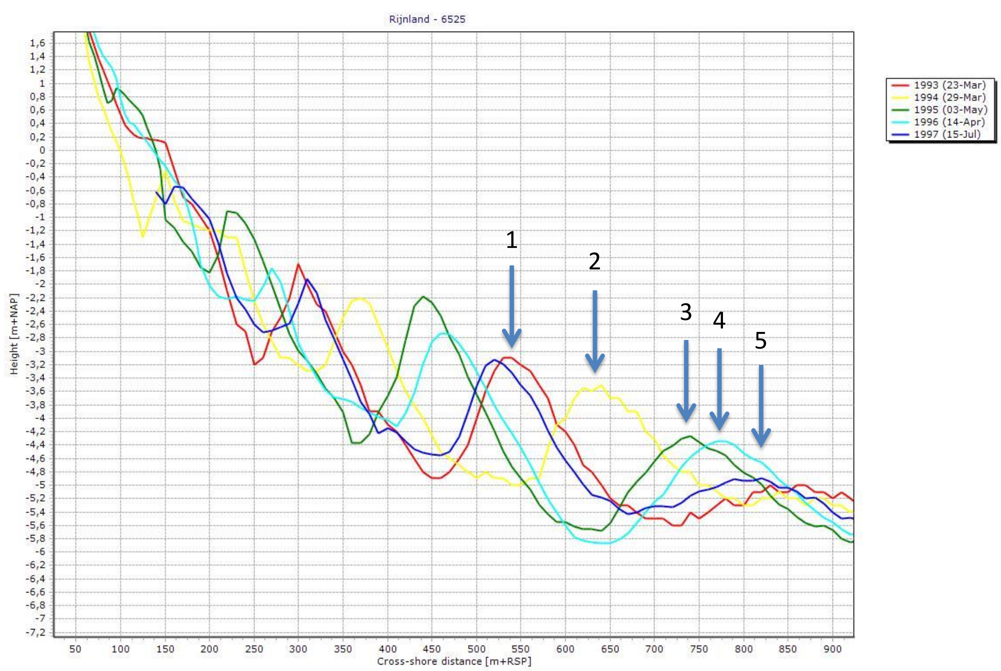


Figure 63: Example of the bathymetry from 1993 (red line) until 1997 (blue line) at Zandvoort. The bar cycle period is determined with these profiles. The difference in time between two profiles that are the same, is the bar cycle period. For this example, the bar cycle period is four years, the difference between year 1 (red line in 1993) and year 5 (dark blue line in 1997).

The bar cycle period is calculated for the bar system at locations of the involved shoreface nourishments. Results of this calculation are given in Table 5, these results match with the results derived by Ruessink, et al. (2003). In this table, a distinction between cross- and alongshore is made. Because T_r is a cross-shore phenomenon, it is determined for the bar systems with an original cross-shore bar migration. There are locations where T_r is disturbed due to earlier executed shoreface nourishments or other human interferences. The last two shoreface nourishments at Delfland (number 19 and 20) for example. At Monster (number 19), the original bar system is disturbed by the previous shoreface nourishments and at Kijkduin (number 20), the original bar system is disturbed due to the sand motor. Computations on T_r are meaningless for these situations, because T_r is disturbed and is no longer the same as the T_r before execution of the shoreface nourishments. In most situations the bar system has become stable (i.e. the bars do no longer migrate).

In their paper, Spanhoff, et al. (2006) mention that the moment of execution in the bar cycle possibly influences the behaviour of the shoreface nourishment. In Table 5 this moment, at which the shoreface nourishment is placed in T_r, is given.

Table 5: Bar cycle periods and the moment that the shoreface nourishment is placed in this cycle. In these cases, zero represents the beginning of the cycle and one the end of the cycle. If T_r is for example ten years and the moment of execution is given in the table as 0.4, this means that the shoreface nourishment is placed in fourth year of the bar cycle period.

Shoreface nourishment	Original bar behaviour	T_r [years]	Phase in T_r	Phase in T_r [years]
1	Cross-shore	5	0.60	3
2	Alongshore	n/a	n/a	n/a
3	Cross-shore	10	0.90	9
4	Alongshore	n/a	n/a	n/a
5	Cross-shore	15	0.33	5
6	Alongshore	n/a	n/a	n/a
7	Cross-shore	15	0.93	14
8	Alongshore	n/a	n/a	n/a
9	Cross-shore	15	0.87	13
10	Alongshore	n/a	n/a	n/a
11	Cross-shore	n/a	n/a	n/a
12	Alongshore	n/a	n/a	n/a
13	Alongshore	n/a	n/a	n/a
14	Cross-shore	n/a	n/a	n/a
15	Cross-shore	4	n/a	n/a
16	Cross-shore	4	0.50	2
17	Cross-shore	15	0.50	7.5
18	Cross-shore	15	0.00	0
19	Cross-shore	n/a	n/a	n/a
20	Cross-shore	n/a	n/a	n/a

5.1.2 Slope of coastal profile

Walstra (2016) mentioned that a steeper slope results in a higher T_r. The migration of sandbars depends on the slope of the coastal profile. If there is a pattern between sandbar and slope, then it is possible that this pattern also exists for the slope and the migration of shoreface nourishments. The mean profile for different locations is already determined in the process of determining the cross-shore migration. The mean profile for every location is given in Figure 64. In this figure is shown that the coastal profiles of Ameland, Eierland and Zandvoort have the mildest slopes. The slopes at Bergen and De Koog between +3 m and -6 m NAP are not steep, but after -6 m NAP, the slopes become steeper. De slopes at Den Helder, Callantsoog, Monster and Ter Heijde are steep between +3 m and -6 m NAP, but have the same slope as Ameland, Eierland and Zandvoort at +700 m RSP. The research Walstra (2016) performed in his study for Egmond and Noordwijk is comparable to these results.

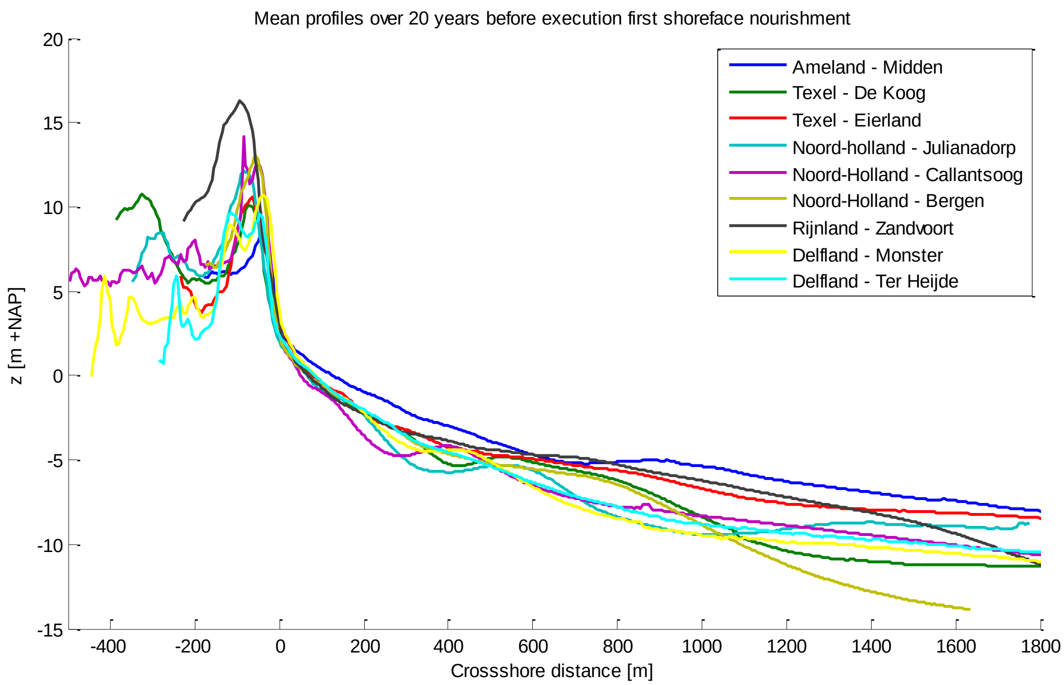


Figure 64: Slope at the location of the shoreface nourishments. The slope given is the average slope over 20 years before the execution of the first nourishment at the location.

Using the distinction between steepness, estimations are made for the Irribarren number, ξ. This Irribarren number, known as the breaker parameter, is used for the definition of breaking wave types. The formula is known as:

$$\xi = \frac{\tan \alpha}{\sqrt{\frac{H}{L_0}}}$$

In this formula α is the slope of the beach profile, H is the wave height and L_0 is the deep-water wavelength. A high Irribarren number means that the waves collapse or surge. A low number leads to spilling waves. In these cases the wavelength and wave height at deep-water are the same for every case, i.e. the number only depends on the slope of the coastal profile. With the formula, conclusions are drawn that a steeper slope (i.e. a higher tan(α)) leads to a higher Irribarren number. In Table 6 is given that the slopes at the barred zone and the Irribarren parameters are in the same range. The only difference between the coastal profiles is the offshore slope. The profile at Ameland is very flat in comparison to the steep slope at Bergen.

Table 6: Slope of the coastal profiles and the Irribarren parameter. A distinction is made between the barred zone (0m -600m) and the offshore zone (600m-1600m).

Location	Slope 1: 0m - 600m [1:x]	tan(α) 1	Irribarren	Slope 2: 600m - 1600m [1:x]	tan(α) 2
Ameland - Midden	73.8	0.0136	0.10	368.1	0.0027
Texel - De Koog	77.8	0.0129	0.10	164.3	0.0061
Texel - Eierland	73.6	0.0136	0.10	311.7	0.0032
Noord-Holland - Julianadorp	78.7	0.0127	0.10	302.3	0.0033
Noord-Holland - Callantsoog	68.2	0.0146	0.11	283.6	0.0035
Noord-Holland - Bergen	76.3	0.0131	0.10	121.9	0.0082
Rijnland - Zandvoort	78.1	0.0128	0.10	213.4	0.0047
Delfland - Monster	57.8	0.0173	0.13	253.4	0.0039
Delfland - Ter Heijde	69.0	0.0145	0.11	264.3	0.0038

5.1.3 Zone of decay for sandbars

When the cross-shore bar migration is dominant, sandbars migrate in general offshore until they decay at a certain zone. This process is already mentioned in section 2.3.3. Spanhoff, et al. (2006) mention in their paper that this zone of decay (they call it a graveyard) influences the migration of shoreface nourishments.

With the JARKUS survey, it is possible to find the decay zone. The cross-shore profiles are plotted for every year in one figure. With these plots, the zone where the sandbars decay is found. This is set as the decay zone of the sandbar. In Appendix F, the zone is determined for every bar system.

The distance between the zone of decay and the execution position of the shoreface nourishment is determined by the distance of the crest of the shoreface nourishment to the decay zone. In Table 7, the results of the position of the decay zone, and the distance between this zone and the shoreface nourishment, are given.

Table 7: Position of the decay zone and the distance to shoreface nourishment. Since the zone of decay is present for locations with dominant cross-shore bar behaviour, it cannot be determined for locations with dominant alongshore or no bar migration (number 4, 6, 8, 10, 12, 13). For number 2 (gully nourishment) and 15 (lack of data) the patterns are not determined and for number 20 the sand motor disturbed the system. A negative distance means that the shoreface nourishment is executed offshore of the decay zone and positive means that the shoreface nourishment is executed onshore of the decay zone.

Shoreface nourishment	Zone of decay [m + RSP]	Shoreface nourishment [m + RSP]	Distance Zone of decay and shoreface nourishment [m]
1	1000	825	175
2	n/a	n/a	n/a
3	820	1100	-280
4	n/a	n/a	n/a
5	525	650	-125
6	n/a	n/a	n/a
7	650	650	0
8	n/a	n/a	n/a
9	500	550	-50
10	n/a	n/a	n/a
11	750	650	100
12	n/a	n/a	n/a
13	n/a	n/a	n/a
14	750	775	-25
15	n/a	n/a	n/a
16	800	1000	-200
17	490	625	-135
18	350	475	-125
19	375	575	-200
20	n/a	n/a	n/a

5.1.4 Distance shoreface nourishment and sandbars

The interaction between the bar system and shoreface nourishment is clearly visible in the visual description in section 4.1. When the distance is large, it might be reasonable that the influence of the shoreface nourishment is less than when the shoreface nourishment is close to the bar system. The formation of a trough onshore of the shoreface nourishment might lead to the conclusion that the migration of the outer bar is influenced by this trough. When the trough is far away from the outer bar, the influence of the shoreface nourishment on the behaviour of the bar system might be less.

The distance between the shoreface nourishment, after execution, and the outer bar is determined. In addition, the distance between the outer bar and the inner bar (or the coast when there is only one bar in the original system) is determined to find a potential correlation between the behaviour of the bar system and the distances. These distances are determined by the distance between the crest of the shoreface nourishments and the sandbars. The crest of the sandbar(s) is determined in the year before execution of the shoreface nourishments and the crest of the shoreface nourishment is determined in the year of execution. In Table 8, the results for this determination are shown.

Table 8: Distance between shoreface nourishment and outer bar and the distance between two bars (or bar and coast when there is only one bar in the system, this is mentioned in the third column). The distances are determined by the crest of the shoreface nourishment and the crest of the sandbar(s).

Shoreface nourishment	Distance crest nourishment and crest outer bar [m]	Distance to next bar of coast	Distance [m]
1	260	Bar	280
2	n/a	n/a	n/a
3	480	Coast	190
4	480	Bar	180
5	140	Coast	420
6	500	Coast	220
7	160	Bar	350
8	120	Coast	260
9	130	Bar	280
10	100	Coast	200
11	200	Bar	240
12	140	Bar	280
13	70	Coast	500
14	50	Bar	370
15	n/a	n/a	n/a
16	400	Bar	200
17	180	Coast	310
18	150	Coast	240
19	90	Bar	270
20	370	Coast	160

5.2 Execution shoreface nourishment

The execution of the shoreface nourishments is different for every situation. This leads to different reactions for the behaviour and migration of the shoreface nourishment. In section 2.8.1 is found that the design depth of shoreface nourishments is around -5 m and -8 m NAP (Spanhoff, et al., 2006). The depth before execution is analysed in this section. In Table 9, the results are given for the execution depth.

In addition, a comparison is made between the execution profiles. In some situations, the shoreface nourishment is placed exactly against the outer bar (e.g. the shoreface nourishment at Callantsoog in 2001). There are also situations where the nourishment is placed independent, offshore of the outer bar (e.g. the shoreface nourishment at Bergen in 2005). In Table 9, is the execution position given. In this table, 'against' means that the shoreface nourishment is executed at the outer slope of the outer bar, like at Callantsoog in 2001 (see Figure 65). The term 'independent' means that the shoreface nourishment is executed offshore of the outer bar (i.e. not at the slope), like at Bergen in 2005 (see Figure 66).

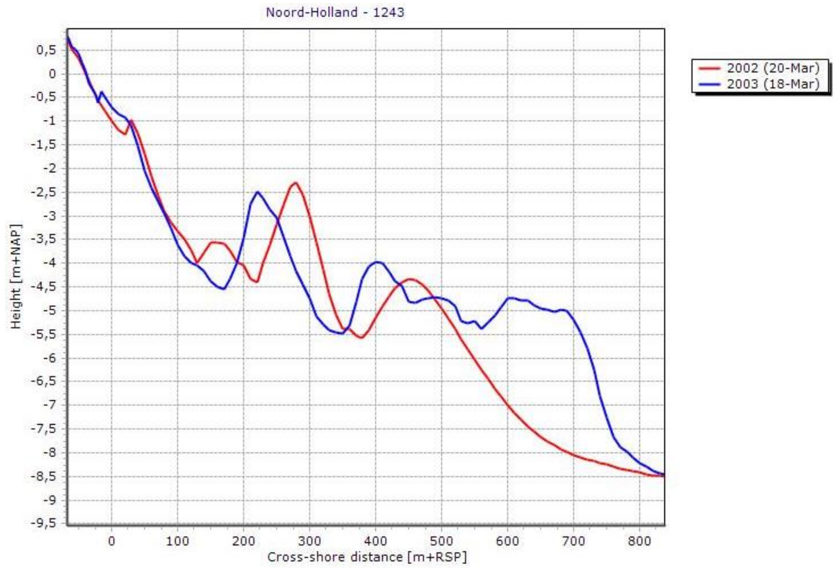


Figure 65: The profiles in 2002 (red) and 2003 (blue) for the shoreface nourishment at Callantsoog executed in 2001. This one is placed against the outer bar.

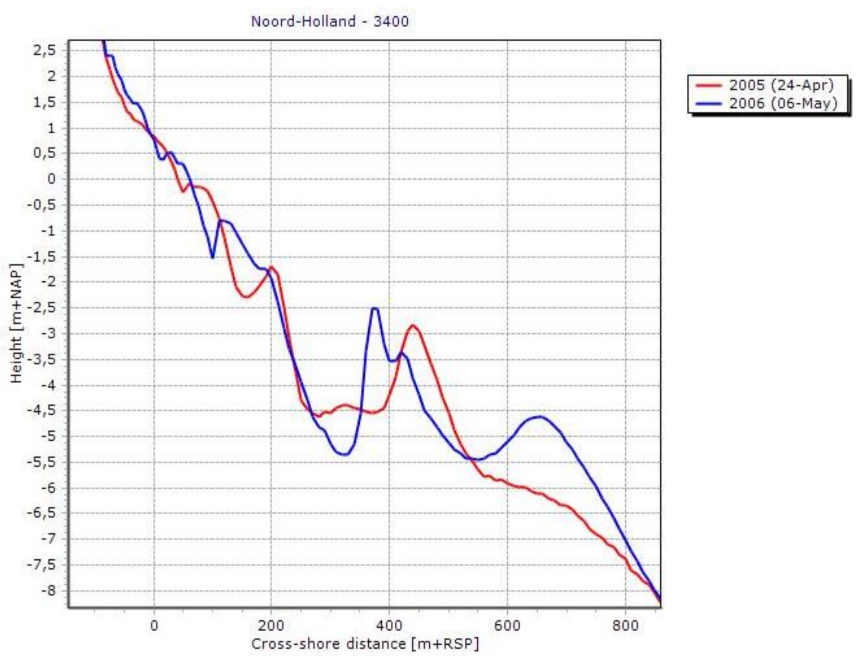


Figure 66: The profiles in 2005 (red) and 2006 (blue) for the shoreface nourishment at Bergen executed in 2005. This one is placed independent of the outer bar.

Table 9: Execution parameters of the shoreface nourishment.

Shoreface nourishment	Execution range [m NAP]	Water depth above crest before execution [m]	Water depth above crest after execution [m]	Execution position
1	-5 and -6.5	6.15	4.50	Independent
2	n/a	n/a	n/a	n/a
3	-5 and -8	6.90	3.85	Independent
4	-5.5 and -7.5	5.80	2.60	Independent
5	-5 and -8	6.65	3.90	Against
6	-5 and -7.5	6.00	2.75	Independent
7	-5.5 and -6.5	5.80	4.80	Independent
8	-5.5 and -7.5	6.30	4.75	Against
9	-5.5 and -8.5	6.70	4.05	Independent
10	-5 and -8	7.30	3.95	Against
11	-5.5 and -7	6.60	4.65	Independent
12	-5 and -7	5.80	2.95	Independent
13	-5.5 and -8	6.30	4.35	Against
14	-5 and -8	6.45	4.30	Against
15	n/a	n/a	n/a	n/a
16	-5.5 and -7	5.90	4.25	Independent
17	-6 and -8	6.90	3.90	Independent
18	-5 and -9	7.15	3.70	Independent
19	-4.5 and -8	5.50	4.35	Against
20	-6 and -9.5	8.10	5.50	Independent

5.3 Waves

De Sonneville, et al. (2012) mention that the influence of waves on growth and decay of sandbars reduces with increasing water depth (according to Walstra (2016)), but the influence of different wave directions on the behaviour of shoreface nourishments is limited.

In this section, the wave conditions during the lifetime of the shoreface nourishments are analysed. For this analysis, the data from Waterbase is used. This data measures the wave height and –direction every hour a day. A wave rose for every situation is made (e.g. Figure 67). The locations at which the data is measured are different. Data from 'IJgeul Munitiestort 1' is used for the shoreface nourishments at Delfland, Rijnland and Noord-Holland. 'Eierlandse Gat boei' is used for Texel. For Ameland 'Schiermonnikoog Noord Boei' is used.

There is a clear difference between the wave roses of Ameland and the wave roses along the Holland Coast and Texel. For Ameland actually most waves are coming from northwest (NW), because there is no wave generation from the south and east due to the presence of land. The wave roses at Texel and the Holland Coast have two strong wave directions. These are NW and southwest (SW). The distinction between those two directions is the height and the percentage of waves. The highest percentage of waves is coming in from SW, but the highest waves are coming in from NW.

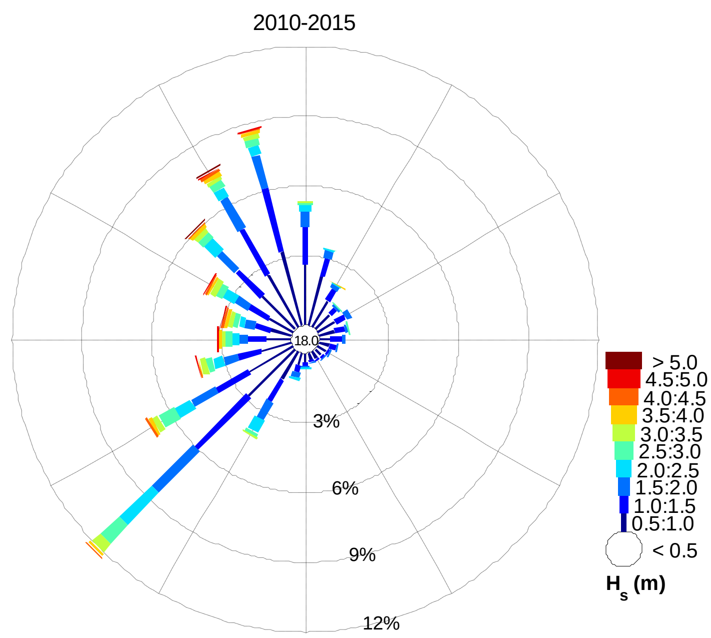


Figure 67: Wave rose for Noord-Holland – Den Helder-Julianadorp from 2010 until 2015.

To determine the pattern between wave forcing and the behaviour of the shoreface nourishments, the wave roses are transformed into one arrow that represents the overall forcing of the waves. To complete this, refraction (see section2.2.2) is included in the determination of the arrow and the energy of the waves is calculated. In Appendix E, the results for all the shoreface nourishments are given.

5.4 Conclusions

In this chapter, the parameters that might influence the morphological behaviour of shoreface nourishments are determined. For the existing bar system, the bar cycle period is determined. This is performed for a selection of nine shoreface nourishments, because at some locations a bar cycle does not exist. At other locations the bar cycle is disturbed by earlier nourishments. Between the slope and Irribarren parameters, no clear difference is found. For bar systems with an original cross-shore migration of the bars is found that the bars migrate to the zone of decay. The sandbars migrate towards this zone and decay here. For bar systems with an original alongshore migration of the bars, this zone does not exist.

The distance between the shoreface nourishments and the sandbars is determined. This results in a high variation of ranges. This matches with the execution of the shoreface nourishment. Where the distance between shoreface nourishment and the outer bar is small, the shoreface nourishment is executed against the outer bar and vice versa. The execution zone of the shoreface nourishments is always between -5 m and -8 m NAP. The crest is more diverse and varies between -2.60 m and -5.50 m NAP. The surrounding structures and environments that might influence the morphological behaviour of the shoreface nourishment are outer deltas of the Wadden Sea and the breakwaters at the harbour of IJmuiden and Rotterdam.

6. Correlation and pattern

In this chapter, the parameters analysed in the previous chapter are compared with the morphological behaviour, analysed in chapter four. This provides an answer on the second sub-research question of this thesis.

6.1 Original bar system

The relation between the original bar system and the executed shoreface nourishment is examined in this section. This relation is twofold: first, the influence of the original bar system on the behaviour of the shoreface nourishment and second, the influence of the shoreface nourishment on the (changed) bar system.

6.1.1 Bar cycle period

In section 5.1.1 is found that the shoreface nourishments with a same bar cycle period of fifteen years (numbers 5, 7, 9, 17 and 18) have a different direction and magnitude of migration. Based on these results, no pattern between the length of the bar cycle period and the migration of shoreface nourishments is found. Neither a pattern exists between the phase of execution in the bar cycle period and the migration of shoreface nourishments. Shoreface nourishments number 1, 16 and 17 have the same moment of execution in the bar cycle period, but the migration of number 1 is totally different than the migration of 16 and 17.

6.1.2 Slope and Irribarren

Based on the difference in the morphological behaviour and the Irribarren parameter that is the same along the Dutch coast, the conclusion is made that there is no pattern between the Irribarren parameter and the morphological behaviour of shoreface nourishments.

The slope of the offshore part of the cross-shore profile is not the same everywhere. Texel Eierland and Ameland Midden do have a mild offshore slope and Noord-Holland Bergen and Rijnland Zandvoort do have a steep slope. Comparing this with the migration of the shoreface nourishments, no clear pattern is found. The shoreface nourishment at Ameland Midden migrates fast offshore and the shoreface nourishments at Texel Eierland migrate fast onshore, while they are in the same range of coastal slope. The shoreface nourishments at Bergen migrate in different directions. Because the slopes are in the same range, there is no pattern between the slope of the coastal profile and the migration of shoreface nourishments found in this thesis.

6.1.3 Zone of decay

Locations where the sandbars migrate dominant cross-shore, i.e. there is a zone of decay, are given in Figure 68. There might be a pattern between the migration of shoreface nourishments and the migration of the existing sandbars. From the figure follows that the shoreface nourishment migrates dominant cross-shore, and not alongshore, when a zone of decay is present (i.e. the original bar behaviour is cross-shore, and the alongshore migration is negligible). If there is no zone of decay in the original bar system, the shoreface nourishment migrates onshore and alongshore. The overall pattern is a dominant cross-shore migration of shoreface nourishments if an original dominant cross-shore migration of the sandbars is present and an onshore and alongshore migration if there is no original dominant cross-shore migration present. This pattern proves the theory of Spanhoff, et al. (2006) that shoreface nourishments migrate towards a 'graveyard' (zone of decay).

The explanation for the occurrence of offshore bar behaviour possibly follows from the onshore migration of sandbars during calm conditions and offshore migration during storm conditions (according to Hoefel, et al. (2003), see section 2.3.1). When in the original system the bars migrate offshore, the contribution of offshore migration is higher than the onshore contribution. For the original system where the sandbars migrate alongshore or do not exist, the contribution of onshore migration is higher than the offshore migration. Since the shoreface nourishment acts as a new sandbar, it consequently follows the cross-shore migration of the original bar system.

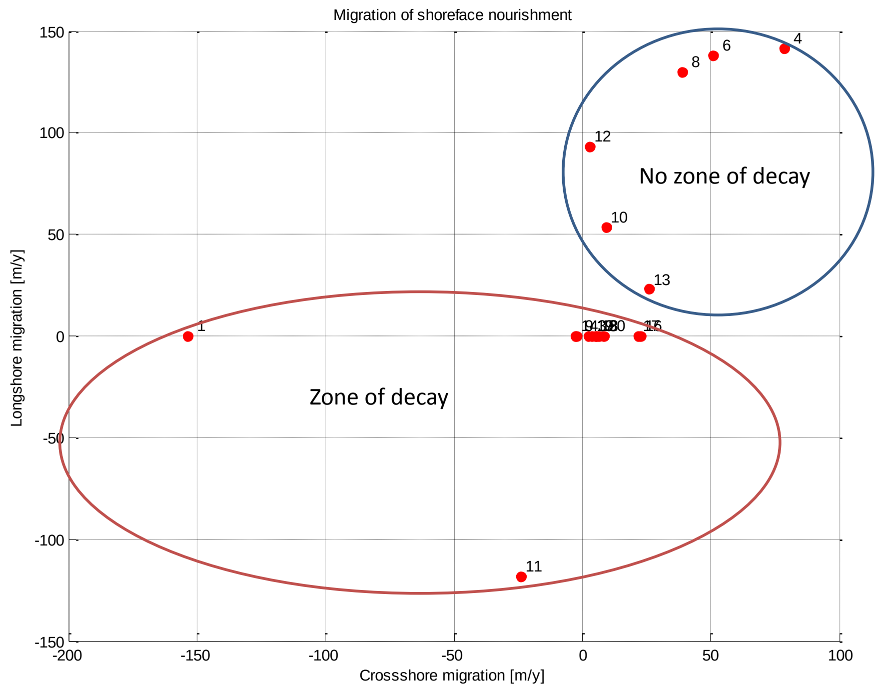


Figure 68: Clusters with and without a zone of decay.

The next step is to compare the cross-shore migration of shoreface nourishments with the distance to the zone of decay. Since the bars in the original system migrate towards the zone of decay (Ruessink, et al., 1994), it is likely that shoreface nourishments follow this trend. In Figure 69, the pattern between the distance towards the zone of decay and the cross-shore migration per year is given. In this figure, a clear pattern is visible between the direction of cross-shore migration and the execution position of the shoreface nourishment. The shoreface nourishment migrates onshore if it is executed offshore of the zone of decay and the shoreface nourishment migrates offshore if it is executed onshore of the zone of decay. A correlation of -0.73 is found between the migration per year and the distance between the zone of decay and the shoreface nourishment (without the outlier from the shoreface nourishment at Ameland-Midden, this correlation is -0.65). In Appendix F is shown that the shoreface nourishments migrate towards the zone of decay and in further detail in Figure 70 (orange cluster), Figure 71 (blue cluster) and Figure 72 (red cluster).

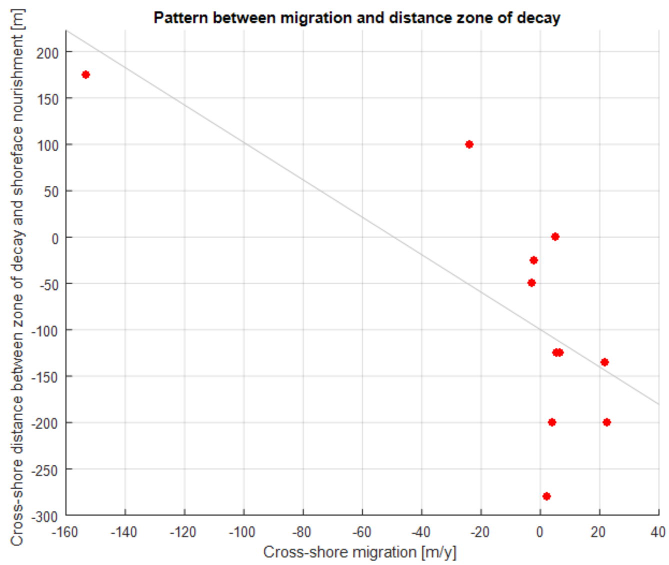


Figure 69: The correlation, -0.73, between cross-shore migration shoreface nourishment and the distance between zone of decay and shoreface nourishment. A positive migration on the x-axis means a migration towards the coast and a positive distance at the y-axis means that the shoreface nourishment is executed onshore of the point of decay.

A clarification for the exact position of the zone of decay and the parameters that might influence this position is until moment of writing not published in literature. A physical explanation for the existence and position might be found in the relation between the depth of the zone and the wave energy (according to Walstra (2016), see section 2.3.3). The shoreface nourishments or sandbars onshore of the zone of decay migrate offshore towards this zone and vice versa. Probably, this zone represents the point where the offshore and onshore migrations are equal and there is no net migration. Offshore of this point, the climate at the crest of the bar is less energetic, because waves have minor influence due to the increased depth, i.e. the shoreface nourishment migrates onshore. Onshore of this point the breaking waves have more influence, which intends the sandbars or shoreface nourishments to migrate offshore.

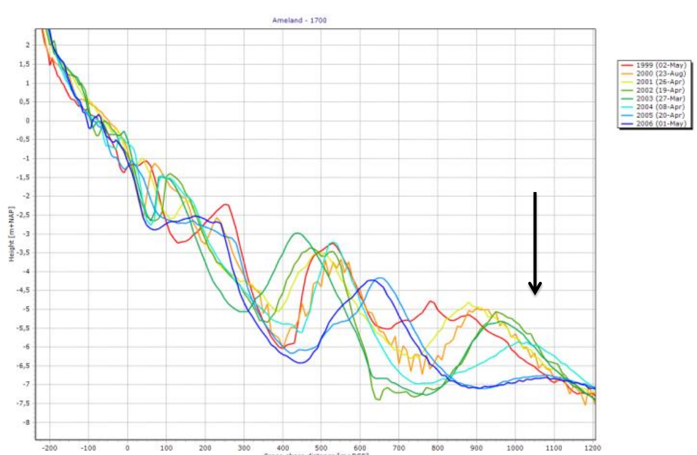


Figure 70: Offshore migration of shoreface nourishment at Ameland (orange cluster) towards zone of decay (given by the arrow).

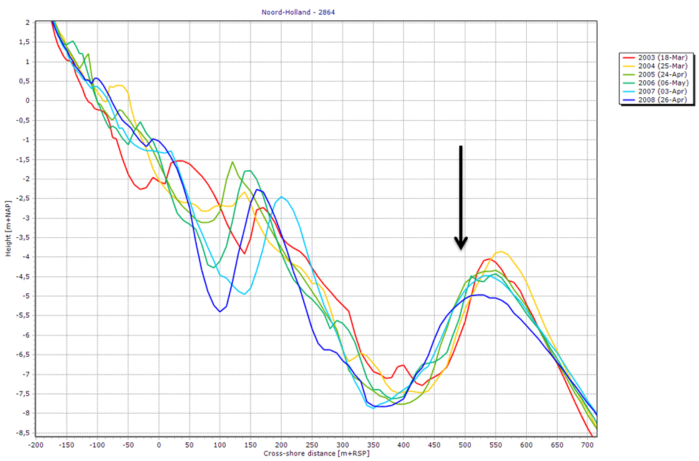


Figure 71: Minimal migration of shoreface nourishment at Camperduin (blue cluster) towards zone of decay (given by the arrow).

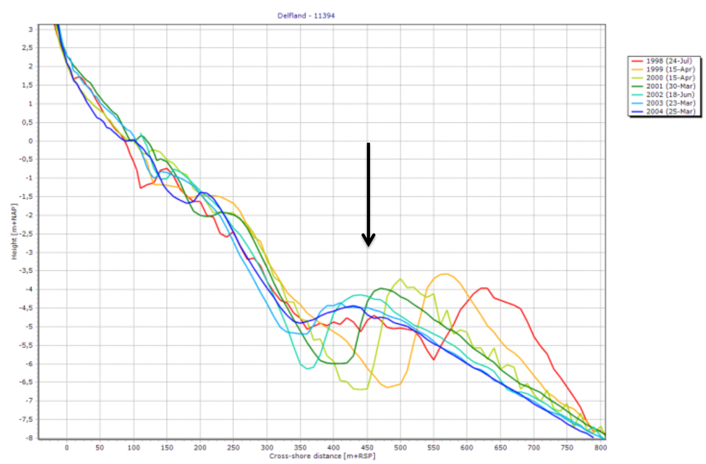


Figure 72: Onshore migration of shoreface nourishment at Ter Heijde (red cluster) towards zone of decay (given by the arrow).

Whether a trough develops or not is analysed with the visual description. In this analysis is found that at Eierland, Den Helder and Callantsoog no trough is developed. These are locations where no zone of decay exists and the bar behaviour is dominant alongshore. At the other locations, where clear cross-shore bar behaviour is found, troughs are developed.

6.1.4 Distance nourishment and bars

The cross-shore distance between the shoreface nourishment and the outer bar, at moment of execution, is compared with the migration of shoreface nourishments. In Figure 73, this pattern is given. With this figure, the conclusion is drawn that there is no dependency between the distance and the migration.

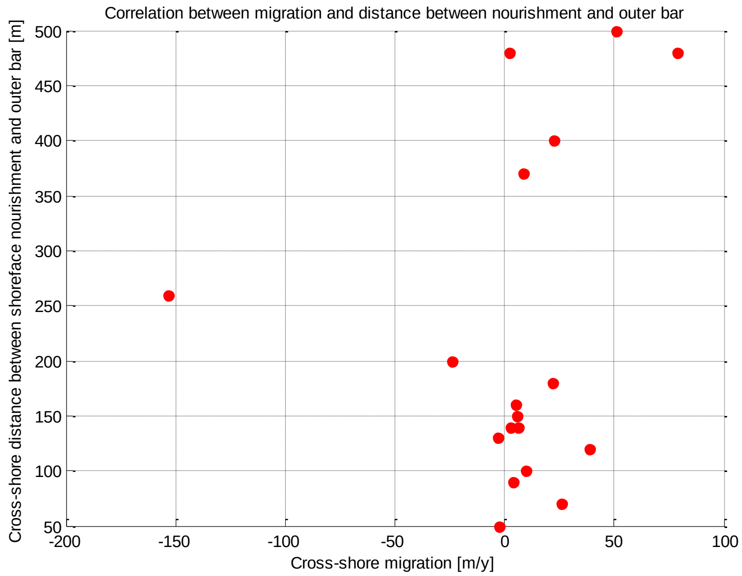


Figure 73: Relation between the cross-shore migration of shoreface nourishments and the distance between the shoreface nourishment and the outer bar at moment of execution.

Because the distance between bars is not the same for all locations, the relation between the cross-shore migration of shoreface nourishments and the relative distance between the shoreface nourishment and the outer bar is determined. This distance is relative to the distance between the bars in the original system. This relation is given in Figure 74. In this figure, a location, where more than one bar in the system is present, is taken into account (nine in this study). This figure shows very clear that, based on the results, no relation between the distance and the cross-shore migration of shoreface nourishments exists.

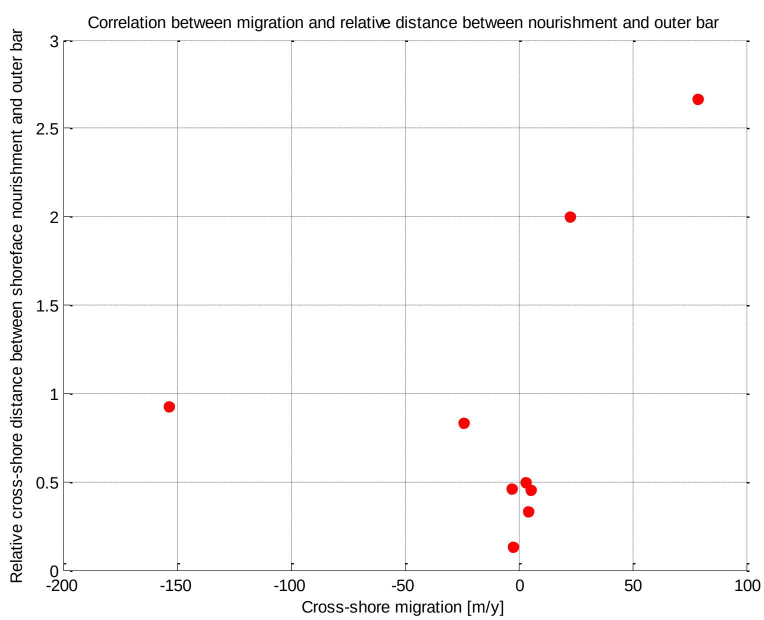


Figure 74: Relation between the cross-shore migration of shoreface nourishments and the relative distance between the shoreface nourishment and the outer bar. This distance is relative to the distance between the bars in natural the system.

6.2 Execution shoreface nourishment

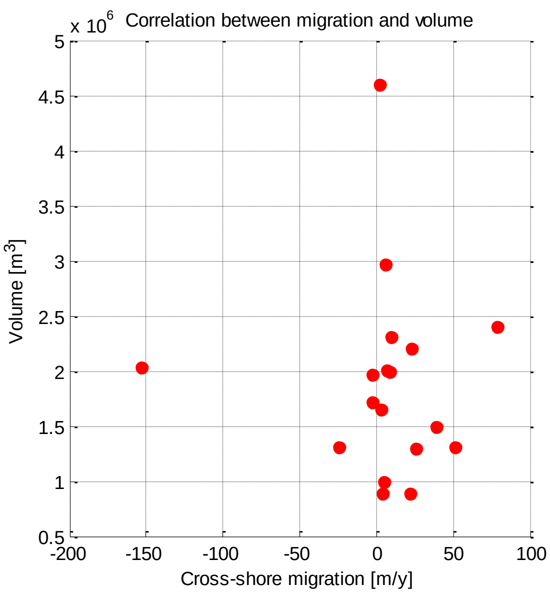
In this section, the execution parameters are compared with the behaviour of shoreface nourishments and the reaction of the bar system. The dimensions are discussed first. Second the type of execution is discussed and finally the interaction with earlier shoreface nourishments.

6.2.1 Volume and length

The volume and length are given in the database with execution parameters of Rijkswaterstaat. The volume, length and volume per length are compared with the cross-shore migration to find a pattern between these variables.

The dependency between the migration and the volume and length is given in Figure 75. In the left figure, the volume is given and in the right figure, the length is given. Both of the scatterplots do not have a clear pattern between the migration and their parameter. Based on these figures, the conclusion is drawn that no relation exists between the migration and the length or volume, in contrast to what De Sonneville, et al. (2012) mention.

The volume per length is a better parameter to analyse, because both volume and length are taken into account. In Figure 76, this dependency is given. Analysing this figure, no clear pattern is found and this results in the conclusion that, based on these results, the length and volume do not have a clear pattern with the migration of the shoreface nourishment.



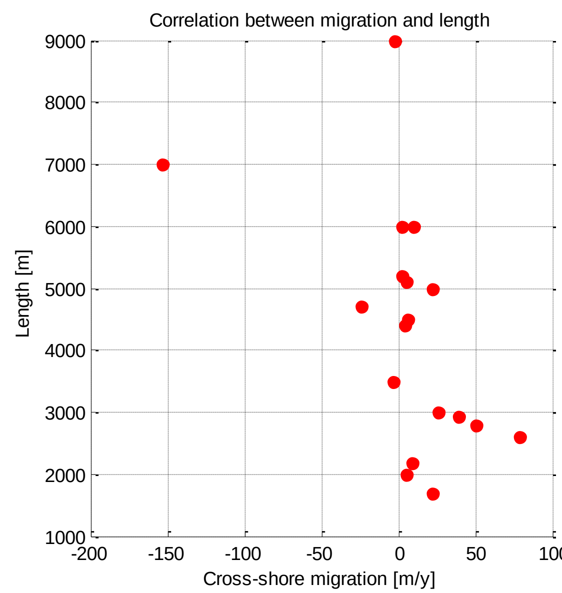


Figure 75: Dependency between the cross-shore migration of shoreface nourishments and the volume in the left figure and the length in the right figure.

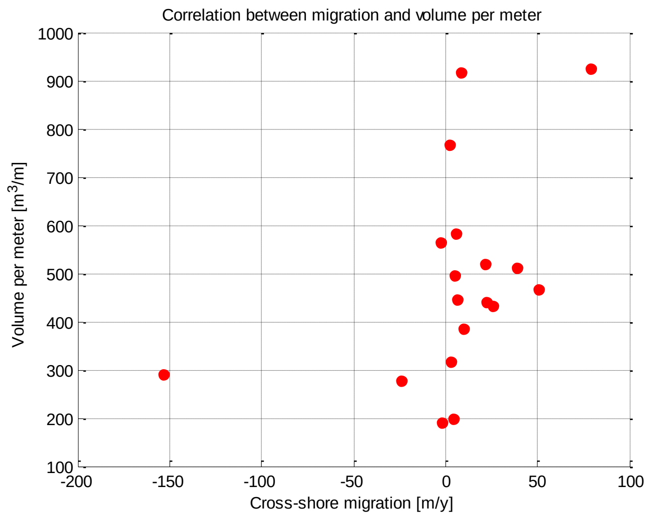


Figure 76: Dependency between the cross-shore migration of shoreface nourishments and the volume per meter.

6.2.2 Water depth above the crest

The water depth above the crest after execution of the shoreface nourishment is determined in section 5.2. This depth might have an influence on the migration of the shoreface nourishments, but even on the bar system. With the analysis of the behaviour of shoreface nourishments in chapter 4 was found that the crest changes in time. In this part of this thesis, the water depth after execution is taken into account.

In Figure 77, the dependency between the cross-shore migration of shoreface nourishments and the water depth above the crest after execution is given. This figure shows the absence of a clear pattern between the migration and the depth, concluding that, based on these results, the depth of the crest does not influence the cross-shore migration of the shoreface nourishment.

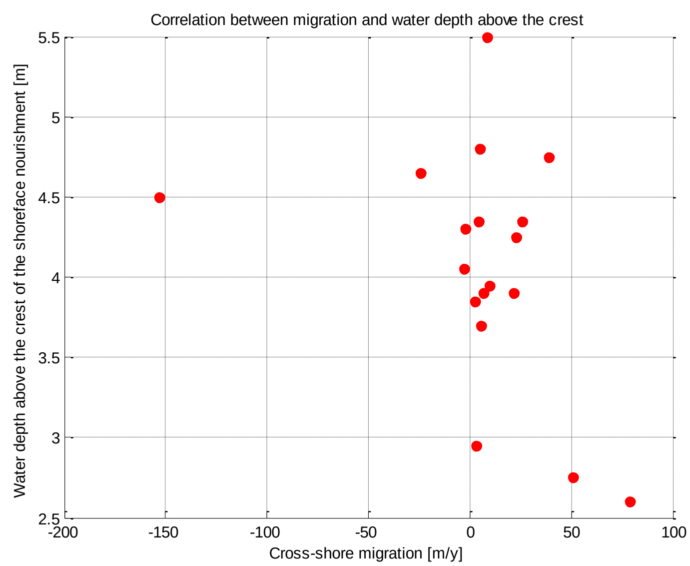


Figure 77: Dependency between the cross-shore migration of shoreface nourishments and the water depth above the crest after execution of the shoreface nourishment.

The depth above the crest is compared with the results from the visual description. There is minor trough formation for a deeper crest. For the first shoreface nourishment at Bergen (2000) and the last one at Ter Heijde (2011), this is clearly visible. The crests are not high and a small trough develops. For shoreface nourishments with a high crest, Texel Zuidwest (2007), Camperduin (2002) and Ter Heijde (1997 and 2001), a deep trough develops at the landward side of the shoreface nourishment. Based on these visual patterns, it looks like there is a high dependency between the depth of the crest and the formation of a trough. This dependency can be explained by the effect of breaking waves on the sediment transport. At shoreface nourishments with a high crest, waves tend to break earlier. This wave breaking induces more energy dissipation (Van Duin, et al., 2004) and sediments are stirred up at the landward side of the shoreface nourishment and then transported cross- and alongshore. Probably, the stirred up sediment is transported cross-shore and alongshore downstream. This alongshore transport is found at locations where the trough develops from upstream tot downstream.

The alongshore transport can be explained by the visual analysis of the trough formation. There are different shoreface nourishment where the trough develops from upstream to downstream, Ter Heijde (2001 and 2005), Monster (2005) and Zandvoort (2004). Based on the behaviour, it is assumed that the sediments are stirred up by cross-shore processes and transported by the alongshore sediment transport rate and thus the trough is started upstream and develops downstream.

6.2.3 Repeated nourishment at same location

At Eierland, Bergen, Callantsoog and Ter Heijde more than one shoreface nourishment is executed within a short period. For Bergen and Ter Heijde is given that the migration is dependent on the zone of decay. For Eierland and Callantsoog this is not the case. There is no zone of decay and the shoreface nourishments migrate onshore.

For these two locations, the pattern is found that the first shoreface nourishment executed migrates faster towards the coast than the subsequent ones. This might be explained by the demand for sediments. At locations with a demand for sediments, the first shoreface nourishment is adopted fast by the coastal system and for the subsequent ones the demand for sediments decreases and the migration is lower. This is based on two locations, so the pattern is still not very reliable.

6.2.4 Influence on bar behaviour

In the visual description, in section 4.1.2, is shown that the execution of a shoreface nourishment influences the original bar system. For all situations, the migration of sandbars changes after the execution of the shoreface nourishment from offshore directed towards stable or onshore-directed migration. This might be explained by the breaking of waves by the shoreface nourishment. This breaking of waves decreases the energy behind the shoreface nourishment and creates a calmer climate (see theory in section 2.8.2 by Van Duin, et al. (2004)). The offshore-directed component for bar migration becomes smaller and this results in a stable or onshore-directed migration of the sandbars. When the shoreface nourishment is disappeared after some years, the offshore-directed migration resumes.

Why the bar migration is sometimes onshore and other times stable, is not found in the analysis of the parameters and the migration of the shoreface nourishment. It might be reasonable that shoreface nourishments with a higher crest break more waves and induce a calmer climate onshore of the shoreface nourishment, but this is not very clear in the results of the analysis of data and parameters.

6.3 Waves

The resultant wave characteristic is determined in section 5.3 by looking at the height and direction of the waves. The difference in migration in cross- and alongshore direction is not found in the wave forcing. Based on the results, the conclusion can be made that the migration of shoreface nourishments is not influenced by yearly first-order wave energy and the differences in wave direction (this proves the expectation of De Sonneville, et al. (2012)). Since wave conditions force the morphologic behaviour, it might be reasonably likely that the migration depends not on the first-order, but more on short-term, second order, wave conditions (e.g. storm conditions) in relation with the water depth. These second-order conditions are not studied in this thesis. This assumption might explain the behaviour of the original bar system. At Eierland, Den Helder and Callantsoog, waves from the north are partially blocked by the outer delta of the Wadden Sea. In the yearly wave conditions, this is not visible, but for short-term storm conditions, outer deltas might have influence. The wave energy decreases by outer deltas of the Wadden Sea and this induces that sandbars do not migrate offshore, because the offshore component reduces.

6.4 Sediment volume

The development of the sediment volume in the cross-shore profile is determined and given for the different clusters, in section 4.3. The trends are not the same for every cluster. The reaction of the volume trends are different per bin and so the total volume trend. A pattern between the migration of the shoreface nourishments and the trend of the volume exists.

For shoreface nourishments in the blue cluster, the nourished sand remains in the bin where the shoreface nourishment is executed. The total volume in the cross-shore profile increases on the long term. For shoreface nourishments in the red cluster, the same trend for total volume is found as for the blue cluster. The volume trends for the green cluster are different from the previous two. In this cluster, the total volume is not decreasing after some time, but remains constant. This might be explained by the salient effect mentioned by Van Duin, et al. (2004). The sediments from the shoreface nourishment are leaving downstream. Upstream, more landward than the shoreface nourishment, sediments are trapped and the total volume of sediment increases. For the orange cluster, based on Ameland Midden, a negative total volume trend is present. The shoreface nourishment does not influence the volume trend of the bins landward of the shoreface nourishment. The shoreface nourishment migrates offshore and the total volume trend is negative over a few years. This trend might be influenced by land subsidence due to gas mining.

6.5 Conclusions

The analysed parameters, found in chapter five, are compared with the morphological behaviour, found in chapter four. In this section, a conclusion is given for important correlations and patterns found in this chapter. These conclusions are validated in the next chapter and they finally give an answer on sub-research question two.

6.5.1 Migration

The migration of shoreface nourishments depends on the position relative to the zone of decay. In case there is a zone of decay, the shoreface nourishments migrate to this zone. If the shoreface nourishments are executed onshore of the zone of decay, they migrate offshore to this zone. If the shoreface nourishments are executed offshore, they migrate onshore to this zone.

If the cross-shore bar cycle does not exist in the original bar system, sandbars do not migrate to a zone of decay. In these situations the alongshore behaviour is dominant. If the shoreface nourishments are executed at this location, they start to migrate towards the coast and alongshore. In some situations, the first shoreface nourishment executed in a row migrates faster towards the coast than the subsequent ones. The locations where there is no cross-shore behaviour are in areas where at the northern region an outer delta of the Wadden Sea is present. This might lead to a reduction of the energy of storm conditions from the north and results in a calmer climate, i.e. the sandbars do not migrate offshore. Another reason might be the tide that becomes asymmetrical around the outer deltas of the Wadden Sea.

6.5.2 Reaction bar system

Due to the execution of shoreface nourishments, the original bar behaviour is disturbed. The offshore migration of sandbars turns into an onshore-directed migration or zero bar migration. This likely happens because waves break at the shoreface nourishment and the energy dissipates. This creates a calmer climate landward of the shoreface nourishment and reduces the offshore-directed migration of sandbars.

6.5.3 Trough formation

At locations where the cross-shore behaviour is dominant, usually a trough is formed landward of the shoreface nourishment. A higher crest results into a higher depth of the trough. The explanation for this phenomenon is given by the waves that break at the shoreface nourishment and stir up the sediments. If the crest is higher, more energy dissipates and more sediment stirs up landward of the shoreface nourishment. The stirred up sediment is transported cross-shore and alongshore downstream. This alongshore transport is found at locations where the trough develops from upstream tot downstream.

6.5.4 Sediment volume

Shoreface nourishments, which migrate onshore or are stable, induce a net increase of sediment over a few years in the cross-shore profile, especially in the upper profile. If the shoreface nourishment migrates offshore, the influence on the sediment volume of the onshore part is minimal and does not compensate the erosion in the upper parts of the profile. This is actually the case at Ameland, where land subsidence occurs. This conclusion must be researched in further detail. For shoreface nourishments that migrate onshore and alongshore (the green cluster), the sediment volume does increase in the profile, also in the upper parts of the profile. This might be possible due to the salient effect.

7. Validation

In this chapter, the correlations and patterns found in the previous chapter are validated with a new set of ten shoreface nourishments. This is executed to prove if the found correlations and patterns are correct.

7.1 Selection

In the beginning of this research, a set of ten shoreface nourishments is set apart for the validation of the results. The selection is given in Table 10. The name of the shoreface nourishments is given with their year of execution, location and length.

Table 10: Selection of ten shoreface nourishments to perform the validation.

	Shoreface nourishment	Year	First JARKUS transect	Last JARKUS transect	Length [m]
1	Am – Midden	2005	12	17	5000
2	Tex – Centrale Kust	2005	13.52	16.9	3380
3	Tex – De Koog	2006	17	23	6000
4	NH – Egmond	1999	36.9	39.1	2200
5	NH – Egmond aan Zee	2004	36.2	40.2	4000
6	NH – Heemskerk	2011	45.75	50	4250
7	Rijn – Bloemendaal	2008	61	63	2000
8	Delf – Scheveningen	1999	97.73	100.5	2770
9	Delf – ‘s Gravenzande-HvH	2007	113	118	5000
10	Walch – Westkappelse Zeedijk	2008	17.55	19.7	2150

7.2 Analysis of selection

In this section, the shoreface nourishments of the validation selection are analysed for original bar behaviour, the crest and position of the shoreface nourishment and the influence of other shoreface nourishments or structures. In addition, the volume trends are determined to check whether the patterns for the volume trends are correct.

7.2.1 Behaviour original bar system

In the previous chapter was found that a relation between the behaviour of the original bar system and the migration of the shoreface nourishment exists. In this section is analysed what the dominant migration of the sandbars in the original system is. This is given by cross-shore, alongshore or no bar behaviour. If there is cross-shore dominant behaviour, a zone of decay exists. This zone is analysed and in the second and third column Table 11, the results of this analysis are given.

In this table is shown that the migration for the first seven situations is dominant cross-shore (for shoreface nourishment number 3, Texel – Midden, a small northern part does have an alongshore behaviour). For the bar behaviour at Scheveningen and the Westkappelse Zeedijk, no bar behaviour is found. The bar cycle at ‘s Gravenzande is disturbed, because of the execution of the sand motor.

7.2.2 Water depth and position of the crest of the shoreface nourishment

The position of the shoreface nourishment, in combination with the zone of decay, tells something about the migration direction of the shoreface nourishment. The pattern that shoreface nourishments migrate towards the zone of decay is validated by comparing the distance to the zone of decay and the migration. In de fifth column in Table 11, the positions are given.

The crest of the shoreface nourishment is analysed to say something about the trough formation. A lower water depth above the crest induces a larger trough, if there is cross-shore dominant bar behaviour. In de fourth column in Table 11, the water depth above the crest is given for the shoreface nourishments.

7.2.3 Other shoreface nourishments and structures

In this section, the area around the shoreface nourishment is analysed. Research is performed into the occurrence of earlier shoreface nourishments and surrounding obstacles.

The influence of earlier shoreface nourishments did decrease the migration if the original bar behaviour was not cross-shore. In Table 11, the occurrence of earlier shoreface nourishments is shown in the sixth column. In the seventh column, the surrounding obstacles are given.

Table 11: Analysis of the original bar systems and shoreface nourishments.

	Bar behaviour	Zone of decay [m +RSP]	Water depth above the crest [m]	Position of crest [m +RSP]	Earlier nourishments	Surrounding obstacles
1	Cross-shore	800	4.75	700	Yes	Outer deltas Wadden Sea
2	Cross-shore	650	4.15	700	No	Outer deltas Wadden Sea
3	Partly cross-shore, partly alongshore	800 for the cross-shore part	4.10	1100	Yes	No
4	Cross-shore	700	4.90	650	No	No
5	Cross-shore	700	4.40	700	Yes	No
6	Cross-shore	600	4.55	750	No	IJmuiden Harbour
7	Cross-shore	600	4.30	950	No	IJmuiden Harbour
8	No bar behaviour	n/a	3.90	650	No	Scheveningen Harbour
9	Disturbed	n/a	5.45	750	Yes	Sand motor
10	No bar behaviour	n/a	4.20	300	No	No

7.3 Behaviour predictions

The parameters, analysed in the previous section, are combined with the correlations and patterns from chapter 6. This combination of data results in predictions for shoreface nourishments in this selection.

7.3.1 Migration of the shoreface nourishment

The migration of the shoreface nourishment can be predicted by the original migration of the bar system. If the behaviour is dominant cross-shore directed and a zone of decay exists, shoreface nourishments migrate towards this zone. The alongshore migration is negligible in this situation. If the bar system has a dominant alongshore migration, shoreface nourishments migrate onshore and alongshore. If sandbars do not exist, the shoreface nourishments migrate also onshore and the alongshore.

In Table 12, the results for the migration are given. For the bar system with dominant cross-shore behaviour, the distance (on- or offshore) towards the zone of decay is determined. This distance results in the conclusion for a stable, off- or onshore migration. This is the case for shoreface nourishment one until seven. For number eight and ten no clear bar behaviour is found, so the migration is dominant onshore and alongshore directed. Number three is a special one, because this shoreface nourishment is executed on a location where the bar system is dominant cross-shore at the southern part and alongshore in the northern part. The expectation is that the shoreface nourishment has two different migration patterns, the southern part onshore and the northern part onshore and alongshore. For number nine the prediction is difficult, because the sand motor disrupts the system.

Table 12: Predictions of the migration directions of shoreface nourishments for the validation.

	Cross-shore	Alongshore
1	Offshore	Negligible
2	Negligible	Negligible
3	Onshore	Partly alongshore, partly negligible
4	Negligible	Negligible
5	Negligible	Negligible
6	Onshore	Negligible
7	Onshore	Negligible
8	Onshore	Alongshore
9	Onshore	Unknown
10	Onshore	Alongshore

7.3.2 Bar behaviour

An exact reaction of the bar system is not found in the analysis on correlations and patterns. The only pattern found, is the change in cross-shore directed migration. For locations where cross-shore behaviour is dominant, the bar system changes from offshore directed migration into a stable bar system or a system with onshore migration.

For the selection of this validation, cross-shore migration is dominant for shoreface nourishments number one until seven. For the bar systems at these locations the expectation is that the bar behaviour changes from offshore into onshore or stable.

7.3.3 Trough formation

The formation of troughs is present where the original bar system migrates cross-shore. In addition, the depths depend on the height of the crest of the shoreface nourishment. For shoreface nourishments numbers eight, nine and ten it is predicted that there is no or negligible trough formation. For the other shoreface nourishment, the expectation is that a trough develops. In the left column in Table 13, the results for the predictions are given. For shoreface nourishments with a low crest, a trough partially develops.

7.3.4 Volume trend

The volume trends at the locations for the different shoreface nourishments might be predicted with the patterns found in the previous chapter. For shoreface nourishments with an onshore migration or no migration (the blue, red and green cluster), the expectation is that the net total volume trend is positive for the lifetime of the shoreface nourishment and for the shoreface nourishments that migrate offshore, the expectation is that the net volume trend is negative. The predictions are given in the right column in Table 13.

Table 13: Prediction of trough formation and the net volume trend for the lifetime of the shoreface nourishment.

	Trough formation	Net volume trend
1	Small	Negative
2	Yes	Positive
3	Yes	Positive
4	Small	Positive
5	Yes	Positive
6	Yes	Positive
7	Yes	Positive
8	No	Positive
9	No	Positive
10	No	Positive

7.4 Real behaviour

Now that the predictions are made, the real behaviour is analysed in this section. The real behaviour is compared with the predictions and this leads to a validation of correlations and patterns.

7.4.1 Behaviour analysis with BodemViewer

The shoreface nourishments are analysed as performed in section 4.1. The focus is on the direction of migration of the shoreface nourishment, the reaction of the bar system and the formation of troughs. These variables are compared with the predictions.

Ameland – Midden – 2005

The first nourishment at this location, from 1998, has already disappeared when the shoreface nourishments in 2005 is executed. The influence of the outer delta of the Wadden Sea, between Terschelling and Ameland, is visible. The main part of the shoreface nourishment migrates offshore and not alongshore, but the western part migrates onshore and alongshore, under influence of the outer delta. A small trough develops in the years after execution and the bar system changes from offshore directed into a stable system.

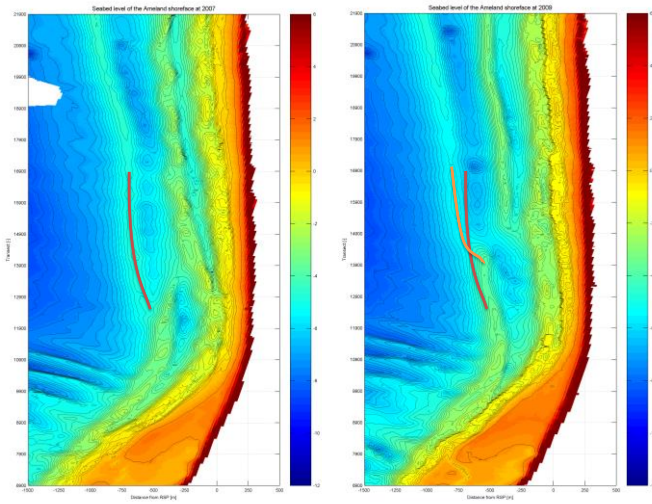


Figure 78: Migration Ameland – Midden from 2007 until 2009. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Texel – Centrale Kust – 2005

This shoreface nourishment is executed in 2005 and only visible in 2006 and 2007, because in 2007 a new shoreface nourishment is executed. The migration in cross- and alongshore direction is negligible and a trough develops immediately after execution. The original bar system changes from offshore-directed migration into no bar migration.

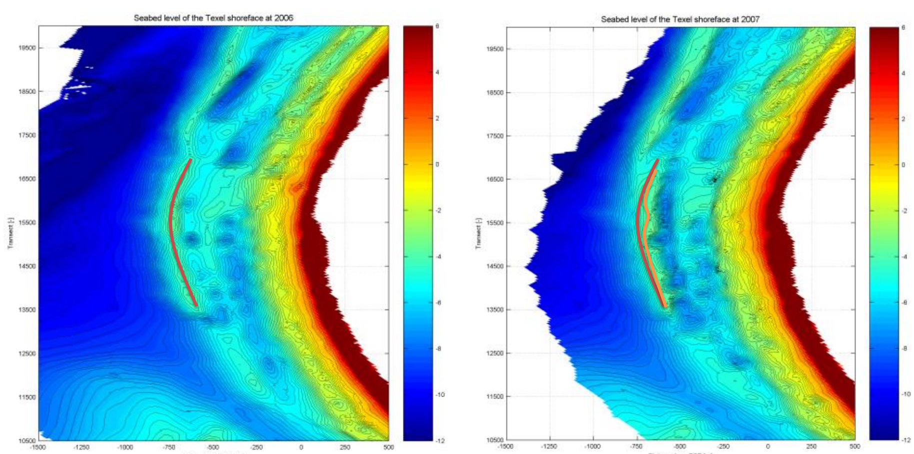


Figure 79: Migration Texel – Centrale Kust from 2006 until 2007. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Texel – De Koog – 2006

The shoreface nourishment at De Koog in 2006 is executed against the earlier shoreface nourishment from 2002. The migration is described in two parts. The northern part migrates onshore and slightly alongshore, but the middle and southern parts migrate a bit onshore and the alongshore migration is negligible. For the shoreface nourishment executed in 2002 at this location, this different migration was also occurred. This might be possible because of a measuring pole that exists at the position of the shoreface nourishment (Schrijvershof, 2016). The formation of a trough is clearly visible. The bar migration was already stable, because of the earlier shoreface nourishment, and this remains the same.

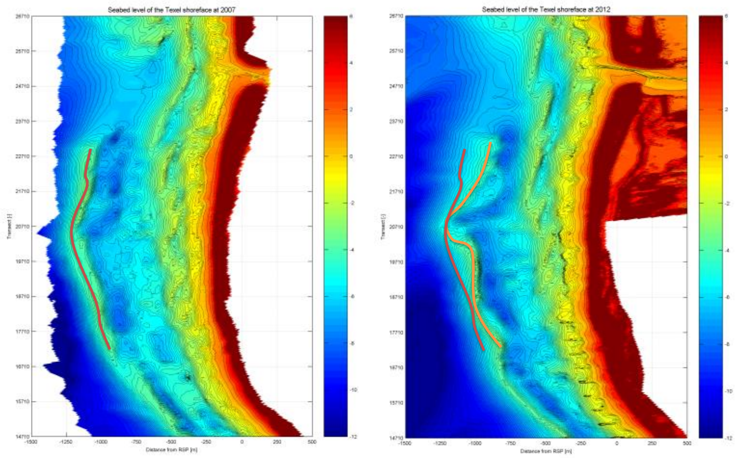


Figure 80: Migration Texel – De Koog from 2007 until 2012. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Noord-Holland – Egmond – 1999

This is a relative smaller shoreface nourishment and executed against the outer bar. The shoreface nourishment has negligible cross- and alongshore migration. The bar system and the shoreface nourishment merge into each other and the original bar system changes from offshore directed migration to a stable bar system. There is no formation of a trough.

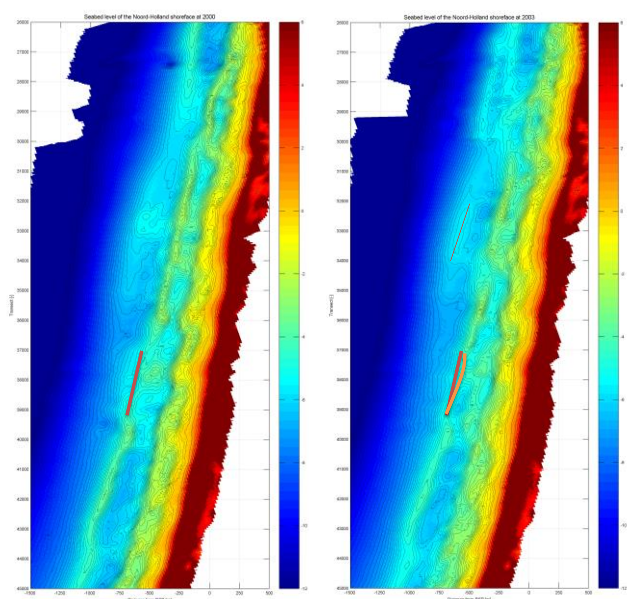


Figure 81: Migration Noord-Holland – Egmond from 2000 until 2003. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Noord-Holland – Egmond aan Zee – 2004

The shoreface nourishment at Egmond aan Zee in 2004 is a larger one than the previous one executed at almost the same location. The cross- and alongshore migrations are negligible. The bar migration after execution changes in a small onshore directed migration and a small trough develops.

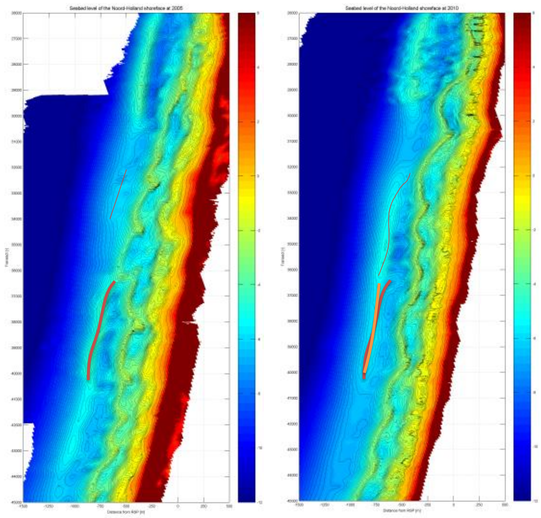


Figure 82: Migration Noord-Holland – Egmond aan Zee from 2005 until 2010. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Noord-Holland – Heemskerk -2011

This shoreface nourishment is executed in two parts: a northern part and a southern part. The parts are observed independent but have the same behaviour. After execution, they migrate onshore and there is a small alongshore migration towards the south. The original bar system does not change that much, the offshore directed migration remains. A small trough develops.

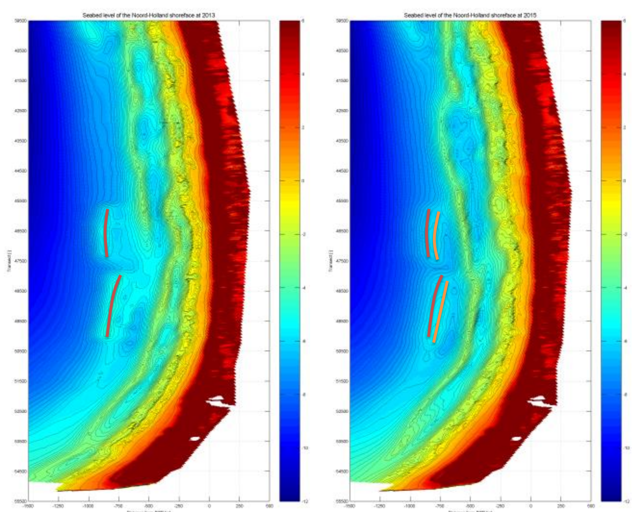


Figure 83: Migration Noord-Holland – Heemskerk from 2012 until 2015. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Rijnland – Bloemendaal – 2008

This shoreface nourishment is executed southward of the inlet of the IJmuiden harbour. After execution the shoreface nourishment migrates fast towards the coast and the alongshore migration is negligible. In the first two years, there is no trough formation, but after these years, a trough develops. The direction of migration of the bar system changes from offshore into onshore.

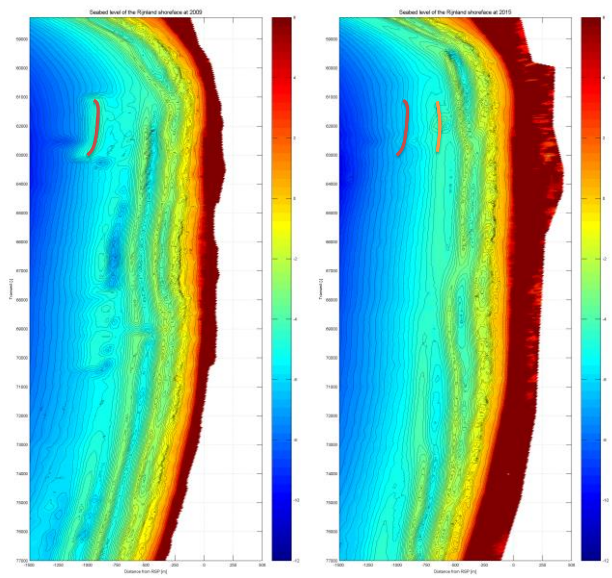


Figure 84: Migration Rijnland – Bloemendaal from 2009 until 2015. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Delfland – Scheveningen – 1999

The shoreface nourishment at Scheveningen in 1999 migrates fast onshore. The alongshore migration is towards the south, towards the inlet of the Scheveningen harbour. Because there is no original bar behaviour, there is no change in bar system. The occurrence of a trough is not visible.

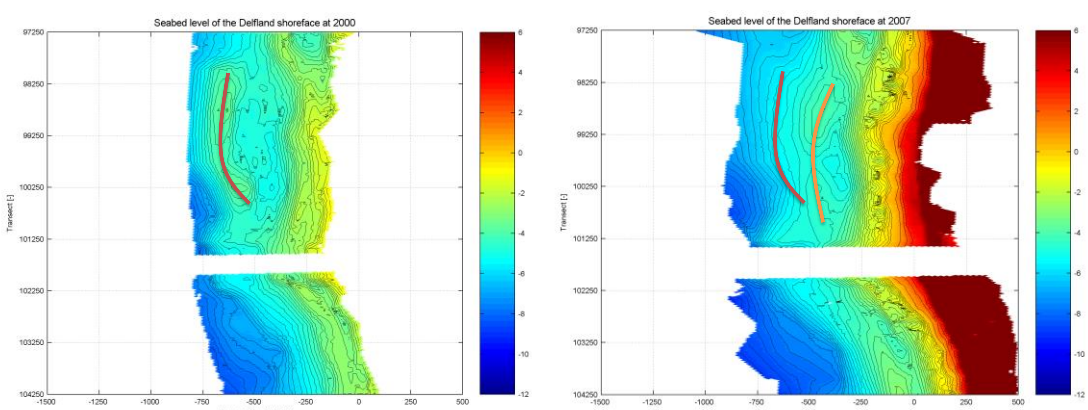


Figure 85: Migration Delfland – Scheveningen from 2009 until 2015. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Delfland – 's Gravenzande-Hoek van Holland – 2007

This shoreface nourishment is hard to analyse, because of sand nourishments and the sand motor. After execution, the shoreface nourishment migrates onshore to the beach and merges into the beach. There is no clear bar behaviour and no trough develops.

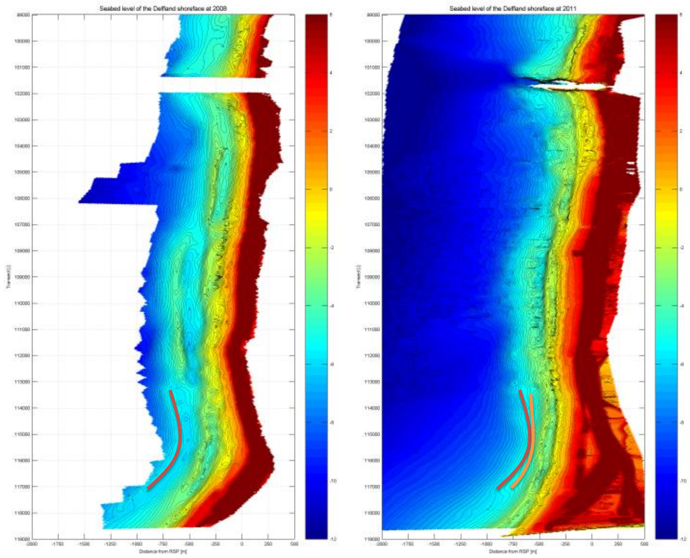


Figure 86: Migration Delfland – 's Gravenzande-Hoek van Holland from 2008 until 2011. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

Walcheren – Westkappelse Zeedijk – 2008

This shoreface nourishment is executed in the Delta Coast. After execution, the shoreface nourishment migrates onshore, but there is no alongshore migration. Because there is no original bar behaviour, there is no change in system and no trough formation.

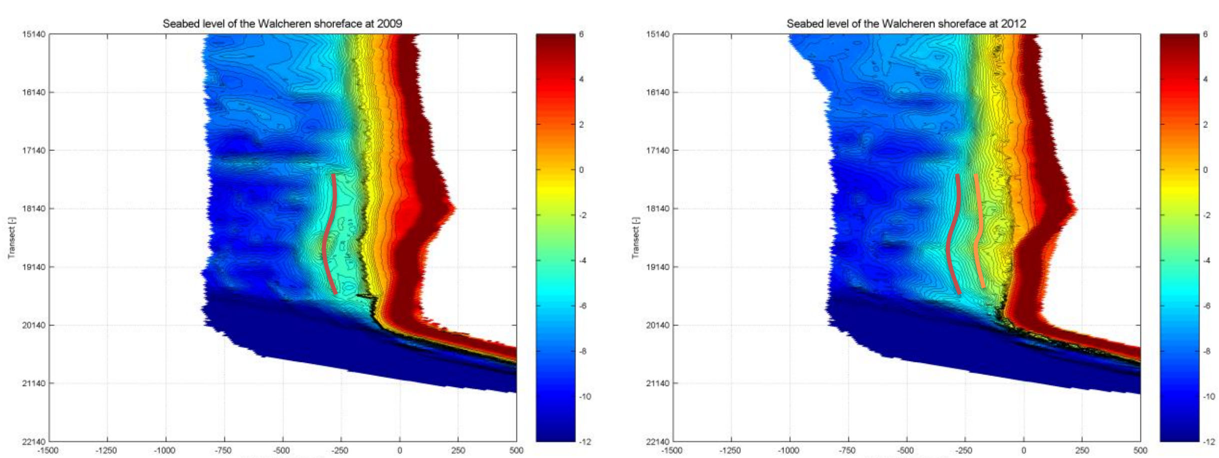


Figure 87: Migration Walcheren – Westkappelse Zeedijk from 2009 until 2012. The red line represents the execution position and the orange line the final position. The x-axis (cross-shore) is divided in distances of 250m and the y-axis (alongshore) is divided in distances of 1000m.

7.4.2 Overview of behaviour shoreface nourishments

For the ten shoreface nourishments, an overview is given in Table 14. In this table, the migration direction, bar behaviour and trough formation results are given. These results are compared with the predictions in the next section.

Table 14: An overview of migration direction, bar behaviour and trough formation of the shoreface nourishments.

	Cross-shore migration	Alongshore migration	Bar behaviour	Trough formation
1	Offshore	Negligible	Offshore to stable	Partially
2	Negligible	Negligible	Offshore to stable	Yes
3	Onshore	Partly stable, partly alongshore	Remain stable	Yes
4	Negligible	Negligible	Offshore to stable	No
5	Negligible	Negligible	Offshore to onshore	Small
6	Onshore	Southward	Remain offshore	Small
7	Onshore	Negligible	Offshore to onshore	Yes
8	Onshore	Southward	No behaviour	No
9	Onshore	Negligible	No behaviour	No
10	Onshore	Negligible	No behaviour	No

7.4.3 Volume trends

In Appendix G, volume trends for the shoreface nourishments are given. The trends for the shoreface nourishments are different in detail, but for the most, the volume trend is positive over time. Only for the shoreface nourishment at Texel - De Koog, a negative volume trend is present.

7.5 Comparison predictions and real behaviour

The predictions from section 7.3 and the real behaviour in section 7.4 are compared in this section. The results of this comparison conclude whether the correlations and patterns found in chapter six are correct. In Table 15, the results of the comparison are given.

Table 15: Comparison between predictions and real behaviour of the migration of the shoreface nourishment. A '1' stands for correct predictions and a '0' stands for incorrect prediction. For case eight, nine and ten no bar migration exists.

	Cross-shore migration	Alongshore migration	Bar behaviour	Trough formation	Net total volume trend
1	1	1	1	1	0
2	1	1	1	1	1
3	1	1	1	1	0
4	1	1	1	0	1
5	1	1	1	0	1
6	1	0	0	0	1
7	1	1	1	1	1
8	1	1	n/a	1	1
9	1	n/a	n/a	1	1
10	1	0	n/a	1	1

7.5.1 Cross-shore migration

For the cross-shore migration, the predictions are all correct. All shoreface nourishments follow the trend of migration towards the zone of decay, if present, or migration onshore if no zone of decay exists.

7.5.2 Alongshore migration

For the alongshore migration eight of the ten shoreface nourishments have a correct prediction. The shoreface nourishments at Heemskerk and at Walcheren have an incorrect prediction. For the Heemskerk shoreface nourishment, the prediction is that no alongshore migration occurs because of the occurrence of dominant original cross-shore bar behaviour. The real behaviour is towards the zone of decay, but also a bit alongshore. This occurs probably because of the influence of the inlet of the IJmuiden harbour. This creates a local southward sediment transport. The southern part of the shoreface nourishment migrates faster towards the south than the northern part, which explains this local sediment transport effect. The shoreface nourishment at Walcheren does not migrate in alongshore direction, where the prediction is that an alongshore migration occurs because there are no bars in the original system.

7.5.3 Bar behaviour

The expected bar behaviour is correct for six of the seven shoreface nourishments (there are only seven shoreface nourishments with a clear bar behaviour). Just as with the alongshore migration, the shoreface nourishment at Heemskerk is not correct predicted. The expectation was that the bar migration should change, but it remains offshore. Probably this happens because of the influence of the inlet of the IJmuiden harbour. For most of the other shoreface nourishments, the direction of migration of the bar changes from offshore into onshore or a stable bar system.

7.5.4 Trough formation

The formation of a trough is not always correct predicted. For shoreface nourishments five and six, a normal trough is predicted, but finally there is just a small trough. This probably happens because of the influence of the inlet of the IJmuiden harbour. As shown in the previous sections, the behaviour of shoreface nourishment number six is different. Shoreface nourishment number four is executed at the outer bar and is relative small. It merges immediately into the outer bar and disappears. This is probably the reason why there is no trough formation. Still the pattern, that a trough develops at locations with original cross-shore bar behaviour and is deeper for a higher crest, is reasonable, based on the validation, but further research is needed.

7.5.5 Volume trend

Looking at the volume trends, the most are positive over time, just as predicted. Only the shoreface nourishment of Texel De Koog has a negative volume trend over time. For the other cases, if dominant cross- or alongshore migration occurs or no bars exist, the trend is positive over time. The conclusion is that for shoreface nourishments with offshore migration the total volume trend must be researched in further detail and for shoreface nourishments with no migration or onshore migration, the total volume trend is positive.

7.6 Conclusions

With the validation executed in this chapter, the patterns and correlations from chapter 6 are proved and this leads to the next findings:

- If natural cross-shore bar behaviour occurs, shoreface nourishments migrate cross-shore to the zone of decay and do have negligible alongshore migration.
- If alongshore bar behaviour or no bar behaviour exist, shoreface nourishments migrate onshore and probably follow the direction of the local alongshore net sediment transport rate.
- Trough formation occurs if natural cross-shore bar behaviour exists and a higher crest of the shoreface nourishment leads to a deeper trough.
- Due to the execution of shoreface nourishments, the migration of the bar system (if this exists) changes from offshore directed into onshore directed or into a system without migration of bars.
- Surrounding structures influence the migration of shoreface nourishments.
- Sediment volumes onshore and in front of the shoreface nourishment increase because of the execution of shoreface nourishments. Independent of dominant cross- or alongshore migration of the original bar system.

8. Future design

Based on the results performed in this thesis, sub-research question three is answered in this chapter. A proposal is given for future projects of shoreface nourishments along the Dutch coast to compensate the erosion in the upper profile. This is given by a roadmap. The route on this roadmap is based on correlations and patterns found and validated in this thesis.

8.1 Roadmap for execution position

To find the optimal position for the execution of shoreface nourishments to compensate the erosion in the upper profile, the roadmap in Figure 88 is given. The first assumption made in this roadmap is that the decision for shoreface nourishments is already made. The decision for the type of nourishment is outside the scope of this thesis. The red boxes are decision points, represented by a number. The decision points are explained in further detail.

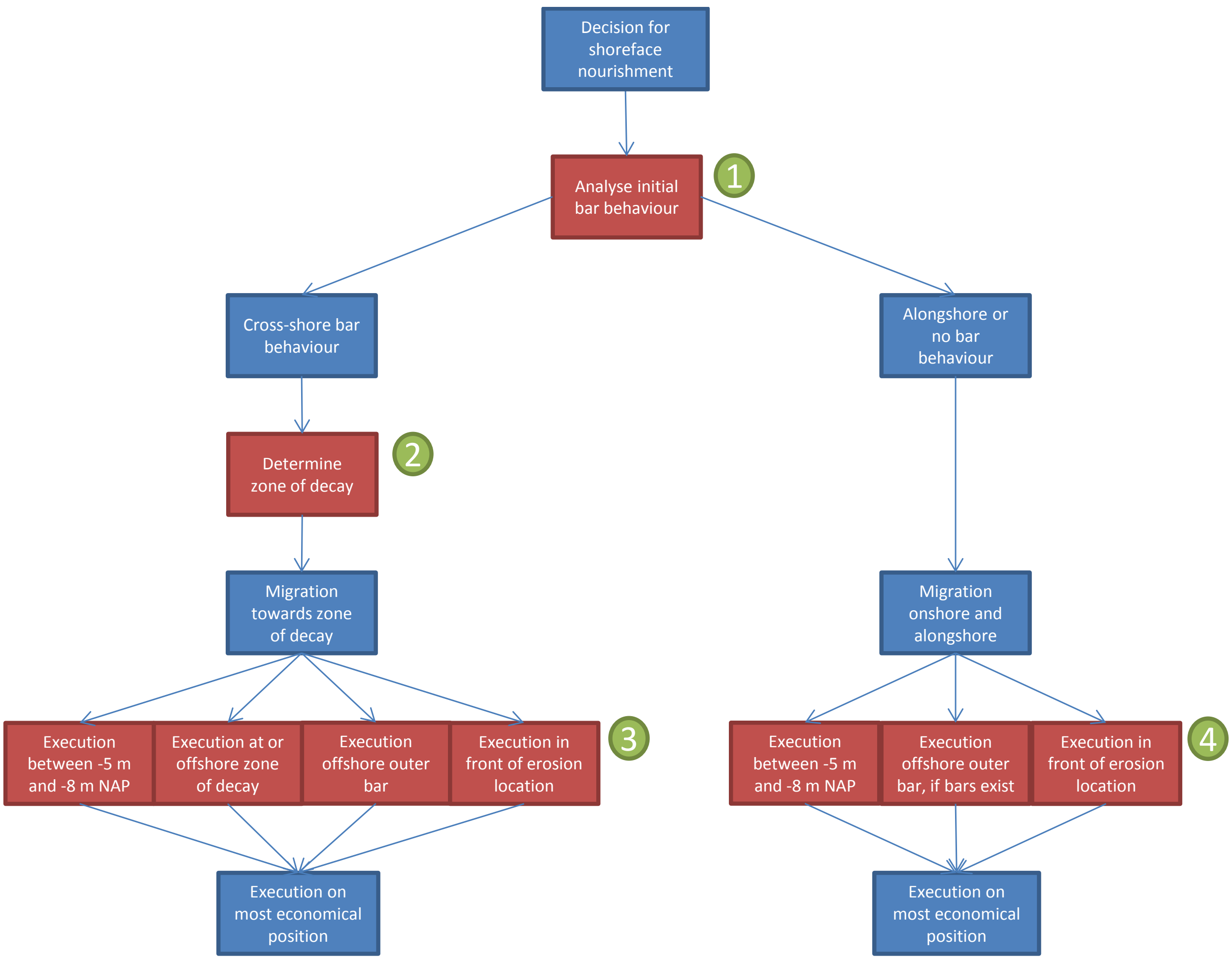


Figure 88: Roadmap to determine the execution position of the shoreface nourishment. In the red boxes, action is needed for a determination or decision. The numbers at the boxes represents the explanation given in the different sections in this chapter.

8.1.1 Step 1: Analyse original behaviour

With the behaviour of the original bar system, a major part of the behaviour of shoreface nourishments can be described. This determines the execution position of the shoreface nourishment in the shoreface zone. In chapter six and seven was proven that that the shoreface nourishment follows the original bar system. This leads to the first decision step in the roadmap: Determine the migration of the original bar system. There are two options to choose: 1) Original cross-shore bar behaviour or 2) alongshore or no bar behaviour. The determination of migration can be performed with MorphAn. The first step is to choose the middle JARKUS transect and plot the bathymetry for the years before shoreface nourishments were executed at this location. With the trend for the different years, the category is found: cross-shore, alongshore or no bar behaviour.

8.1.2 Step 2: Determine the zone of decay for cross-shore situation

For the situation with cross-shore original bar behaviour, the second step is to determine the zone of decay. The determination of the zone of decay might be performed with the MorphAn plots of the JARKUS transect. In these plots, the offshore boundary of the sand bars (where they disappear), is the zone of decay. An example is given in Figure 89, where the original bar system at Bergen aan Zee is given. In this figure is visible that sandbars migrate offshore to the zone of decay.

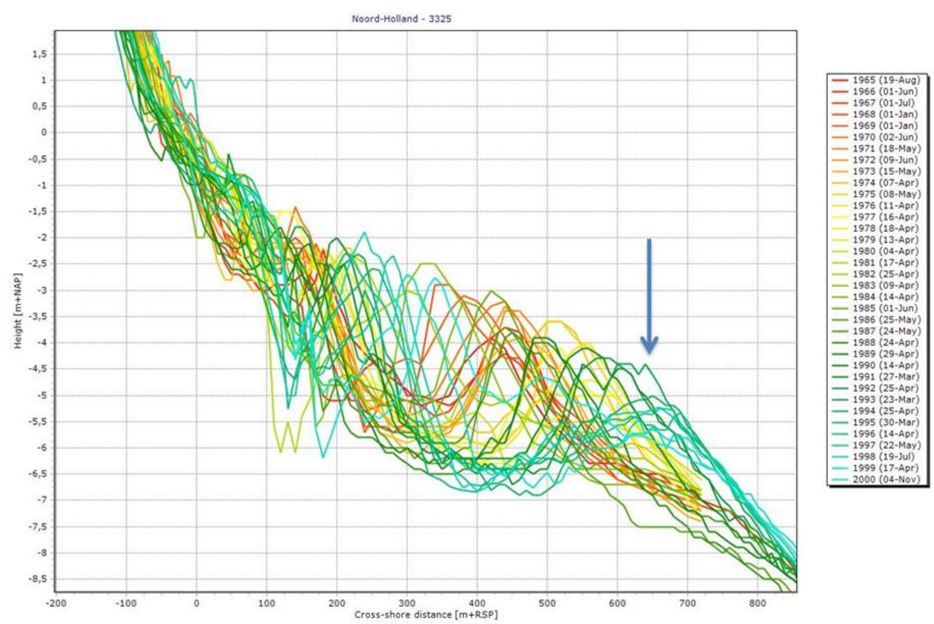


Figure 89: Example of the determination of the zone of decay for the situation if there is dominant cross-shore original bar behaviour. The zone of decay is given by the blue arrow.

8.1.3 Step 3: Determine execution position for cross-shore situation

For the situation with dominant cross-shore bar behaviour, the execution of the shoreface nourishment depends on more parameters. The first one is the execution in the shoreface zone between -8 m and -5 m NAP. The second factor is the zone of decay. The advice is to execute the shoreface nourishment on the zone of decay or offshore, because this results in a positive volume trend in the upper profile. There is no clear difference between the influence on the volume at the beach for shoreface nourishments executed offshore of the zone of decay and at the zone of decay. The execution offshore of the outer bar is the third parameter to keep in mind. No research is performed on execution of the shoreface nourishment on the outer bar or onshore of it, but the advice is to avoid this. The fourth, and last, issue that influences the execution position is the alongshore location of the shoreface nourishment. The advice is to perform the shoreface nourishment in front of the location at the beach where more sediment is needed. This follows from the volume trends, the shoreface nourishment migrates dominant cross-shore and the volume trends increase at this area.

8.1.4 Step 4: Determine execution position for alongshore situation

For execution of the shoreface nourishment in the situation where there is dominant alongshore or no bar migration, the decision is almost the same as for the cross-shore situation. The execution must be between -5 m and -8 m NAP and offshore of the outer bar. However, the zone of decay is not an issue, since this zone only exists for locations with dominant cross-shore original bar behaviour. Despite the alongshore migration of the shoreface nourishment, the advice is to execute the shoreface nourishment in front of the location at the beach where sediment is needed. This is based on the volume trends. The volume in the upper profile increases over time. This happens probably because the sediment transport rate is decreased behind the shoreface nourishment, called the salient effect.

8.2 Design parameters of the shoreface nourishment

The second part of sub-research question three is about the design parameters of the shoreface nourishment. In the data analysis, the volume, length, volume per length and the water depth above the crest are taken into account. The result of this analysis is that only the water depth above the crest has a small influence on the behaviour of trough formation. There is no clear dependency between the migration of the shoreface nourishment and the length and/or volume. This is probably because the volumes and lengths are in the same range. When the shoreface nourishment is applied with a length of only a few hundred meters or a volume of 2000 m^3/m, the reaction of the migration might be different, but this is never applied in the Netherlands.

A lower water depth above the crest does influence the behaviour. In general, this leads to a deeper trough. A deeper trough is not desirable, since the possible negative effect of the development of rip currents and problems for navigability of boats (not researched in this thesis), the advice is to have a minimal water depth above the crest of 4.0 m.

9. Conclusions and recommendations

In this chapter, conclusions and recommendations are discussed. First, the conclusions and answers on research questions are presented. Next, the performed research and aspects that require more elaboration are discussed. Finally, recommendations are provided.

9.1 Conclusions

In this thesis, a broader study into morphological behaviour of shoreface nourishments is completed. In this section, the main- and sub-research questions are discussed.

9.1.1 Conclusions towards research questions

This research aims to get more insight in the morphological behaviour of shoreface nourishments. The main research question of this thesis is:

"What are the driving factors for the morphological behaviour of shoreface nourishments?"

This main research question is supported by three sub-research questions. Therefore, these sub-research questions are answered first, in order to combine them into answering the main research question.

Morphological behaviour and parameters

The first sub-research question is about the morphological behaviour of shoreface nourishments and the parameters that might influence this behaviour:

What is the morphological behaviour of shoreface nourishments and what are the drafted parameters?

Detailed research into migration of shoreface nourishments (see section 4.1) shows different migration directions. These migration directions are clustered in groups with the same migration. Some shoreface nourishments remain at the same position after execution, others migrate on- or offshore and have negligible alongshore migration. Another group of shoreface nourishments migrates on- and alongshore. Shoreface nourishments executed at the same location show the same type of migration.

During the determination of volume trends, no clear pattern is found. The overall trend is an increase of sediment volume over time. In the year of execution, the volume of sediments increases and in the following years, the volume slightly decreases, but not that much it transcends the increase in the first year. Between the year before execution and the last year of occurrence of the shoreface nourishment, a net positive volume trend exists.

For the original migration of the bar system, three different situations exist. Cross-shore directed migration, alongshore directed migration or the absence of sandbars. For the situations with original cross-shore migration, sandbars migrate towards the zone of decay. In this zone, the sandbars disappear. In case of original alongshore bar migration, the cross-shore migration is negligible and the sandbars migrate alongshore. The direction of migration for sandbars, before and after the execution of the shoreface nourishment, changes for most cases (see section 4.1.2). For situations with a dominant cross-shore bar behaviour, usually the original migration of the bar system is offshore directed. After the execution of the shoreface nourishment, no migration is present or the migration is onshore directed.

Patterns and correlations

The second sub-research question is about the indicators that might steer the morphological behaviour:

Is it possible to define indicators for the morphological behaviour of shoreface nourishments?

Based on the results in this thesis, it seems that the water depth above the crest does not influence the migration of shoreface nourishments. However, the formation of a trough depends on the water depth above the crest. A lower water depth above crest leads to a deeper trough onshore of the shoreface nourishment. This is only the case if original cross-shore bar behaviour occurs. For original alongshore bar behaviour, development of a deep trough is not present.

The volume, length and volume per length do not influence the migration of the shoreface nourishment, based on the data and results in this thesis. For these parameters, different migrations and no clear pattern are found. A higher volume per meter did increase the volume trend in the first year, but no difference in behaviour and volume trend is found for high or low volumes, neither for a long or short length of the shoreface nourishment.

The behaviour of the original bar system has a clear influence on the migration of the shoreface nourishment and even on the formation of a trough. Based on nine situations in this thesis, no pattern is found between the migration of the shoreface nourishment and the bar cycle period of the sandbars, neither between the moment of execution of the shoreface nourishment in the bar cycle period and the migration of shoreface nourishments. Based on the data and results in this thesis, the slope, Irribarren parameter (see section 6.1.2) and distance between the shoreface nourishment and the outer bar do not give a clear dependency with the migration (see section 6.1.4).

The migration of the original sand bars influences the migration of the shoreface nourishment and the formation of a trough. Locations exist with dominant cross-shore, alongshore or no original bar behaviour. At locations with an original cross-shore bar migration, the shoreface nourishments have only a cross-shore migration. The shoreface nourishments do not migrate alongshore in this case. Similar to the sandbars, the shoreface nourishments migrate towards the zone of decay. This explains that shoreface nourishments migrate both on- and offshore. If the shoreface nourishment is executed offshore of the zone of decay, it migrates onshore. If the shoreface nourishment is executed onshore of the zone of decay, it migrates offshore. If no cross-shore bar cycle exists in the original bar system, the sandbars do not migrate to a zone of decay or do not even exist. The alongshore behaviour is dominant in these situations. In Figure 90, an overview is given for the migration of the shoreface nourishment in relation to the original bar behaviour.

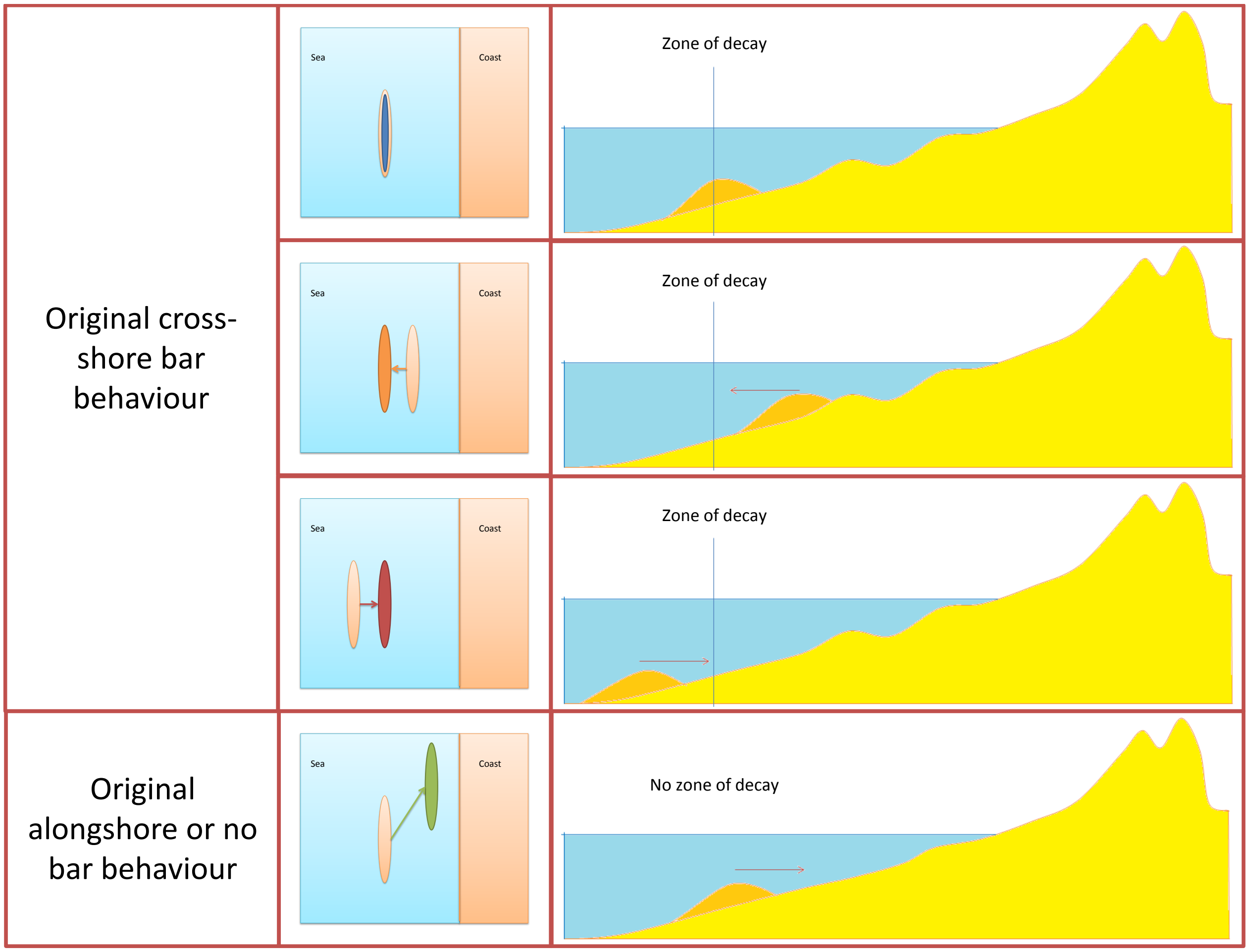


Figure 90: Overview of migration of shoreface nourishments (shown by the different clusters) in relation to the original bar behaviour.

Trough development is found predominantly at locations with original cross-shore bar behaviour. A higher crest results in a deeper trough. It seems that if the crest is higher, more energy dissipates and more sediment stirs up landward of the shoreface nourishment. Probably, the stirred up sediment is transported cross-shore and alongshore downstream. This alongshore transport is found at locations where the trough develops from upstream to downstream.

The migration of the bar system changes after execution of the shoreface nourishment. Why the bar migration is sometimes onshore and in other cases stable, is not found in the analysis of the parameters and the migration. No pattern between the yearly wave conditions and the migration is found. It is still reasonable that short-term, second-order, wave conditions in relation with the depth do have a major role in the morphological behaviour of shoreface nourishments.

Future application

The third, and last, sub-research question is about the future design of shoreface nourishments:

What is the optimal generic design to apply a shoreface nourishment?

A roadmap is drafted to determine the optimal position. The optimal position, to compensate the erosion in the upper profile, depends on the original bar behaviour. If this is cross-shore, then the zone of decay must be determined. The advice is to perform the shoreface nourishment at the zone of decay or offshore of this zone. Execution offshore of the outer bar is desirable, since the execution of shoreface nourishments between bars might disturb the whole bar system and is more expensive (not researched in this thesis). Since the shoreface nourishment migrates cross-shore and the volume trends show a positive volume trend in the upper profile, the best location for the execution of the shoreface nourishment is in front of the erosion location. If the original bar behaviour is alongshore, the design advice is almost the same as for the cross-shore situation. The only difference is the occurrence of the zone of decay. For the alongshore situation, the advice to perform the shoreface nourishment at the zone of decay or offshore of this zone expires. In this case the most economical position should be chosen (economic issues are not treated in this thesis). For the volume trends is found that execution of the shoreface nourishment in front of the erosion location, has a positive influence on the sediment volume.

For the design parameters, the water depth above the crest of the shoreface nourishment must be taken into account. Based on the results in this thesis, the length and volume of the shoreface nourishment do not influence the migration. The water depth above the crest influences the formation of a trough. A lower water depth leads to a deeper trough. Since the possible negative effect of the development of rip currents and problems for navigability of boats (not researched in this thesis), the advice is to have a minimal water depth above the crest of 4.0 m.

Driving factors behind morphological behaviour of shoreface nourishment

The main research question in this thesis is about the driving factors behind the morphological behaviour of shoreface nourishments. Now that the three sub-research questions are answered, the main research question is answered.

The behaviour of the original bar system is the factor that predominantly influences the morphological behaviour of shoreface nourishments. This influences both the migration of the shoreface nourishment and the formation of a trough.

The difference between cross-shore or alongshore bar behaviour determines the migration of the shoreface nourishment. Locations with dominant alongshore or no bar migration are southward of outer deltas of the Wadden Sea or near coastal structures (such as groynes). In these regions, the asymmetry of the tide might play a major role, but also a part of the waves seems to be blocked, which results in a calmer climate. A calmer climate leads typically to more onshore bar behaviour. The influence of short-term waves determines the state of the climate and thus of the migration of sandbars and shoreface nourishments on- or offshore.

Another factor is the water depth above the crest. A lower water depth results in a deeper trough. The process of breaking waves at the crest of shoreface nourishments influences the formation of a trough and thus the morphological behaviour of the shoreface nourishments. In addition, the development of the trough, from upstream to downstream, indicates that the alongshore sediment transport might influence the morphological behaviour. However, this is not researched in further detail in this thesis.

9.2 Discussion

In this section, a critical reflection is performed regarding several important issues relevant for this thesis.

Selection

In total, 38 shoreface nourishments are performed along the Dutch coast. Twenty shoreface nourishments are used for research into correlations and patterns and ten are used for validation. This means that eight shoreface nourishments are not used, this is done to save time. Taking the other eight shoreface nourishments also into account, would lead to conclusions that are more robust. Based on the diverse selection of the shoreface nourishments, omitting these shoreface nourishments likely does not change the results.

JARKUS survey

The JARKUS survey is not consistent for each year. In this thesis is found that sometimes a gap in the data occurs. For example at Rijnland, in 2004 and 2007, a part of the shoreface nourishment at Zandvoort is missing and at Delfland, the land surveys are missing sometimes. This is a problem for the migration of the centroids and the determination of the volume trends. The centroid in 2007 at Zandvoort is not determined because of this problem and consequently the mean migration is based on fewer years. This results in a lower accuracy of the migration. For the determination of the volume trend at Delfland, the missing land surveys are a problem. The volume of sediments could not be determined for the area onshore of 110 m +RSP. Since only the volume trends are analysed, this is not a major problem, but because it is impossible to determine the volume of sediments at the beach, there are no valid conclusions for the sediment volume change at the beach.

Alongshore migration

The detailed alongshore migration is based on the visual description. This method is not as exact as the method applied for the cross-shore migration in section 4.2. Because the JARKUS survey is measured cross-shore, it is difficult to determine a detailed alongshore migration with these surveys. For this thesis, the method used satisfies. It gives clear results on the alongshore migration of shoreface nourishments. For better results for the detailed alongshore migration, other measurement methods must be performed and a better analysis method must be used.

Volume trends

The volume trends in this thesis are based on a mean profile of the shoreface nourishments. This is a simplification of the situation and less accurate then when the volume trend is determined for every JARKUS transect.

The volume trends are not the main subject in this thesis. They merely give an impression of the overall response of the sediment volume on the shoreface nourishment. That is why the volume trend is only determined for the mean profile. For a more detailed research into the effects on the sediment volumes in the surrounding, the volume should be determined per JARKUS transect and up- and downstream of the shoreface nourishment.

Parameter analysis
The analysis of the bar cycle period and the beach slope is not performed in detail. For the determination of the bar cycle period and the slope of the beach profile, very detailed methods can be used. In this thesis, the bar cycle period is performed with a visual study. Based on this visual study, it turns out that no pattern occurs between the bar cycle period and the migration of the shoreface nourishment. Assumed is that a detailed research would give probably the same results.

For the beach slope a more detailed research could be performed. Again, with the simple method used for the parameter analysis it turns out that no pattern occurred between the slope of the beach profile and the migration of the shoreface nourishment. Again, assumed is that a detailed research would give probably the same results.

In addition, for the exact determination of the zone of decay, the above-mentioned parameters might influence the position of the zone and detailed research is recommended. However, since research into the zone of decay is not in the scope of this thesis, the parameters are not investigated in detail.

9.3 Recommendations for further research

In this thesis, insight is obtained about the behaviour of shoreface nourishments and bar systems that can be useful for further research. Recommendations are written down in this section to contribute to the improvement of further research into the behaviour of shoreface nourishments and the behaviour of bar systems.

Behaviour bar system

1. In this thesis is proven there is a difference in bar systems. Sandbars can migrate cross- or alongshore or they do not exist. More insight must be obtained regarding specific bar behaviour along the Dutch coast, i.e. why there is cross-shore bar behaviour and why not. Two things must be compared with the behaviour of the bar system to check whether it might influence the occurrence of cross-shore bar behaviour.
    a. Short-term, second-order, waves might influence this behaviour, since the difference in storm or calm climate results in an on- or offshore-directed migration. It might be possible that at locations with a higher energetic climate, bars migrate offshore. At locations with a lower energetic climate, it might be possible that the bars are constant or do not even exist. In these situations, the alongshore current might have a high influence. For further research, the influence of short-term, second-order, wave conditions on the bar behaviour must be researched. The best way to perform this research is to analyse the short-term conditions and the behaviour of the bar system. For this research, the daily bar behaviour must be measured. After this analysis, a detailed model study must be performed based on the results of the analysis and this will turn out what the relation is between the bar behaviour and the wave climate.
    b. The asymmetry of the tide might also influence the occurrence of cross-shore bar behaviour. In the region of outer deltas of the Wadden Sea, the tide becomes more asymmetrical. This might influence also the behaviour of the bar system. The expectation is that due to the tidal symmetry along the Holland Coast, the waves will

have a major influence on the migration of the shoreface nourishments, but in the regions with a tidal asymmetry (in the area of the outer deltas of the Wadden Sea) the tide will have a major influence. This results in a difference in bar behaviour. The advice for further research is to determine the tidal (a)symmetry and wave climate along the Dutch coast, first with historical data and next with models, and compare this with the characteristics and migration of the bar system. This comparison will give more insight in the influence of waves and tide on the characteristics of the bar system.

2. In this thesis is proven that sandbars and shoreface nourishments migrate towards the zone of decay if dominant cross-shore bar behaviour occurs in the original bar system. At the zone of decay, the bars and nourishments dissipate. More research on this zone is recommended. It is not clear why this zone exists and what are the processes that influence the position of this zone. It might be possible that the zone of decay changes in time. In addition, it looks like the offshore-directed migration during storm and onshore-directed migration during calm conditions is in balance in this zone, this might be also an explanation why the zone in not constant in time. It might be possible that the wave climate, the slope of the coastal profile, the grain size diameter, the depth and the alongshore current determine the position of the zone of decay. For robust conclusions about the zone of decay, more research must be obtained into these parameters and the position. This can be performed by analysing the parameters mentioned before and position of the zone of decay. The results of this analysis must be validated by a model study to get the best results.
3. The influence of land subsidence due to gas mining in the Wadden area, might influence the behaviour of the bar system and the sediment volume development. The results found in this thesis for Ameland must be adjusted for situations with land subsidence. With this adjustment, conclusions that are more robust can be made for the volume development in the area with land subsidence due to gas mining.

Behaviour shoreface nourishment

4. More research is needed on the influence of breaking waves on trough formation. In this thesis is found that a higher crest results in a deeper trough. This might be possible because more wave energy is dissipated on high crests than on low crests. The higher amount of dissipated energy results in more sediment that is stirred up. This assumption needs to be validated by an extended (model) research. The advice is to determine the wave climate and the dissipated energy around the crest of shoreface nourishments and to compare this with the formation of a trough. This must be validated with a model research to find a clear pattern between wave climate and trough formation.
5. The knowledge about the influence of wave conditions on shoreface nourishments needs to be extended. Since the wave conditions are not measured at the exact location of the shoreface nourishment and only the yearly wave conditions are determined, it is difficult to conclude anything on the influence of short-term, second-order, wave conditions on the migration of shoreface nourishments. The advice is to monitor specific the migration of a few shoreface nourishments and the wave climate at that location on short-term, to prove if there is a relation

between short-term, second-order, wave conditions and the migration of shoreface nourishments. This may also lead to a clarification about the difference in migration each year.

6. This thesis focusses on the migration of the shoreface nourishment. The volume trends are determined for the mean profile at the location of the shoreface nourishment, but not in the surroundings. For a better insight in the volume trends, the advice is to perform more research on the volume trends per JARKUS transect and up- and downstream of the shoreface nourishment. This provides a better insight in the influence of shoreface nourishments in alongshore direction. The advice is to use again different bins to see the volume trend for different sections.
7. Only the Dutch shoreface nourishments are taken into account. For a wider view on the morphological behaviour of shoreface nourishments, the shoreface nourishments performed in other countries must be evaluated as done in this thesis. The advice is to perform a research like this thesis for several other countries and to compare the results. Since this data in other countries is not always available or does not have the same range and frequency, the data availability in other countries must be researched and adjusted to perform a same data analysis as performed in this thesis. This must be completed by collecting all data of other countries and find an overall method to analyse the data on the same way. This will make it possible to compare shoreface nourishments and will result in a better overview of the morphological behaviour of shoreface nourishments worldwide.
8. At Eierland and Callantsoog, the first shoreface nourishment migrates faster towards the coast than the successive shoreface nourishments. This might be explained by the demand for sand by the system, but this assumption should be improved. This can be performed by looking at the historical sediment development for different areas. This will turn out if there is a demand for sediments. This must be compared with the migration of different shoreface nourishments and the behaviour of the bar system. Results of this comparison can be proved by a detailed model research.

Economical decision

9. In this thesis, the economic issues are not taken into account. The decision for the best position to perform the shoreface nourishment is based on physical aspects. Additional research is needed into the costs and benefits of shoreface nourishments executed in the zone of -5 m and -8 m NAP. Since the position of execution, found in section 8.1, might advocate a wider range, it is recommended to perform research on the execution methods and the costs and benefits of it.

Safety effect

10. The effect on safety of the hinterland, as a result of the execution of shoreface nourishments, is not performed in this thesis. It is recommended to perform research into the effect of shoreface nourishments on the safety against flooding. This can be performed by looking at the effect of the shoreface nourishments on the growth of the dune system and by analysing the width of the beach.

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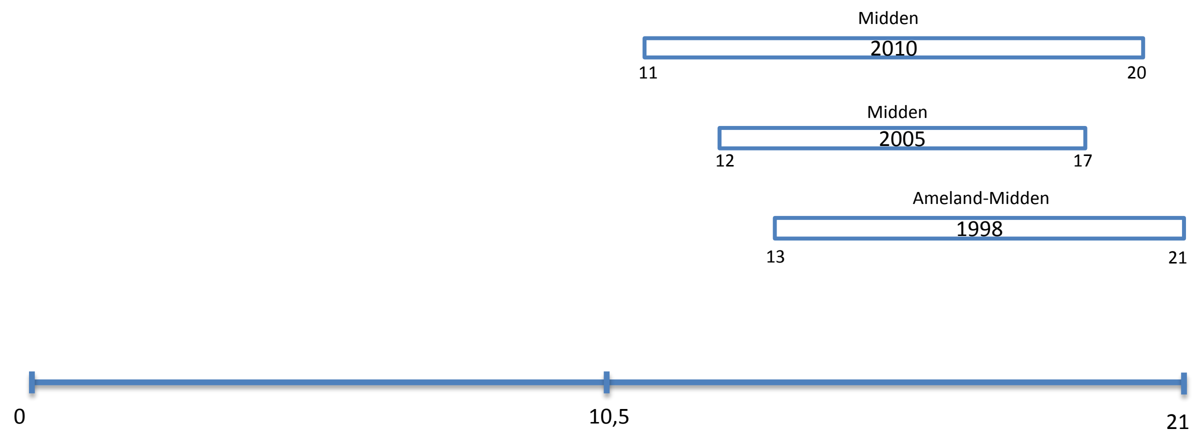
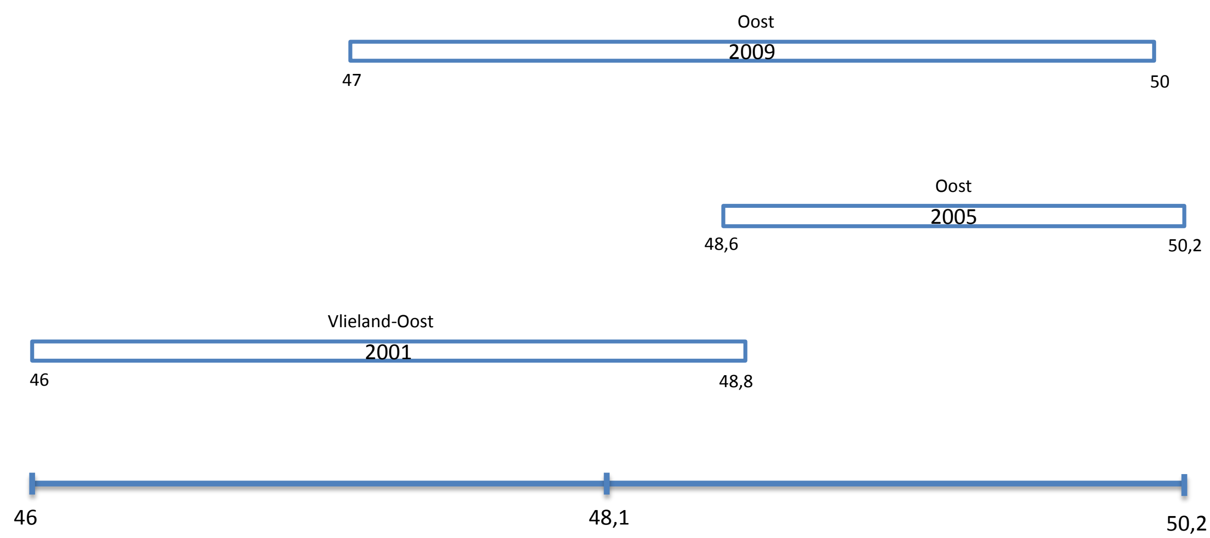
Appendix A: Overview of shoreface nourishments in each coastal section

	Shoreface nourishment	Year	First JARKUS transect	Last JARKUS transect	Length [m]
1	Am – Midden	1998	13	21	7000
2	Am – Midden	2005	12	17	5000
3	Am – Midden	2010	11	20	9000
4	Vlie – Oost	2001	46	48.8	2800
5	Vlie – Oost	2005	48.6	50.2	1600
6	Vlie – Oost	2009	47	50	3000
7	Tex – De Koog	2002	17	23	6000
8	Tex – Eierland	2004	25.2	27.8	2600
9	Tex – Centrale Kust	2005	13.52	16.9	3380
10	Tex – De Koog	2006	17	23	6000
11	Tex – Zuidwest	2007	9	13.5	4500
12	Tex – Eierlandse Dam	2009	26	28.8	2800
13	Tex – Midden	2012	12	21.11	9110
14	NH – Egmond	1999	36.9	39.1	2200
15	NH – Bergen aan Zee	2000	32.25	34.25	2000
16	NH – Zijpe	2001	14.01	11.08	2930
17	NH – Camperduin	2002	26.5	30	3500
18	NH – Callantsoog-Zwanenwater	2003	10	16	6000
19	NH – Egmond aan Zee	2004	36.2	40.2	4000
20	NH – Bergen	2005	31.5	36.2	4700
21	NH – Callantsoog-Zwanenwater	2006	10	15.2	5200
22	NH – HBPZ	2008	15	29.5	14500
23	NH – Den Helder-Julianadorp	2009	7	10	3000
24	NH – Egmond-Bergen	2010	31	40	9000
25	NH – Heemskerk	2011	45.75	50	4250
26	NH – Callantsoog	2013	10	14	4000
27	Rijn – Noordwijkerhout	2002	73	80	7000
28	Rijn – Zandvoort Zuid en Noord	2004	62.75	67.75	5000
29	Rijn – Noordwijk-Katwijk	2006	81.5	89	7500
30	Rijn – Bloemendaal	2008	61	63	2000
31	Delf – Ter Heijde	1997	113.15	114.85	1700
32	Delf – Scheveningen	1999	97.73	100.5	2770
33	Delf – Kijkduin-Ter Heijde	2001	107.4	112.5	5100
34	Delf – Monster	2005	108.6	113	4400
35	Delf – 's Gravenzande-HvH	2007	113	118	5000
36	Delf – Kijkduin-Ter Heijde	2011	111.76	113.94	2180
37	Delf – Hoek van Holland	2013	114	118	4000
38	Walch – Westkappelse Zeedijk	2008	17.55	19.7	2150

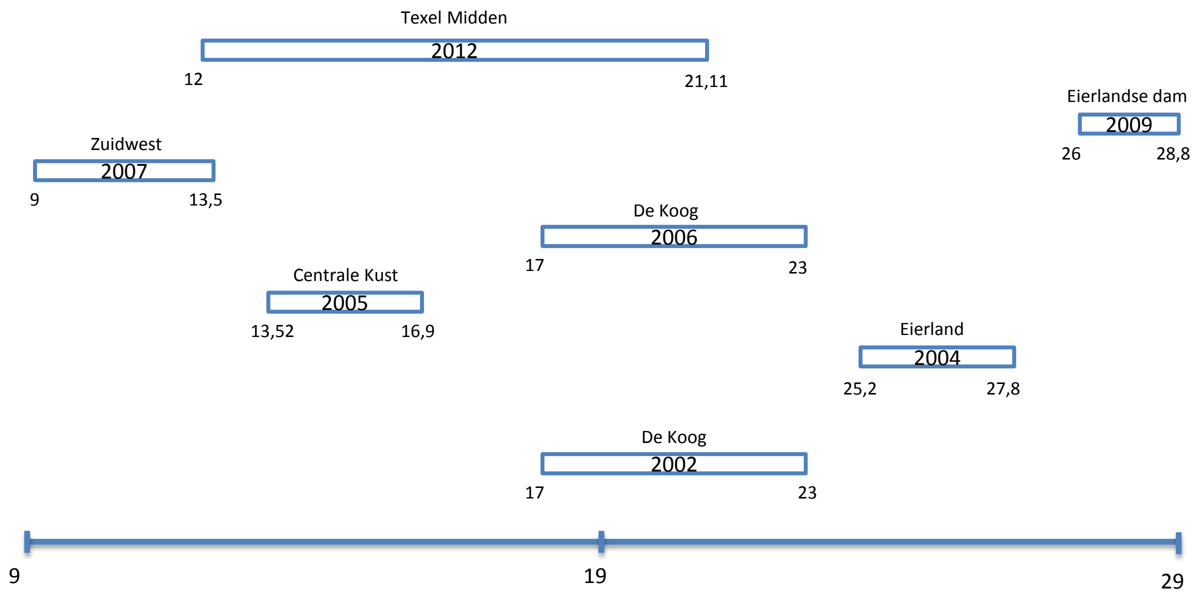
Shoreface nourishments at Ameland with year and JARKUS transects of execution



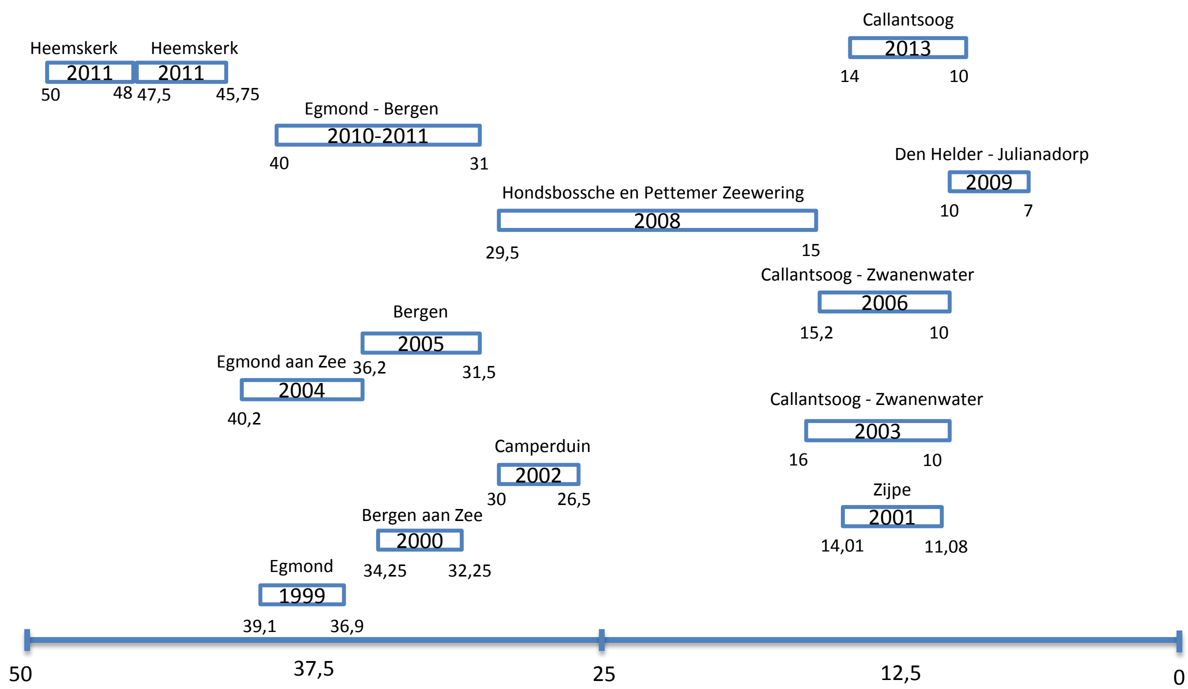
Shoreface nourishments at Vlieland with year and JARKUS transects of execution



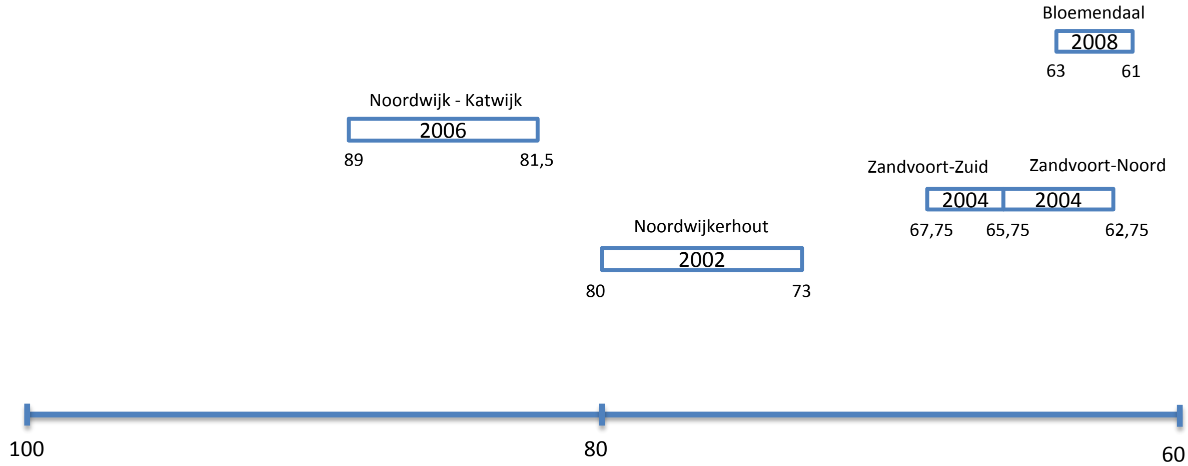
Shoreface nourishments at Texel with year and JARKUS transects of execution



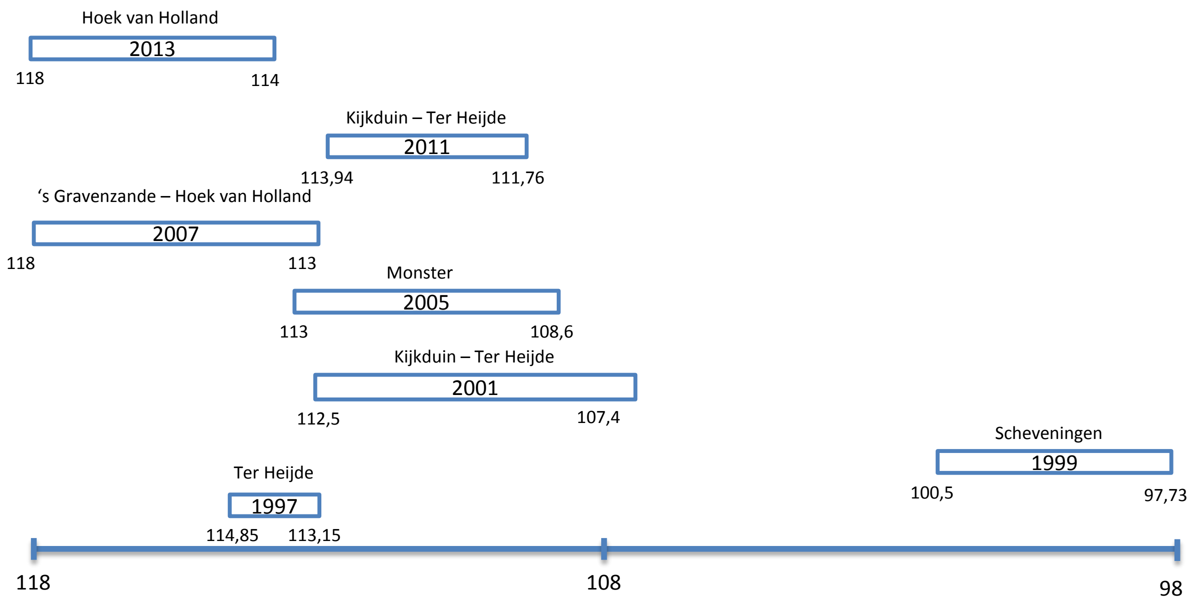
Shoreface nourishments at Noord-Holland with year and JARKUS transects of execution



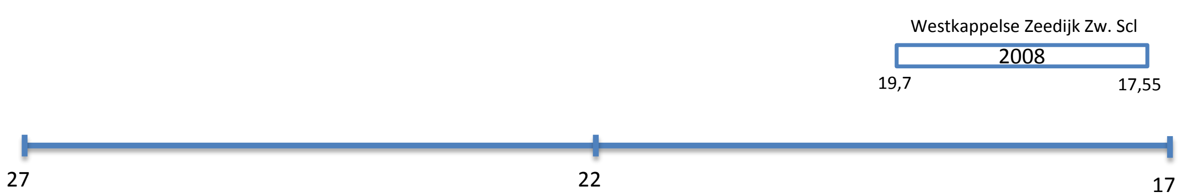
Shoreface nourishments at Rijnland with year and JARKUS transects of execution



Shoreface nourishments at Delfland with year and JARKUS transects of execution

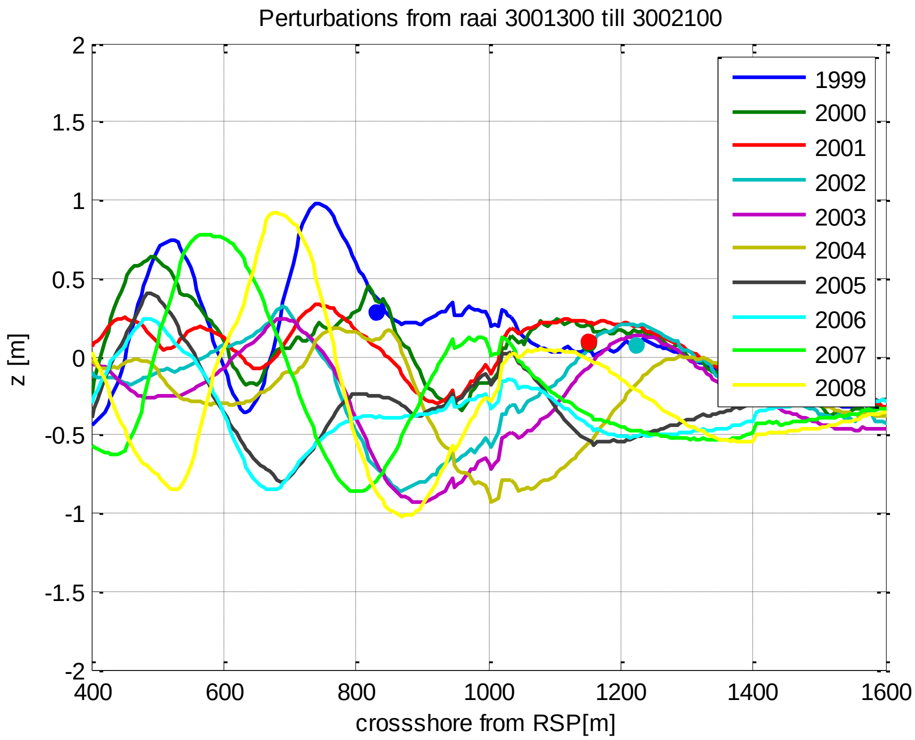


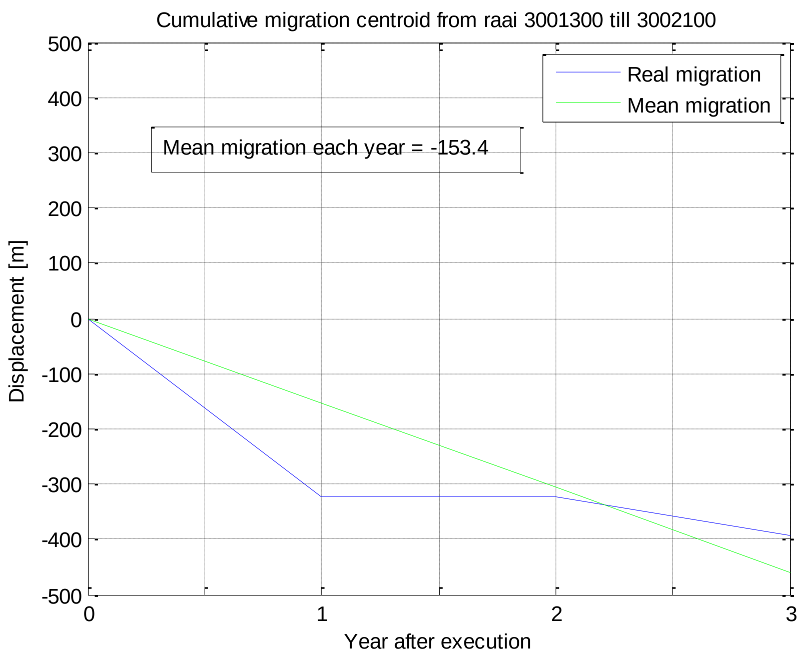
Shoreface nourishments at Walcheren with year and JARKUS transects of execution



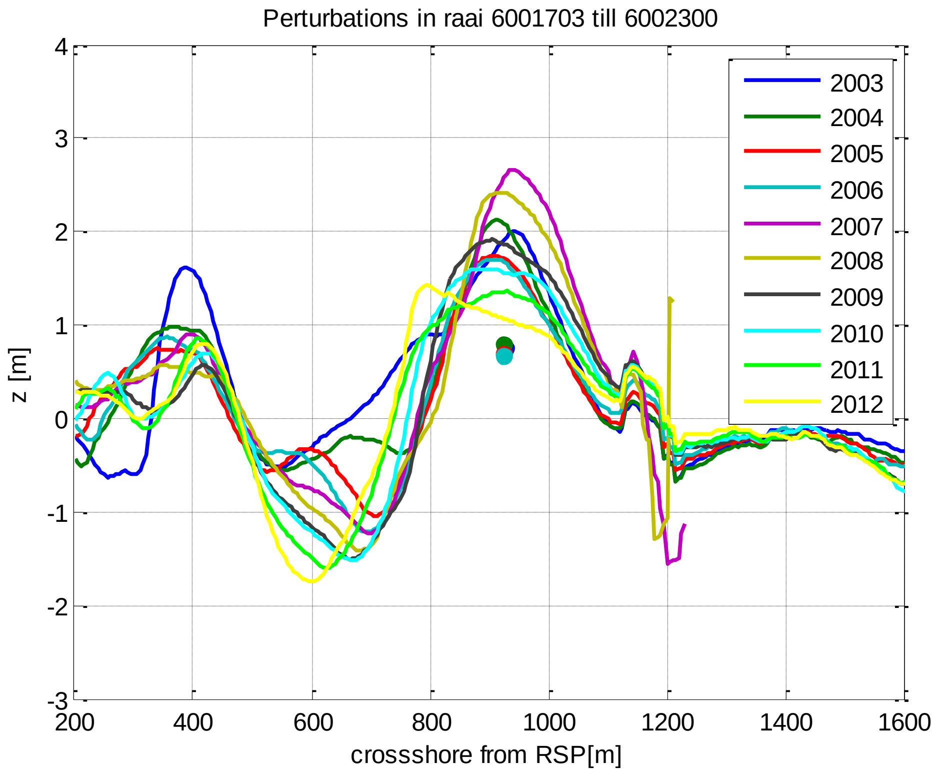
Appendix B: Detailed cross-shore migration shoreface nourishments

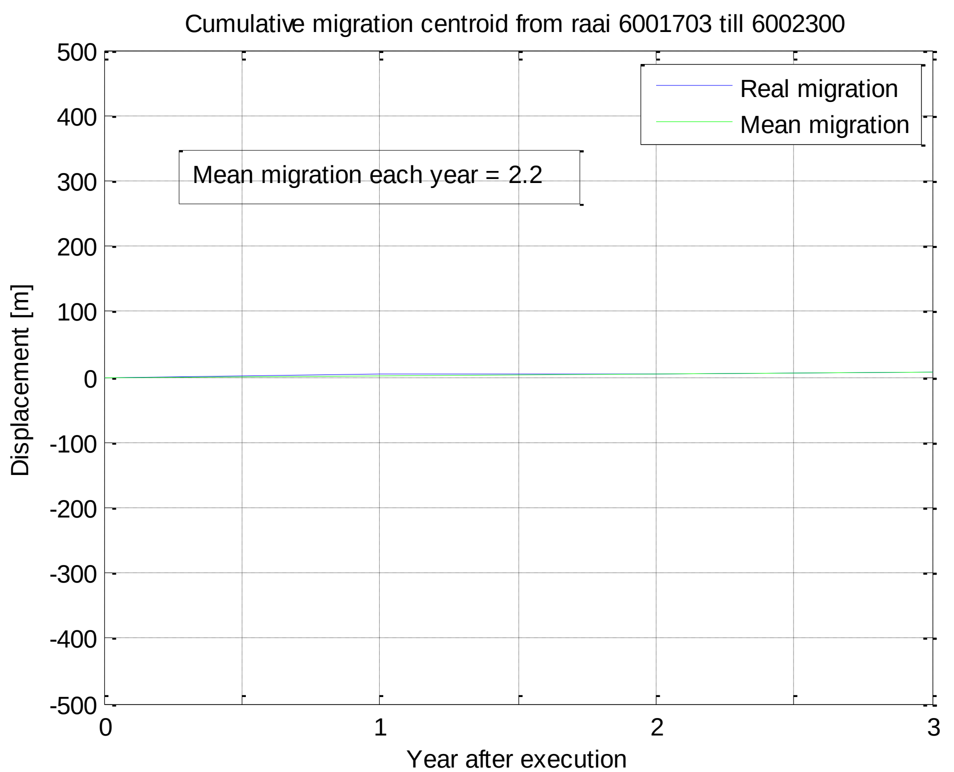
Ameland – Midden – 1998



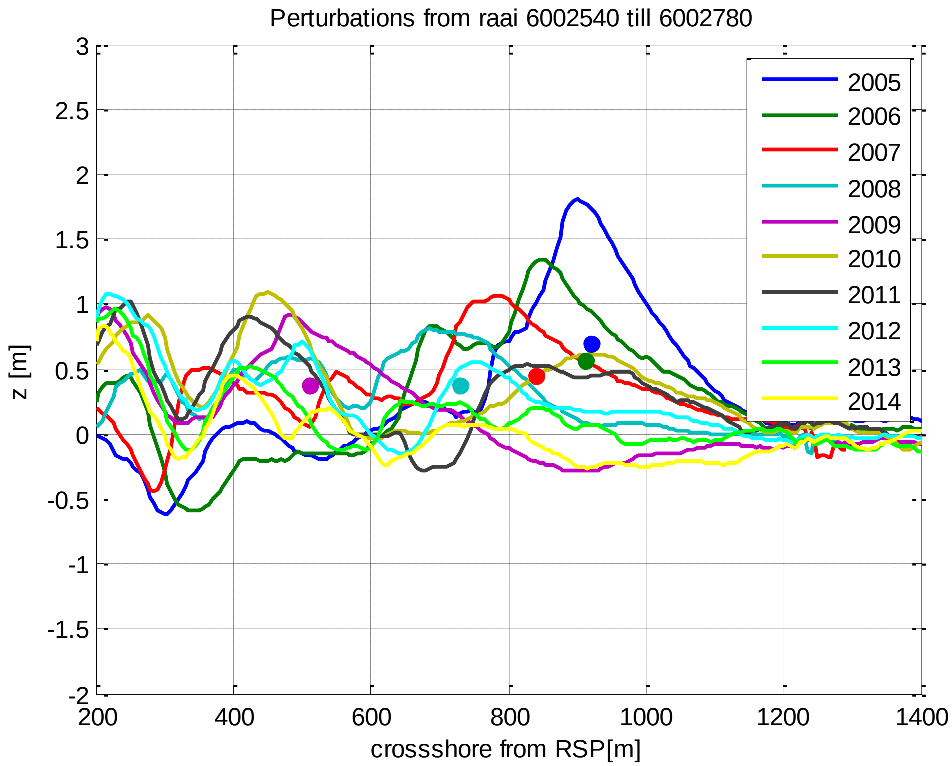


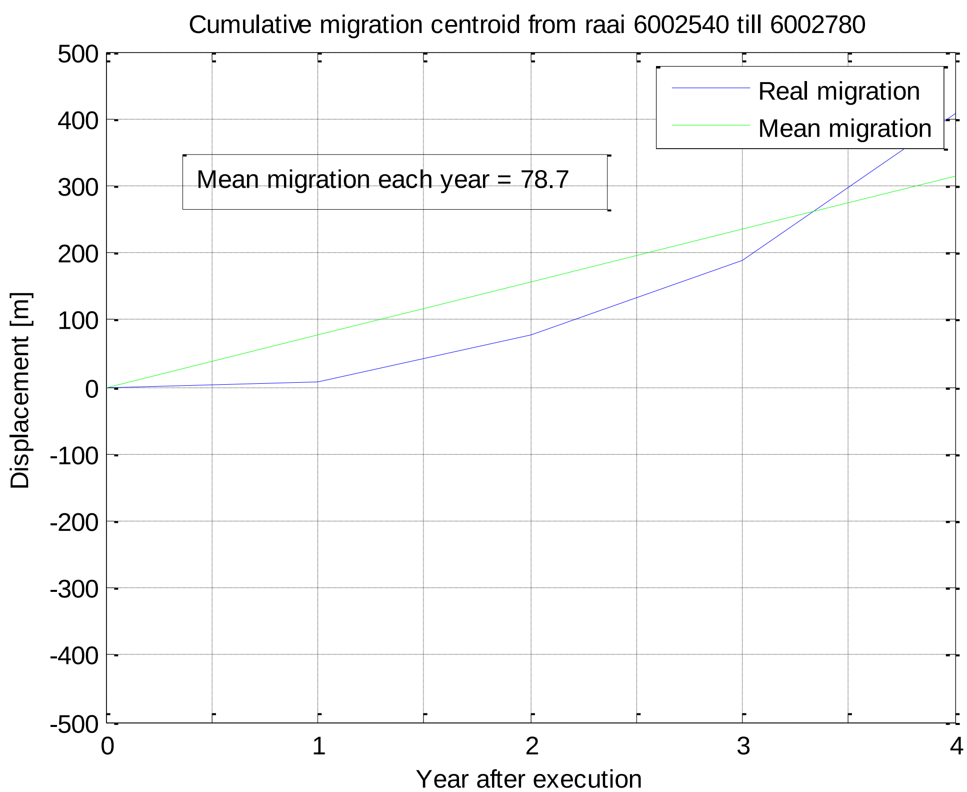
Texel – De Koog – 2002



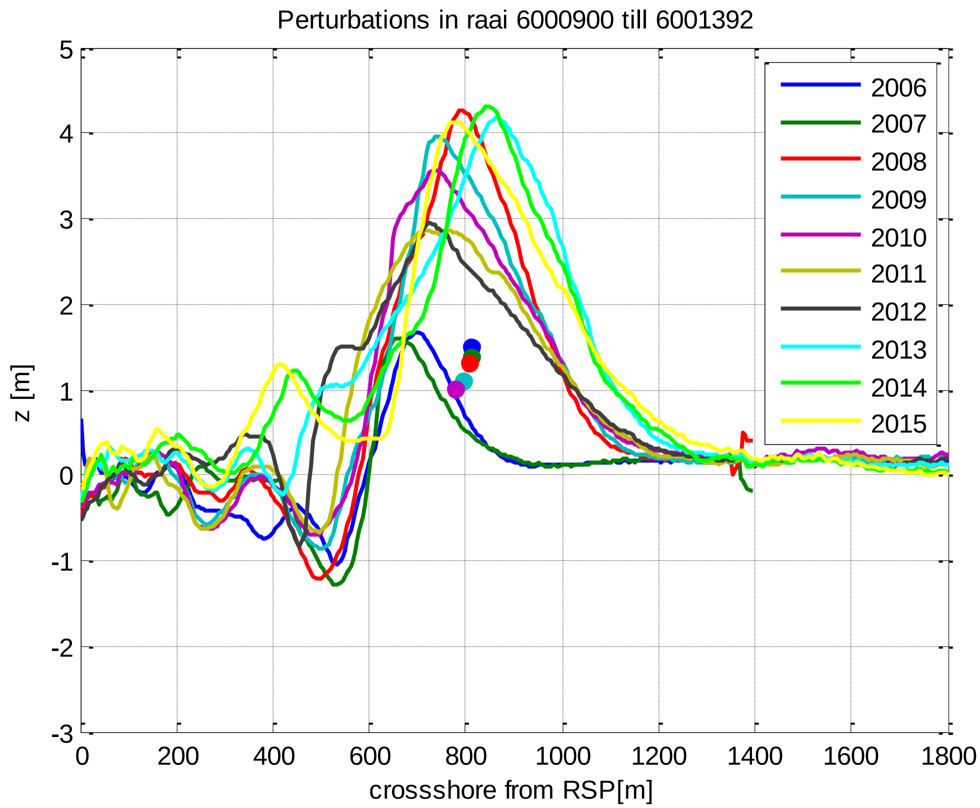


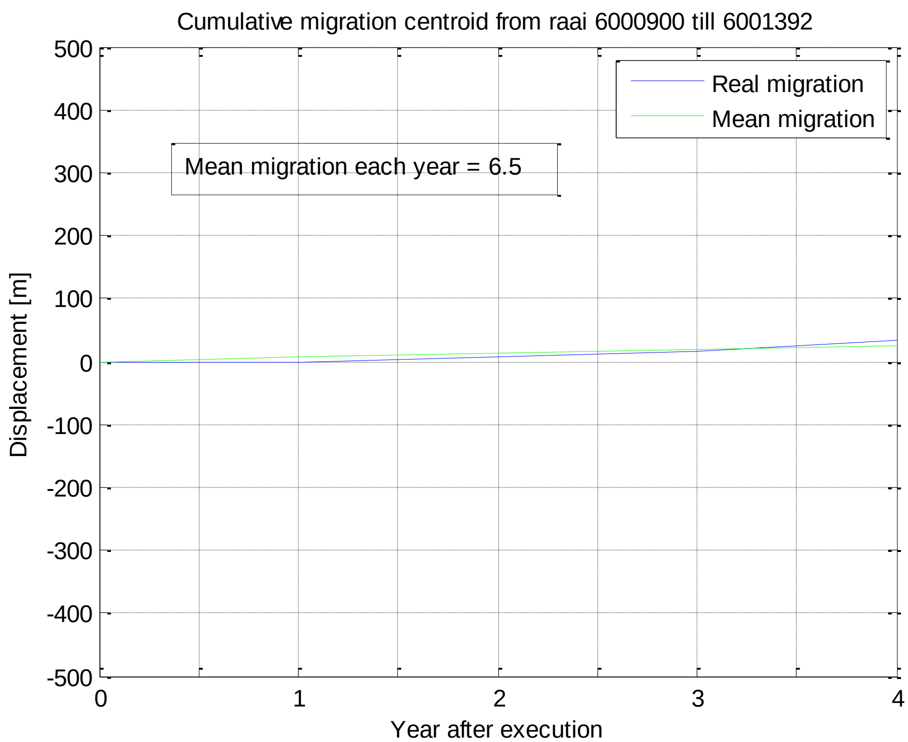
Texel – Eierland – 2004



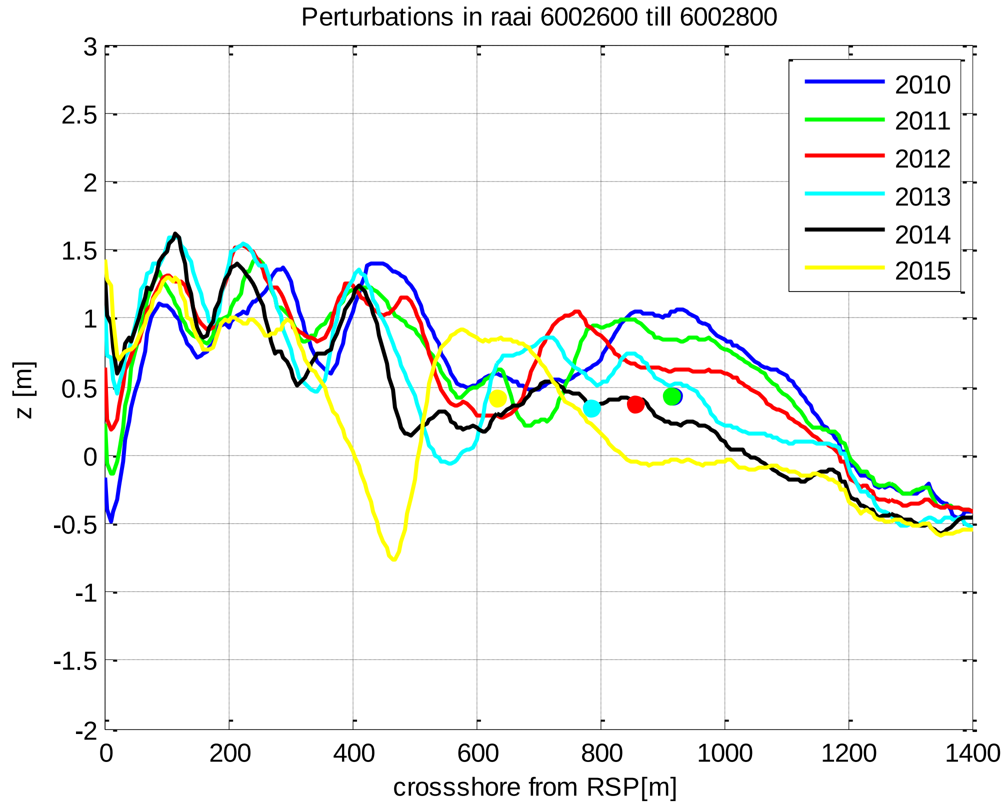


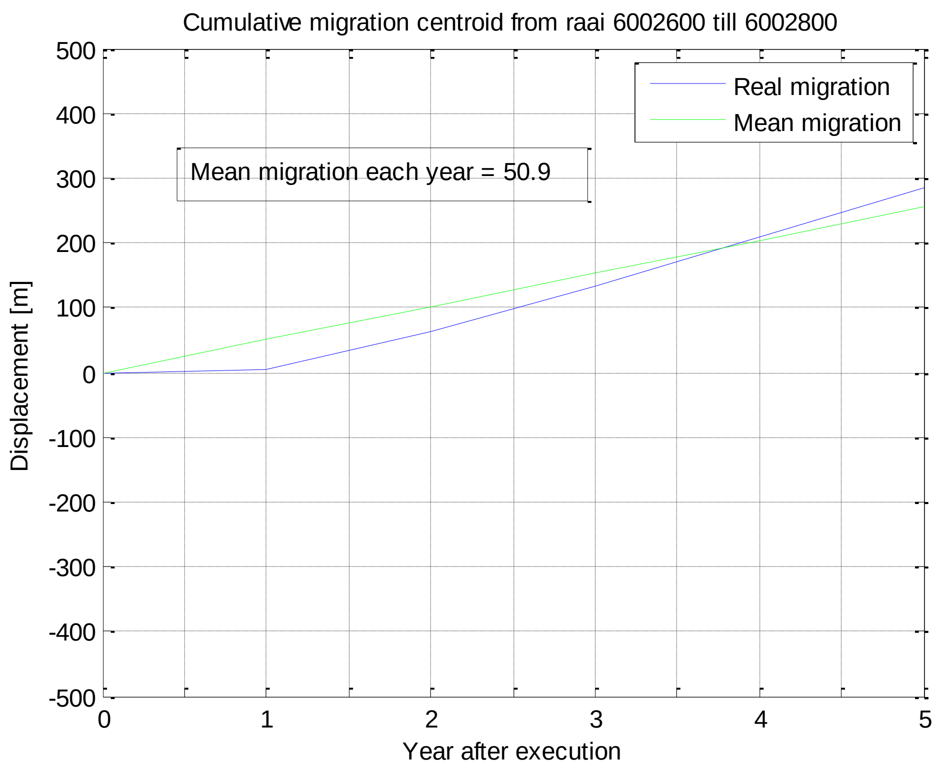
Texel – Zuidwest – 2007



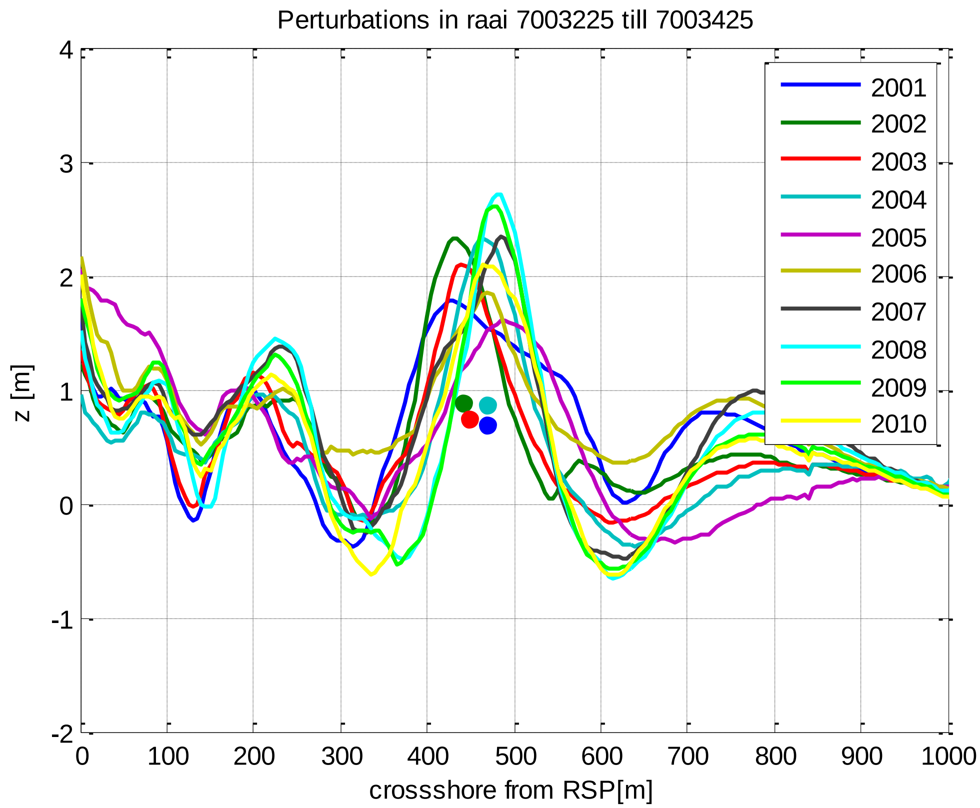


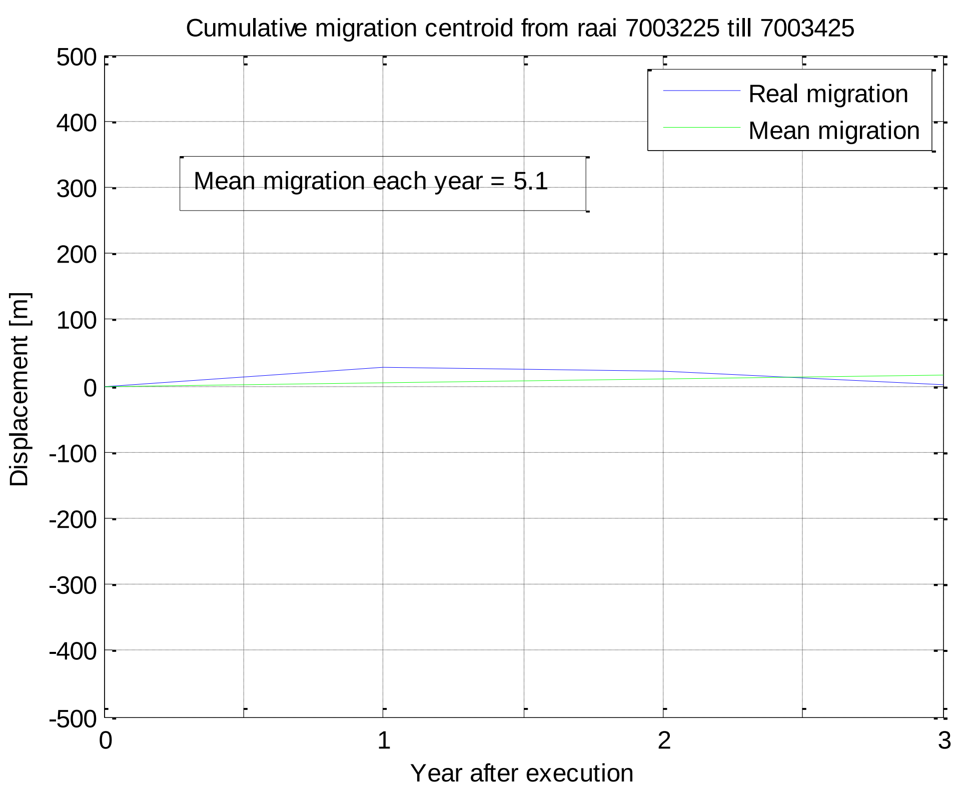
Texel – Eierlandse Dam – 2009



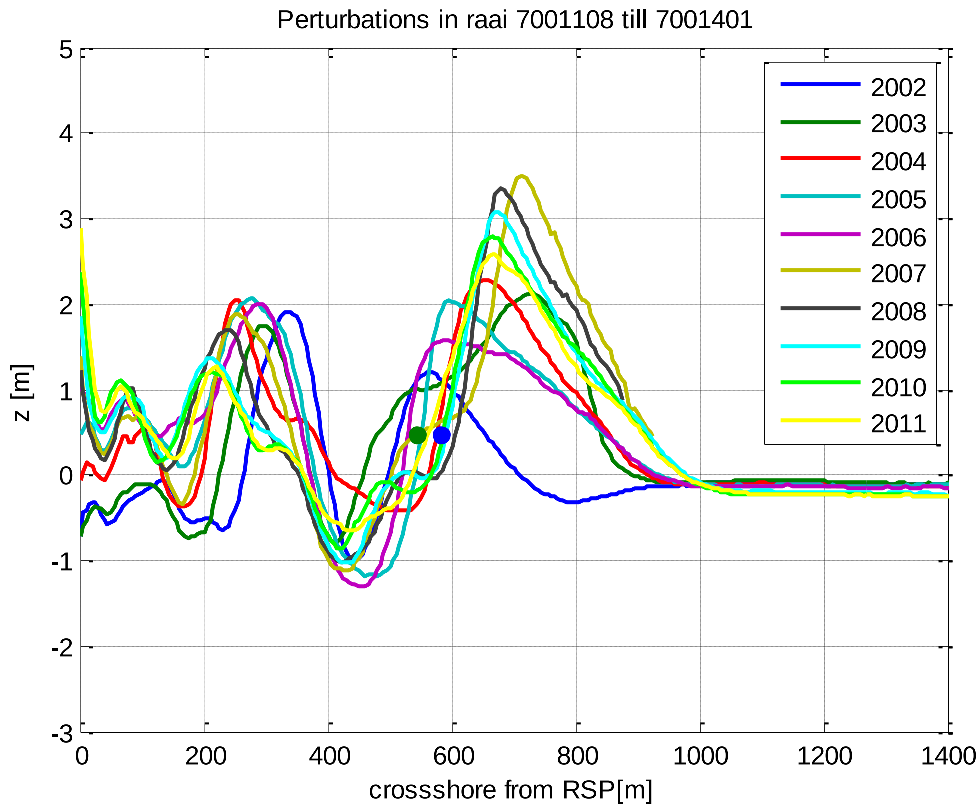


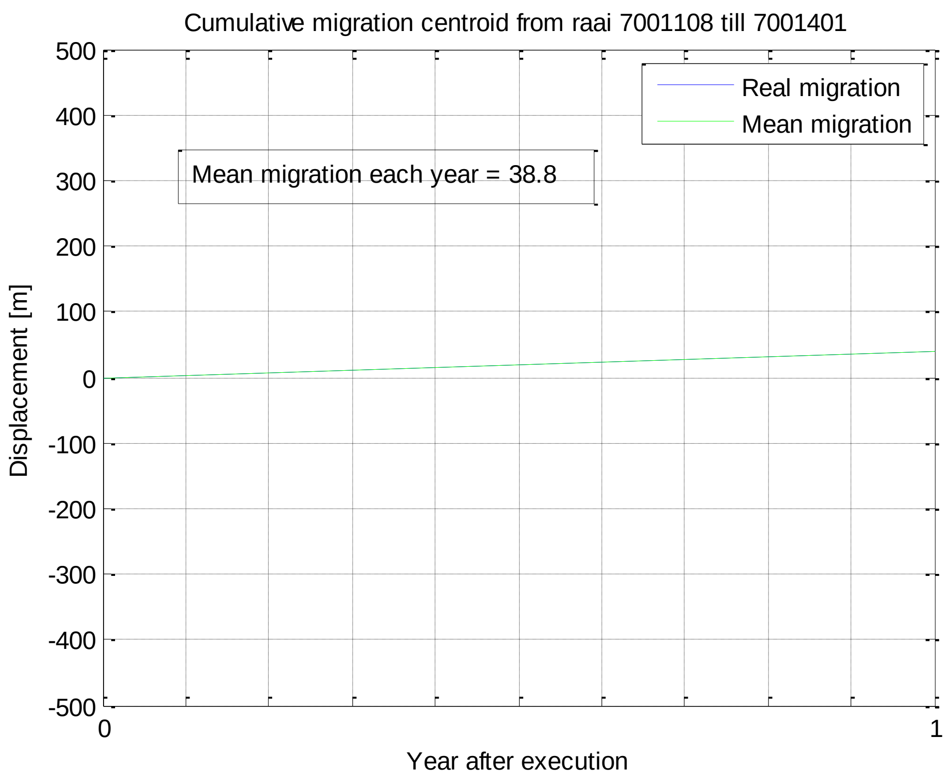
Noord-Holland – Bergen aan Zee – 2000



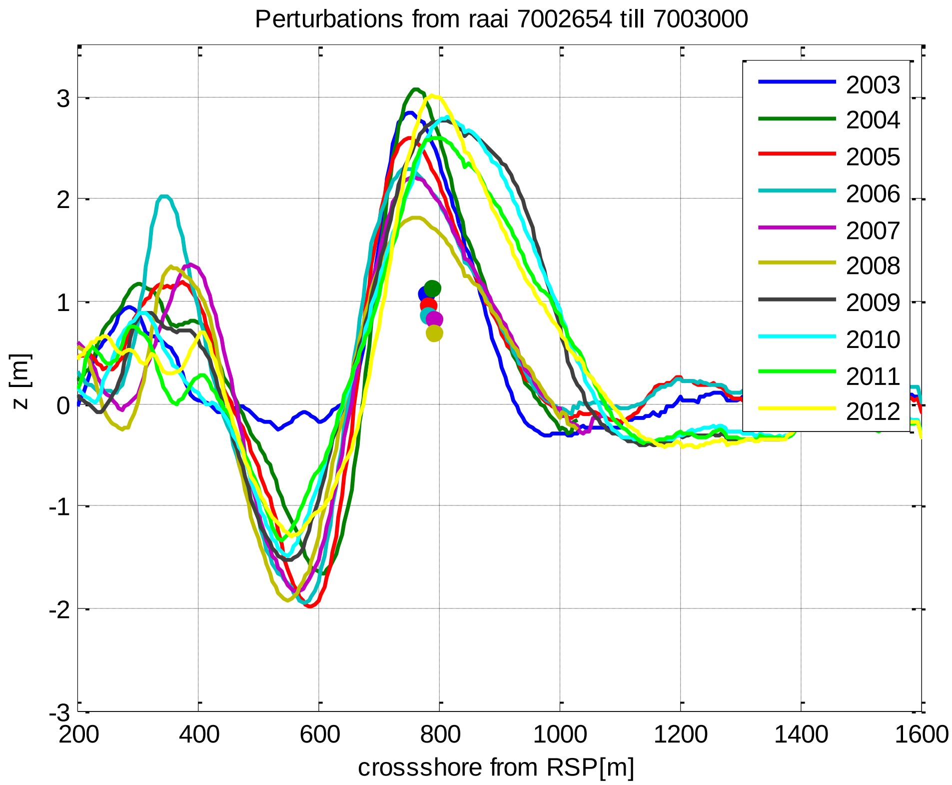


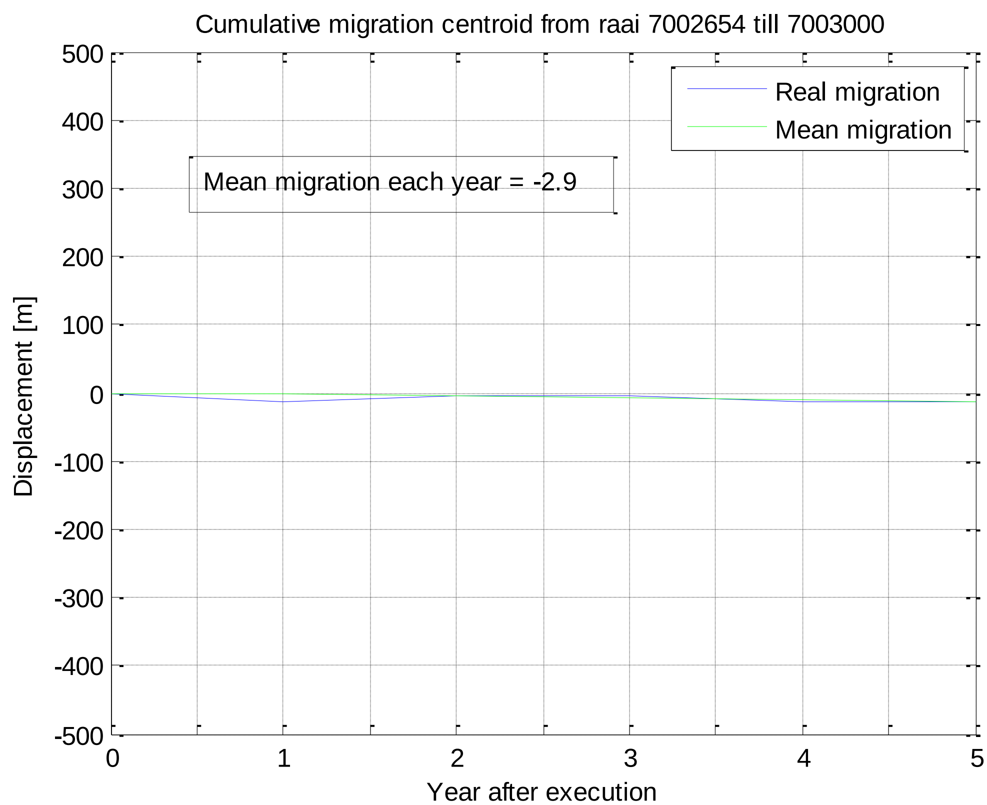
Noord-Holland – Callantsoog – 2001



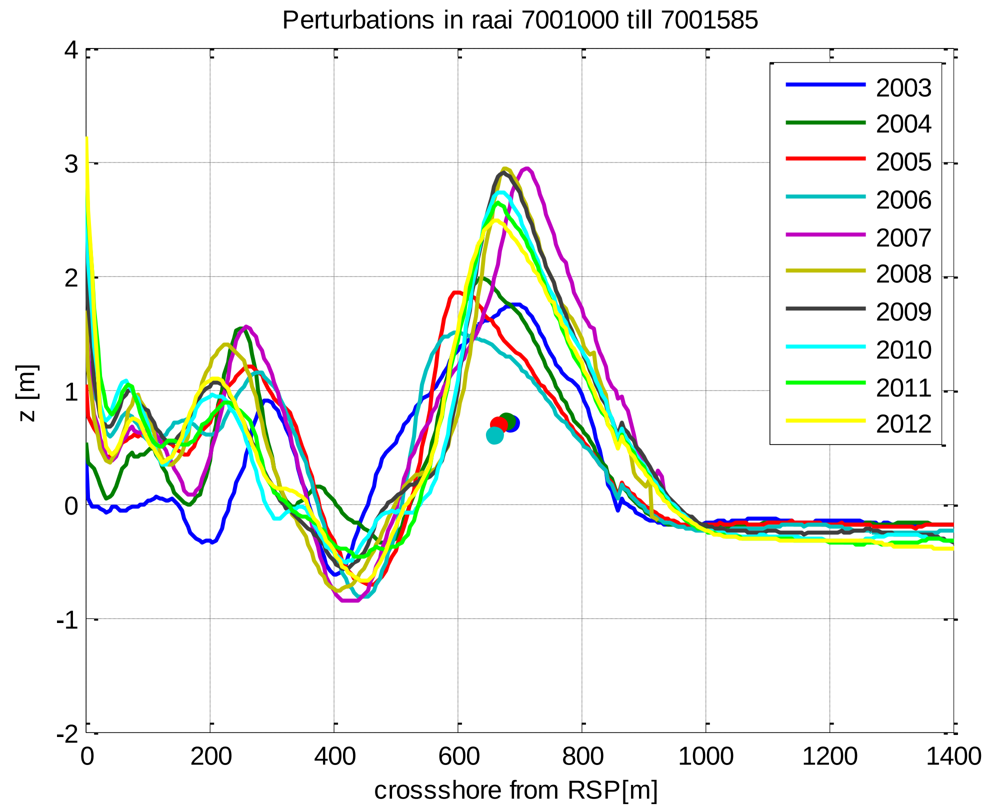


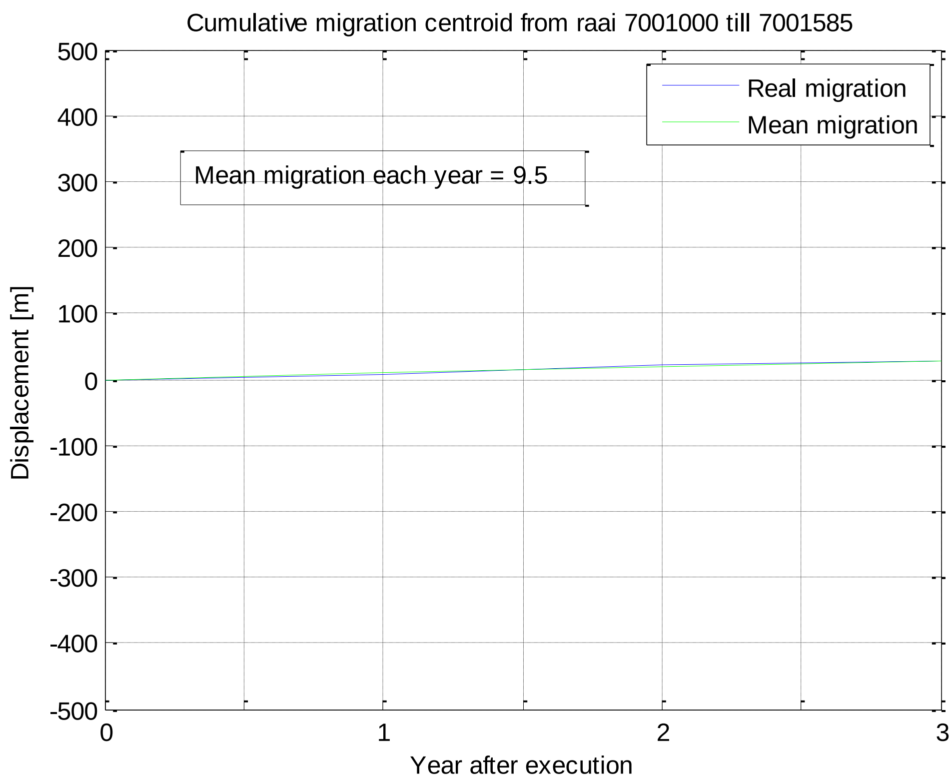
Noord-Holland – Camperduin – 2002



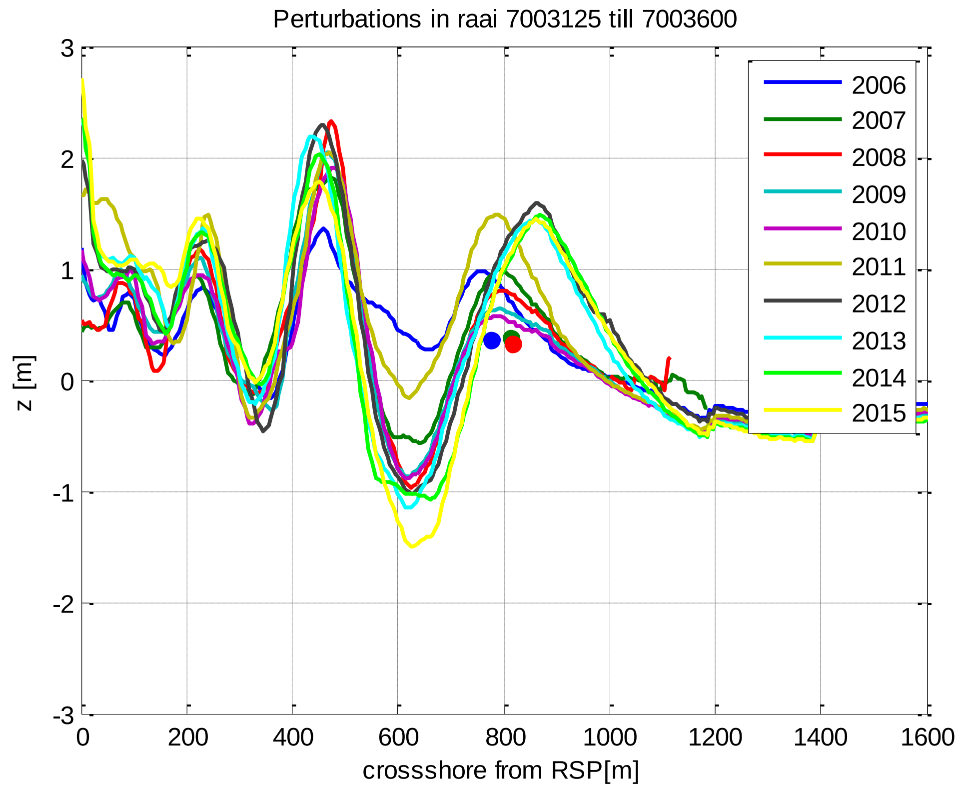


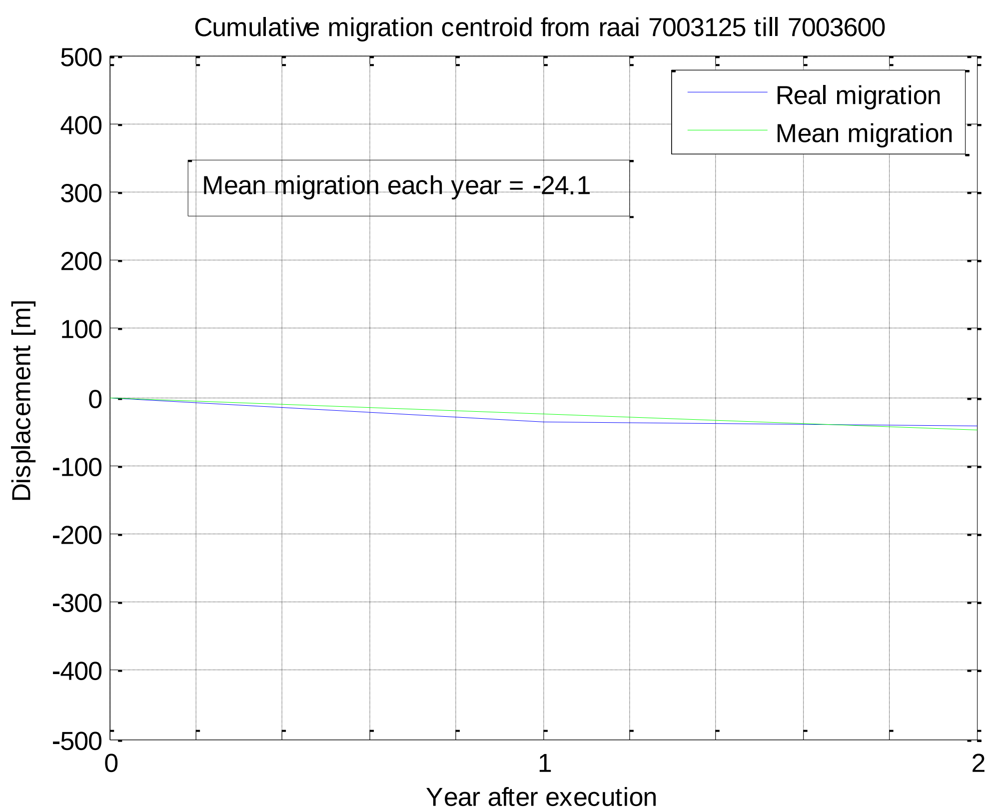
Noord-Holland – Callantsoog-Zwanenwater – 2003



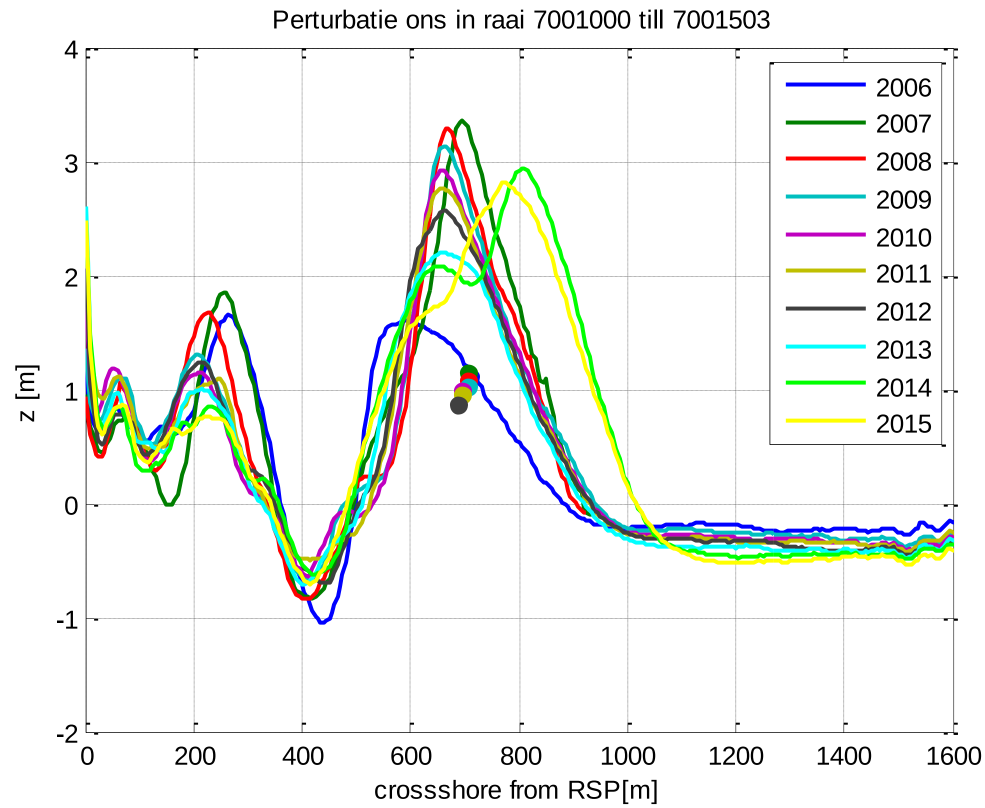


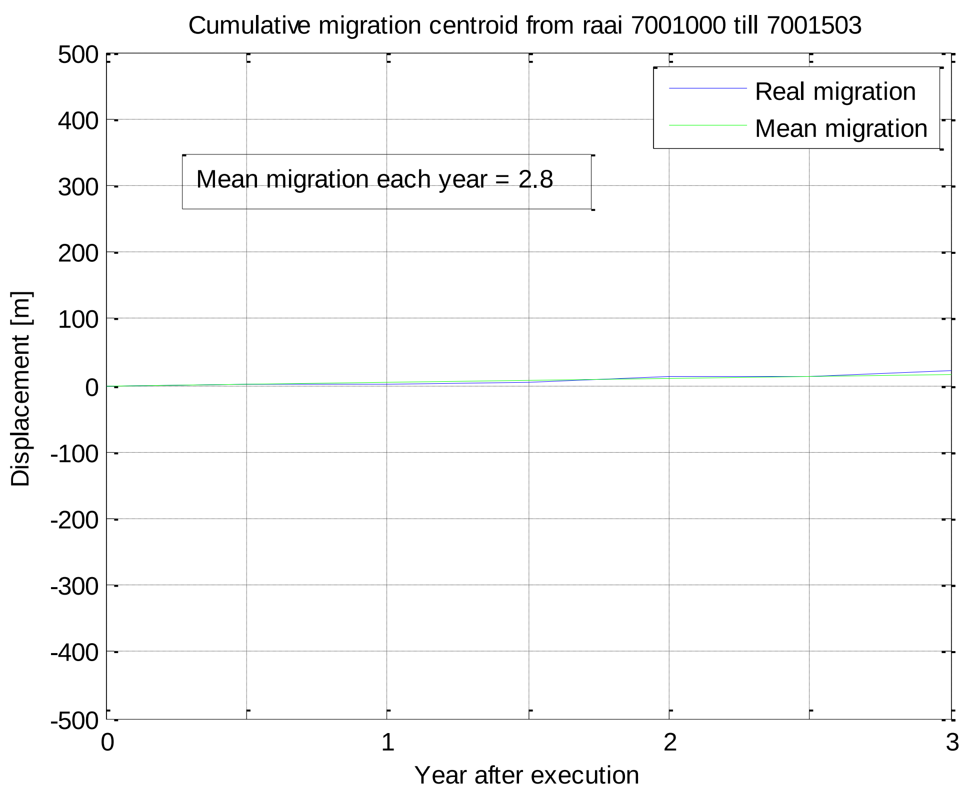
Noord-Holland – Bergen – 2005



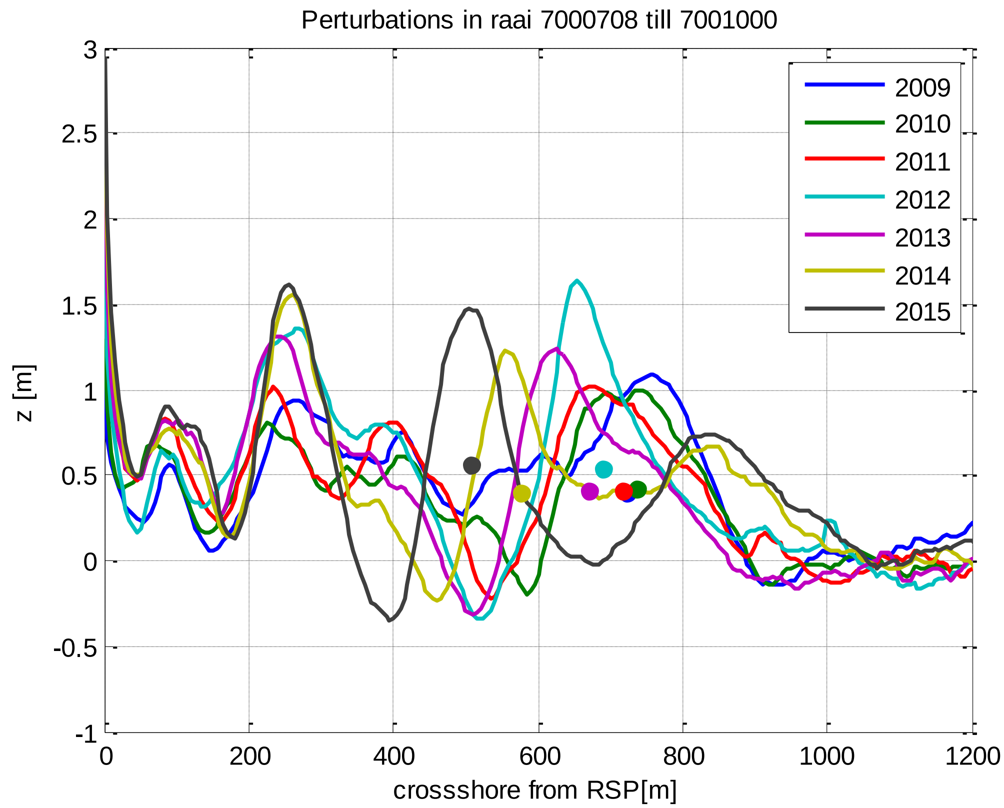


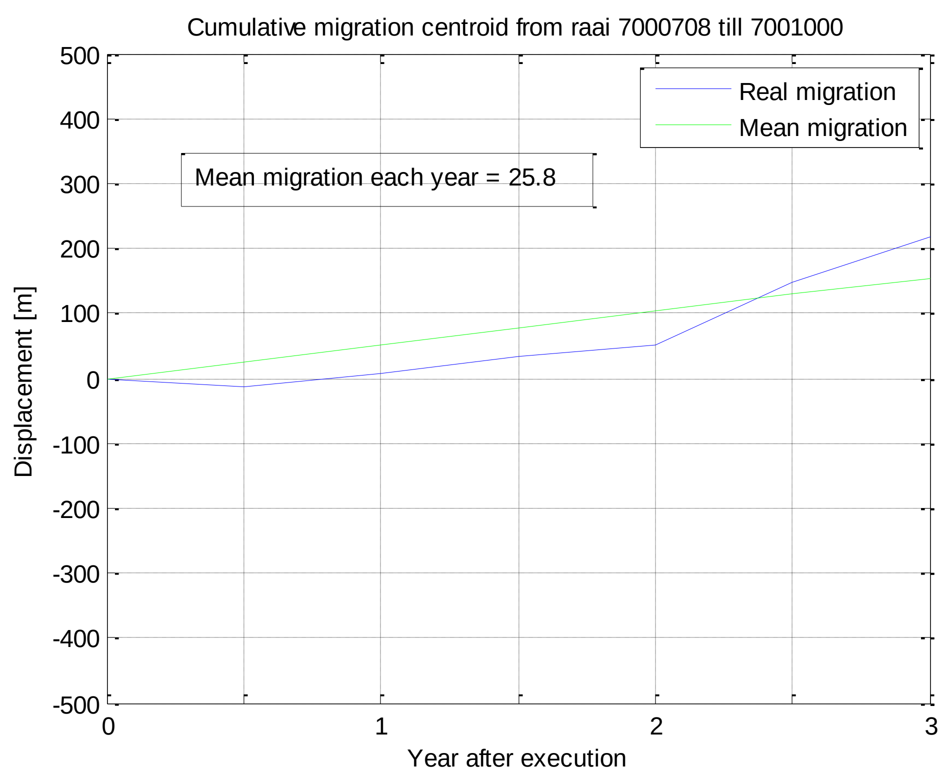
Noord-Holland – Callantsoog-Zwanenwater – 2006



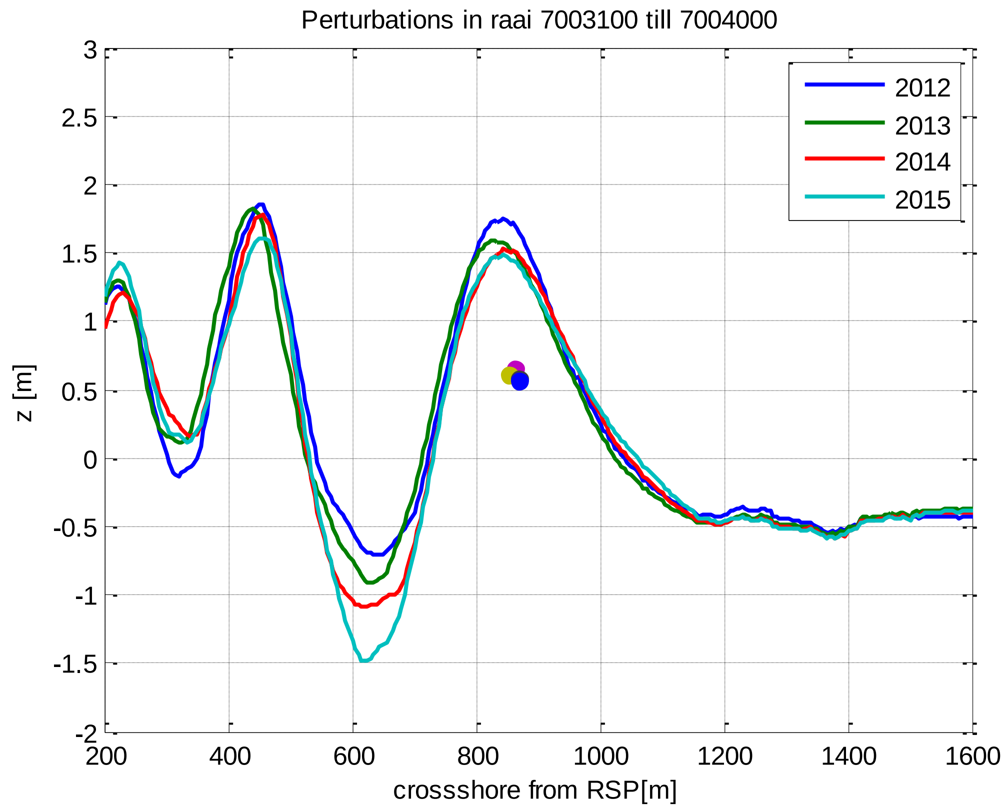


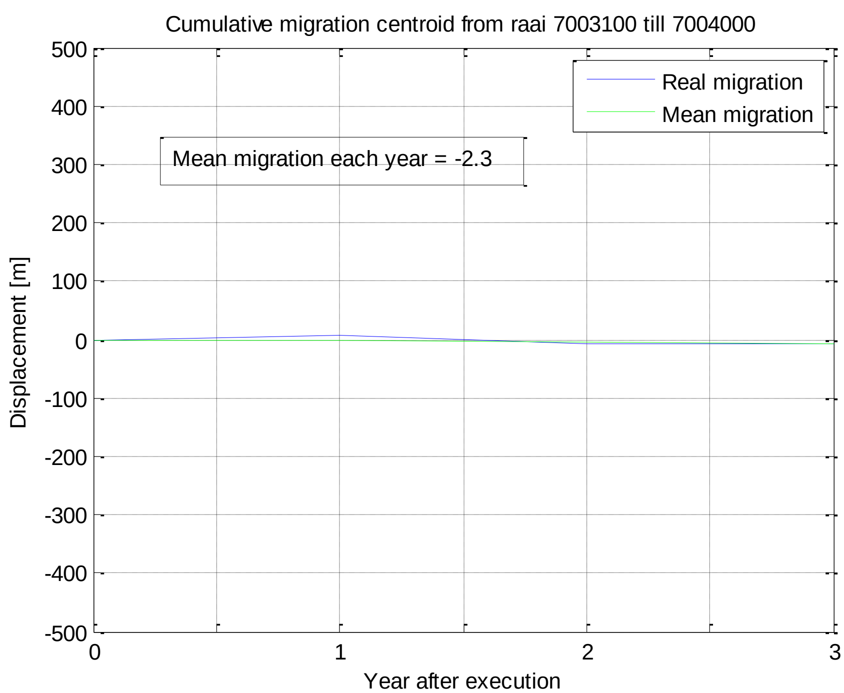
Noord-Holland – Den Helder-Julianadorp – 2009



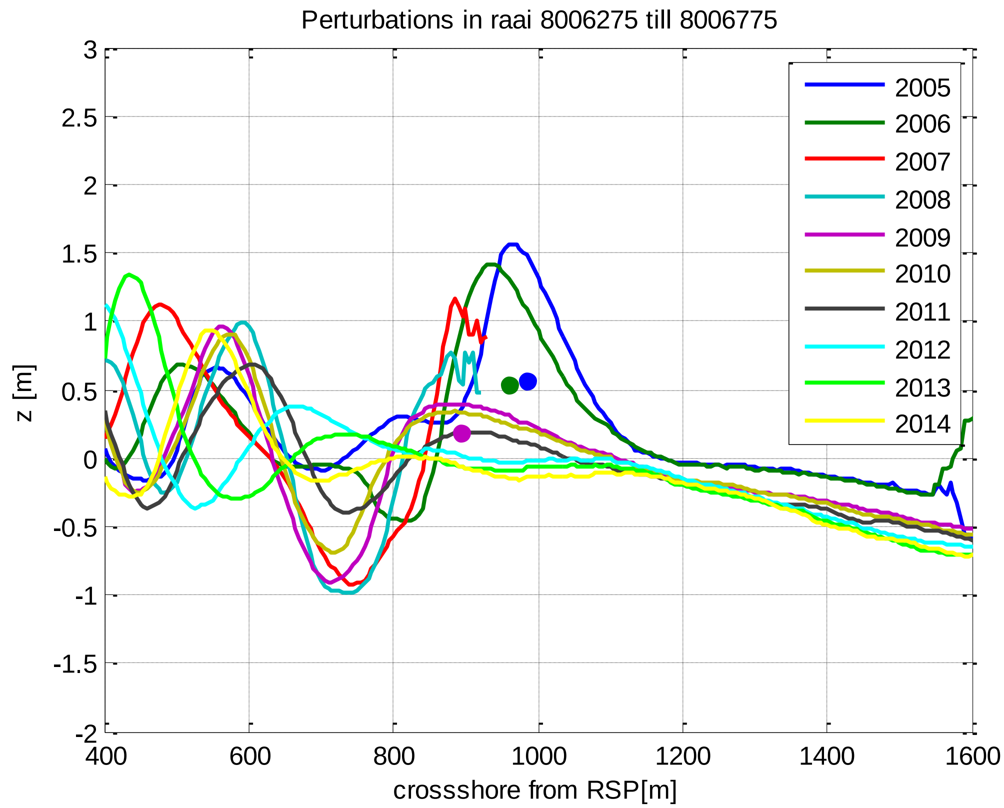


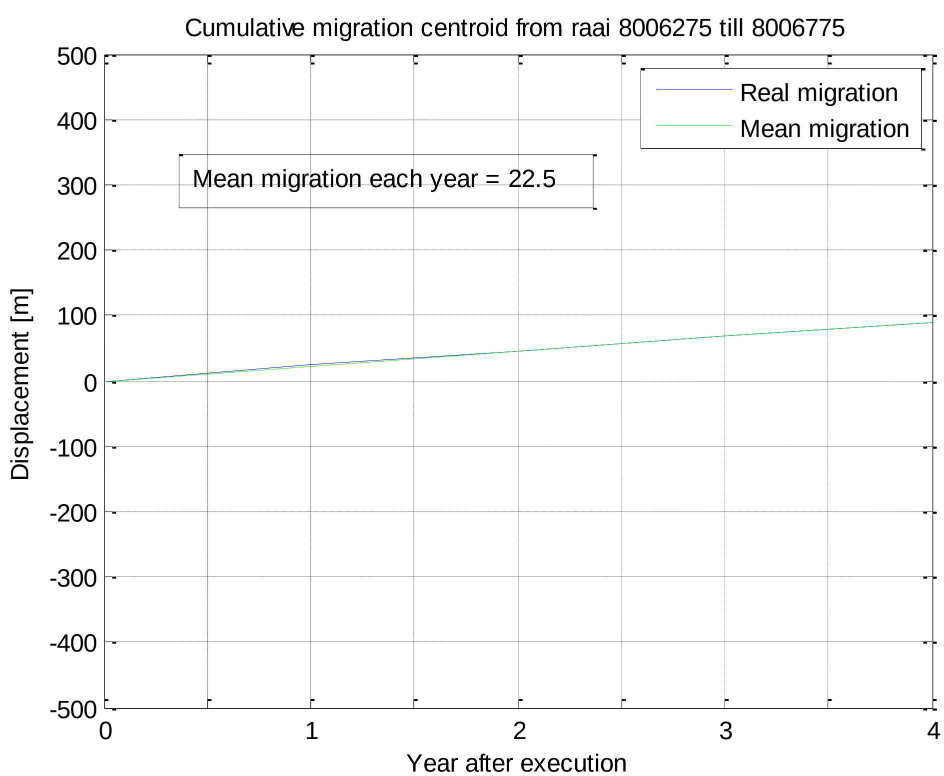
Noord-Holland – Egmond-Bergen – 2010



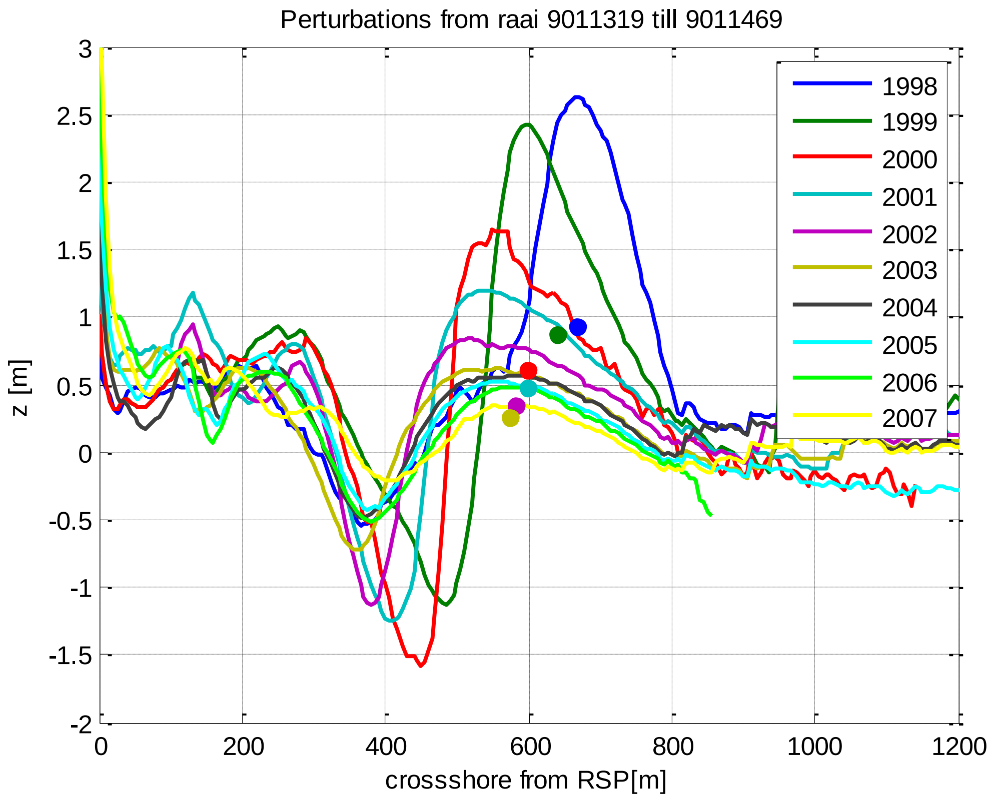


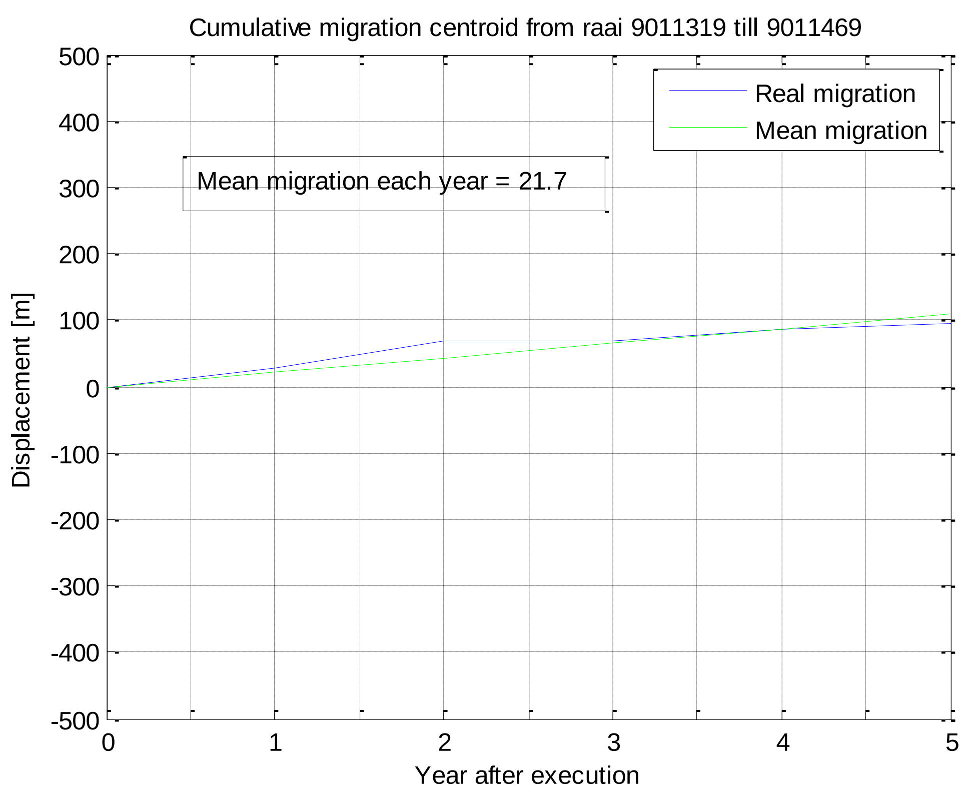
Rijnland – Zandvoort Zuid and Noord – 2004



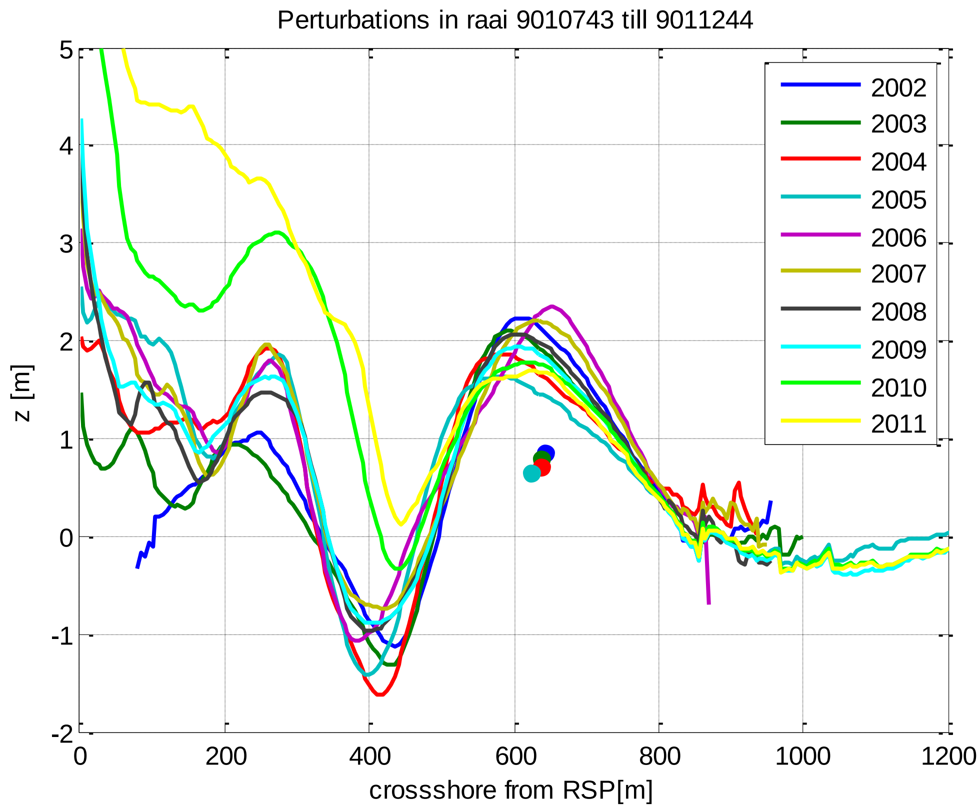


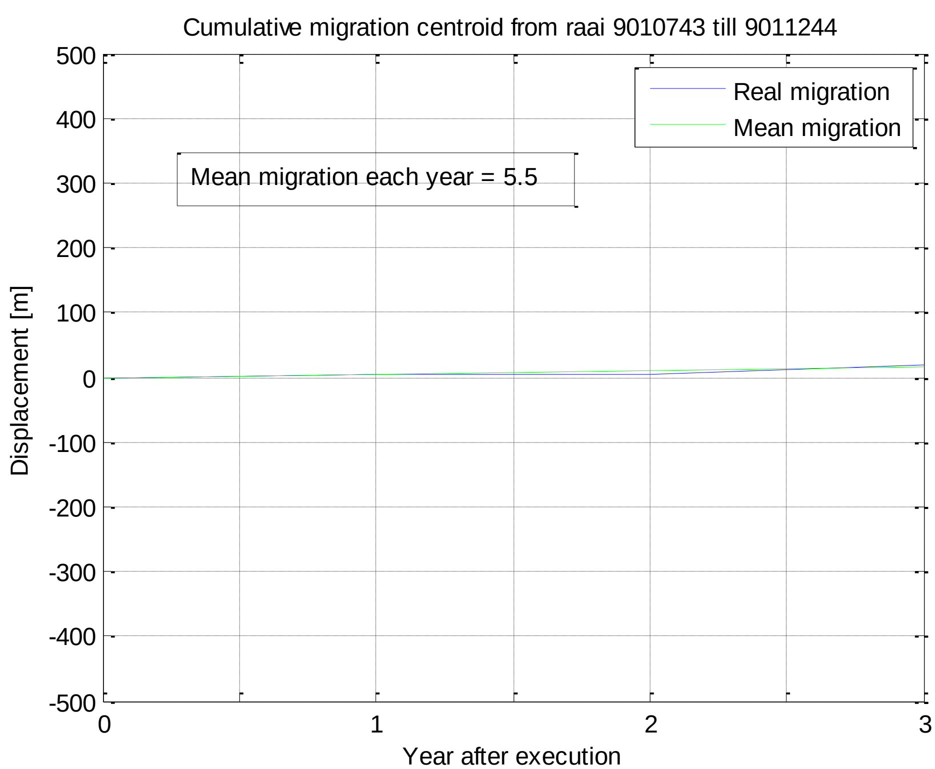
Delfland – Ter Heijde – 1997



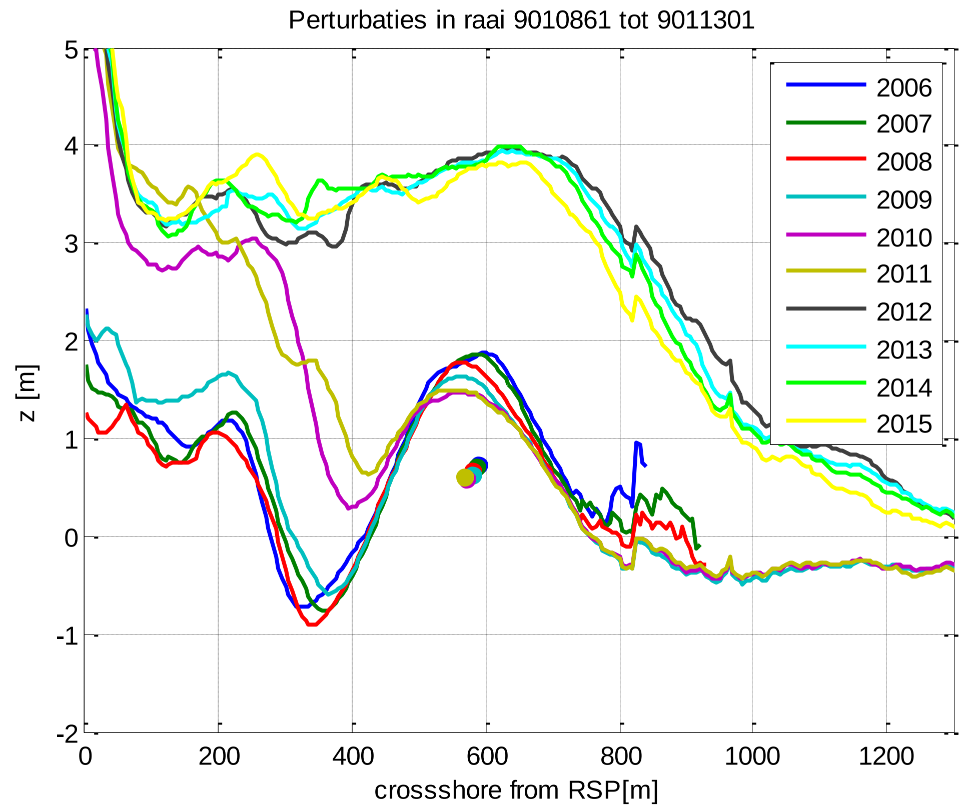


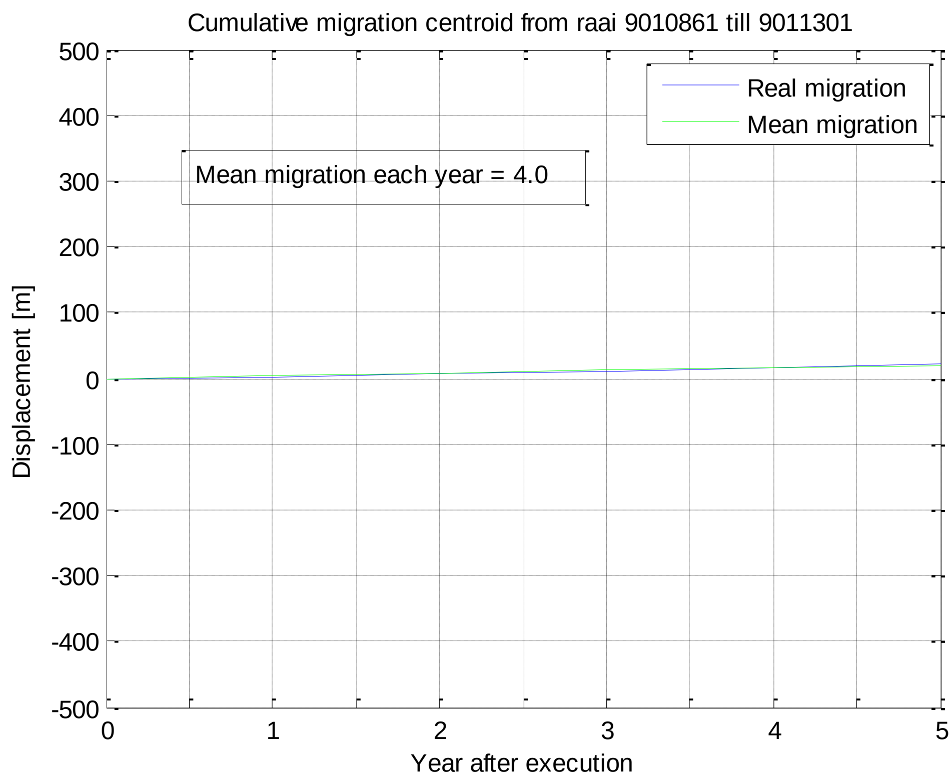
Delfland – Kijkduin-Ter Heijde – 2001



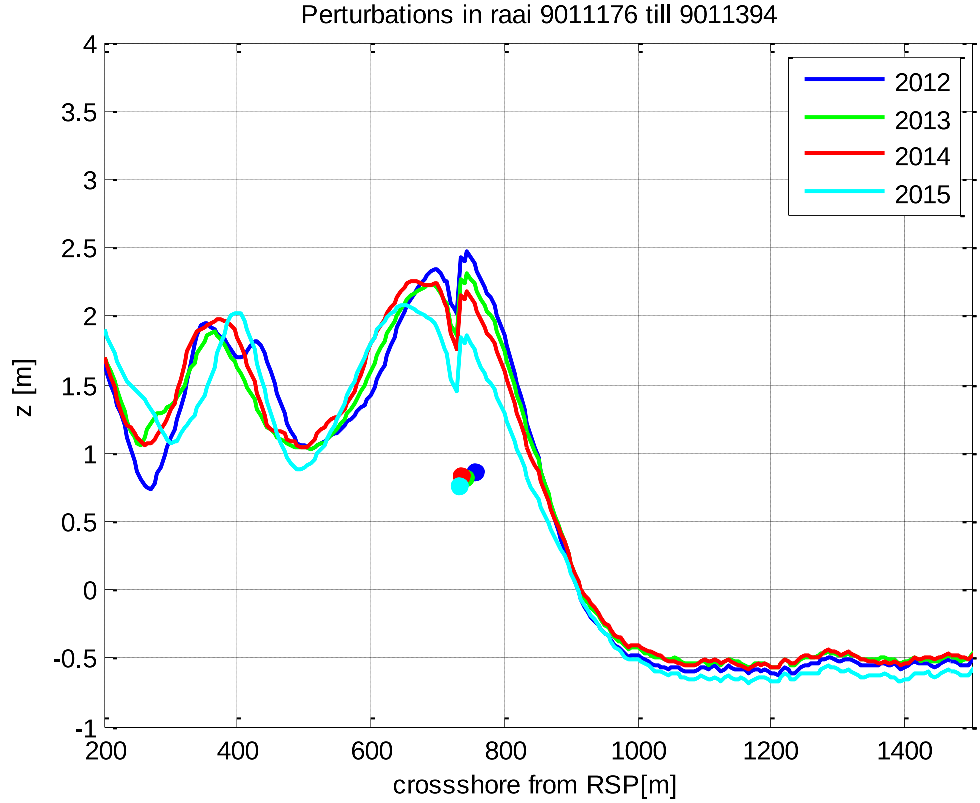


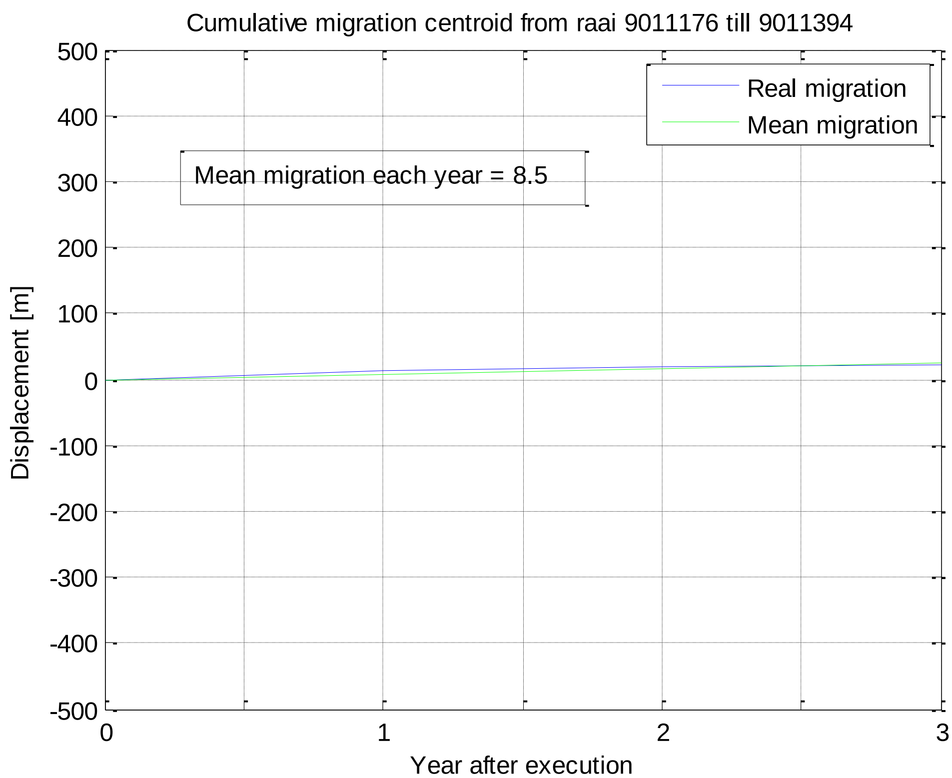
Delfland – Monster – 2005





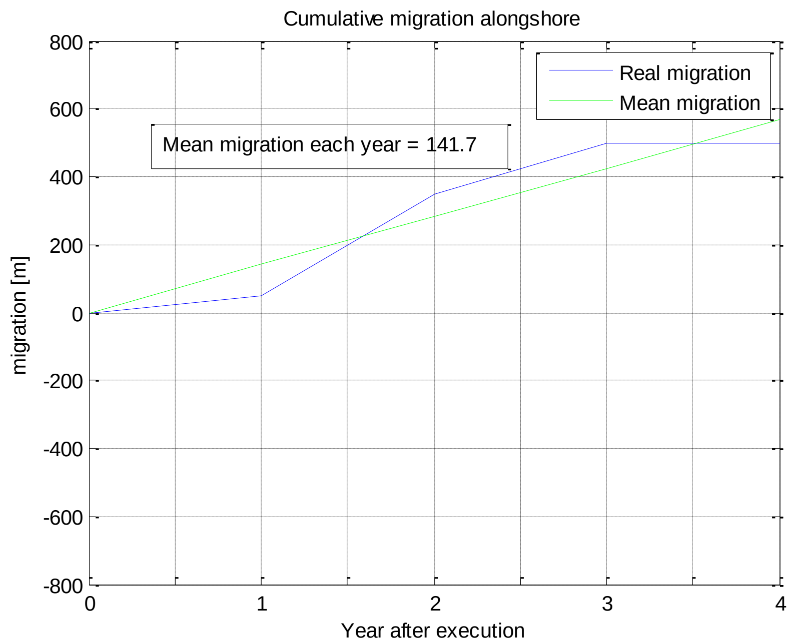
Delfland – Kijkduin-Ter Heijde – 2011



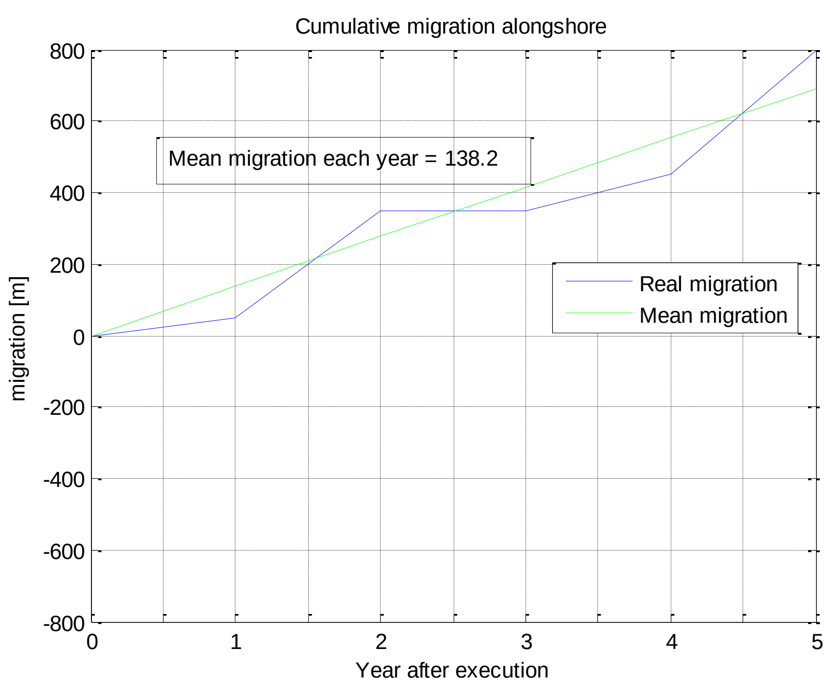


Appendix C: Detailed alongshore migration shoreface nourishments

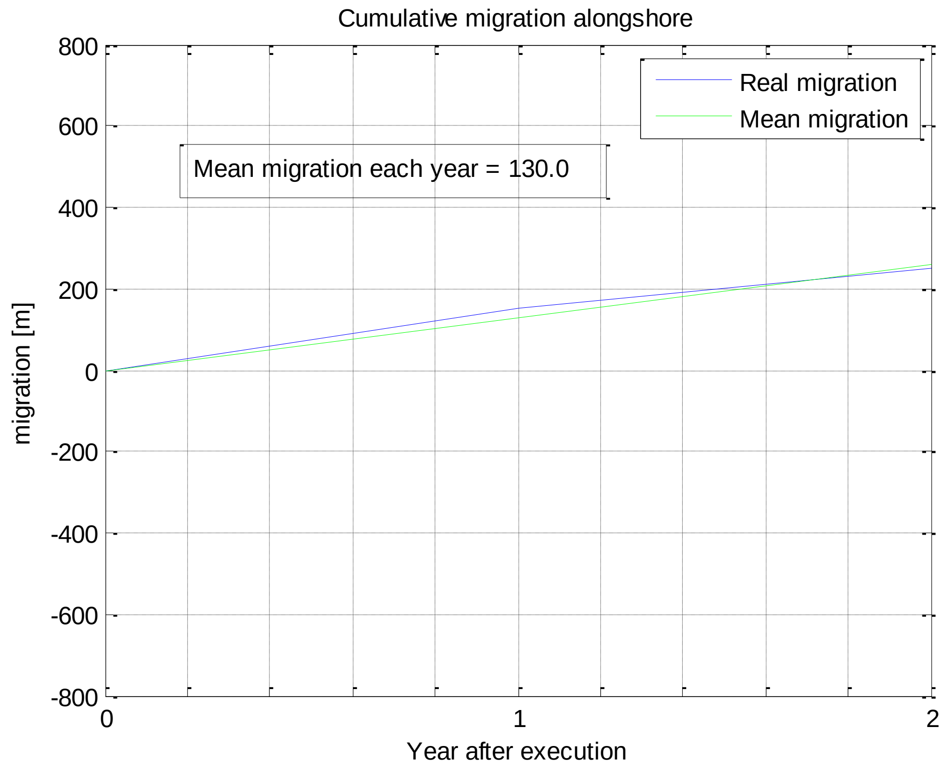
Texel – Eierland – 2004



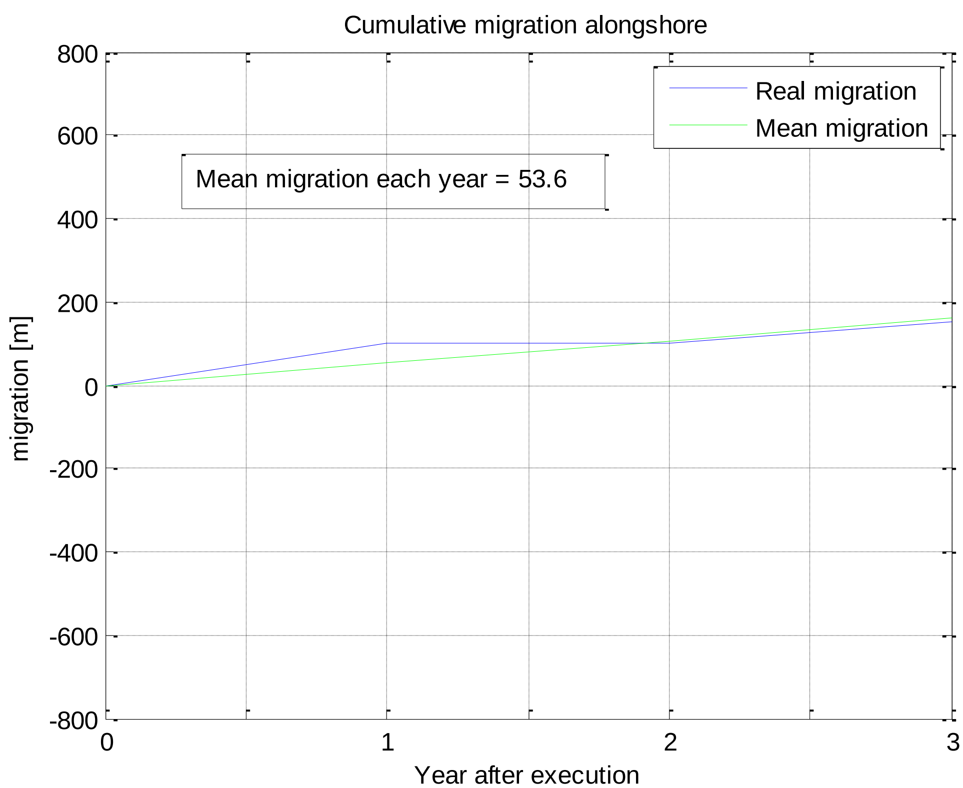
Texel – Eierlandse Dam – 2009



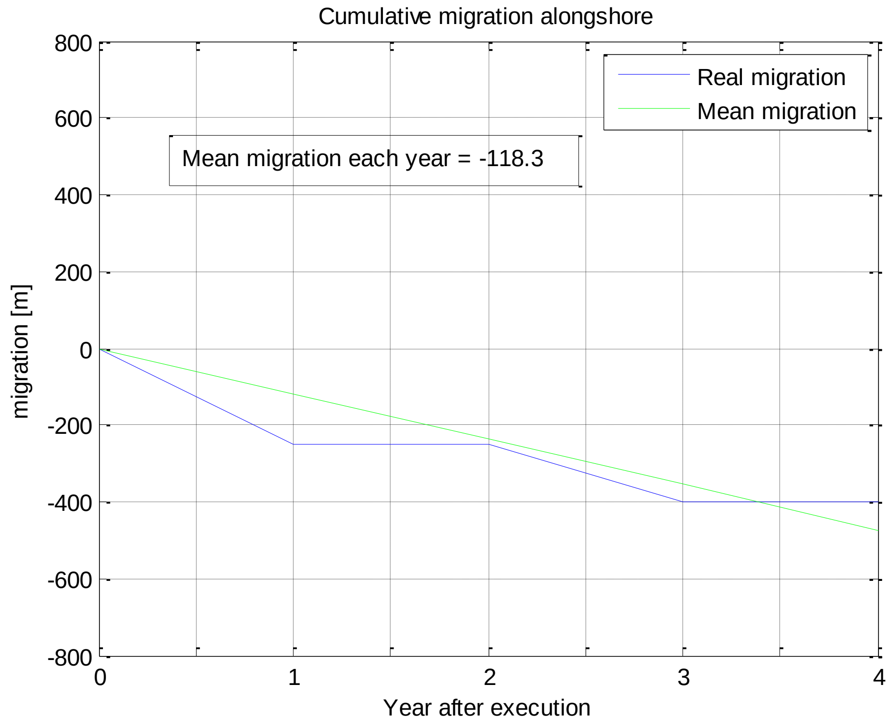
Noord-Holland – Callantsoog – 2001



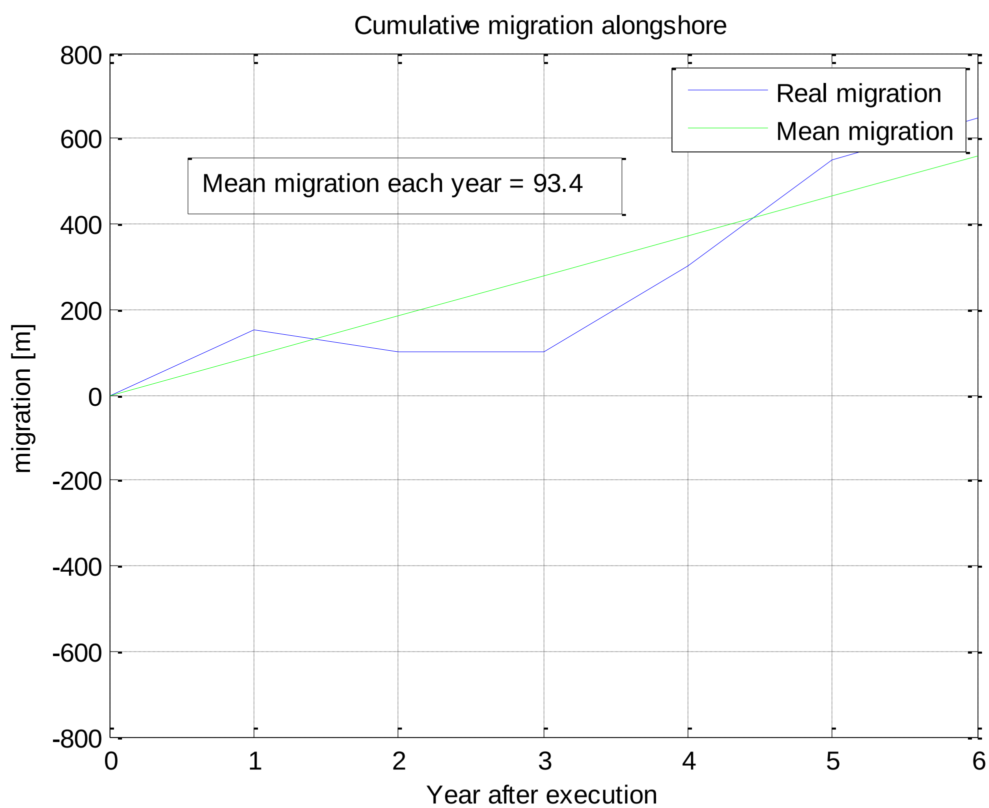
Noord-Holland – Callantsoog-Zwanenwater – 2003



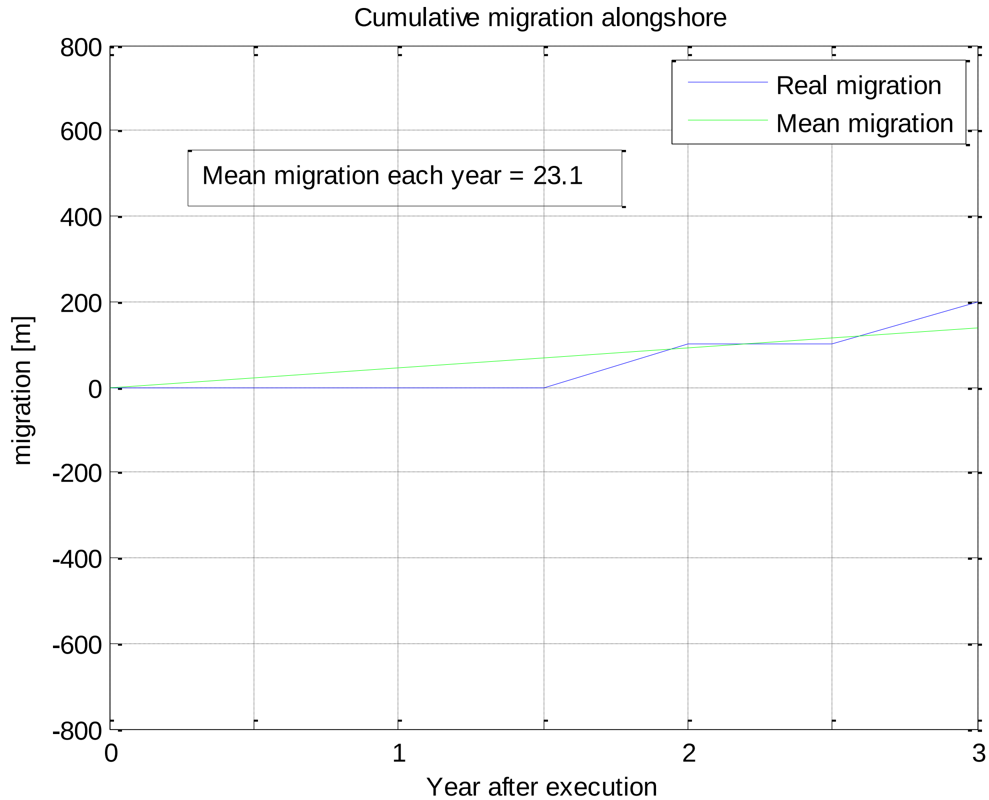
Noord-Holland – Bergen – 2005



Noord-Holland – Callantsoog-Zwanenwater – 2006

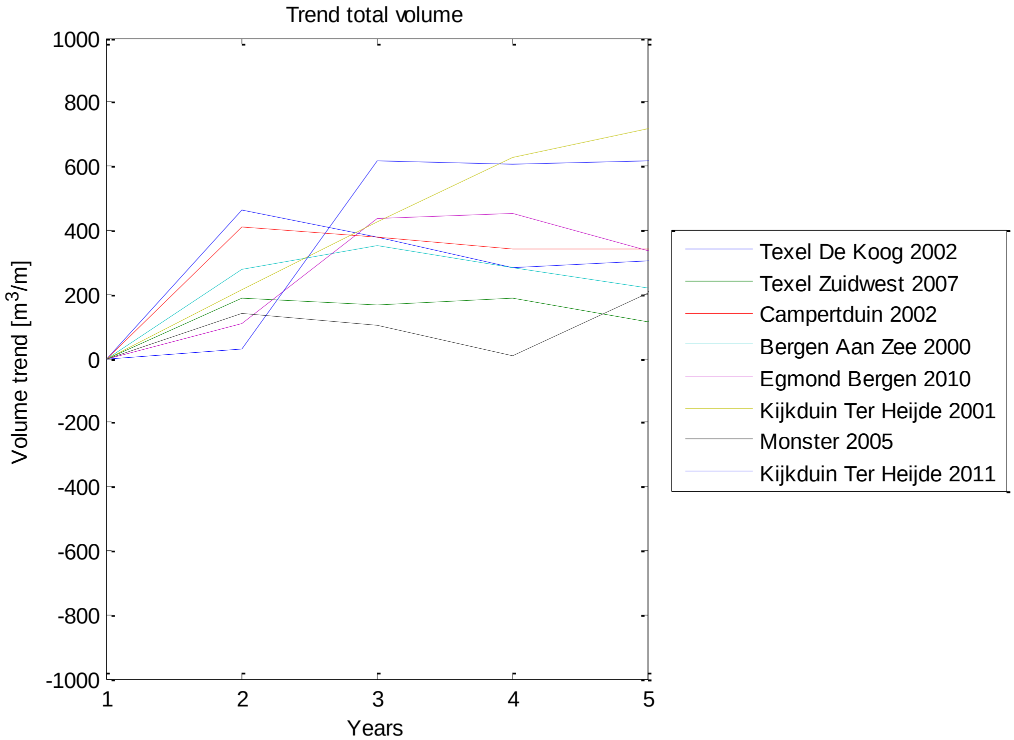


Noord-Holland – Den Helder-Julianadorp – 2009

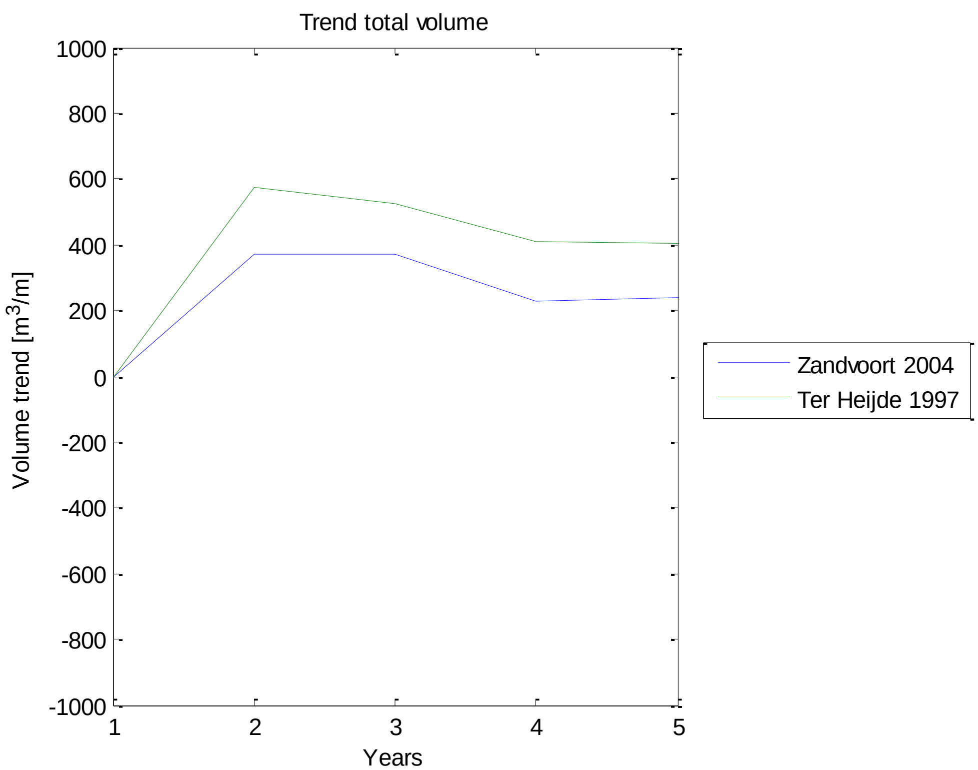


Appendix D: Volume trends shoreface nourishments

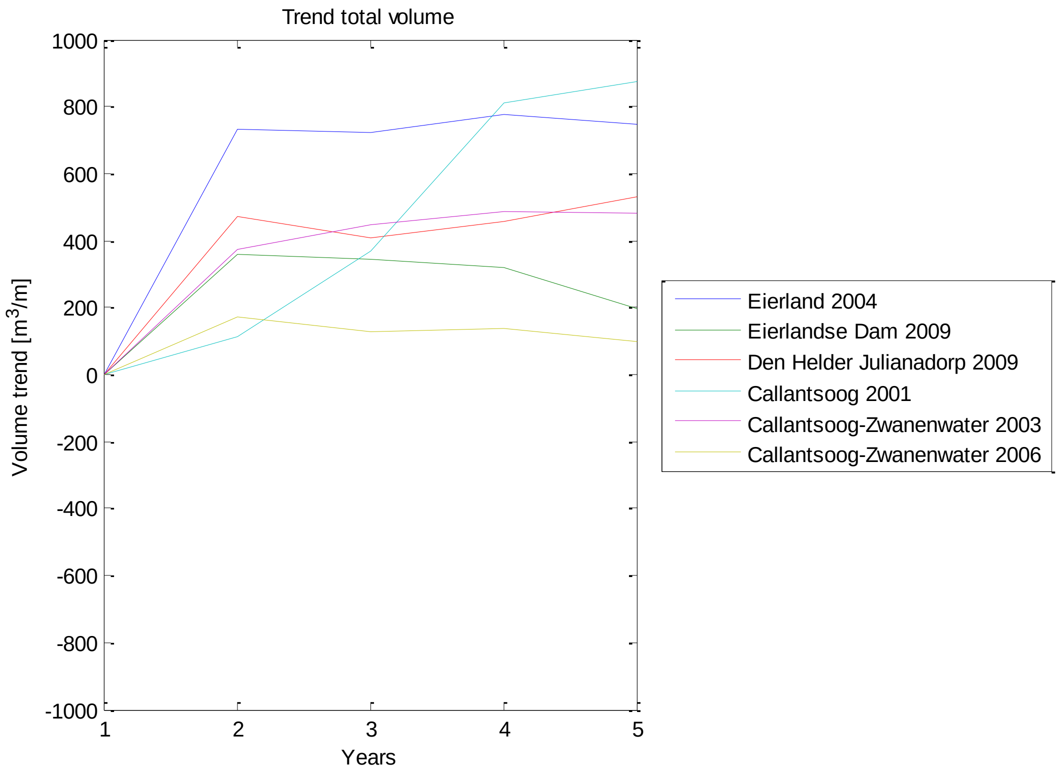
Total volume trends Blue cluster



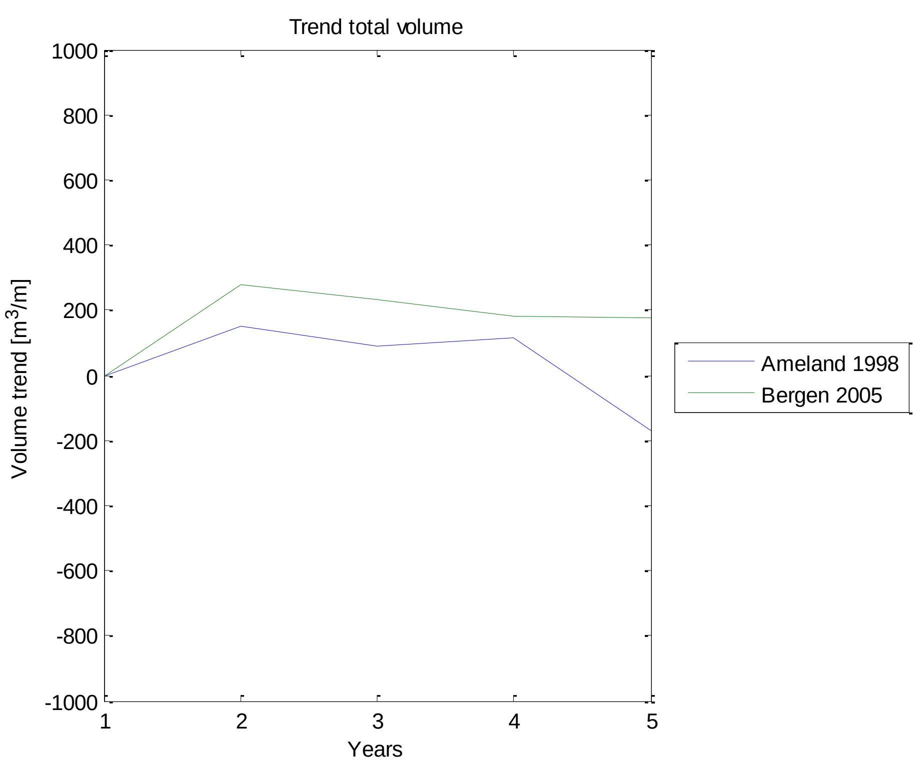
Total volume trends Red cluster



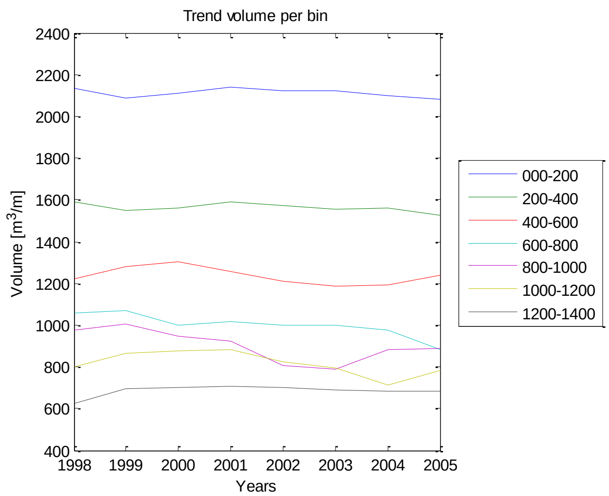
Total volume trends Green cluster

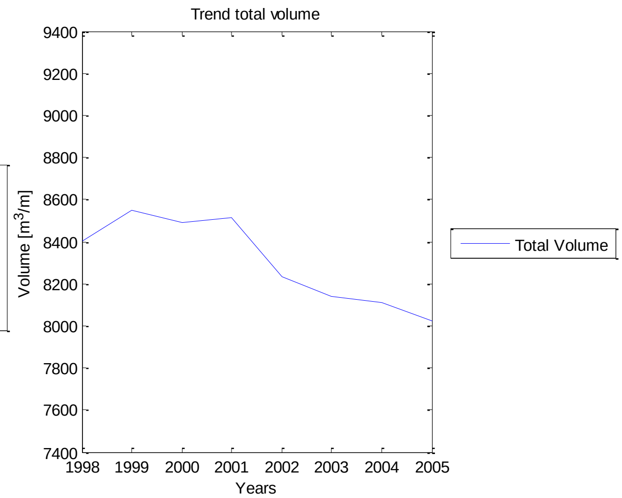


Total volume trends Orange cluster

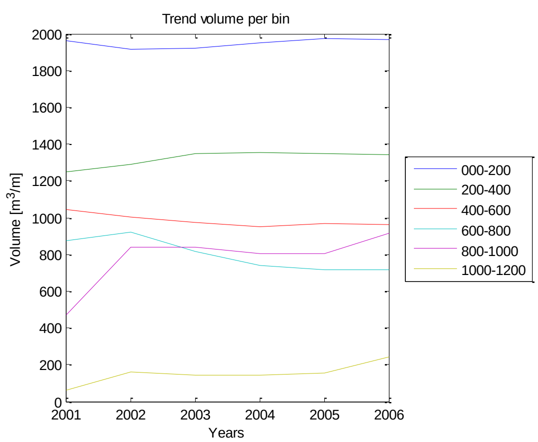


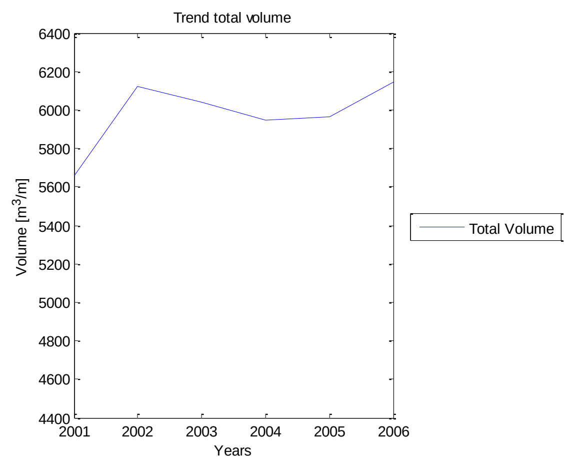
Ameland – Midden – 1998



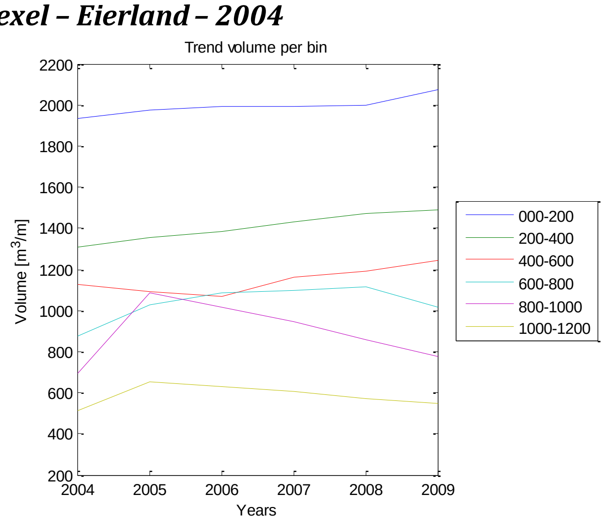


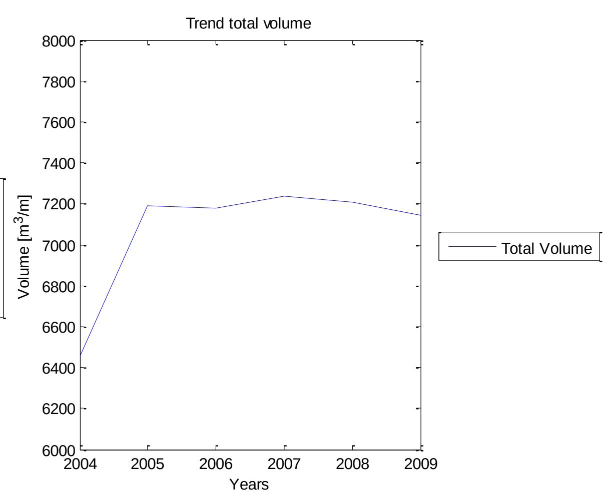
Texel – De Koog – 2002



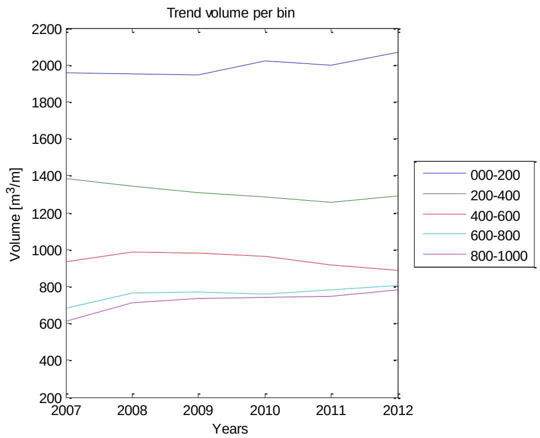


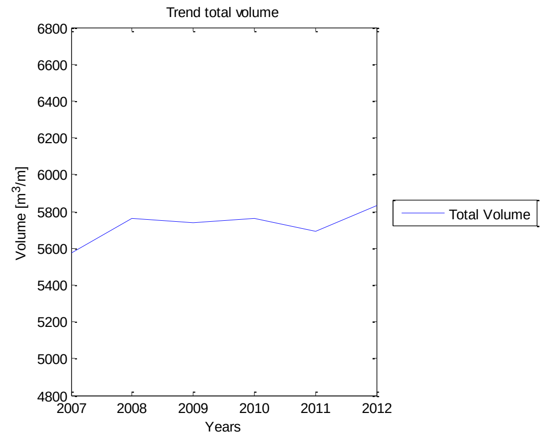
Texel – Eierland – 2004



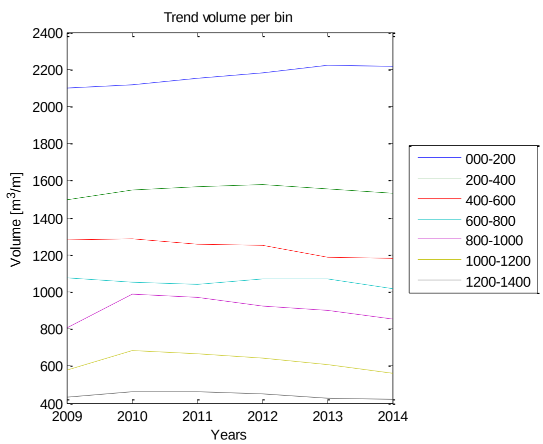


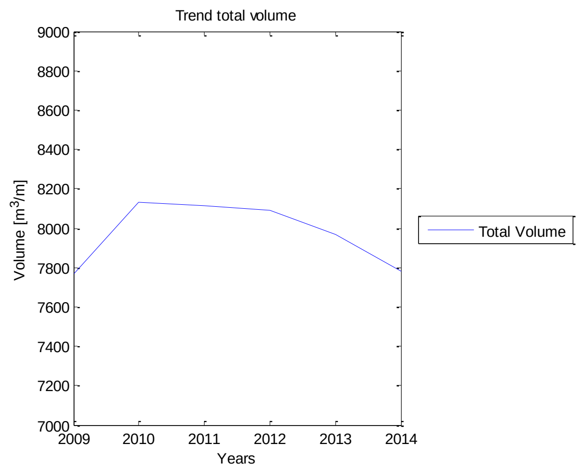
Texel – Zuidwest – 2007



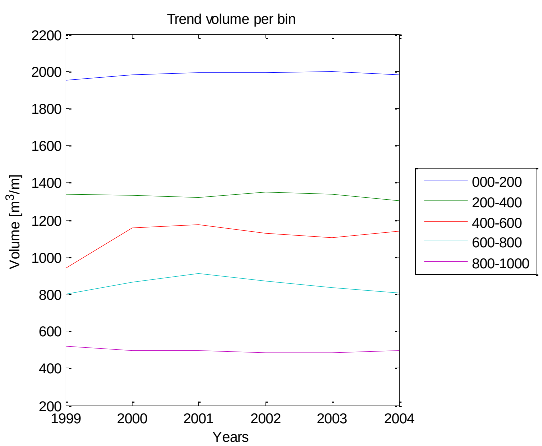


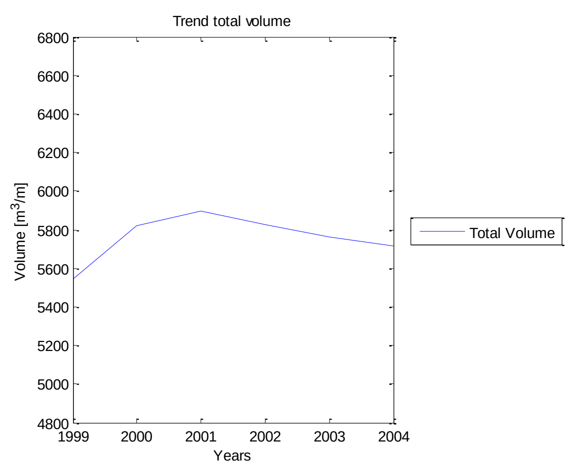
Texel – Eierlandse Dam – 2009



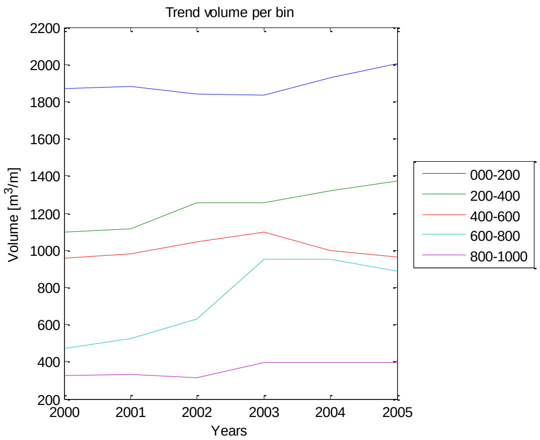


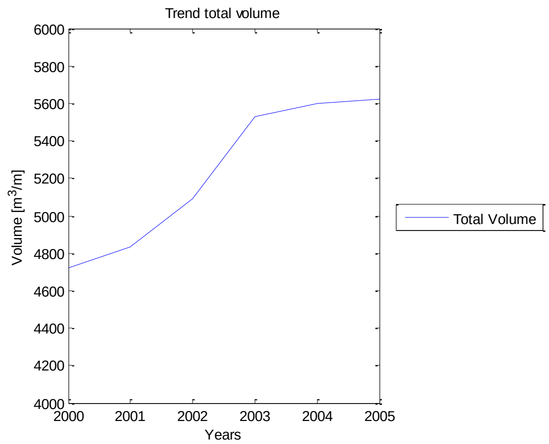
Noord-Holland – Bergen aan Zee – 2000



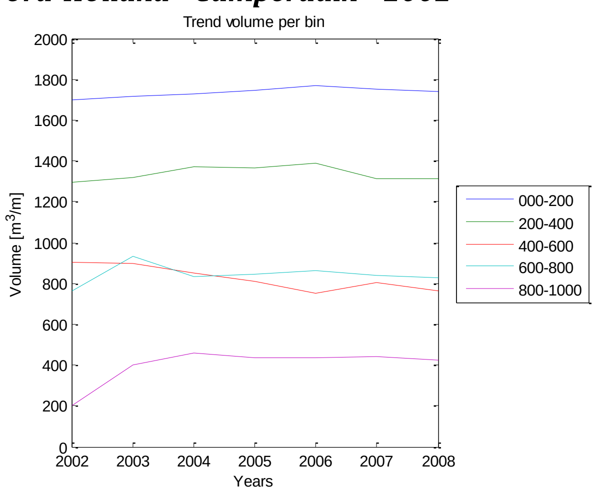


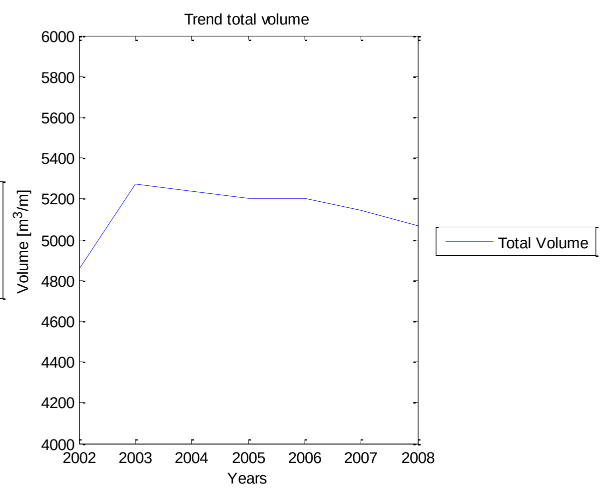
Noord-Holland – Callantsoog – 2001



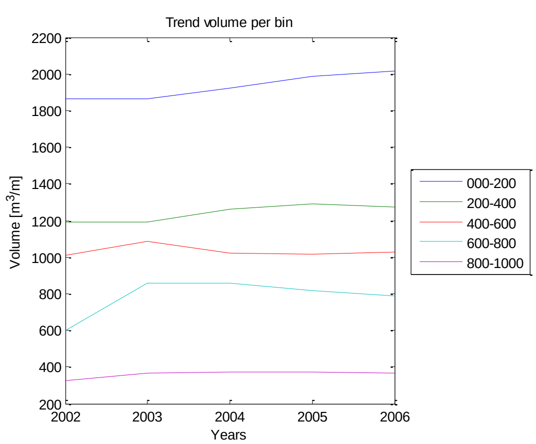


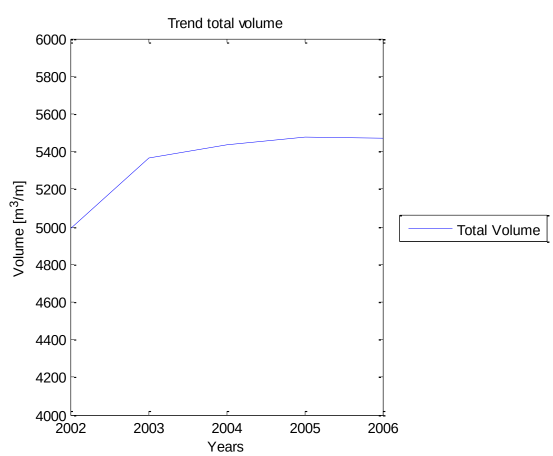
Noord-Holland – Camperduin – 2002



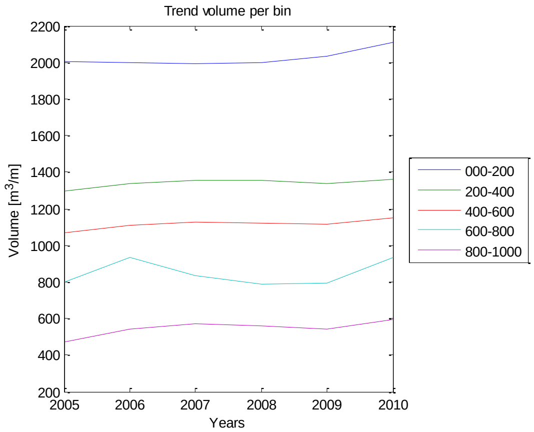


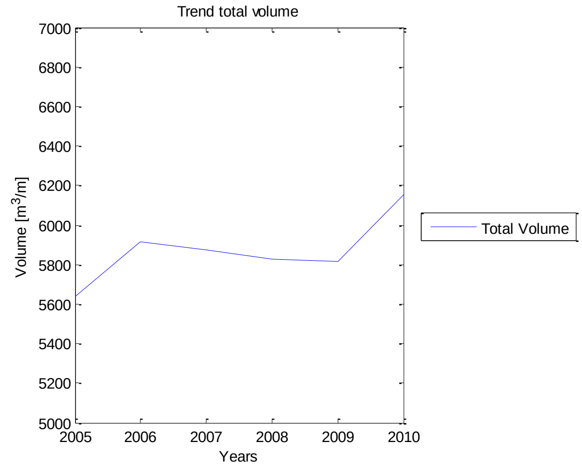
Noord-Holland – Callantsoog-Zwanenwater – 2003



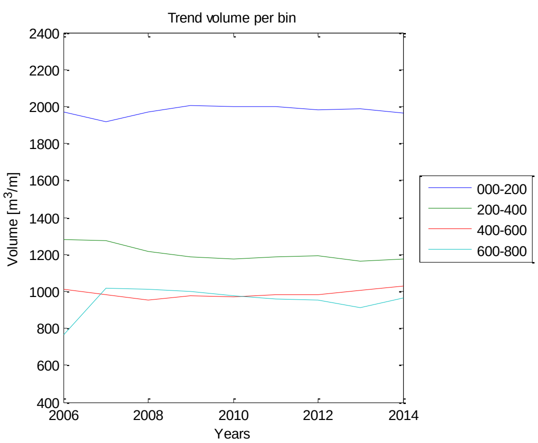


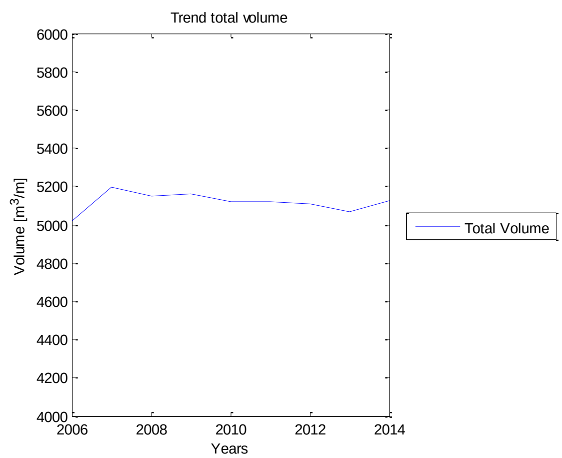
Noord-Holland – Bergen – 2005



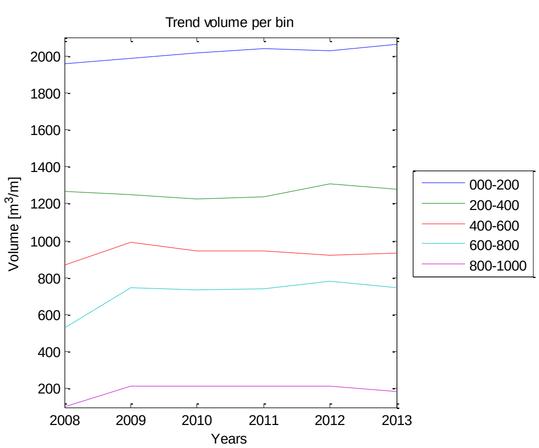


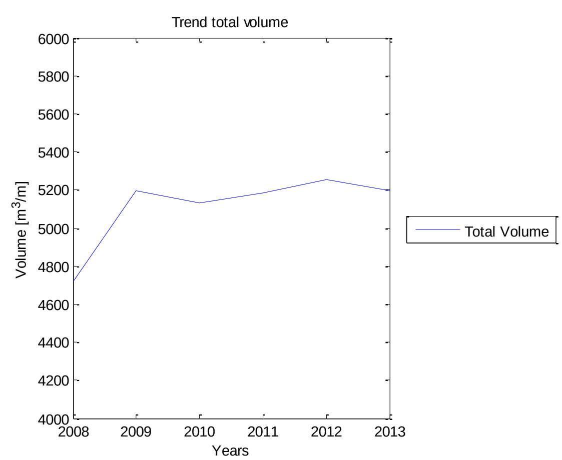
Noord-Holland – Callantsoog-Zwanenwater – 2006



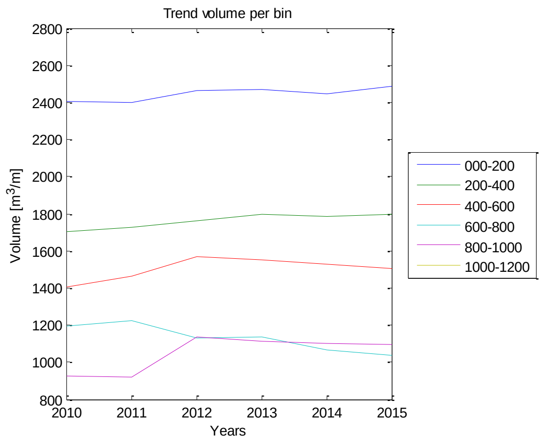


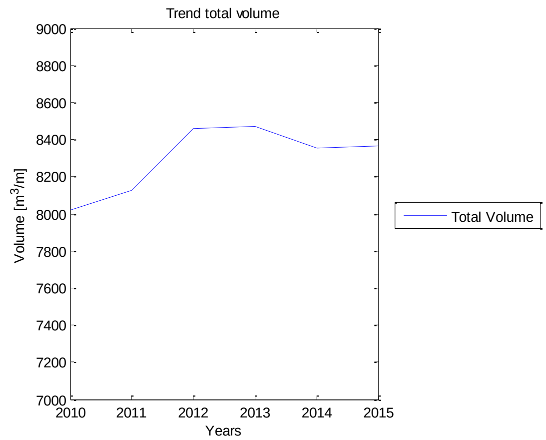
Noord-Holland – Den Helder-Julianadorp – 2009



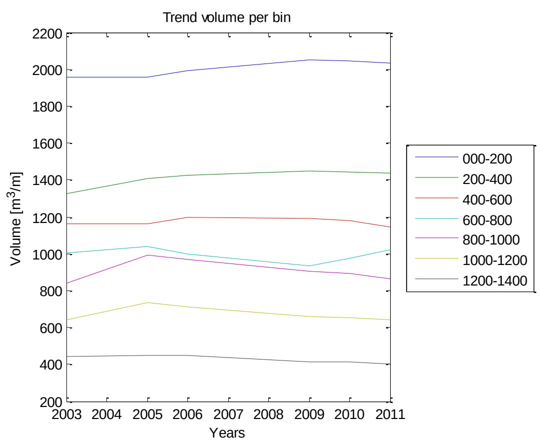


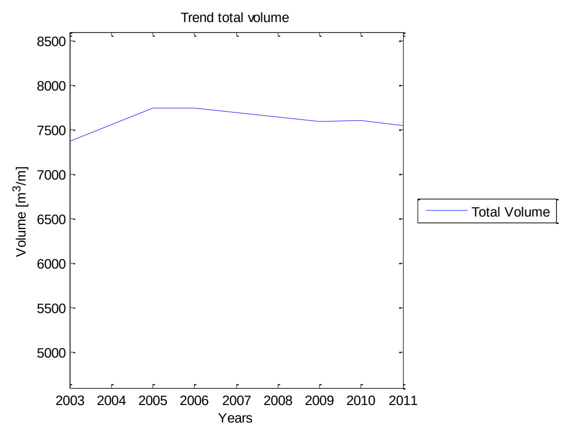
Noord-Holland – Egmond-Bergen – 2010



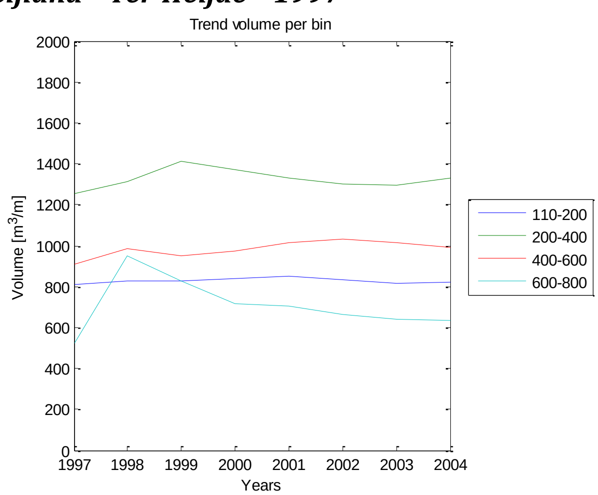


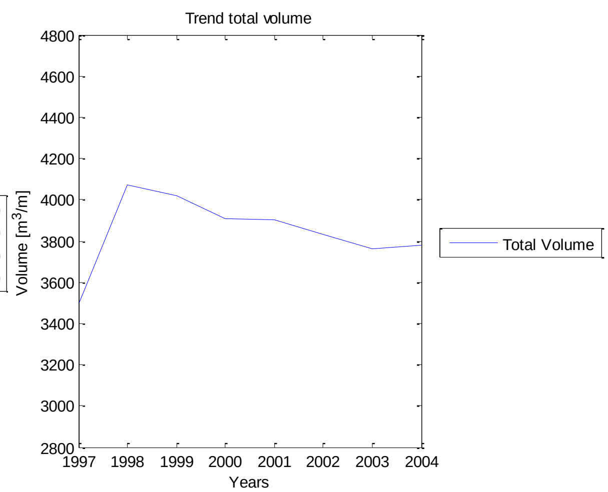
Rijnland – Zandvoort Zuid and Noord – 2004



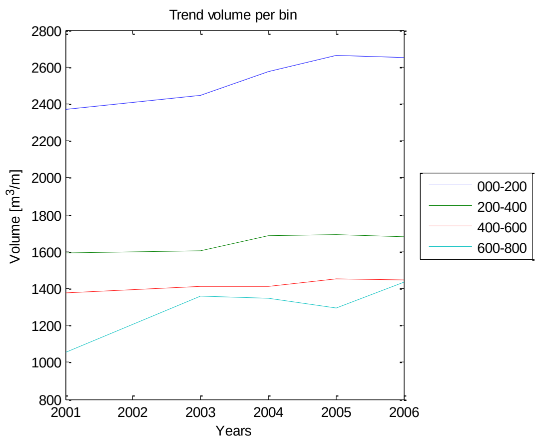


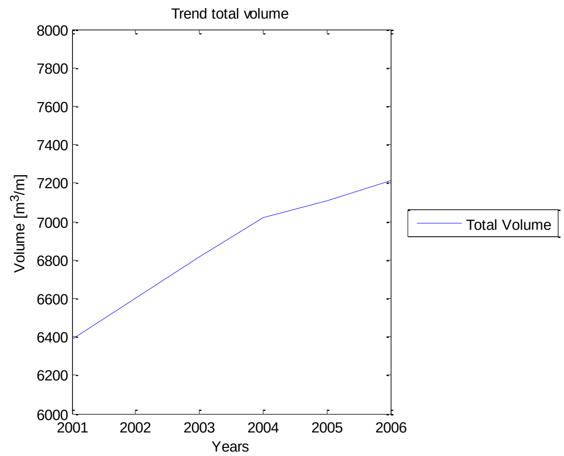
Delfland – Ter Heijde – 1997



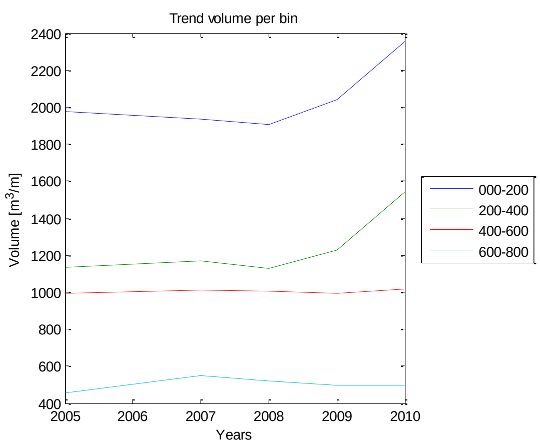


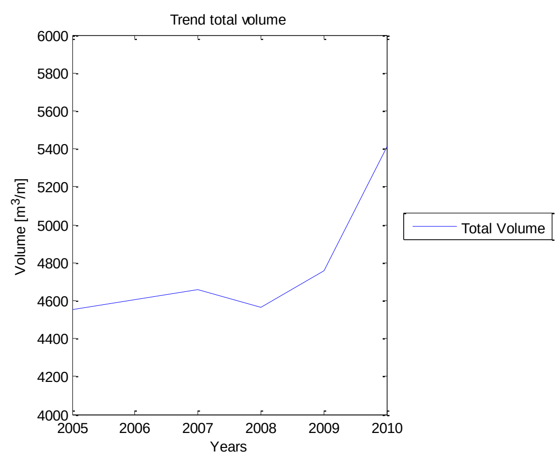
Delfland – Kijkduin-Ter Heijde – 2001



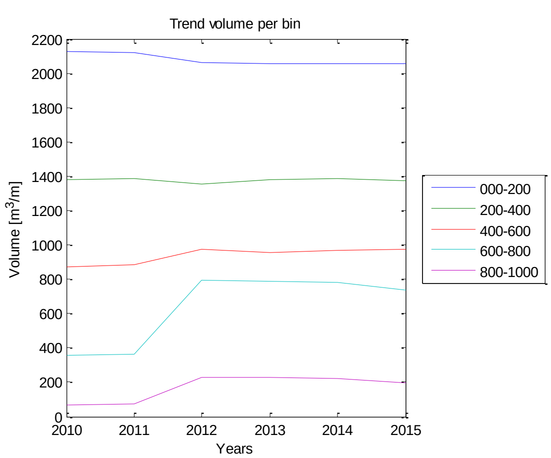


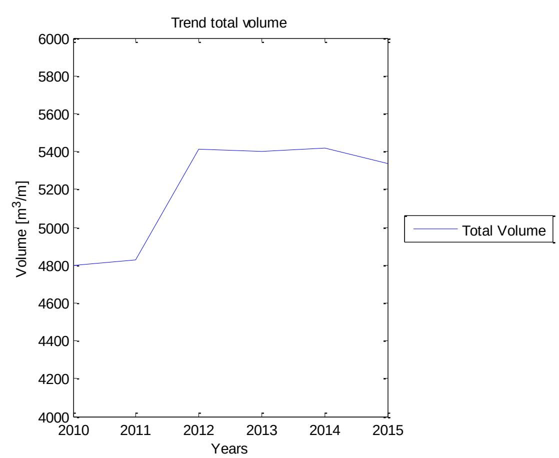
Delfland – Monster – 2005





Delfland – Kijkduin-Ter Heijde – 2011





Appendix E: Migration and wave resultant shoreface nourishments

In the figures in this appendix, the resultant wave characteristic is given for the selected shoreface nourishments. In these figures, the yellow beam represents the shoreface nourishment with the orientation of the coast. The red arrow represents the direction and length of the migration (also given in Figure 48 in an overview), relative to the other figures. The blue arrow represents the resultant wave characteristic, relative to the other figures. The wave roses found this resultant wave characteristic. Refraction is adjusted for the different waves-directions and –heights. Subsequently the heights are transformed into energy each year and the blue arrow represents this. The blue arrows are scaled for all the shoreface nourishments and the length of the arrow represents the energy relative to the other shoreface nourishments.

Refraction

Bending of waves towards the coast is called refraction. Waves approach the coast under an angle and when the depth is decreasing, the waves are bending towards the coast and the width is increasing. Because of the increasing width, the wave spreads out over a larger area and loses his height (Schwartz, 2005). The new wave height can be determined with Snell's law:

$$\frac{sin\theta}{C} = \frac{sin\theta_0}{C_0}$$

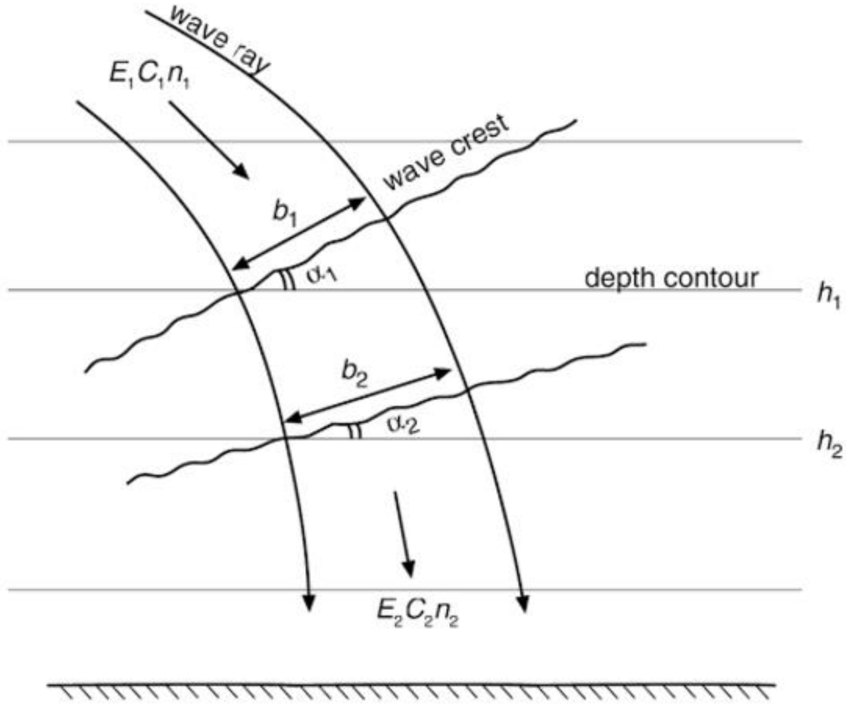
In which the C represents the velocity of the waves [m/s], θ is the angle of wave incidence [°] and the subscript '0' denotes deep water. The refraction coefficient, K_r, can be expressed in terms of the wave angles and is used to determine the new wave height (Dean, et al., 2002):

$$K_r = \sqrt{\frac{cos\theta_0}{cos\theta}}$$

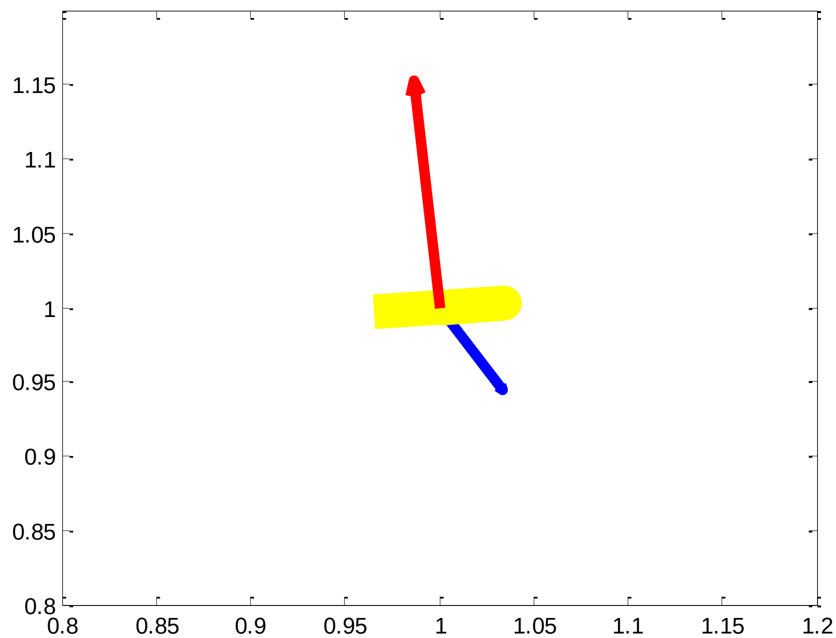
Because the height is decreasing, the energy of the waves is decreasing since the wave height determines the wave energy (Holthuijsen, 2007):

$$E = \frac{1}{8}\rho_w g H^2$$

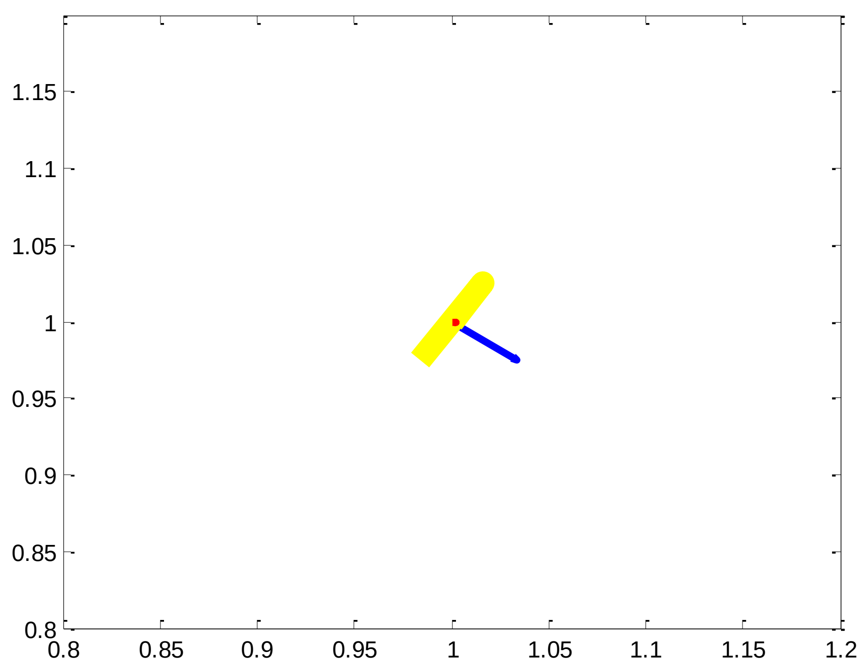
In the formula E is the mean wave energy per unit horizontal area [J/m^2], ρ_w is the density of water [kg/m^3], g is the acceleration by gravity [m/s^2] and H is the wave height [m].


wave ray
$E_1C_1n_1$
wave crest
b_1
α_1
depth contour
h_1
b_2
α_2
h_2
$E_2C_2n_2$

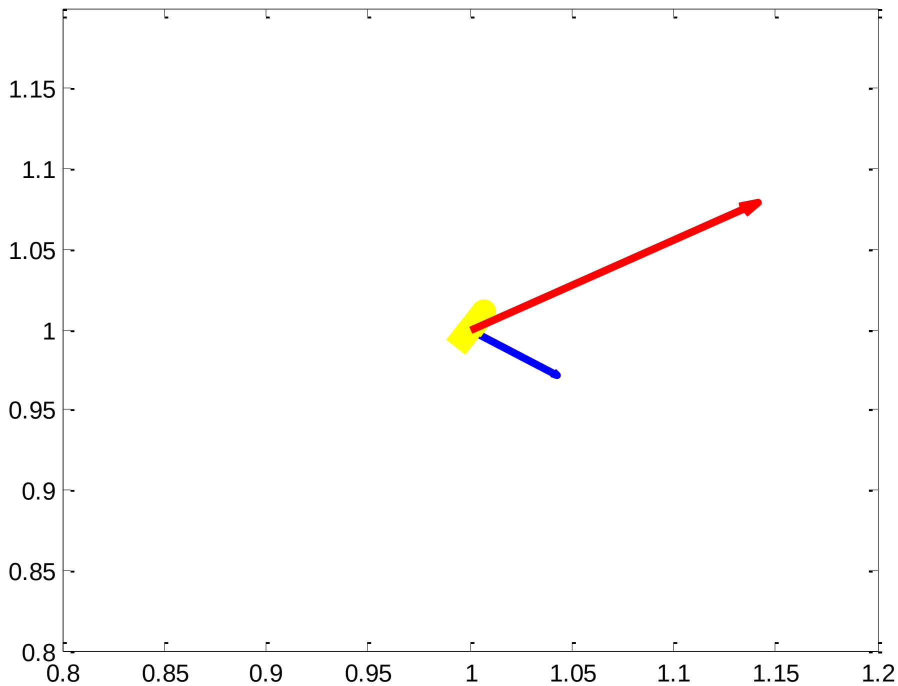
Ameland – Midden – 1998



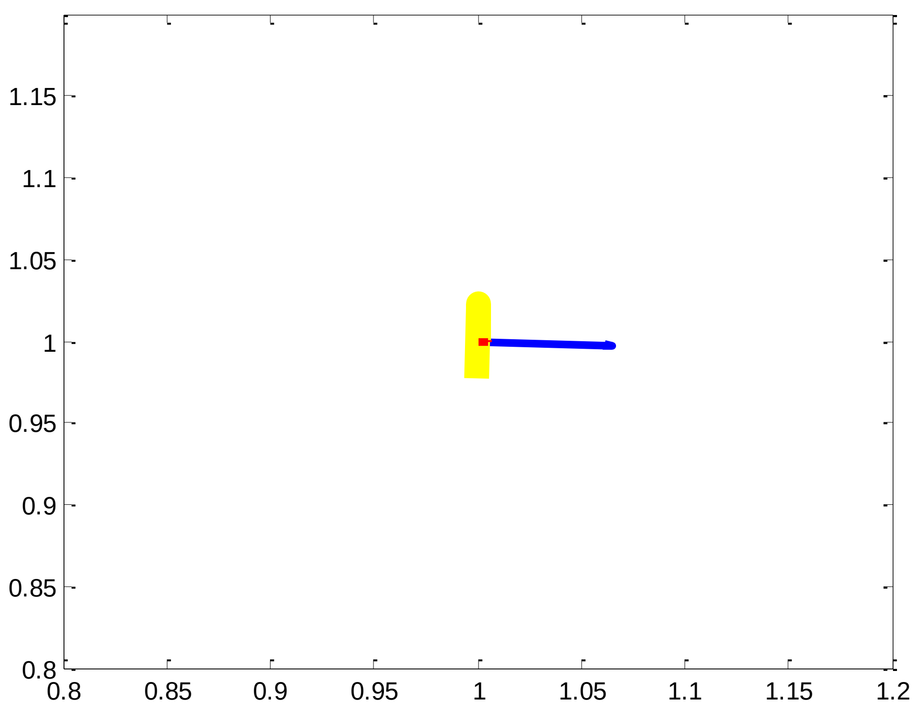
Texel – De Koog – 2002



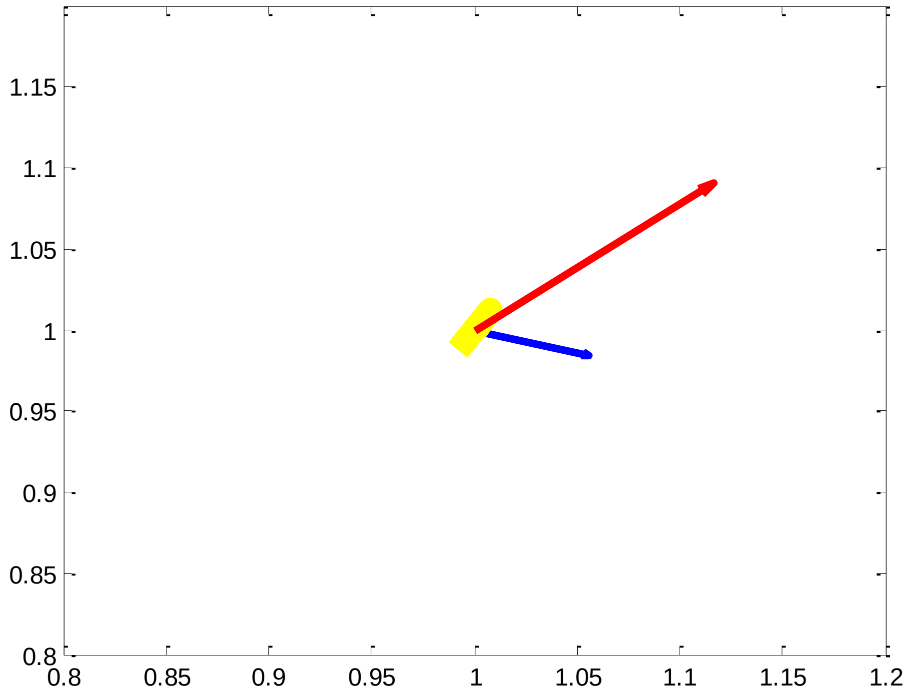
Texel – Eierland – 2004



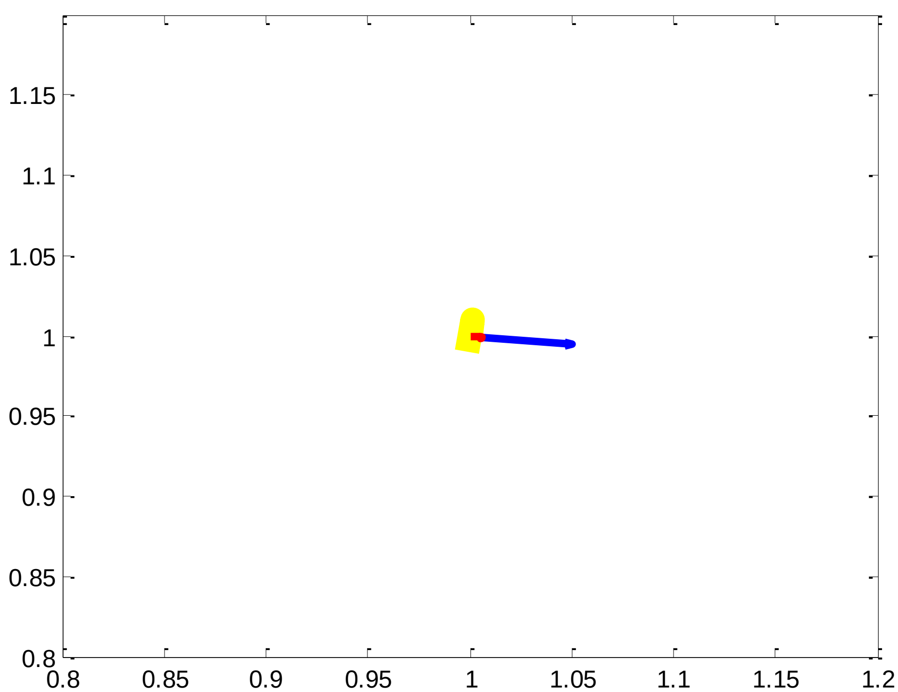
Texel – Zuidwest – 2007



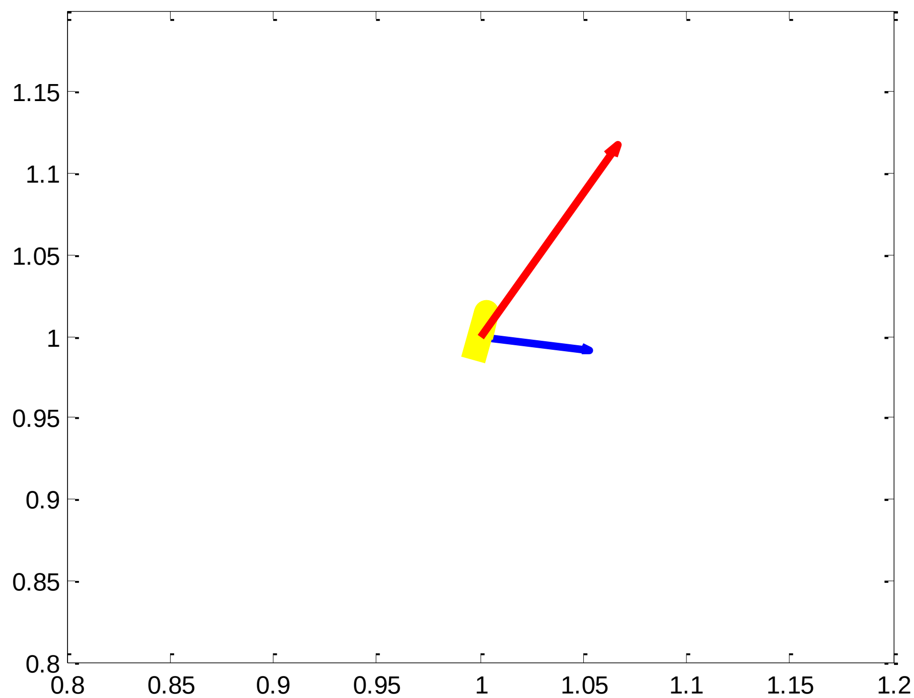
Texel – Eierlandse Dam – 2009



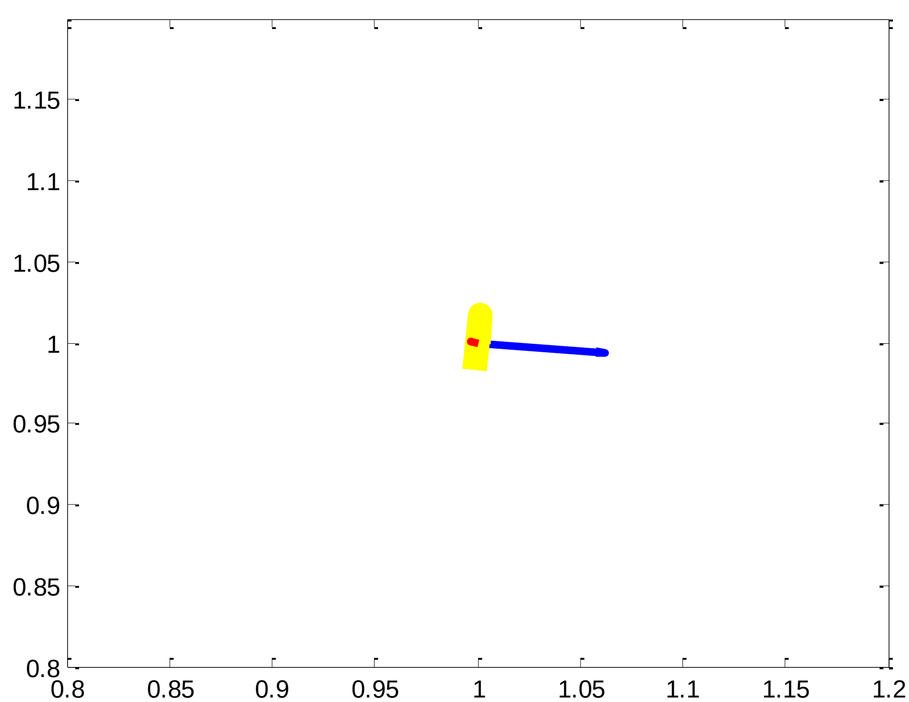
Noord-Holland – Bergen aan Zee – 2000



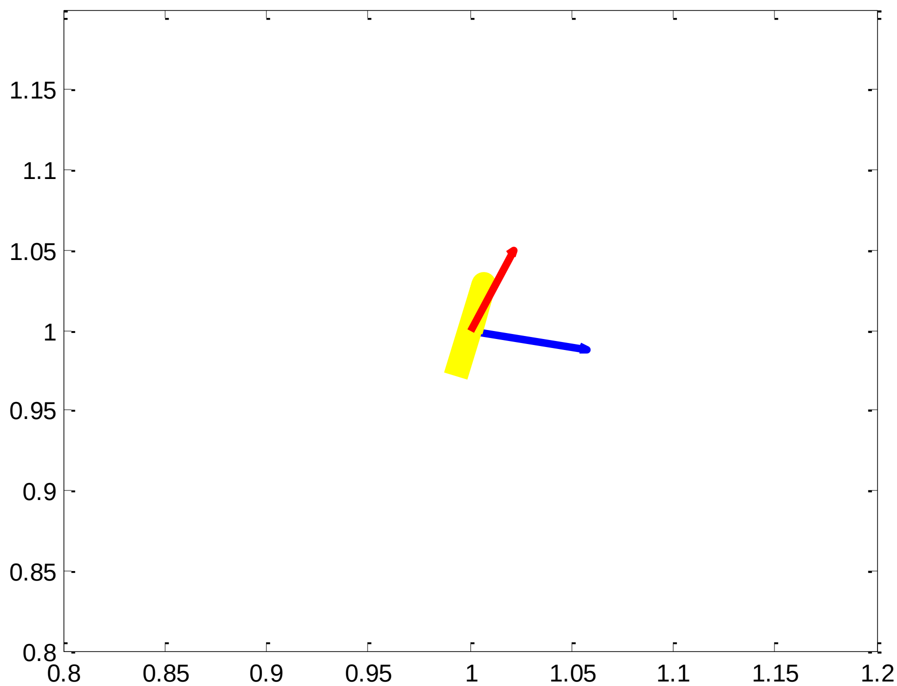
Noord-Holland – Callantsoog – 2001



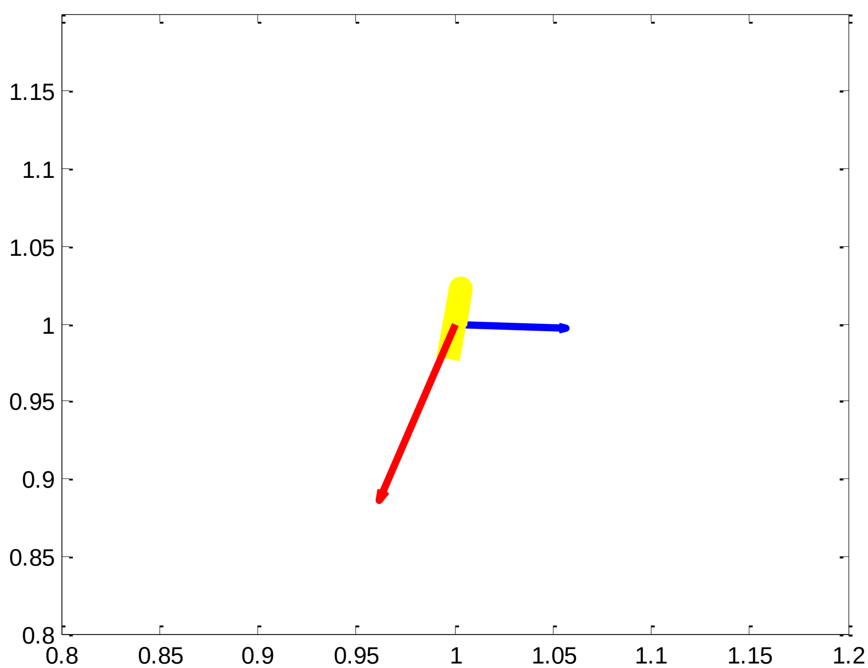
Noord-Holland – Camperduin – 2002



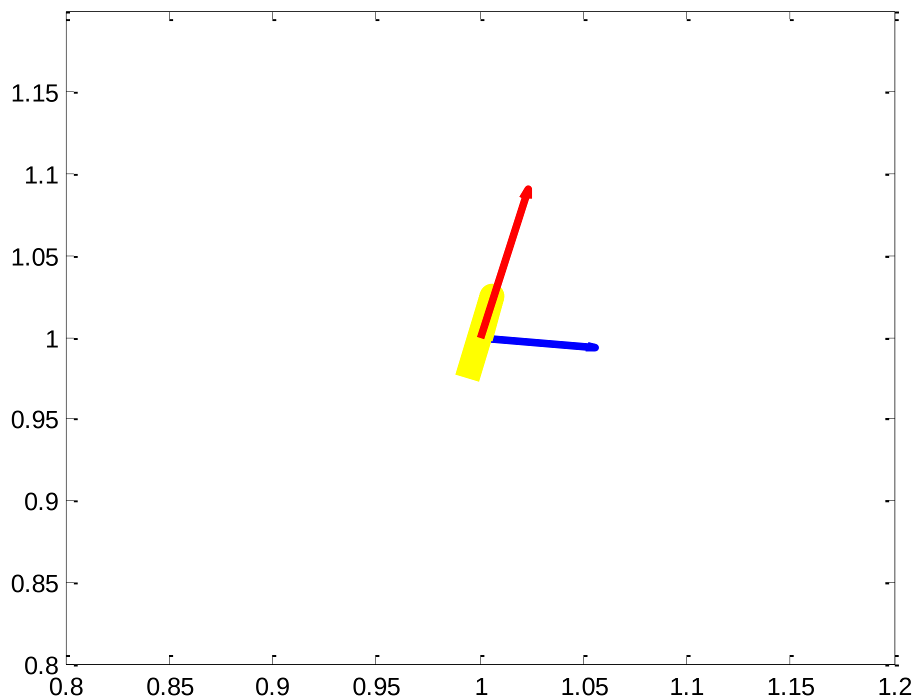
Noord-Holland – Callantsoog-Zwanenwater – 2003



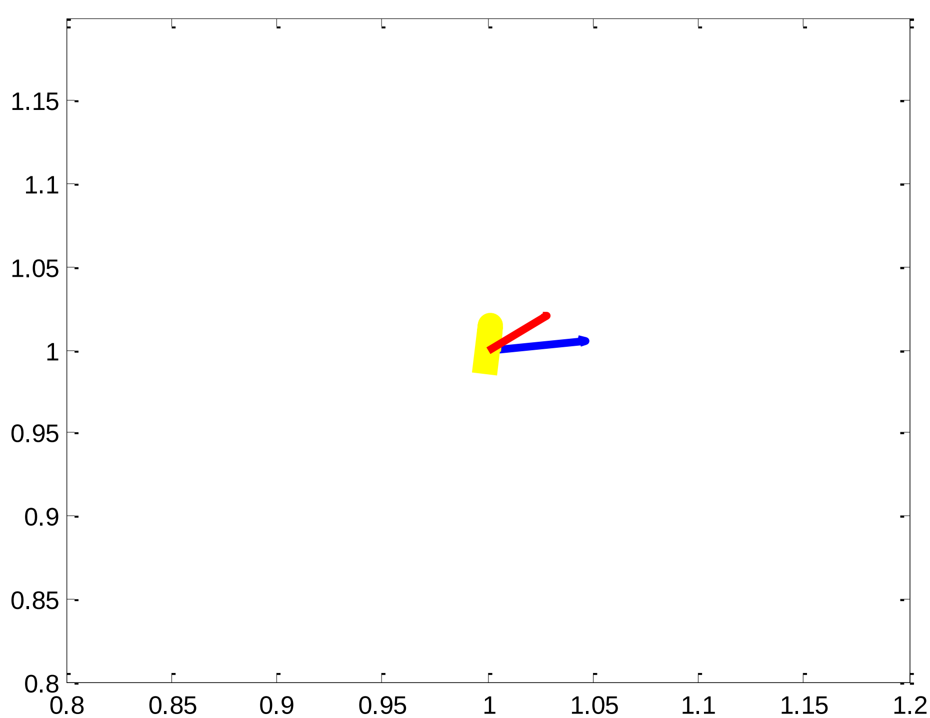
Noord-Holland – Bergen – 2005



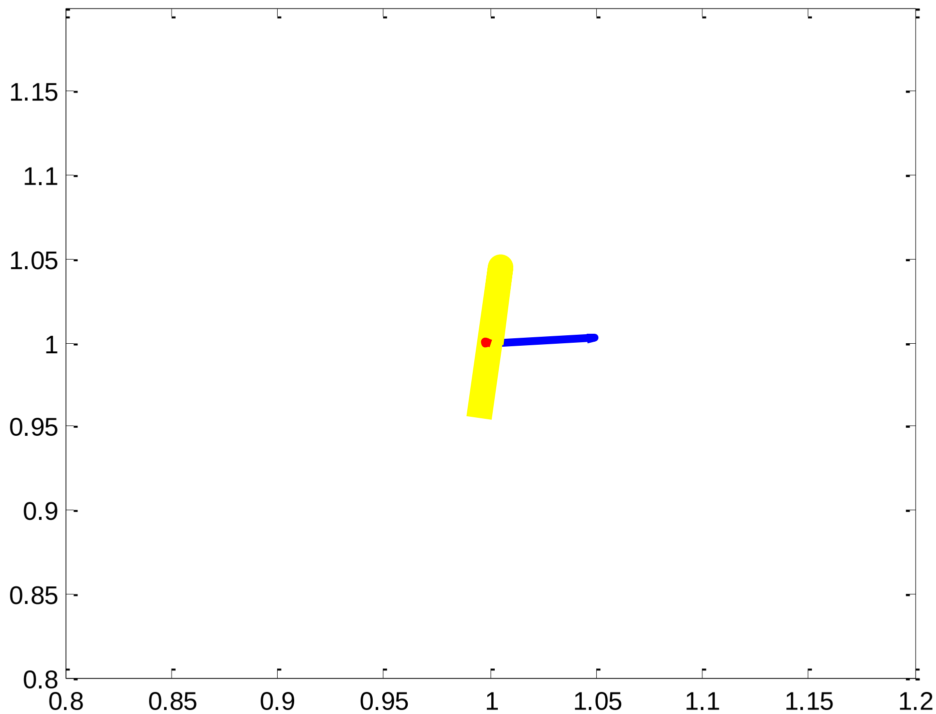
Noord-Holland – Callantsoog-Zwanenwater – 2006



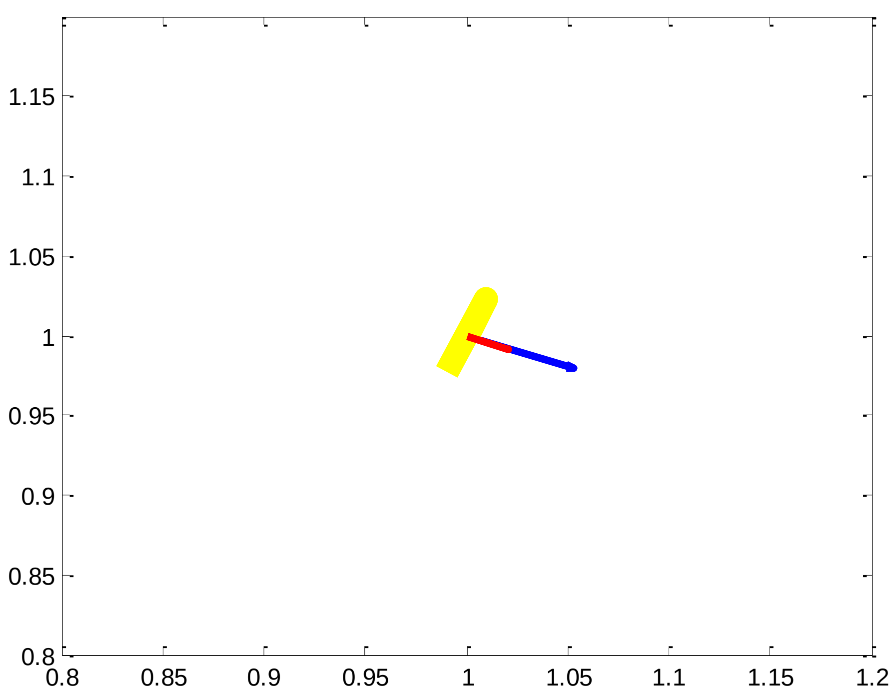
Noord-Holland – Den Helder-Julianadorp – 2009



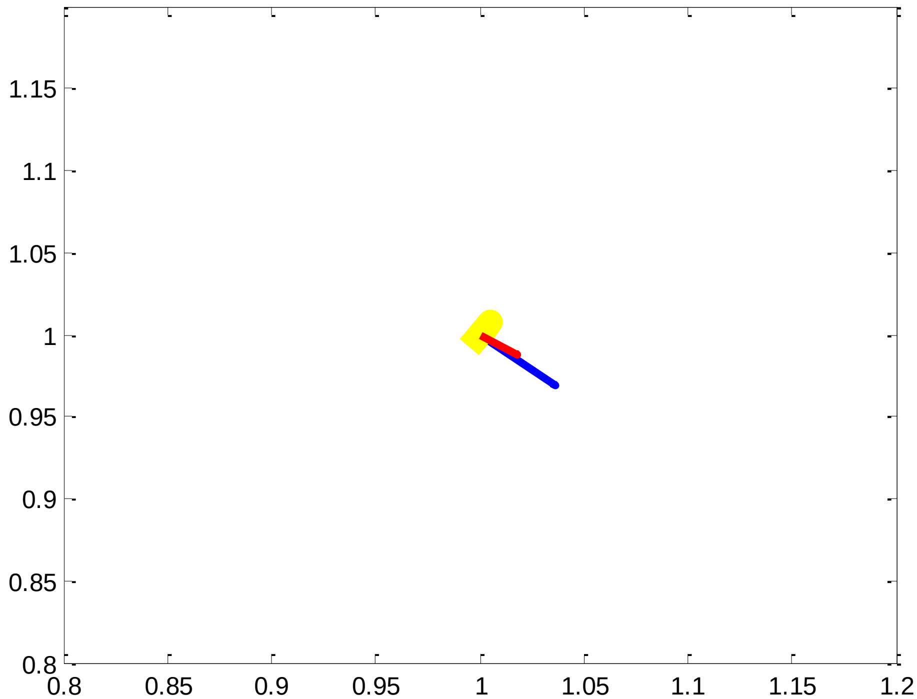
Noord-Holland – Egmond-Bergen – 2010



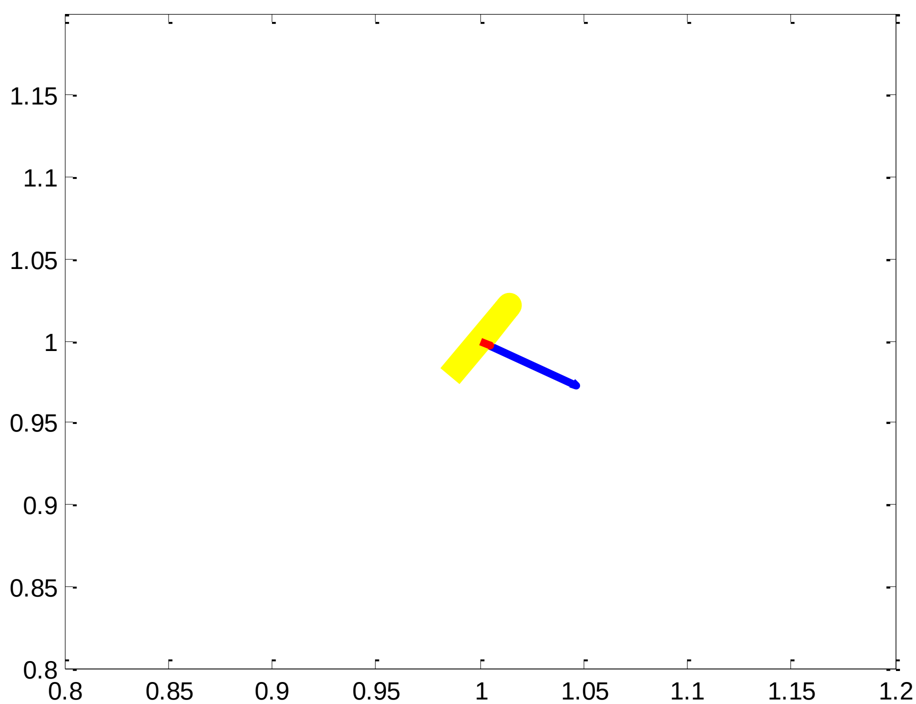
Rijnland – Zandvoort Zuid and Noord – 2004



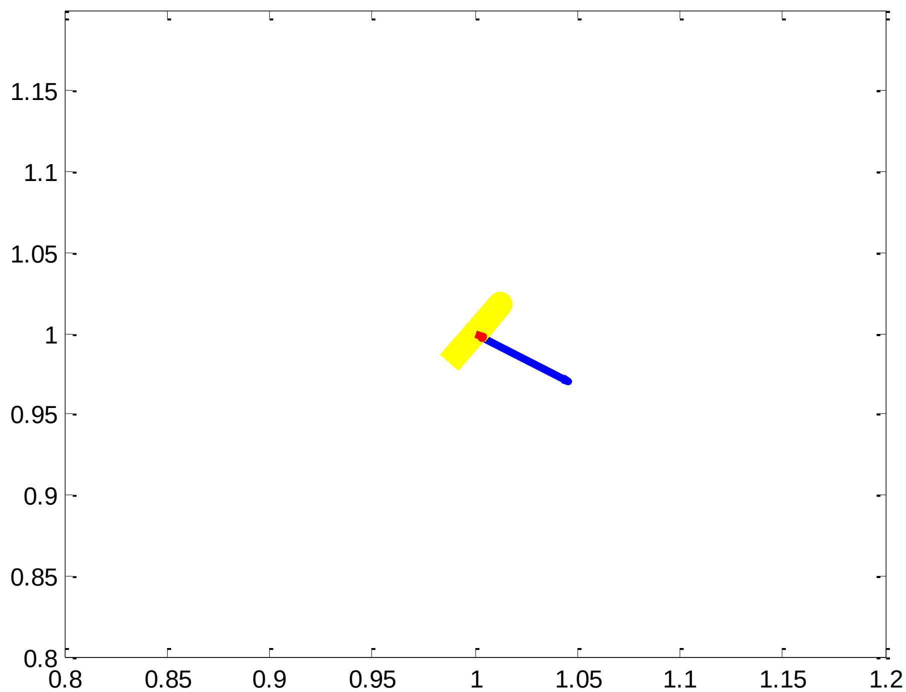
Delfland – Ter Heijde – 1997



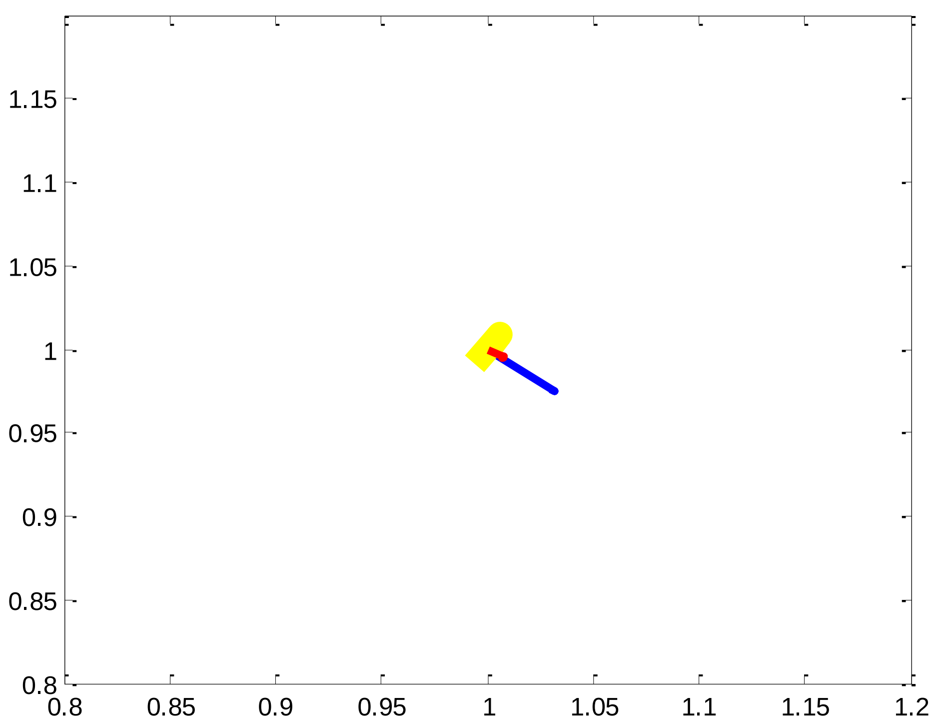
Delfland – Kijkduin-Ter Heijde – 2001



Delfland – Monster – 2005



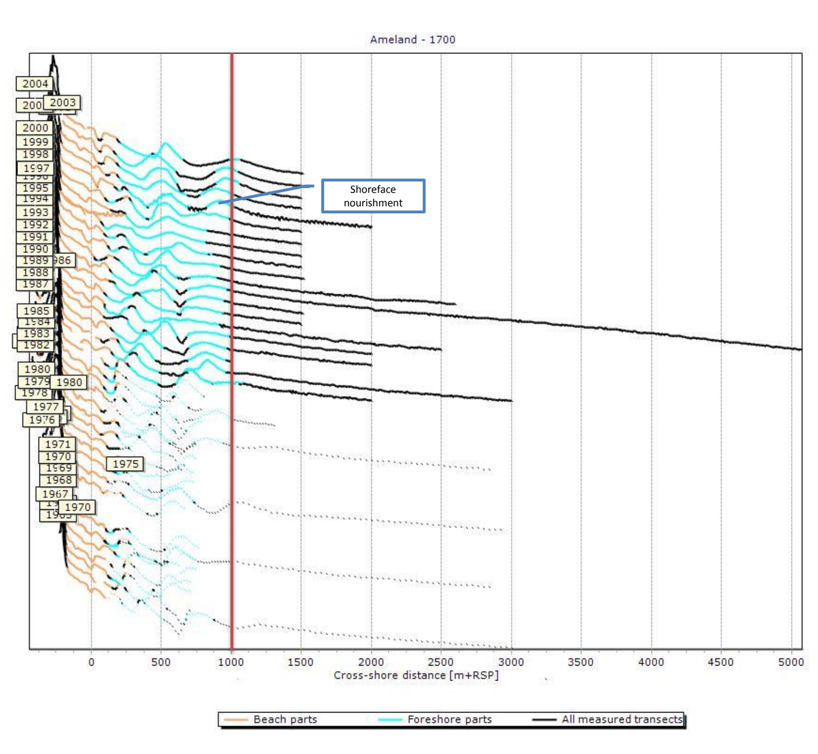
Delfland – Kijkduin-Ter Heijde – 2011



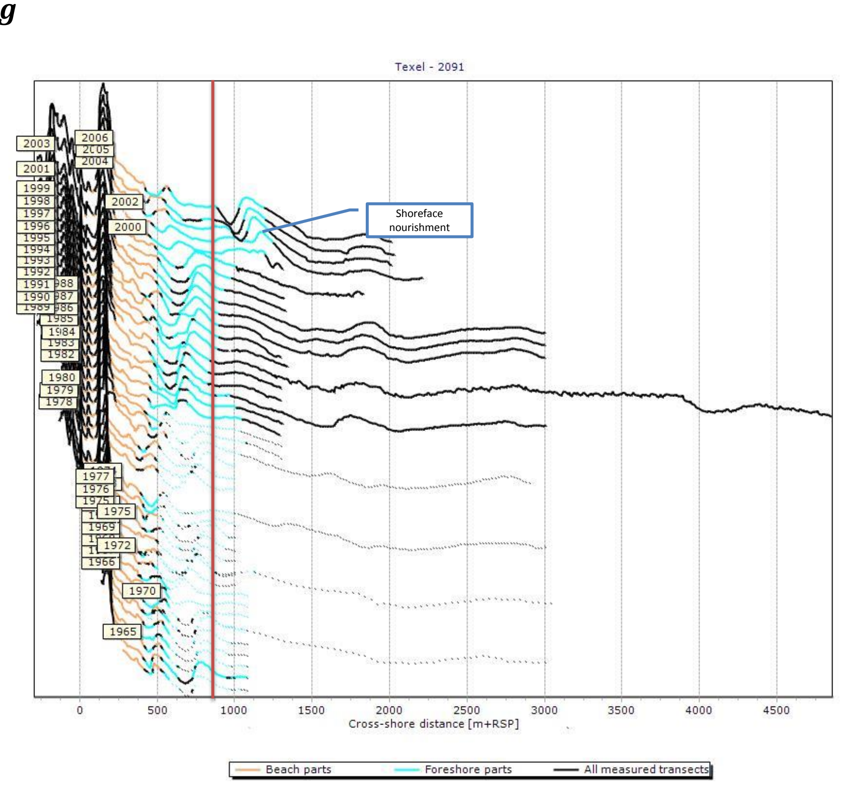
Appendix F: Zone of decay shoreface nourishments

In this appendix, the zone of decay is shown for locations with dominant cross-shore bar behaviour. This zone is based on the historical position where sandbars decay. The red line in the figures represents the zone of decay. The execution of the shoreface nourishment is given by the textboxes.

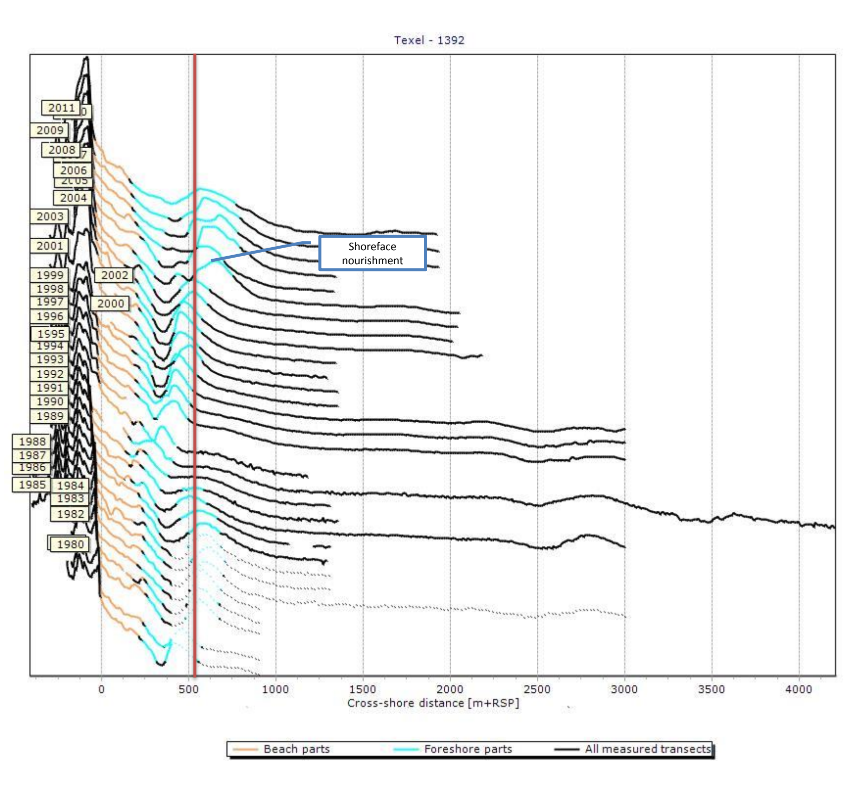
Ameland – Midden



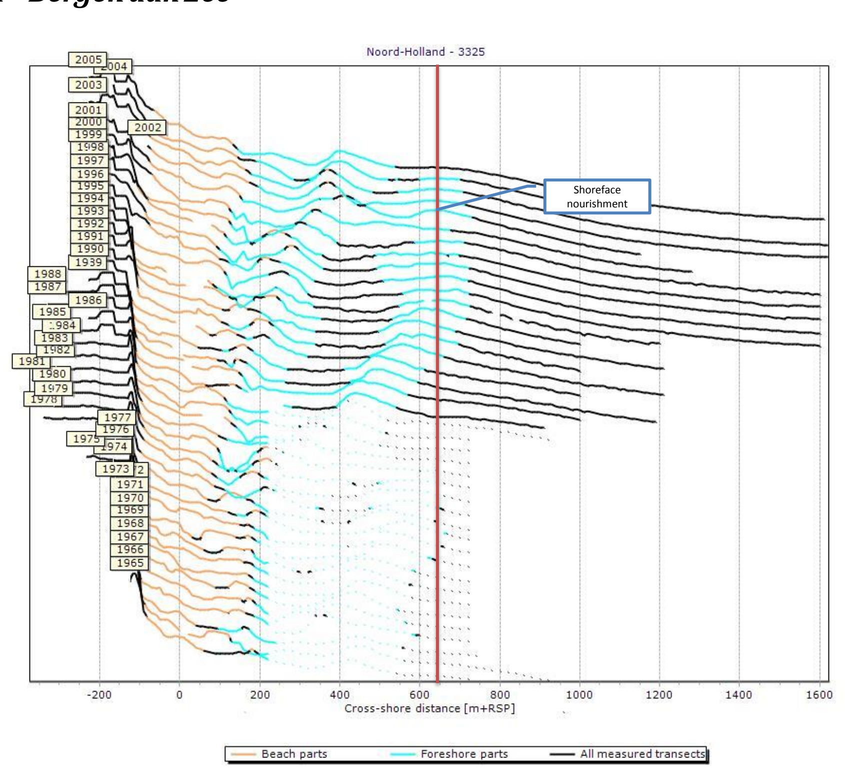
Texel – De Koog



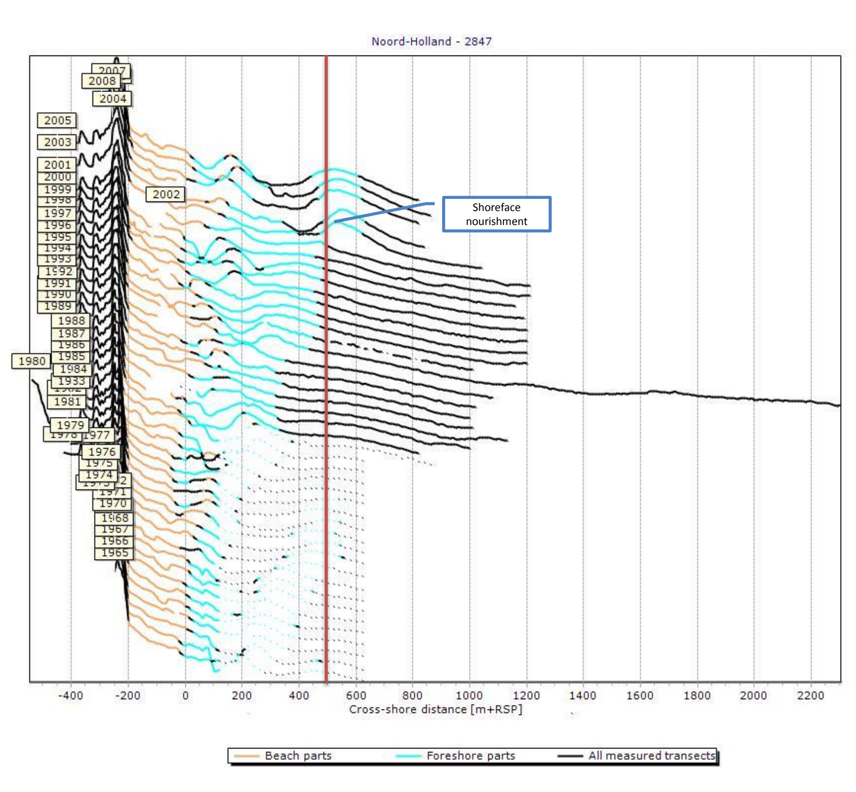
Texel – Zuidwest



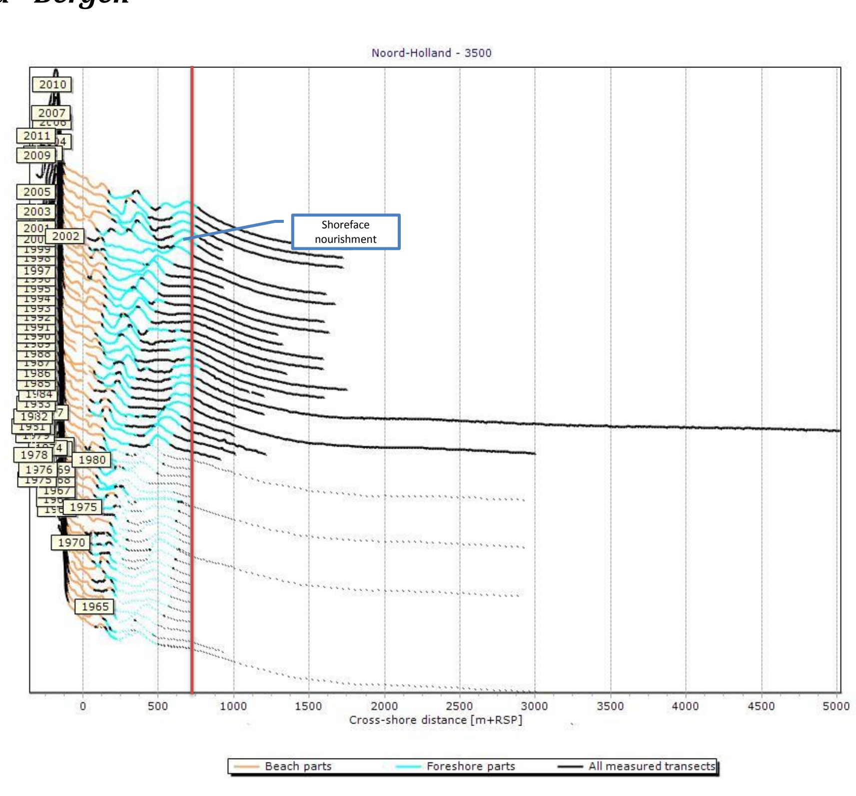
Noord-Holland – Bergen aan Zee



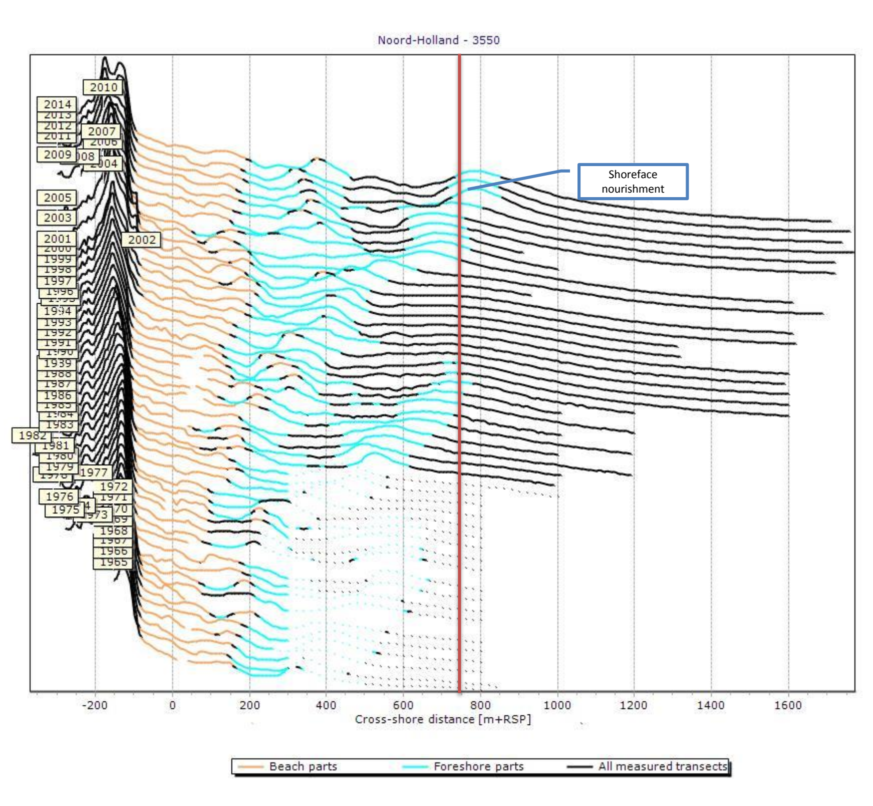
Noord-Holland – Camperduin



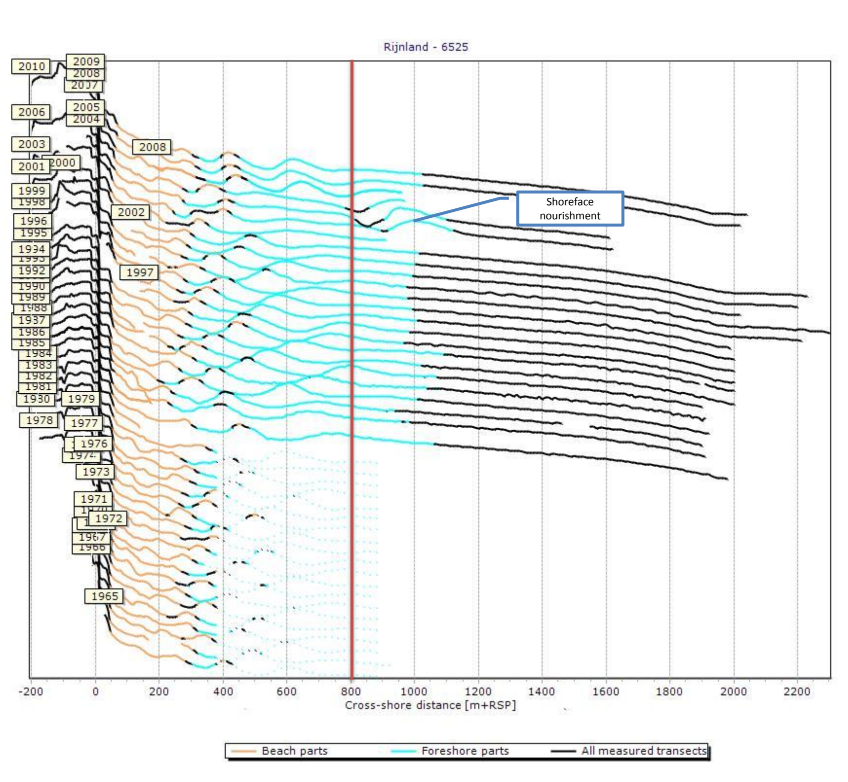
Noord-Holland – Bergen



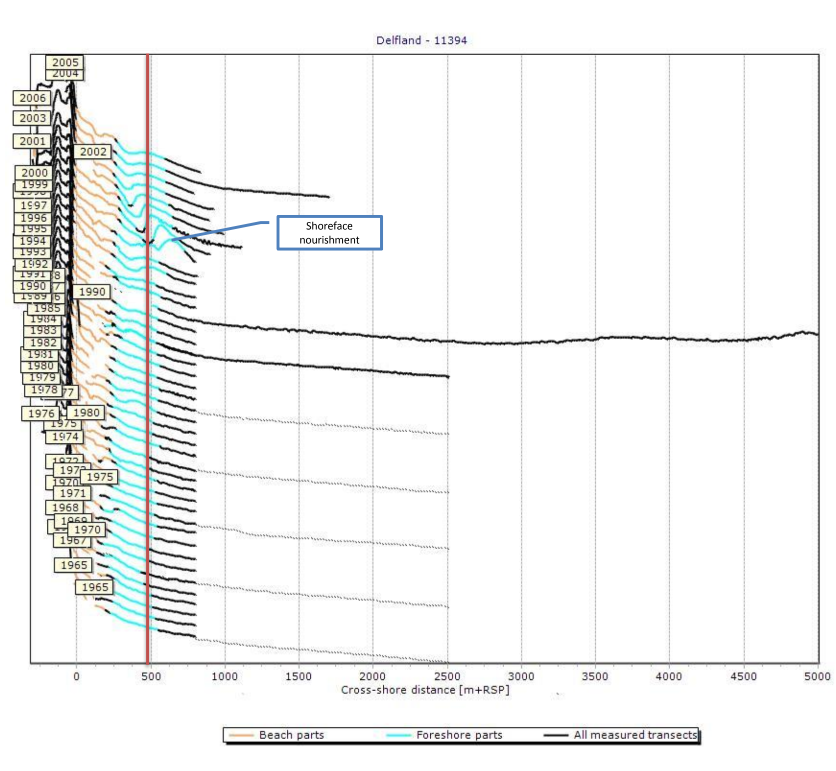
Noord-Holland – Egmond-Bergen



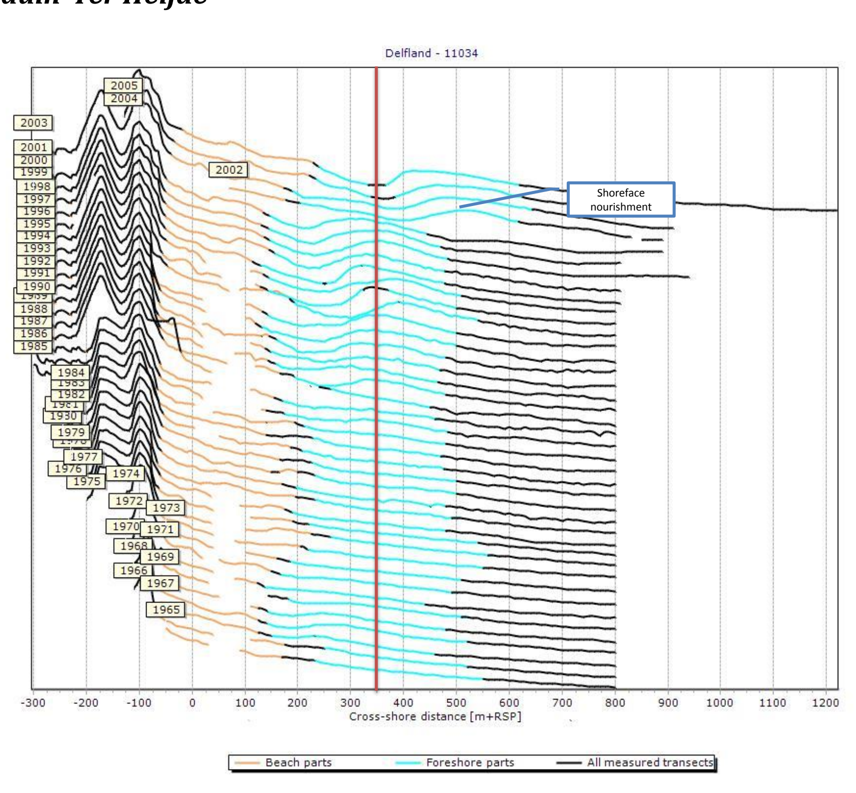
Rijnland – Zandvoort



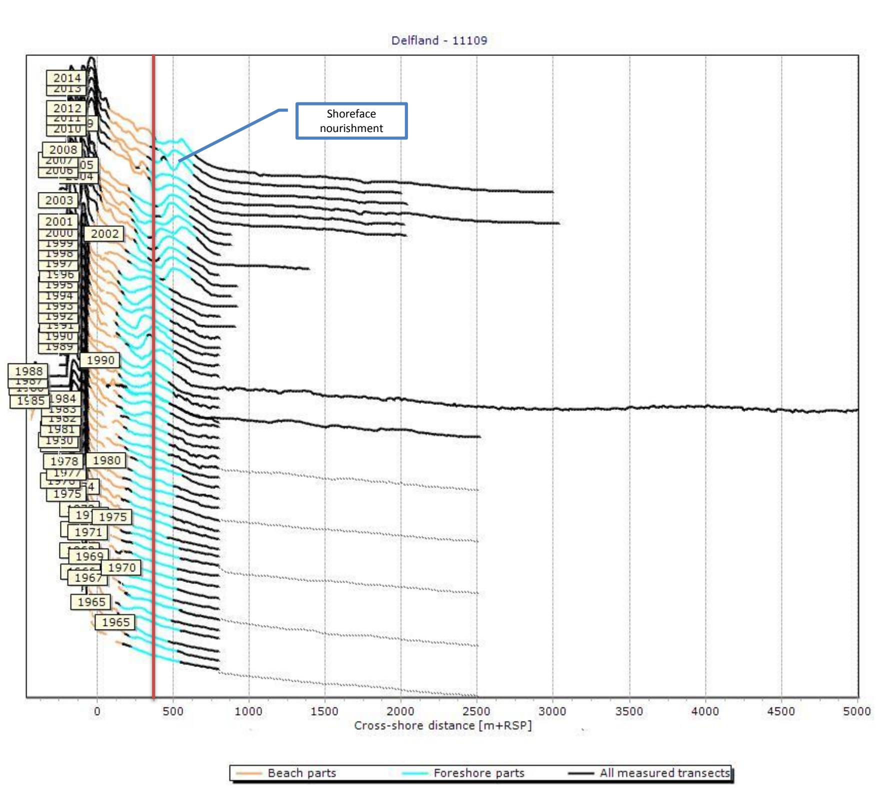
Delfland – Ter Heijde



Delfland – Kijkduin-Ter Heijde

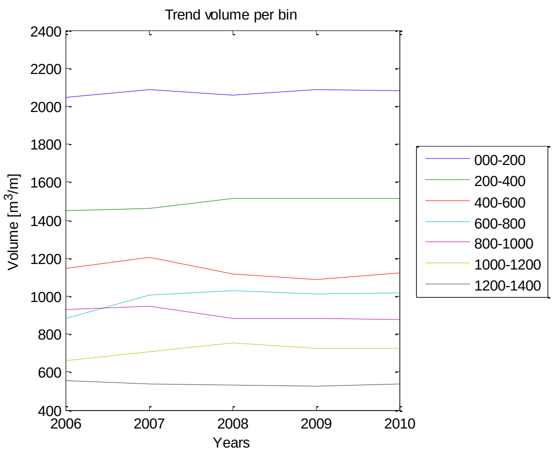


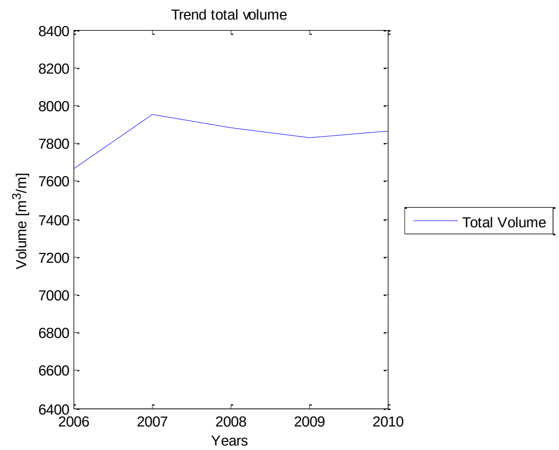
Delfland – Monster



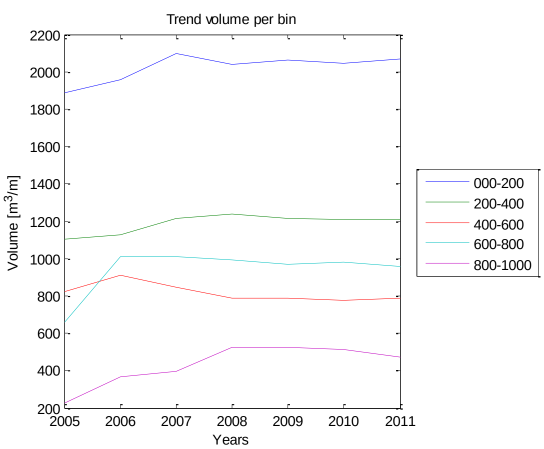
Appendix G: Volume trends for shoreface nourishments of validation

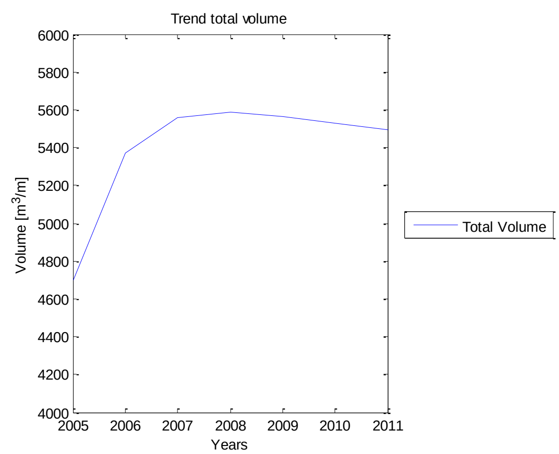
Ameland – Midden – 2006



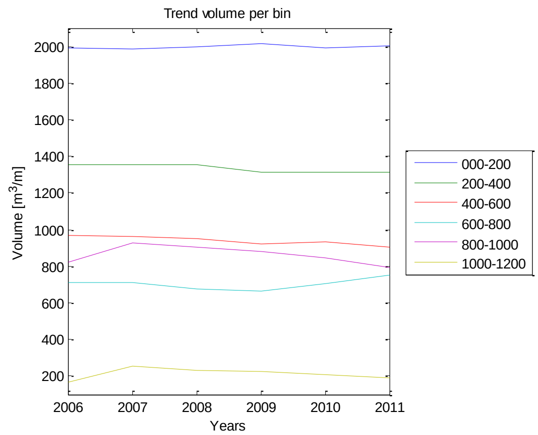


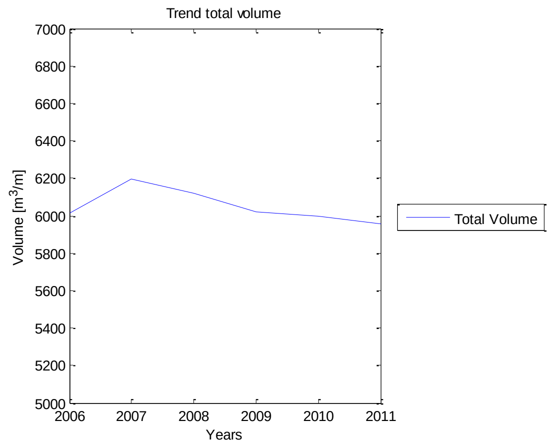
Texel – Centrale Kust – 2005



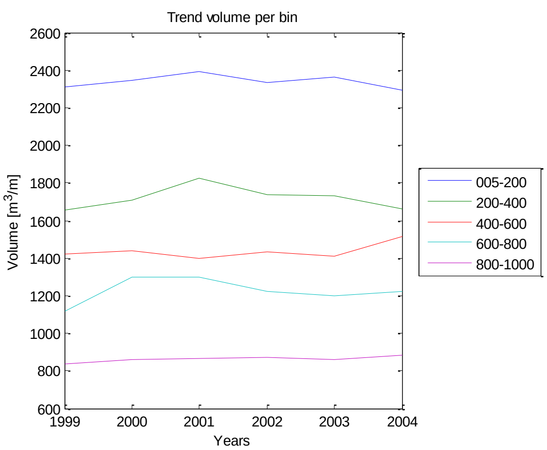


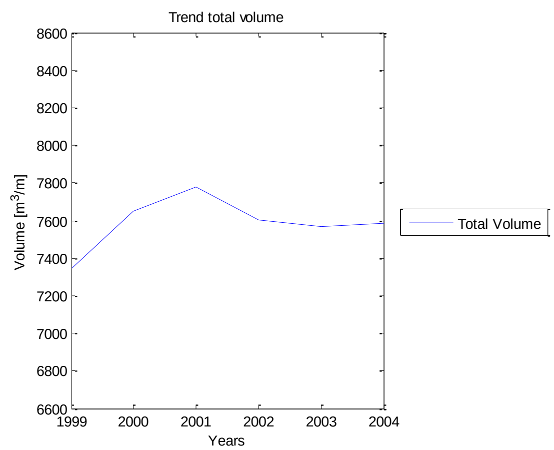
Texel – De Koog – 2006



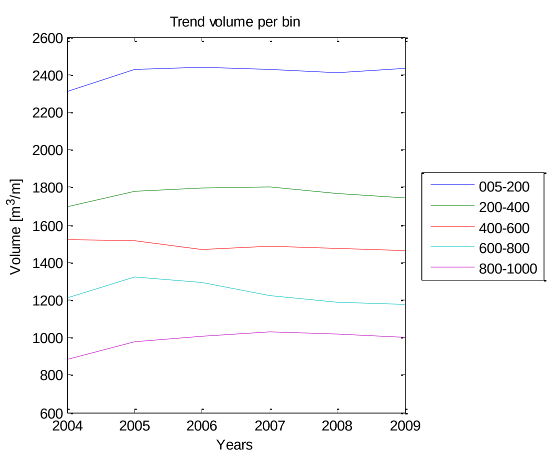


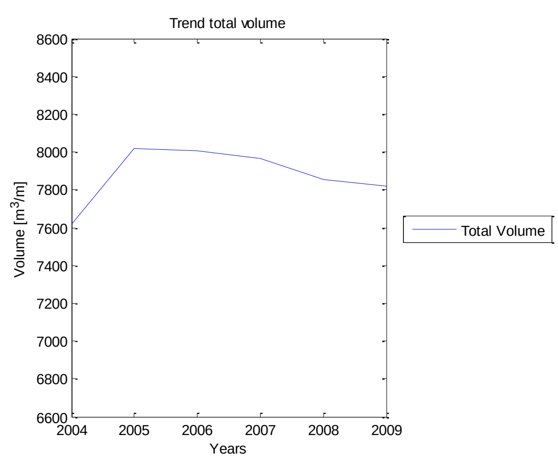
Noord-Holland – Egmond – 1999



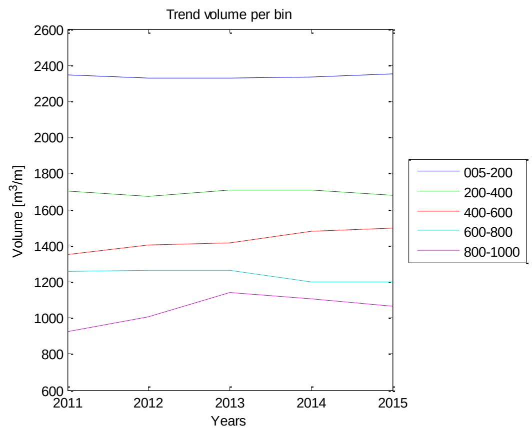


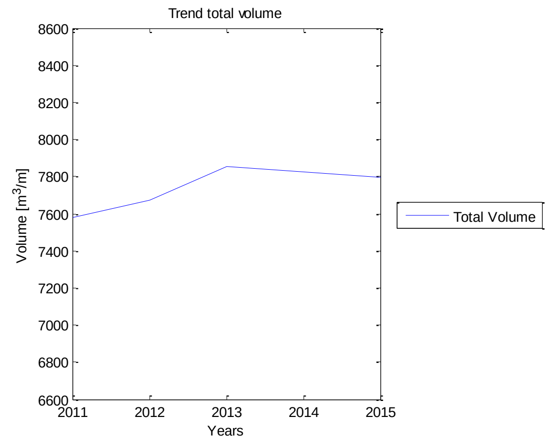
Noor-Holland – Egmond aan Zee – 2004



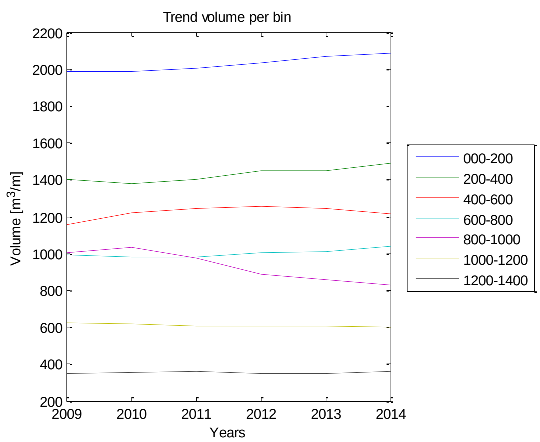


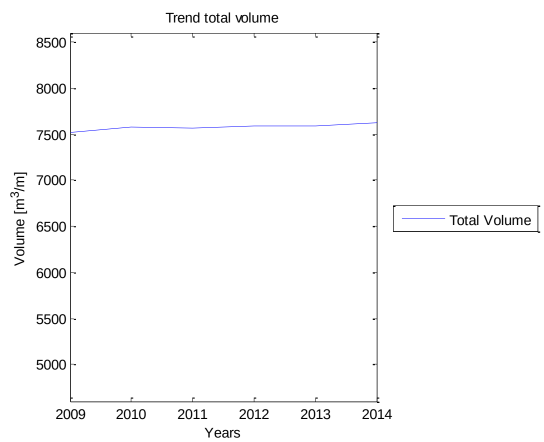
Noord-Holland – Heemskerk -2011



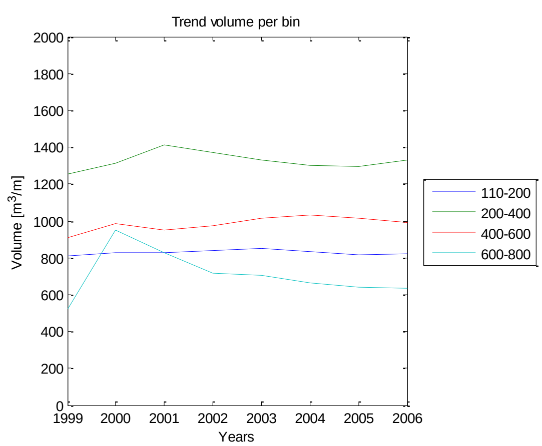


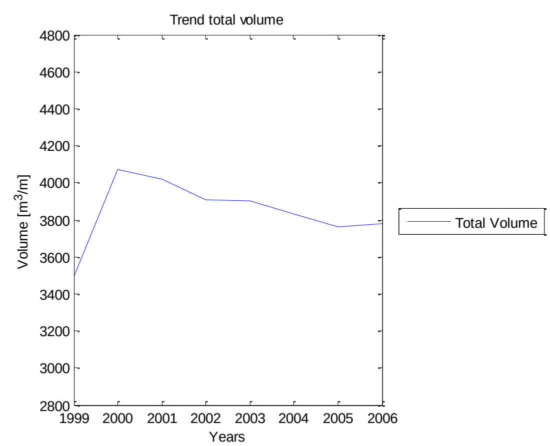
Rijnland – Bloemendaal – 2008



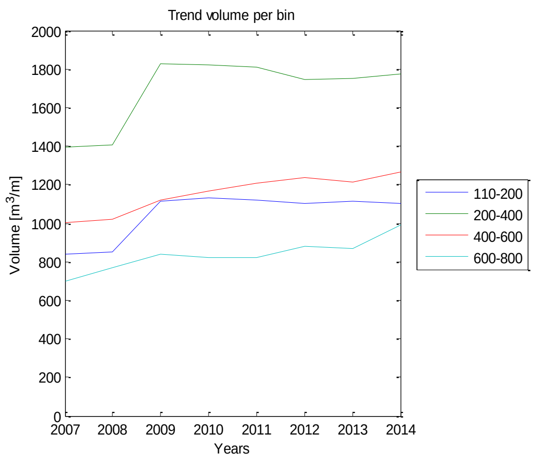


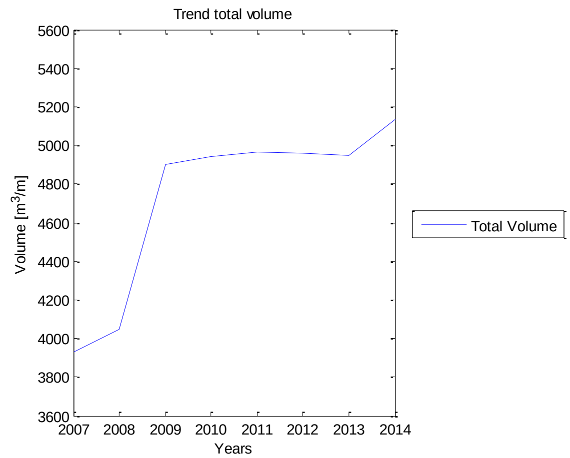
Delfland – Scheveningen – 1999





Delfland – 's Gravenzande-Hoek van Holland – 2007





Walcheren – Westkappelse Zeedijk – 2008