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The state of the coast

Toestand van de Kust

Case study: **Wadden islands**

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Summary
The Wadden islands are located in the northern part of The Netherlands. The barrier islands border on the north-western side the North Sea and on the south-eastern side the Wadden Sea. Both-, tides and waves play an important role in shaping and maintaining those islands. Next to it, the islands have been undergoing large anthropogenic changes during the centuries which culminated in the construction of the Afsluitdijk and the closure of the Zuiderzee, completed in 1932. Next to it, other major interventions have taken place in the area (e.g. closure of the Lauwerszee, hard structures for coastal protections, nourishments).

Due to the strong anthropogenic impact, the assessment of the morphological evolution of the region is complex. Next to it, a number of morphological features along the coastline (i.e. sand waves and tidal channels) have a very large impact on the coastline development. Moreover, those natural features also interact with the different human interventions. It is therefore very important for coastal managers to account for their effect on the coastline morphology, while planning further interventions along the coast.

In this study, the morphodynamic development of the coastline of the Wadden islands has been assessed using an indicator approach. The scope of this analysis is to derive useful information by looking at past morphological changes (natural and anthropogenic) to be used as a basis for the planning of future nourishment works. In particular, the following indicators have been used in the analysis: MKL, mean low- and mean high-water line, dune foot position, and probability of breaching of the first dune row. Moreover, the impact of different natural morphological features has been analysed: the sand wave development along the entire coastline and the morphological development of a number of tidal channels. The relative importance of those features for this stretch of coast is in fact often much larger than that one of the single nourishments. The same also holds for the large-scale developments (i.e. effects of closures), which makes the morphological development of the Wadden islands quite different with respect for example to that one of the Holland coast. It is for this reason nearly impossible to derive direct relationships between the effects of the nourishments and the indicators, which can be extrapolated to the entire region.

References
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	sept. 2015	Alessio Giardino		Albert Oost		Frank Hoozemans	
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Contents

1 Introduction

The Netherlands is a low-lying country, where approximately 26 per cent of the territory is located below mean sea level and 59 per cent is prone to flooding (PBL Netherlands Environmental Assessment Agency). Moreover, the area below sea level is extremely densely populated with about 9 millions of inhabitants, representing about 56% of the total population of The Netherlands.

Protection against flooding is traditionally the primary objective of coastal policy in the Netherlands. However, since 1990 coastal policy has been subject to a number of modifications. New objectives such as the preservation of values and functions in the dune area and the sustainable maintenance of safety have been added to cope with the structural erosion problems of the Dutch coast. To fulfil these new objectives, the yearly volume of sand for nourishments was set at 6 $*10^6$ m^3 in 1990 and increased to 12 $*10^6$ m^3 in 2001 (Mulder et al., 2011). According to predicted sea level rise scenarios, higher volumes of sand will probably be necessary in the future for the sustainable maintenance of the safety levels, implemented by maintaining the sand in the entire coastal foundation.
On the other hand, the effect of the global economic crisis is pushing coastal managers to the development of optimal efficient and cost-effective nourishment strategies. Deltares has been commissioned by Rijkswaterstaat – WVL to develop the knowledge needed to carry out an effective nourishment strategy (spatially and temporally). Deltares organised the project *KennisvoorPrimaireProcessen – Beheer en Onderhoud van de kust* (Knowledge for Primary Processes - Coastal Management and Maintenance) in a number of sub-projects. In order to link the project results to the actual nourishment practice of Rijkswaterstaat, the subprojects focus on the validation of a number of hypotheses on which the present nourishment strategy is based. “Toestand van de Kust” (State of the Coast) is one of the sub-projects of this multi-year program, with the aim of identifying the impact of nourishments for a number of indicators along the Dutch coast. During this fourth year of the project, the analysis has focused on the coast of the Wadden islands.

This report summarizes the main findings from the study. In Chapter 2 the main objectives are described, while Chapter 3 summarizes the assumptions used in the study. The study area is described in Chapter 4. The anthropogenic interventions and natural forcing which have affected the morphological development of this stretch of coast are respectively described in Chapter 5 and 6. The large-scale development of the Wadden Islands is described based on an indicator approach in Chapter 7. The effect of sand waves and tidal channels on the coastline development, next to the impact of nourishments, is studied in Chapter 8. Chapter 9 provides a number of discussion points derived from the study while the main conclusions are given in Chapter 10.

The present study is part of the project KPP – Beheer en Onderhoud van de kust (Coastal Management and Maintenance). We would like to acknowledge comments and remarks from Stanford Wilson, Quirijn Lodder, Rena Hoogland, Petra Damsma and Gemma Ramaekers (WVL), which have resulted into an improved manuscript.

2 Objectives

The objective of the present study is twofold:

- *To support WVL (Rijkswaterstaat) in determining where to nourish.*
  This is achieved by indicating on which spots along the coast the sediment buffer is limited. The buffer does not only concern sediment volumes, but a wider range of coastal indicators. On spots that encounter limited buffers, the morphological development can be examined. If the buffer tends to get lower than a reference buffer and a (natural) increase in sediment volume is not expected on a short term, WVL can consider to nourish this part of the coast. The state of the coast can facilitate the prioritization of the nourishments, as choices are needed due to limited financial resources.
- *To advise WVL on the most efficient nourishment strategy.*
  This is achieved by deriving the effect of the previous nourishment strategies (1990 till present). Learned lessons from the past can be used to improve future nourishment strategies.

In addition, the following hypotheses[1] are assessed within this study:

Hypotheses
1) The nourishment strategy of the past years has led to a positive[2] development of a number of "indicators" along the Dutch coast.
2) As a consequence, nourishments contribute to an increase of the safety level through a seaward shift of the erosion point.

By looking at the development of coastal indicators in the past, recommendations are derived to design the future nourishment programme at time scales up to 10 years. The focus area of this report are the Wadden islands. In particular, as the focus of the study is on coastline care, the part of the islands facing the North Sea, and the part near the tidal inlets, are included in the analysis. Similar studies have already been completed for North-and South-Holland coast and for the South-Westerly Delta.

To be able to achieve the objectives and to verify the hypothesis, a number of indicators have been defined. These indicators 1) are representative of the morphological development of the Dutch coast at different temporal and spatial scales and 2) relate to policy objectives (e.g. safety, nature and recreation).

Given the fact that nourishments are just one of the several mechanisms influencing the morphological development of the Wadden islands, considerable effort has been put into the evaluation of the effects of other man-made interventions as well as natural forcing, next to the effects of the nourishments.

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[1] *Background of the hypothesis and the link with the present management choices are described in an integral report of the project KPP-B&OKust.*

[2] *In this report, it is assumed that "positive" development means a " decrease" of the probability of breaching of the first dune row, a "seaward" shift of the MKL and dune foot, an " increase" in beach width and sediment volumes.*

3 Assumptions

A number of assumptions were defined to verify the basic hypothesis.

Assumption 1
The morphological development is dominated by the long-term natural development and by the major human interventions: the construction of the Delta Works and the nourishment program. Therefore, the analysis was subdivided in three periods of time (Chapter 7):

- 1843 – 1931. During this time window, it is assumed that morphological changes were mainly driven by natural processes. This is only partially true as the construction of dykes, sand drift fences and planting of marram grasses is at some islands (e.g. Texel) a much older practice dating back at least since 650 BP (Oost, 1995).

- 1932 – 1989. Two major artificial interventions are completed in this time window: the closure of the Zuiderzee with the Afsluitdijk in 1932 (Section 5.3) and the closure of the Lauwerszee in 1969 (Section 5.4). Those two interventions affected slowly respectively the hydrodynamics and morphology of the western and the eastern part of the Dutch Wadden Sea. Also, the inlet coast of west Ameland has been reinforced with stonework during this period.

- 1990 – 2012. During this time window, large nourishments have been implemented especially at Texel and Ameland (Section 5.5).

The choice of the three time windows depending on the interventions is however arbitrary.

Assumption 2
Morphological changes within each time window can be described by “linear” trends.

Assumption 3
This assumption is related to the spatial scale at which the analysis has been carried out: at first the Jarkus transect level, and in second place a larger scale defined in the report as region (*kustvak*).

Assumption 4
The last assumption concerns the choice of the indicators, which best describe the morphological evolution and can be related to policy objectives. In this study, for the large scale analysis, we focused on the following indicators: mean high- and mean low-water line, and dunefoot position, because those datasets are already available starting from half of the nineteenth century. Moreover, changes in short-term safety were also analysed by looking at the probability of failure of the first-dune row, but only available for the last 50 years, starting from the year when JARKUS profiles were measured. Medium-term safety was derived by looking at MKL development during the same time span based on JARKUS data.

Next to the choice of the indicators, a further assumption relates to the procedure chosen to compute those indicators. The mean high water and mean low water lines identify the position of the average high water and low water lines along the coastline. As tidal range is not constant along the coast, those values also change moving at different locations. Moreover, mean high-water and mean-low water are also influenced by long term trends in time such the effect of sea level rise.

The dune foot position before the start of the Jarkus measurements was determined visually as the location of the sharp bend in the profile, usually where the vegetation starts (Damsma, 2009). For the most recent data (approximately after 1965) this is defined as the intersection between the profile and the +3 m NAP. Although, this is a generally adopted assumption, it should be remarked that the dune foot position so determined might differ from the real dune foot position. On-going research between Deltares and WVL is looking into methods to possible improve this definition.

The probability of breaching of the first dune row was derived based on a stochastic analysis of dune erosion simulations based on the DUROS+ model for all JARKUS transects as described in Van Balen et al. (2012).

The MKL is defined according to the standard procedure described, among others, by Van Koningsveld and Mulder (2004), where the seaward boundary defining the MKL volume might be adapted locally i.e. in presence of tidal channels close to the coastline.

4 Description study area

4.1 Morphological characterization of the study area

The Wadden islands are located in the northern part of The Netherlands. They border on the north-western side the North Sea and on the south-eastern side the Wadden Sea. From south to north, the Wadden islands located in The Netherlands are: Texel, Vlieland, Terschelling, Ameland, and Schiermonnikoog. On the eastern side, two smaller islands are part of The Netherlands: Rottumerplaat and Rottumerhoog. However, those two last islands are uninhabited. Towards the north-east, the barrier island system continues further in Germany and Denmark.

Since the focus of the project is on coastal management, the focus area is on the stretches of coast of the islands facing the North Sea as well as the tidal inlets. Those areas are more strongly influenced by the dynamics of the coastal system and by anthropogenic interferences which have taken place during the years. On the other hand, the stretches of coast facing the Wadden Sea, mainly influenced by the morphodynamic development of the Wadden Sea tidal basin, are not part of the study.
JARKUS profile measurements are available at the seaward side of the islands and at the tidal inlets, as for the rest of the Dutch coast. This makes the study consistent with the other ones carried out for the other regions.

The name of the different islands ("kustvakken"), with the length covered by the Jarkus measurements, is indicated in Table 4.1. It should be noted that some parts of the islands, such as the island tails, are not covered by Jarkus measurements. The total length of the covered part is approximately 140 km. The two uninhabited islands (Rottumerplaat and Rottumerhoog) are not investigated in the study as there is no relevant anthropogenic action which has taken place in those areas during the past years. For information on their development see Van Rooijen and Oost (2014). Moreover, no Jarkus measurement is available at those locations. The islands located in Germany and Denmark are also not considered in the study.

Table 4.1 Names of the different islands ("kustvakken") part of the Wadden Sea with the approximate alongshore length covered by the Jarkus measurements.

Kustvakken	Length (km)
Texel	32
Vlieland	25
Terschelling	32
Ameland	30
Schiermonnikoog	22

Both tides and waves (section 4.2) play an important role in shaping and maintaining those islands. Next to it, the islands have been undergoing large anthropogenic changes during the centuries (Chapter 5) which culminated in the construction of the Afsluitdijk and closure of the Zuiderzee, completed in 1932. In general, following the classification of Hayes (1979), the islands quantify as mixed-energy environment with a relative increase of the influence of tides with respective to waves moving from south to north (Section 4.2). However, the morphology of the major inlets show tide dominated characteristics such as a large ebb-tidal delta and deep entrance channels. These result from large tidal prisms, partially induced by tidal resonance due to the closure of the Zuiderzee, and relatively low wave energy (Elias et al., 2012). On the ebb-tidal deltas, waves redistribute the sediments and contribute to the sediment bypassing mechanisms (FitzGerald, 1988).

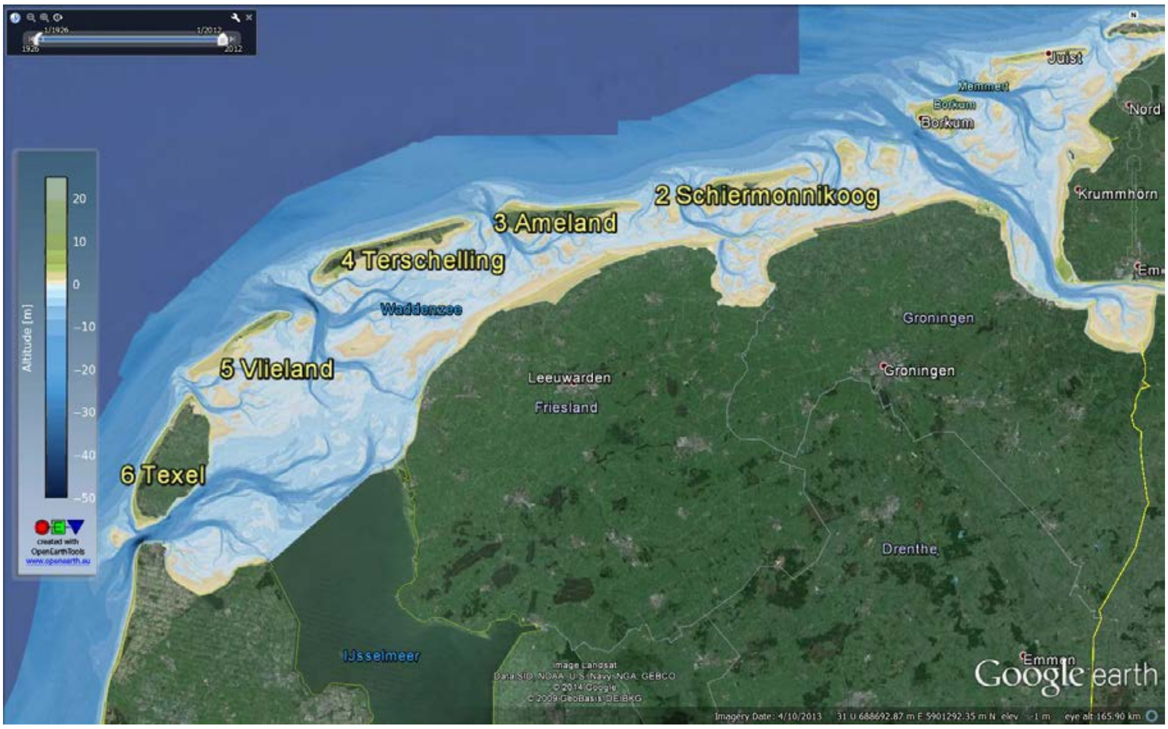


Figure 4.1 Bathymetry of the Wadden Sea region. In yellow, the different islands (kustvakken) are given with their respective numbering.

4.2 Tides and waves

The area is characterized by a tidal regime increasing from micro-tidal to meso-tidal moving from west to east. In particular, the tidal range at Texel is about 1.4 m, increasing up to 2.5 m in the Ems estuary (Eems-Dollard inlet) and even further along the German Wadden coast. This is due to the combination of a northward-travelling tidal wave, moving along the Dutch coast, which meets near Texel with a second eastward travelling tidal wave (Pugh, 1987). Residual tidal currents follow a quite complex pattern, as shown in Figure 4.2 for the western part of the Wadden Sea.

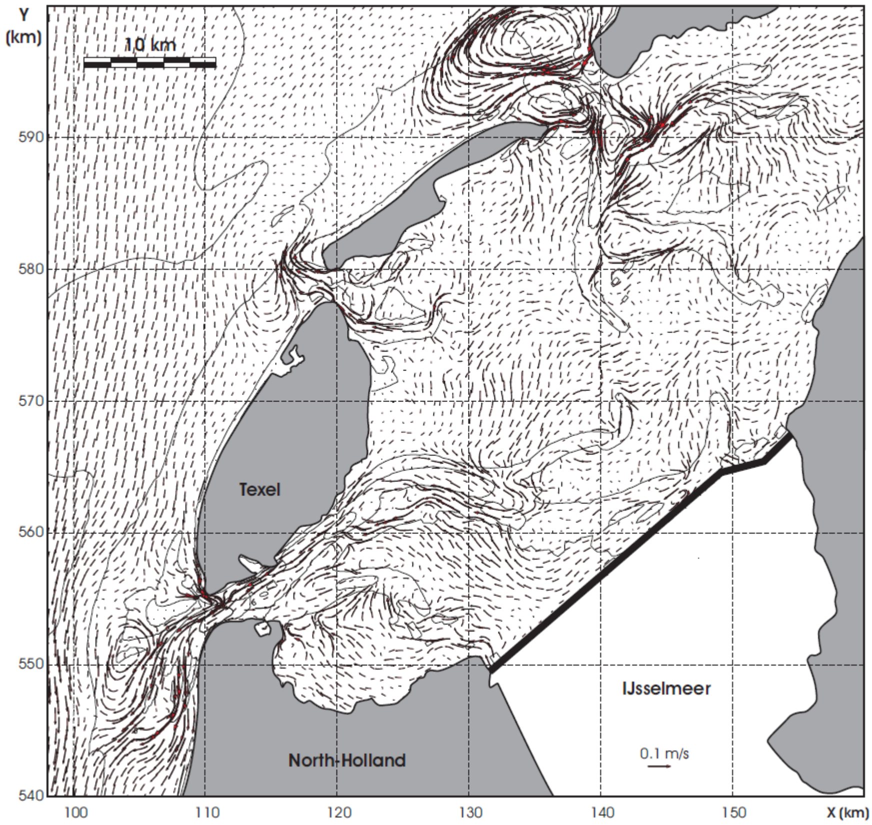


Figure 4.2 Residual tidal currents in the Western part of the Wadden Sea (Elias, 2006).

The wave climate in front of the Wadden islands is shown in Figure 4.3. The figure shows a wave climate dominated by waves coming from the NNW, with increasing relative importance of waves from the SW moving towards Texel. The mean significant wave height is 1.3 m. During storm, wind-generated wave reach heights of above 6 m; additional surge water-levels of more than 2 m have been measured (Elias et al., 2012).

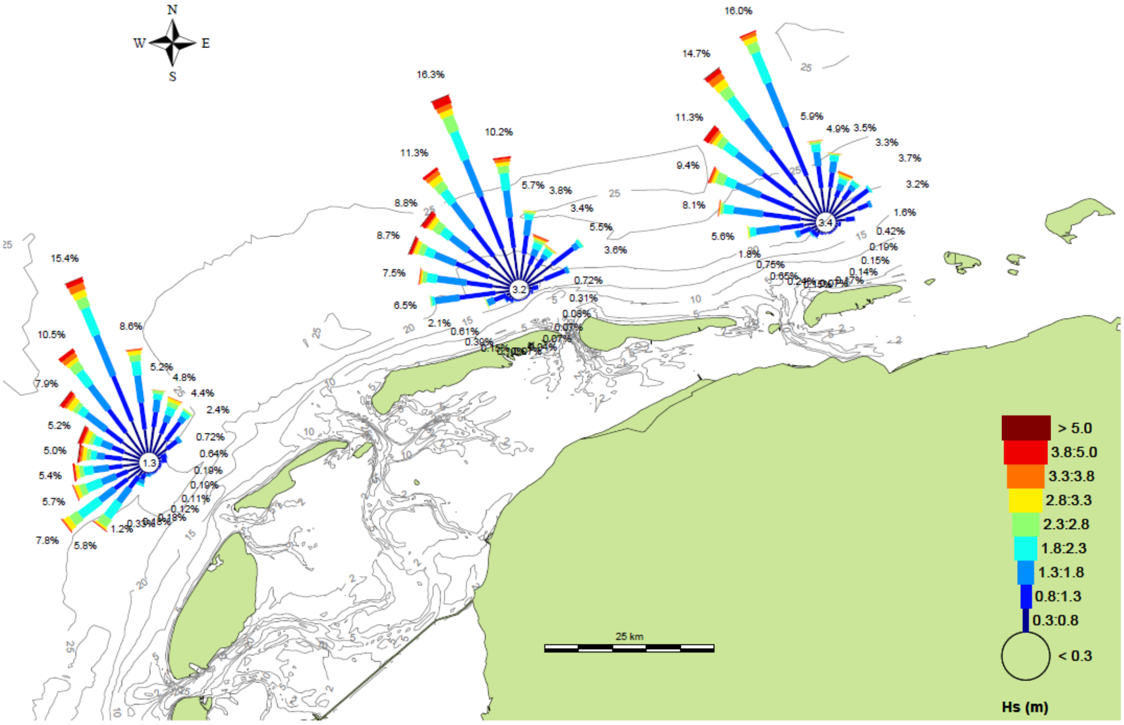


Figure 4.3 Wave climate at three stations in front of the Wadden islands. From left to right: Eierlandse Gat, Schiemonnikoog Noord, AZB 12 (De Fockert, 2008).

4.3 Sediment characteristics

The median grain size (D_{50}) on the foreshore ranges approximately between 150 μm and 210 μm, which is in general considerable smaller than what can be observed in the rest of the Dutch coast (Figure 4.4). This is partially explained by the fact that the sediments of the Wadden Sea are mainly derived from Northern sources during the Pleistocene and in general have a smaller grain size, whereas the more southern sediments are derived from the Rhine and Meuse (Eisma, 1968). This grain size might be locally affected by nourishments with different grain size. Moreover, the figure shows a general decrease in sediment size away from the tidal inlets (e.g. Terschelling, Ameland), most likely related to a difference in hydrodynamic regime and sediment sorting process (alongshore currents versus inflow-outflow at the tidal inlets) (Veenstra and Winkelmolen, 1976; Winkelmolen and Veenstra, 1980).

The average sediment size also decreases moving eastward (Veenstra, 1984). As yet, no clear explanation can be given for this phenomenon.

Figure 4.4 Median grain size (in μm) measured on the first dune row along the Holland coast (TAW, 1984).

5 Man-made interventions

5.1 Introduction

The history of human influence on the Wadden island morphological development is very long and dates back to the Middle Ages, when the first structures to cope with coastal erosion started being built (Section 5.2). However, until the 19th century, due to restrictions in technological means, the anthropogenic impact on the islands was still limited. The biggest human intervention ever realized in the Wadden Sea was the closure of the former Zuiderzee by the construction of the Afsluitdijk (Section 5.3). Although this large engineering project did not take place on the islands, it did influence the hydrodynamics and morphodynamics of the entire Wadden Sea as well as of the outer Delta and Wadden islands. A more recent project was the closure of the Lauwerszee, which although of smaller dimension, did influence the morphological development of Schiermonnikoog, located in front of the area where the project took place (Section 5.4). Finally, during the last decades, soft engineering interventions (i.e. sand nourishments and dune management) have largely been used to counteract the erosive trends and respond in a proactive way to possible future increase of those trends due to sea level rise (Section 5.5 and 5.6).

Another type of anthropogenic intervention which has large influence on the local subsidence at some areas is gas mining (Section 5.7).

5.2 Hard structures for coastal protections

Coastal management in the Wadden islands started developing very early, most likely when the first permanent settlements appeared (Oost et al., 2012). The first examples were related to the construction of mounds (*terpen*) for flood protection, which started at least in the 10th century, for example in Terschelling and Ameland.

Dikes were also constructed very early in time; at Texel for sure starting from 1350, but at other islands (e.g. Terschelling) probably since around year 1000. Another form of coastal defence was the protection and planting of *Ammophila Arenaria* which has been recorded for Rottumeroog as early as the 14th century. A little later (at least from 1630 in Texel) the construction of screens and sand dunes (*stuifdijken)* began. Stones were placed at some locations around the water line since 1700 (e.g. in the Marsdiep).

However, most of the groynes and revetments have been built since around 1800 (Figure 5.1). As an example, Figure 5.2 shows how the island of Ameland and the man-made coastal protection works have changed between 1665 and now. In 1665, coastal defences in the form of dunes were surrounding the villages of Hollum and Ballum, and Nes and Buren. Two dikes were connecting the two dune systems. However, the rest of the island was still free from structures and open to natural developments. Nowadays, dunes and dikes surround almost completely the island. An overview of all structures for each of the islands is given in Appendix B.

Figure 5.1 Groynes at Vlieland, in front of beach with vegetated dunes.

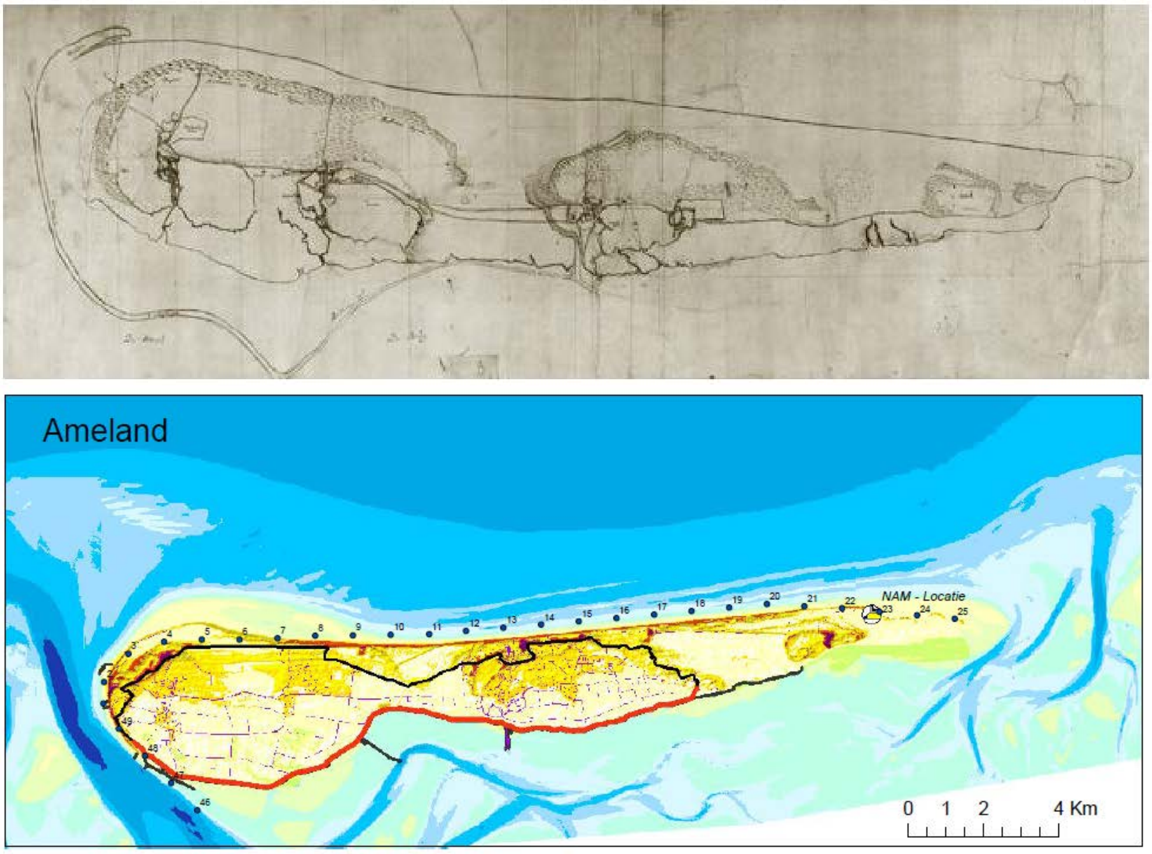


Figure 5.2 Above: Ameland in 1665 (Oost, 2012). Below: Ameland in the current situation (Boers, 2008).The black line indicates the dune row, the red line the dikes.

5.3 The Afsluitdijk

The Afsluitdijk is a major dike, which was built between 1927 and 1932, and which runs over a length of 32 km and a width of 90 m. The dam led to the closure of the Zuiderzee, reducing the Texel and Vlie basins from over 4000 km^2 to roughly 1400 km^2, and to the creation of what is now known as the Wadden Sea (Figure 5.3). As a consequence of the construction of the Afsluitdijk, the tidal characteristics largely changed. The tide changed from a propagating to a standing wave system, and the tidal amplitude drastically increased due to reflection of the tidal wave. This also led to an increase of the tidal prism, despite the aerial reduction of the tidal basin. At Den Helder tidal station the increase was from 1.1 m to 1.4 m, at Den Oever it changed from 0.85 to 1.5 m, but at Terschelling (open sea) the tidal increase was neglectable (Elias et al., 2003; Vroom et al., 2012). The changes in hydrodynamics and geometry resulted in pronounced changes in the overall morphology of the western part of the Dutch Wadden Sea. Over 450 million m^3 of sediment accumulated in the basins of the Texel and Vlie inlets. Nearly 300 million m^3 of sand was eroded from the Texel ebb-tidal delta but also from the adjacent coasts (Elias et al., 2012; Figure 5.4). Therefore, it is essential to consider the effects of the construction of the Afsluitdijk when studying the morphological development of the Wadden islands, in response to natural and anthropogenic changes. On top of this, another reason for observed morphological changes is sea level rise.

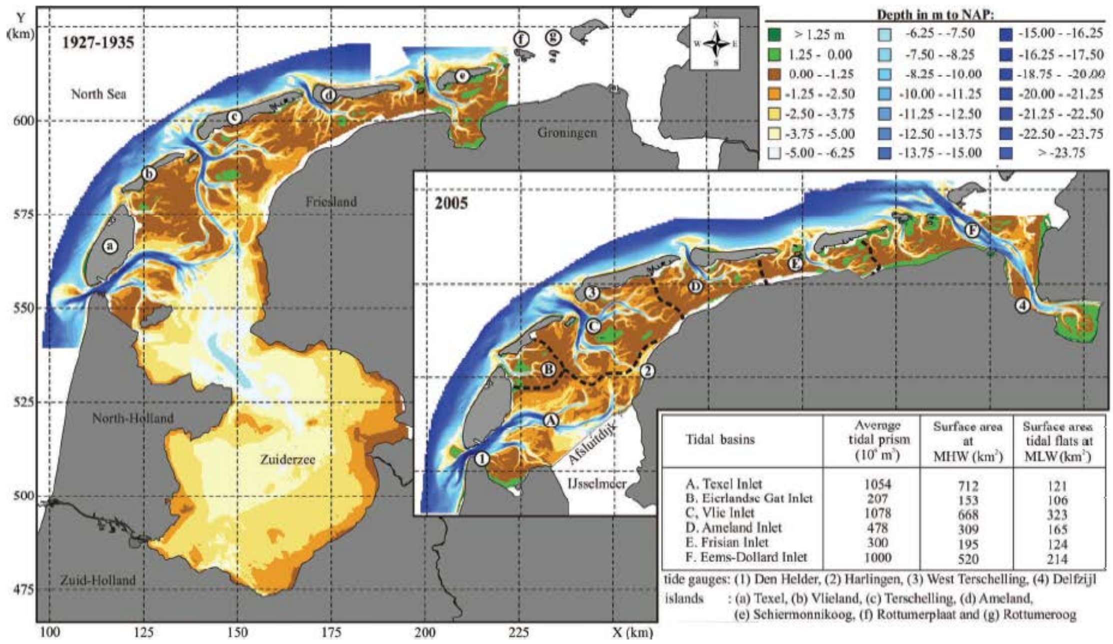


Figure 5.3 The Wadden Sea before and after construction of the Afsluitdijk (after Elias et al., 2012).

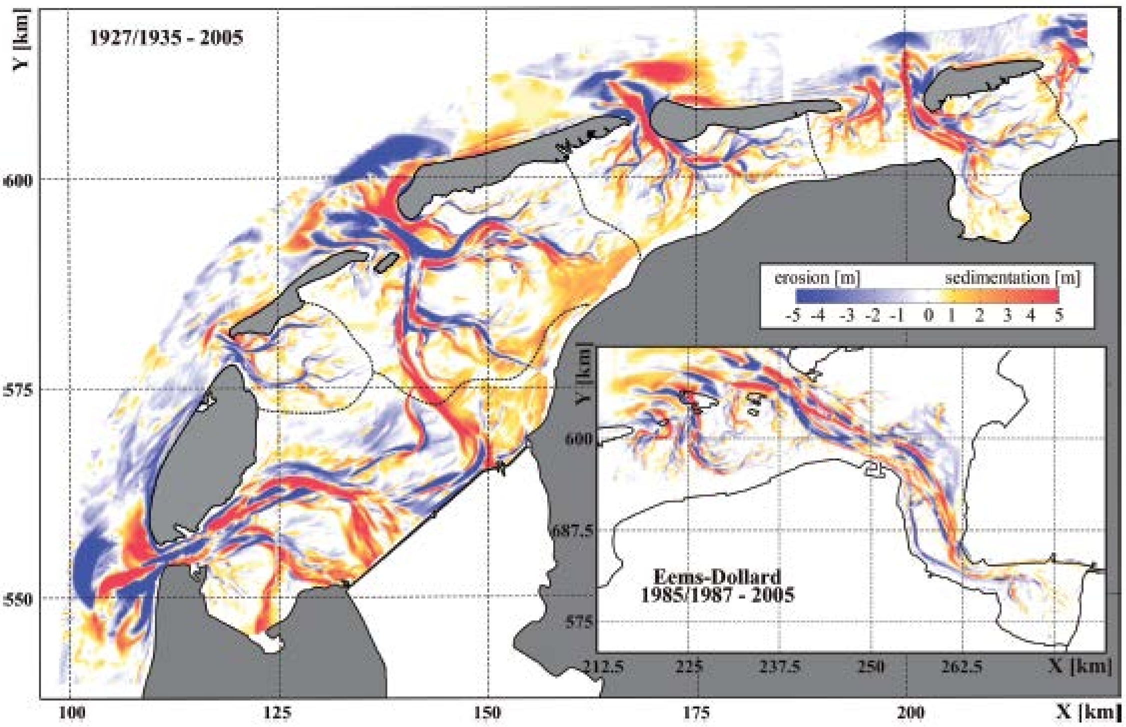


Figure 5.4 Sedimentation-erosion map over the period 1927/1935 – 2005 (after Elias et al., 2012).

5.4 The closure of the Lauwerszee

The closure of the Lauwerszee was completed in 1969. The project led to the creation of an inner basin called the Lauwersmeer. The closure caused a minor increase of the tidal range, differently from what was observed after the construction of the Afsluitdijk. However, due to the decrease of the tidal basin area by about one third, the tidal prism and thereby the magnitude of flow velocity decreased significantly. The tidal asymmetry changed such that it became more flood-dominant favouring sediment import (Oost, 1995; Wang, 2009b).
The project resulted in an infilling of the tidal channels (in particular the Zoutkamperlaag – Section 8.3.6) with erosion of the outer delta, and increase of the wave induced transport towards the coast of Schiermonnikoog (Oost, 1995). Nevertheless, the sedimentation in the basin and the erosion of the ebb-tidal delta are more or less in balance. As a consequence and until present, the closure has not caused a severe erosion problem of the adjacent coasts, in contradiction to the closure of the Zuiderzee. For example, the erosion observed in the north-western part of Schiermonnikoog is not leading to problems until now, due to the massive sedimentation from sand derived from the ebb-tidal delta.

5.5 Nourishments

The first beach nourishments on the Dutch Wadden islands were built in 1979 at Texel and Ameland. Since then, a considerable amount of sand was used in the form of beach and shoreface nourishments. The total volume of nourishments placed on the islands is given in Figure 5.5, with sub-division per island (“kustvak”) and type. The nourishment volumes at each island and subdivided for each Jarkus transect are given in Figure 5.6 - Figure 5.9. The largest amount of nourishments have been applied at Texel and Ameland, while Schiermonnikoog has never been nourished. Nourishment volumes show a general even sub-division between shoreface and beach nourishments. This differs from the other Dutch Delta (the South-Westerly Delta), where the distribution is much more skewed towards beach nourishments.

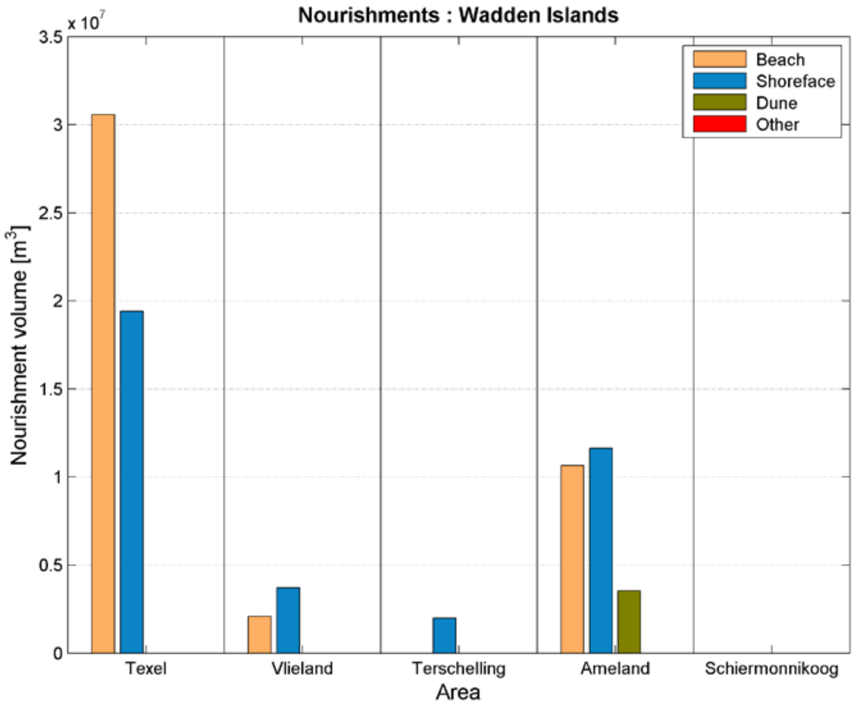


Figure 5.5 Total volume of nourishments applied in the Wadden islands. Sub-division per region and type.

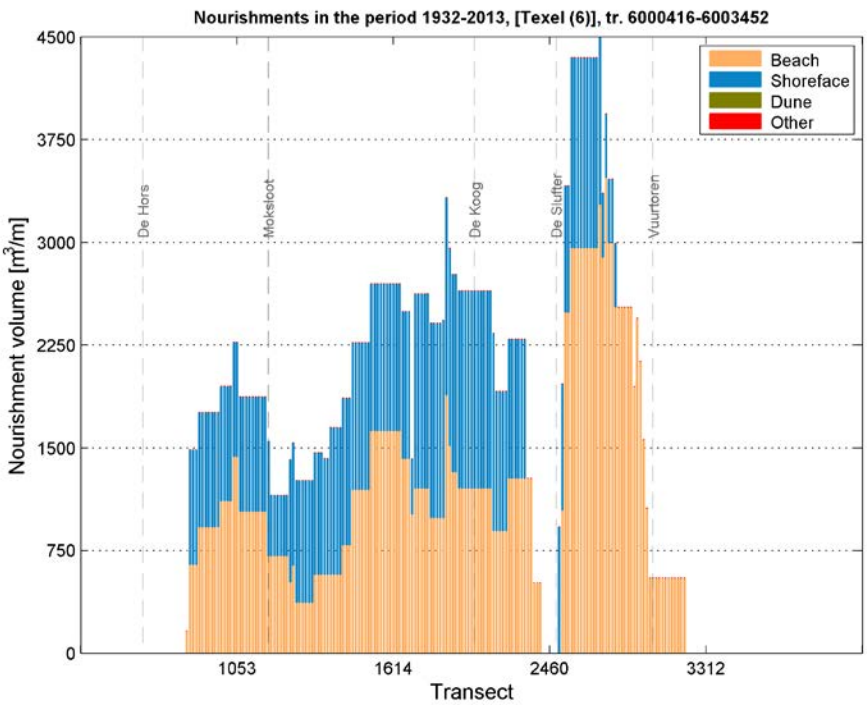


Figure 5.6 Total volume of nourishments in Texel. Sub-division per region and type.

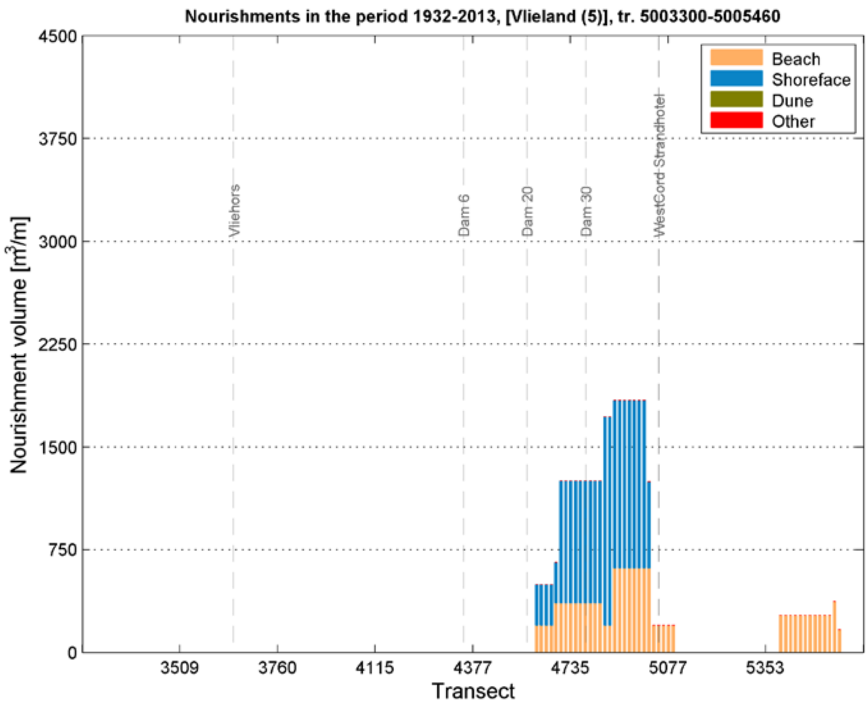


Figure 5.7 Total volume of nourishments in Vlieland. Sub-division per region and type.

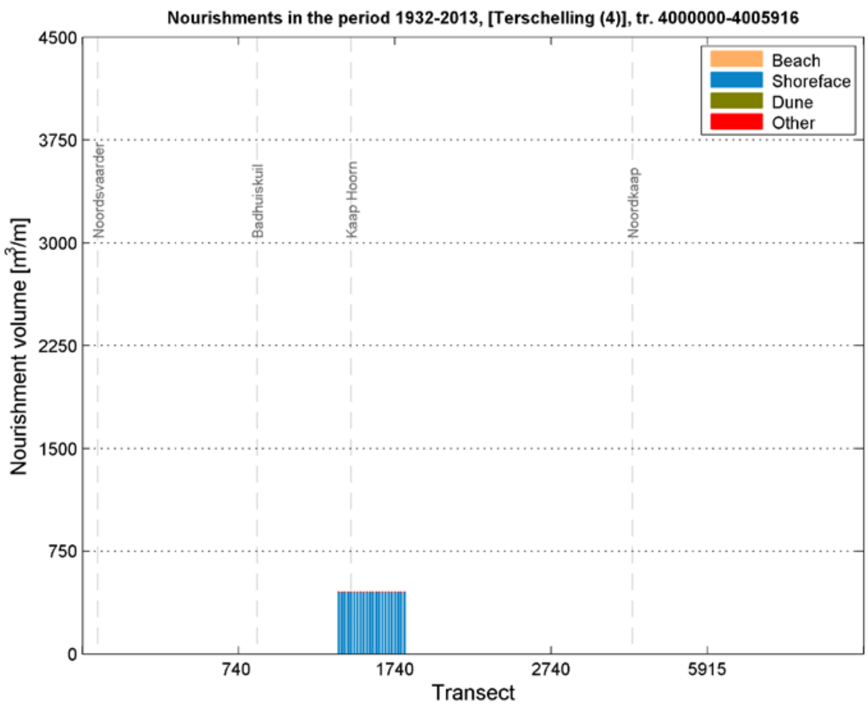


Figure 5.8 Total volume of nourishments in Terschelling. Sub-division per region and type.

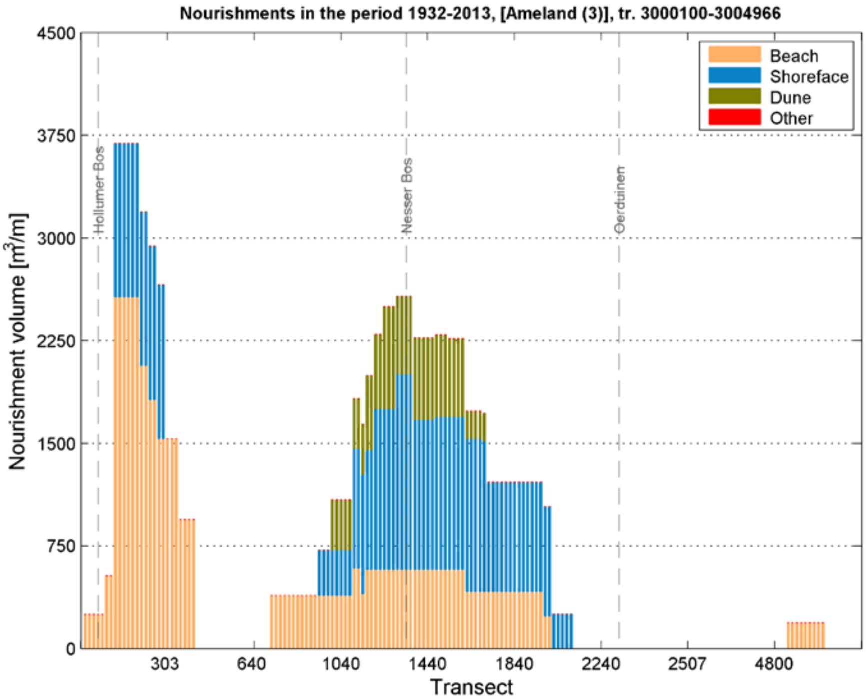


Figure 5.9 Total volume of nourishments in Ameland. Sub-division per region and type.

5.6 Dune management

The management of the coastal dunes is an old practice in The Netherlands, originally for flood protection and to form a sand buffer for coastal erosion and more recently to develop new functions as nature and recreation. Arens and Wiersma (1994) made a classification of the foredunes along the entire Dutch coast based on aerial photographs from 1988. The foredunes were classified according to the most prominent type of intervention at that moment. In general, only 8% of the foredunes along the Dutch Coast is natural, most of which is situated on the Wadden Islands.

Dune reinforcements with sand have taken place only at Ameland in 1980, 1990 and 1992.

5.7 Gas mining

It is commonly accepted that the various parts of a tidal inlet system of the Wadden Sea (ebb-tidal delta, backbarrier area and the islands at either side of the inlet) together form a so-called sediment sharing inlet system. It is assumed that, within such a system, sand or gas mining in one of these parts is in first instance “smeared out” within that part due to natural dynamics. However, on the longer run, as all parts “strive” toward maintaining an hydro-morphological balance between system dimensions and water movements, sediment can be exchanged between the various parts. Thus mining in the backbarrier, as is the case with other forms of relative sea-level rise, leads on the longer run to coastal erosion. Subsidence in the North Sea coastal area also leads to an additional need for sediment.
If the sand is not provided by means of additional nourishments, it is possible that some of the needed sand volume to compensate the subsidence will induce coastal erosion. Analysis of the needed sand nourishment volumes to compensate gas mining have been described in several reports (see for example Wang, 2006; Wang, 2009a).

6 Natural forcing and effects on coastal indicators

6.1 Short-term climatological forcing

The effect of storms on morphological indicators along the South Holland coast was investigated in details in Vuik et al. (2012). This chapter only provides a short summary based on their research, specifically for the Wadden islands.

The analysis focused on the period 1989 – 2010 as before this period information on wave height was not available at all stations. Long-term natural trends in the different indicators were subtracted from the yearly time series, to emphasize the effect of short-term changes due to yearly storminess.

Two storminess parameters were found to better describe the changes in morphological indicators:

- The yearly maximum water level
- The yearly mean wave energy defined as:

$$\text{Average wave energy} = \frac{1}{\text{wave measurements in the year}} \sum_{N=1}^{\text{wave measurements in the year}} H_s^2$$

As a year, the period between two Jarkus measurements was considered. The storminess parameters were derived by using meteorological data derived from different stations and then interpolated at each Jarkus transect (Vuik et al., 2012). In particular, for the Wadden islands, the following stations have been used: “Den Helder” and “Huibertgat” for the water levels and “Eierlandse Gat” and “Schiermonnikoog Noord” for the wave data. The locations of the different stations can be found in Figure 6.1.

The impact of the storminess parameters on different morphological indicators has been described in the following paragraphs.

Figure 6.1 Location water level stations (in yellow) and wave buoy (in red) used for the analysis (Vuik et al., 2012).

6.1.1 Impact of storms on probability of breaching of the first dune row

According to Vuik et al. (2012), the most suitable storminess parameter to describe changes in short term safety is the yearly mean wave energy. In general terms, the higher the wave activity for a specific year, the higher is the expected increase in probability of breaching of the first dune row (Figure 6.2).

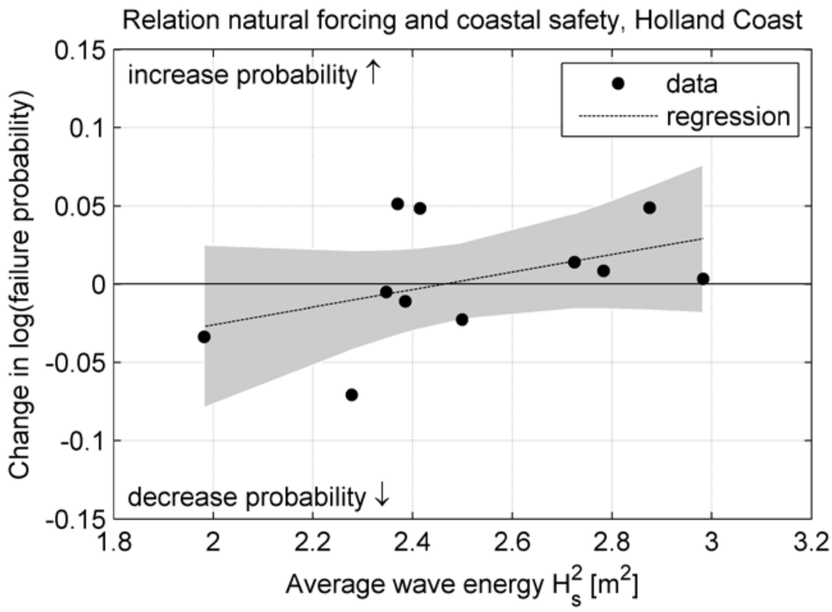


Figure 6.2 Changes in probability of breaching as a function of the yearly averaged wave energy for the Holland coast (Giardino et al., 2014a). The dashed line indicates the regression line between points, while the grey band the confidence interval around the regression.

The relation between changes in probability of breaching and storminess is given by the slope *m* of the fitting line between yearly wave energy and probability of breaching. Table 6.1 shows the relation between those variables through the coefficient *m.* As an example, a year with an average wave height of 1 m higher than at a different year, might increase in average the probability of breaching at Vlieland of a factor 0.14 (in logarithmic scale) or, in the words, a change for example from 10^{-5} to 1.14 x 10^{-5}. In general, the relations are quite weak and the variability in probability of breaching about one order of magnitude smaller than the variability due to nourishments, at least for the Holland coast (Giardino et al., 2014a).

As a reference, the average value of *m* for the Holland coast was equal to 0.06. The average larger values of *m* for the Wadden islands with respect to the Holland coastline, suggest that larger morphological changes are generally observed at the Wadden islands with respect to the Holland coast, leading also to larger variability in probability of breaching.

Table 6.1 Relation between variations in probability of breaching as a function of changes in yearly averaged wave height. (Vuik et al., 2012).

	m =(ΔLog P) / (ΔH_s^2)
Texel	0.39
Vlieland	0.14
Terschelling	-0.03
Ameland	0.15
Schiermonnikoog	0.08

6.1.2 Impact of storms on MKL

The most suitable storminess parameter to describe changes in MKL ("M"omentane "K"ust"L"ijn; Van Koningsveld and Mulder, 2005) is also the yearly averaged wave height (Vuik et al., 2012). In general, it can be expected that an increase of the yearly averaged wave height will lead to an average decrease of the MKL position (Figure 6.3).

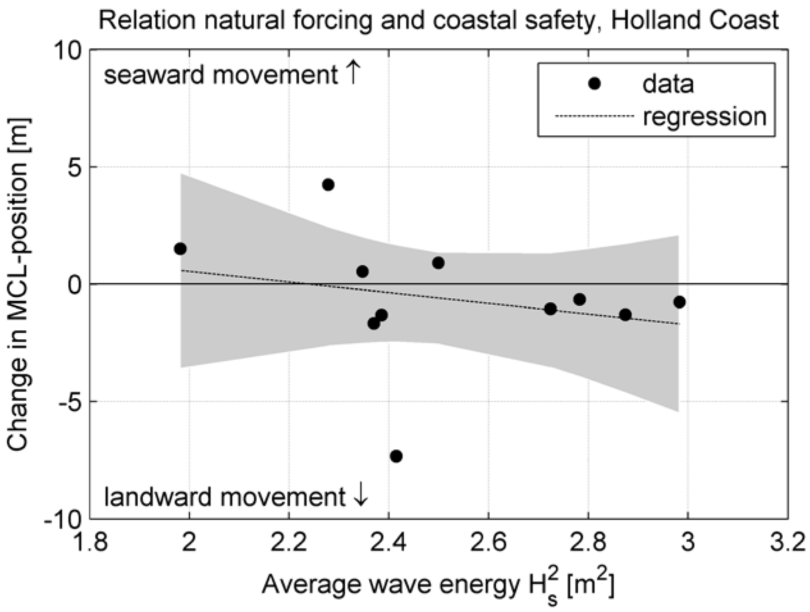


Figure 6.3 Changes in MKL position as a function of the yearly averaged wave energy for the Holland coast (Giardino et al., 2014a). The dashed line indicates the regression line between points, while the grey band the confidence interval around the regression.

Table 6.2 shows the relation between changes in MKL as a function of changes in yearly averaged wave height. Also in this case, the relations are quite weak and the impact on the MKL indicator much smaller than the one due to other anthropogenic changes (e.g. nourishments), at least for the Holland coast.

As an example, in a year with an average wave height of 1 m higher with respect to a different year, an average retreat of MKL position of more than 8 m can be expected at Vlieland. As a reference, the average value of *m* for the Holland coast was equal to -2. In average, also in this case the values of *m* are also larger (in absolute value) at the Wadden islands than at Holland coast, suggesting larger morphological changes at the islands with respect to the Holland coast, leading in turn to larger changes in MKL position.

Table 6.2 Relation between variations in MKL as a function of changes in yearly averaged wave height. (Vuik et al., 2012).

	m =(ΔMKL) / (ΔH_s^2)
Texel	-10.9
Vlieland	-8.6
Terschelling	-7.9
Ameland	0.7
Schiermonnikoog	-32.1

6.1.3 Impact of storms on dune foot position

The most suitable storminess parameter which was identified to describe changes in dune foot position is the maximum yearly water level (Vuik et al., 2012). The dune foot position is in fact only affected by the extreme storm surge events rather than the averaged wave energy. In general, an increase in maximum yearly water level, will lead to a retreat of the dune foot position (Figure 6.4).

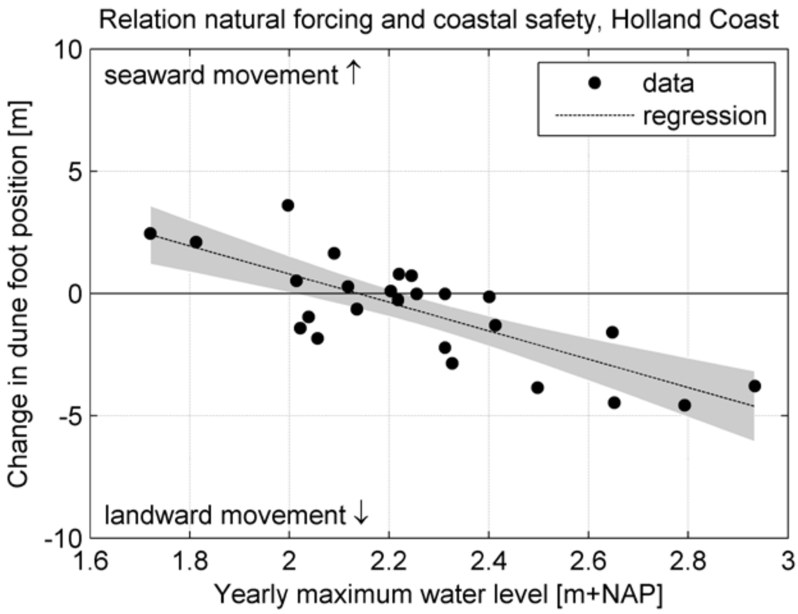


Figure 6.4 Changes in dune foot position as a function of the maximum yearly water level for Holland coast (Giardino et al., 2014). The dashed line indicates the regression line between points, while the grey band the confidence interval around the regression.

In Table 6.3 the relation between yearly maximum water level and changes in dune foot position is highlighted. As an example, in a year with a maximum water level of 1 m higher with respect to a different year, an average retreat of the dune foot position of more than 3 m can be expected at Vlieland. As a reference, the average value of *m* for the Holland coast was equal to -6.

Table 6.3 Relation between variations in dune foot position as a function of changes in yearly maximum water level (Vuik et al., 2012).

	m =(∆DF) / (∆WL)
Texel	-8.5
Vlieland	-3.3
Terschelling	-2.4
Ameland	-8.8
Schiermonnikoog	-1.3

6.2 Long-term climatological and geological forcing

Besides the yearly variation in storminess, other external natural factors have an effect on the long-term coastal morphology of the Wadden islands: the sea level rise and the subsidence. In 2014, the KNMI published new climate scenarios for the Netherlands, known as the

KNMI'14 scenarios (KNMI, 2014). The scenarios estimate sea level rise along the Dutch coast between 15-40 cm by 2050 and 25-80 cm by 2100.
However, the Delta Commission has recently presented new high end scenario's with more drastic figures with sea level rise scenarios (including subsidence) between 0.65 and 1.3 m by 2100 (Deltacommissie, 2008). Nevertheless, it is important to point out that the actual nourishment policy does not consider yet those scenarios to compute the yearly nourishment volume but a constant sea level rise equal to 1.8 mm/year, multiplied with the area of the whole coastal foundation (Figure 6.5). This area does not include the Wadden Sea and the Western Scheldt, part of the larger Coastal System, and which also exchange sediment with the Coastal Foundation.

It should be realized that any deformation within the morphology of the various parts of the sediment sharing inlet system, or any change in mud sedimentation may lead to higher or lower sediment demand. Hence our calculations are under the assumption that on average tidal morphology stays the same.

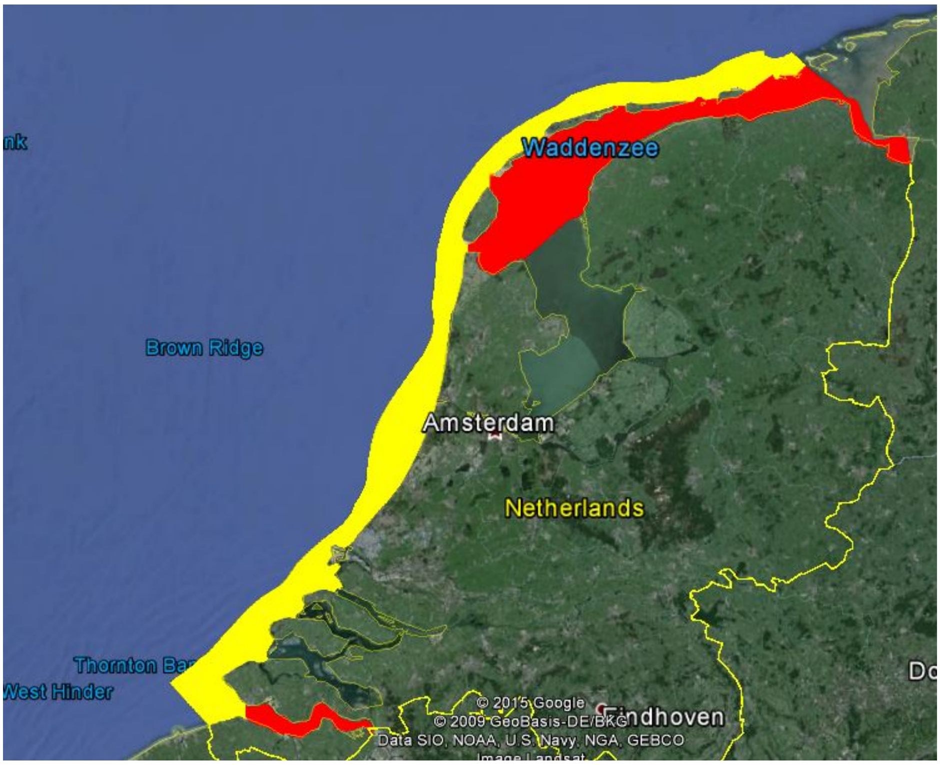


Figure 6.5 Definition of Coastal Foundation (yellow area) and Coastal System (red area + yellow area) (Giardino et al., 2011).

A map showing the possible predicted subsidence by year 2050 is shown in Figure 6.6. The map includes the effects of subsidence due to soil compaction, glacial isostatic adjustments and gas extraction. The map indicates a possible value for subsidence in order of 2 to 10 cm for most of the Wadden islands.

Sea level rise and relative subsidence are not further analysed in the report as, although important for long term effects, they have a secondary effect on the morphological indicators at the time scale of the available measurements.

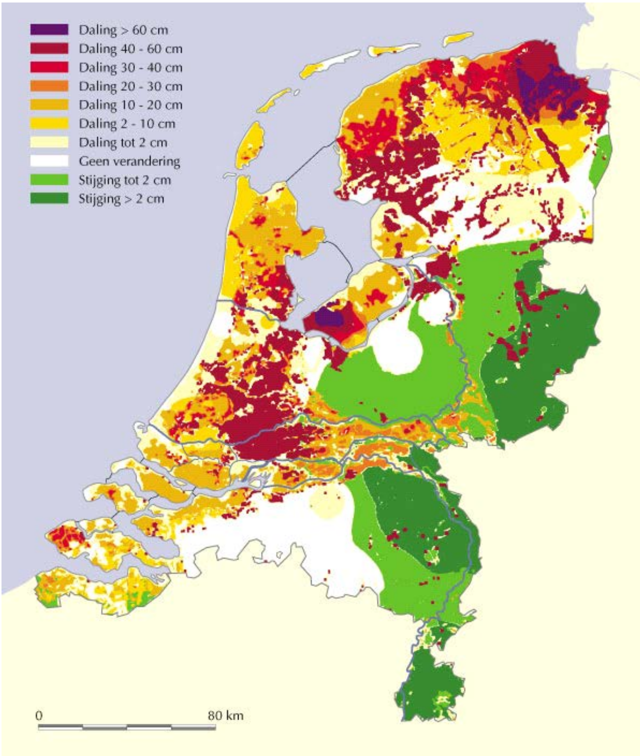


Figure 6.6 Expected subsidence and uplift for the all Netherlands by year 2050 (Rijkswaterstaat, NAM).

7 Large scale development of the Wadden islands based on morphological indicators

7.1 Introduction

In this chapter, a number of morphological indicators have been used in order to assess the impact of natural and anthropogenic forcing on the state of the coast. The indicators selected for the analysis are: the dune foot position, the mean high water and the mean low water position. These indicators are in fact already available starting from half of the nineteenth century, allowing for a comparison of the long term trends versus old and more recent anthropogenic changes (e.g. closure of the Zuiderzee and Lauwerszee, respectively).
As we are looking into the effects of changes considering a long temporal scale, the variations of the indicators are assessed based on large regions ("kustvakken"). Moreover, the complex and dynamic morphology of the Wadden Sea area does not allow performing a detailed trend analysis based on subdivision in smaller areas within the project, which was instead possible for the North- and South Holland cases (Giardino et al., 2012 and Giardino et al., 2013). This more detailed analysis within smaller areas can be found in the Beheerbibliotheek. For more information, refer to the project publicwiki webpage:
https://publicwiki.deltares.nl/pages/viewpage.action?pageId=72844168

7.2 Morphological development

The human impact during the last century has slowly contributed to the morphological development of the Wadden Sea area (Chapter 5). The construction of the Afsluitdijk and the start of 1990 nourishment policy are key events in the morphodynamic evolution of the Wadden Islands. For this reason, the analysis has been performed based on three different time windows:

- 1843 – 1931. During this time window, it is assumed that morphological changes were mainly driven by natural processes. Nevertheless, some anthropogenic actions were already taking place in this area (Chapter 5).

- 1932 – 1989. Two major artificial interventions are completed in this time window: the closure of the Zuiderzee with the Afsluitdijk in 1932 (Section 5.3) and the closure of the Lauwerszee in 1969 (Section 5.4). Those two interventions affected slowly respectively the hydrodynamics and morphology of the western and the eastern part of the Dutch Wadden Sea.

- 1990 – 2012. During this time window, large nourishments have been implemented especially at Texel and Ameland (Section 5.5).

The dataset of dune foot, mean high water and mean low water spans over a period of at least hundred years for any of the islands in the Wadden Sea, but with some differences at different locations. The spatial resolution of the dataset is about 1 km alongshore.
The evolution of the indicators has been analysed for each of the five largest Dutch Wadden Islands. In particular, average absolute changes within each of the regions and linear trends derived from the average of the trends in indicators within each region were computed (Figure 7.1).

The average of the values of the indicator with respect to the values of the same indicator in 1990 is evaluated. Choosing as reference value the year 1990 allows estimating the changes with respect to the year when the policy of “Dynamic Preservation” was applied. The bars around the average values of the indicators represent the maximum and minimum values of the averages for the years within each of the three periods.
The reader should also realize that the length of the three period analysed is different and which might have some influence on the results (e.g. influence of long term tidal variation as due to 18.6 year nodal cycle). Moreover, this has an influence on the length of the vertical line around each middle point (i.e. longer time window in turns leads to a larger bar around the middle value because the expected variability will be larger).

Values in the plots of Figure 7.1 are re-written in Table 7.1. The following conclusions can be drawn:

- In general, the indicators do not show clear trends in time. Moreover, different islands show very different behaviours from each other. The effect of the nourishments is very hard to distinguish at the regional spatial scale.
- The analysis of the trends in coastal indicators suggests that the largest negative trends (erosion) during the last two decades are observed at Terschelling. On the other hand, the largest accretion is suggested at Schiermonnikoog, which followed after the closure of the Lauwerszee.
- The large nourishment volumes implemented at Texel (Section 5.5) are necessary to maintain the coastline close to a stable position.

In Appendix C, the trends in indicators at each transect which were used to compute the average values as reported in Figure 7.1 are also given. From those more detailed plots additional information can be depicted:

- Presence of cyclic shoreline dynamic as for example the alongshore migration of the Bornrif at Ameland (Chapter 8).
- Effect of the construction of the Eierlandse Gat dam at Texel in 2005, close to transect 3041, and which induced a clear change in trend of the indicators between the two last time periods.
- The effect of the closure of the Lauwerszee at Schiermonnikoog is clear in the indicators mean high-water and mean low-water position. After the closure of the Lauwerszee, the reduction in tidal prism induced the migration of a large sand volume towards the coast. This induce first a large seaward shift of the coastline (i.e. approximately between transect 200 and 600) and which further migrated towards the north. Nowadays sever erosion prevails as the merged deposits are being reworked.
- The largest morphological changes in trend generally occur at the tips of the islands. In particular, the heads of the islands are generally characterized by a much wavier pattern, with rapid morphological changes. The tails of the islands are mainly characterized by slow alternating trends of accretion and retreat (see e.g. Terschelling, Ameland and Schiermonnikoog).

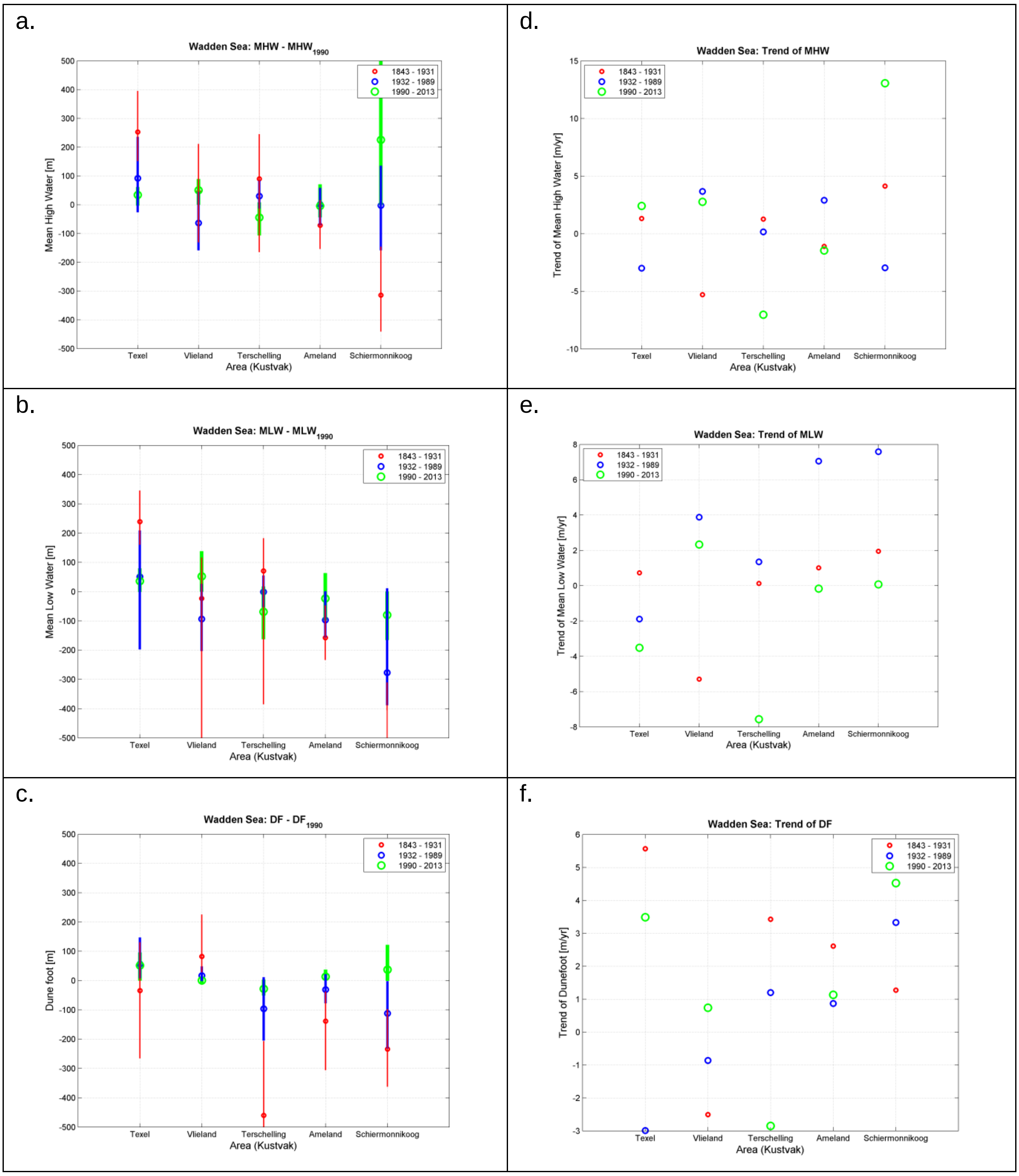


Figure 7.1 MHW, MLW, DF w.r.t. values in 1990 (a., b., c.) and linear trends of MHW, MLW, DF within the three periods 1843-1931, 1932-1989, 1990-2013 (d., e., f.). Negative values mean onshore shift, while positive values offshore migration. Both average values, as well as maximum and minimum value within each period are shown respectively as a circle and as a vertical bar.

Table 7.1 Relative value w.r.t. 1990 and linear trend of MHW, MLW, DF for the Wadden islands.

Texel	Period 1843-1931	Period 1932-1989	Period 1990-2013
MLW - MLW_{1990} (m)	240	51	36
MHW - MHW_{1990} (m)	253	92	34
DF – DF_{1990} (m)	-34	56	52
MLW trend (m/y)	0.7	-1.9	-3.5
MHW trend (m/y)	1.3	-3	2.4
DF trend (m/y)	5.6	-3	3.5

Vlieland	Period 1843-1931	Period 1932-1989	Period 1990-2013
MLW - MLW_{1990} (m)	-23	-94	53
MHW - MHW_{1990} (m)	44	-63	50
DF – DF_{1990} (m)	82	17	1
MLW trend (m/y)	-5.3	3.9	2.3
MHW trend (m/y)	-5.3	3.7	2.8
DF trend (m/y)	-2.5	-0.9	0.7

Terschelling	Period 1843-1931	Period 1932-1989	Period 1990-2013
MLW - MLW_{1990} (m)	71	-1	-69
MHW - MHW_{1990} (m)	90	30	-44
DF – DF_{1990} (m)	-460	-96	-28
MLW trend (m/y)	0.1	1.4	-7.6
MHW trend (m/y)	1.3	0.2	-7
DF trend (m/y)	3.4	1.2	-2.8

Ameland	Period 1843-1931	Period 1932-1989	Period 1990-2013
MLW - MLW_{1990} (m)	-157	-96	-23
MHW - MHW_{1990} (m)	-72	1	-4
DF – DF_{1990} (m)	-138	-30	14
MLW trend (m/y)	1	7.1	-0.2
MHW trend (m/y)	-1.1	2.9	-1.5
DF trend (m/y)	2.6	0.9	1.1

Schiermonnikoog	Period 1843-1931	Period 1932-1989	Period 1990-2013
MLW - MLW_{1990} (m)	-546	-277	-80
MHW - MHW_{1990} (m)	-314	-3	226
DF – DF_{1990} (m)	-234	-112	37
MLW trend (m/y)	2	7.6	0
MHW trend (m/y)	4.1	-2.9	13.1
DF trend (m/y)	1.3	3.3	4.5

8 Effects of sand waves, tidal channels and nourishments on coastal indicators

8.1 Introduction

The effectiveness of nourishments is, among others, dependent on the morphological development of the coastal system at several spatial and temporal scales. This chapter specifically focusses on the morphological development of sand waves and tidal channels in the Wadden islands, including also possible effects on nourishments. We define here as sand wave any time fluctuation of the coastline, independent of the origins of the instability. In other words, we focus here on the effects that those oscillation have on the coastal indicators, while the analysis of the causes (e.g. local hydrodynamic conditions and/or movements of banks and tidal channels in the outer delta) goes outside the scope of this study. Although it is generally accepted that most of the sand waves in the Wadden islands can be explained by sand banks moving in the direction of the longshore currents (Verhagen, 1989).

8.2 Effects of sand waves and nourishments on morphological indicators

8.2.1 Visualization of sand waves

This section describes the way of visualizing the sand waves which is used in this report. Figure 8.1 shows the mean high water position (w.r.t. RSP“Rijks“S”trand”P”aal) at four arbitrary transects at Vlieland. The location of the four transects is shown in Figure 8.2. At the left hand side of Figure 8.1 the absolute mean high water position is shown. At the right hand side, the residual of the mean high water position (absolute value – trend) is shown. The blue line shows the actual changes, the green line the smooth mean high water position, after applying a moving average low-pass filter. In this way, only the signal on a longer time scale is highlighted and yearly oscillations are filtered out. The red line gives the linear trends per transect based on the smoothed signal for the whole time series. The smoothed residual together with the gradient gives the most important information to show how the coastline develops, especially regarding the long-term variations (sand waves). The smoothed residual has been presented in a filled contourplot in Figure 8.3, together with the gradient of the corresponding trends in the top panel. This way of visualizing the results makes it easier to show a larger coastal area (e.g. whole kustvak) and to show not only the information on the mean high water position, but also the dune foot and mean low water lines.

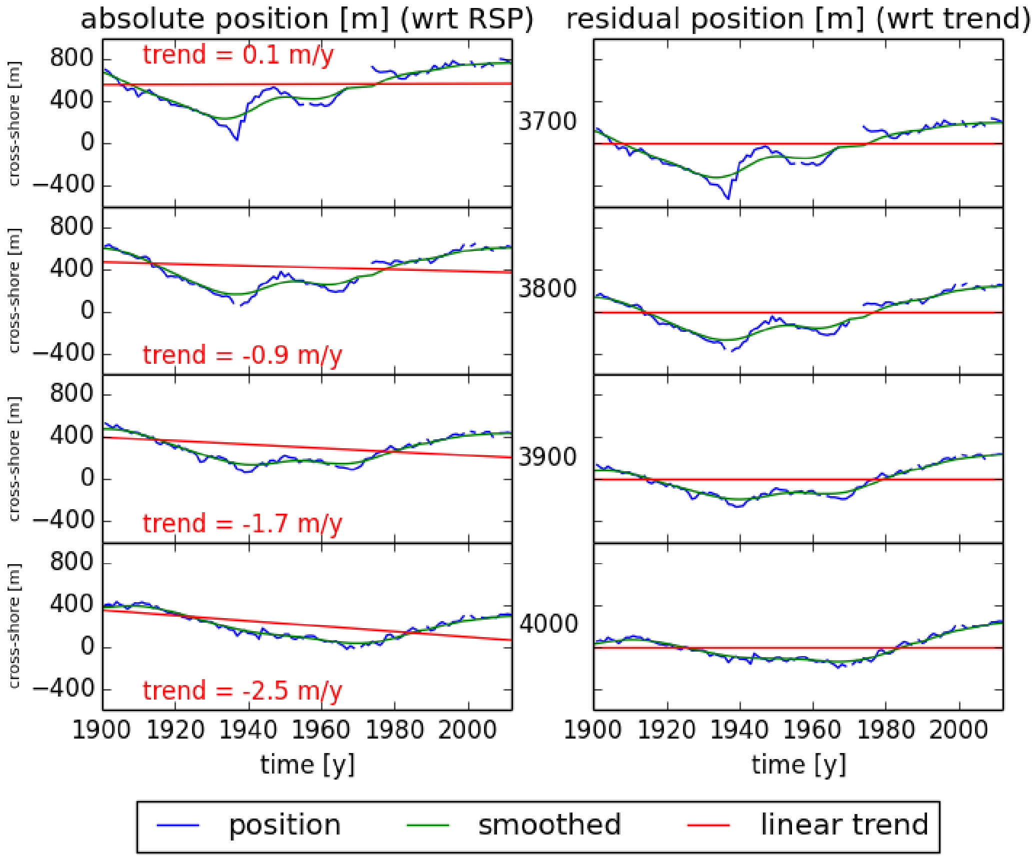


Figure 8.1 Mean high water position for four transects at Vlieland. The blue line represents the actual mean high water position changes, the green line the smoothed mean high water position after applying a low-pass filter, and the red line the linear trend. The figures in the left panel show the absolute values, while the figures in the right panel show the values relative to the linear trends.

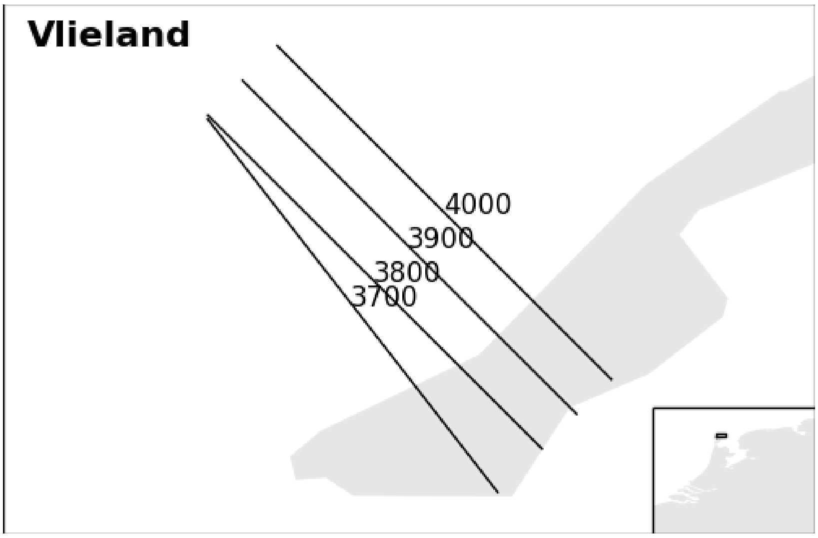


Figure 8.2 Location of the 4 transects analysed in Figure 8.1.

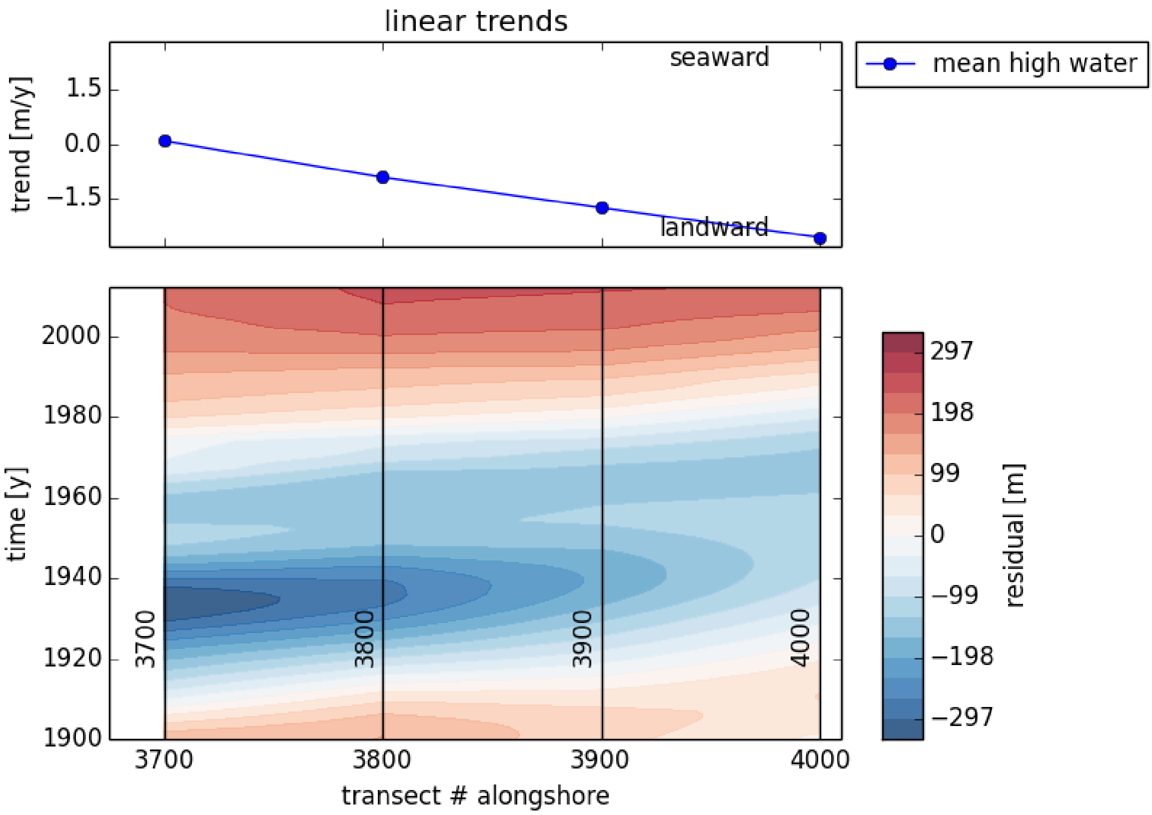


Figure 8.3 Linear trend of mean high water position (top) and contour plot of residual mean high water position (below) for a part of Vlieland. See Figure 8.2 for the location.

Figure 8.4, Figure 8.7, Figure 8.9, Figure 8.11, and Figure 8.13 show the smoothed residuals for dune foot, mean high and mean low water line position, together with the gradient of the corresponding linear trends and the nourishments applied (both in time and space), for all Wadden islands (kustvakken). The size of the colorbar at the right hand side of the figures is proportional to its range. The nourishments are indicated as line segments at the alongshore stretch at construction time. The line width is a proxy for the nourishment volume per running meter of coast and the color indicates the type of nourishment as specified in the legend. Comparison of the three smoothed residuals per area (kustvak), shows that in general similar patterns can be recognized in dune foot, mean high and mean low water lines. Also the underlying trends are almost equal for most areas.

8.2.2 Sand wave characteristics

Verhagen (1989) made an inventory of the sand waves along the whole Dutch coast. He provided indicative figures of horizontal amplitude, celerity and period for all coastal areas. The figures as given by Verhagen, are presented in Table 8.1. It should be noted that Verhagen derived these figures from the shoreline position, defined as a volume based position between mean high and mean low water. As he also observed, sand waves in the Wadden islands are generally very clear, except for Texel. However, a large variation in amplitudes and celerities can be observed. Because of many disturbing effects in the extremely dynamic environment a clear analysis of the sand waves is difficult.

Table 8.1 Sand wave characteristics along the Wadden Coast as found by Verhagen (1989).

Area	Amplitude [m]	Celerity [m/y]	Period [y]
Texel	?	?	?
Vlieland	25-600	220-270	60-80
Terschelling	25-1900	240-400	40-90
Ameland	25-2500	310-450	40-90
Schiermonnikoog	50-850	240-340	50-100

Table 8.2 gives an estimation of sand wave amplitude, celerity and period as obtained from the analysis carried out in this report. Since this is based on dune foot, mean high water and mean low water lines, the figures are not fully comparable to those of Verhagen (1989). Some of the values are in the same order of magnitude, but differences can be found. In particular, the values computed by Verhagen show in general larger celerities and smaller periods, which are somewhat difficult to justify based on our analysis.
At Texel, sand waves are most difficult to detect compared to the other Wadden islands, which is most likely the reason that Verhagen did not provide figures of this island.

Table 8.2 Sand wave characteristics along the Wadden Coast as derived from this study.

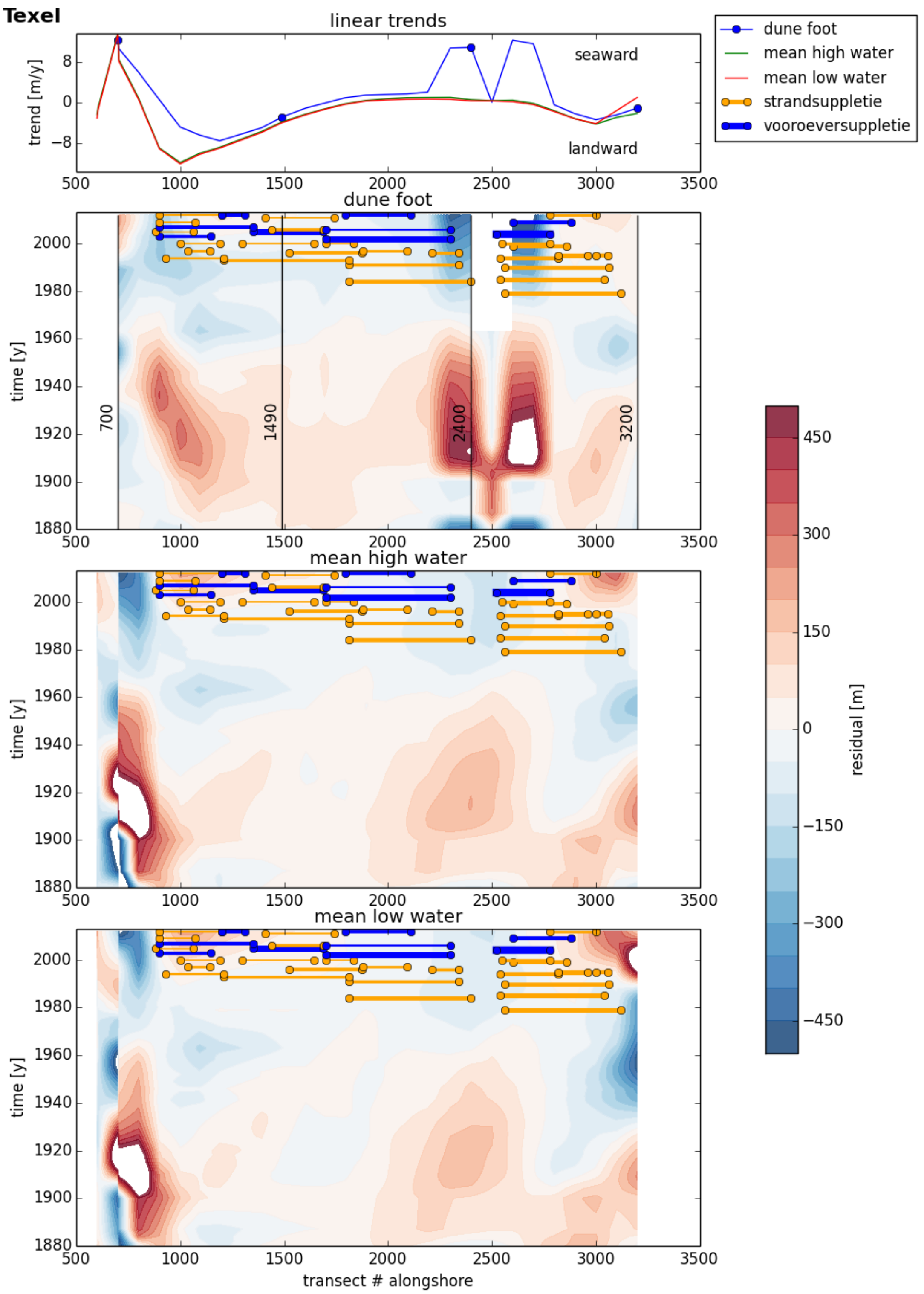
Area	Amplitude [m]	Celerity [m/y]	Period [y]
Texel	50-150	100-150	80-120
Vlieland	25-500	140	100-150
Terschelling	100-500	50-250	70-150
Ameland	50-500	200-250	100-130
Schiermonnikoog	150-250	240-340	50-100

8.2.2.1 *Texel*

At Texel, a number of alongshore time varying features are visible at some locations, but not a typical sand wave pattern traveling along the whole island. In Figure 8.4 (b), wave patterns are most clear at transect 700 to 1400, at 2200 to 2500 and at 3000 to 3200. From the positioning of the transects, as displayed in Figure 8.4 (a), it becomes clear that the sand waves are mainly visible near the island tips and south of the ‘Slufter’, a small tidal inlet located around transects 2400-2600. The Slufter shows the largest morphological changes, at least in terms of dune foot position as shown in Figure 8.4 (b). The largest morphological changes are visible at the two sides of the inlet channel.
Moreover, in the top panel of the same figure, a peak in the linear trend is found at transect 700. This is caused by morphological changes following a staircase pattern which is visible in Figure 8.5, where the changes in dune foot position are plotted for four different transects (transect 700, 1490, 2400, 3200). A similar staircase pattern is also found at transect 2400. Detailed inspection shows that the same behaviour occurs between transects 700 to 800 (near the south-western island tip) and between transects 2300 to 2700 (around the slufter). The reason for the jumps in the dune foot position is most likely related to the emergence of new dune rows. For example, the changes occurred around transect 700 approximately at year 1910 were related to the landing of the shoal Onrust (Figure 8.16). Therefore, this is not related to a typical sand wave feature although can influence the contour plot in Figure 8.4 (b).
The discontinuity in the lower two panels of Figure 8.4 (b), identifying changes in mean high water and mean low water line, around transect 700 is related to the position of this transect at the southern tip of the island and different changes at the two sides of the tip. This tip is named “De Hors”, and it is characterized by very large beaches and dune area.

Several nourishments have been carried at nearly all transects. As there is not a clear sand wave pattern, it is also not possible to correlate the presence of nourishments to alongshore oscillations of the coastline position.

(a)



(b)

Figure 8.4 (a) Map of Texel with the positions of transects used as ticks in (b).(b)Contour plots of residuals (absolute values – trend) of dune foot, mean high and mean low waterline positions of Texel. The respective linear trends for the entire period are in the top panel.

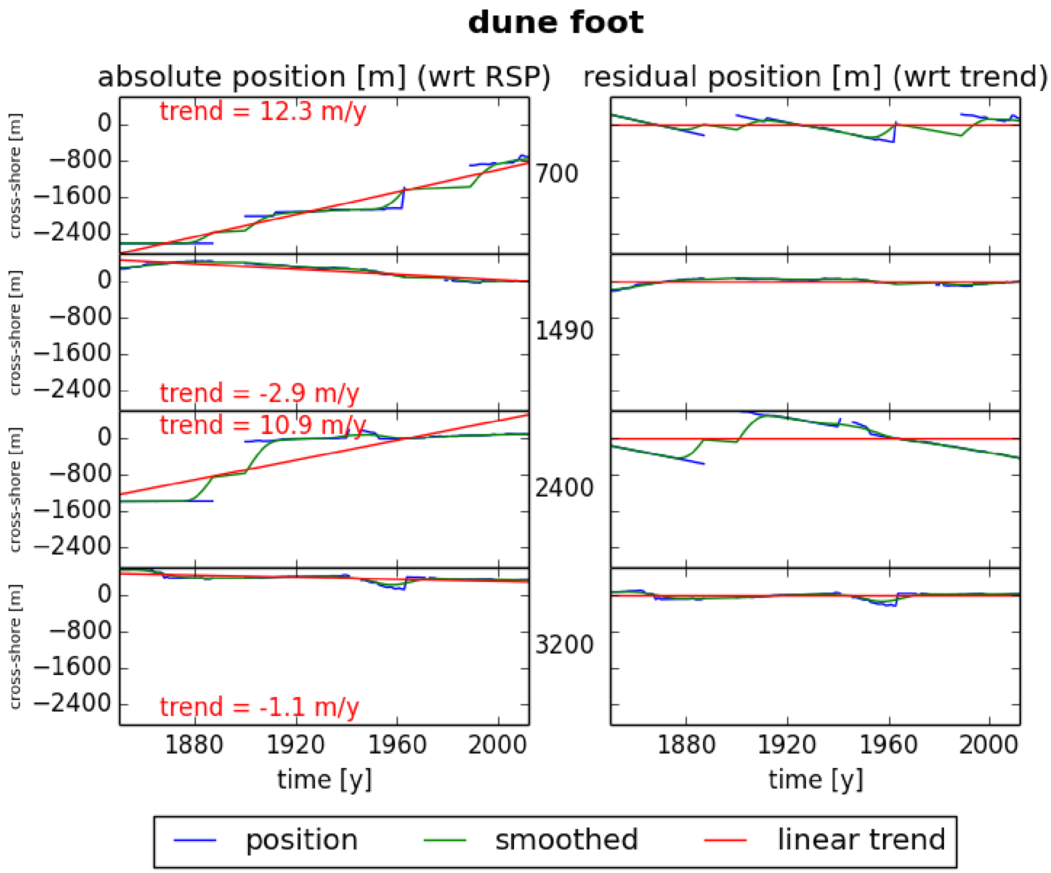


Figure 8.5 Dune foot position for four transects at Texel. The blue line represents the actual dune foot position changes, the green line the smoothed dune foot position after applying a low-pass filter, and the red line the linear trend. The figures in the left panel show the absolute values, while the figures in the right panel show the values relative to the linear trends.

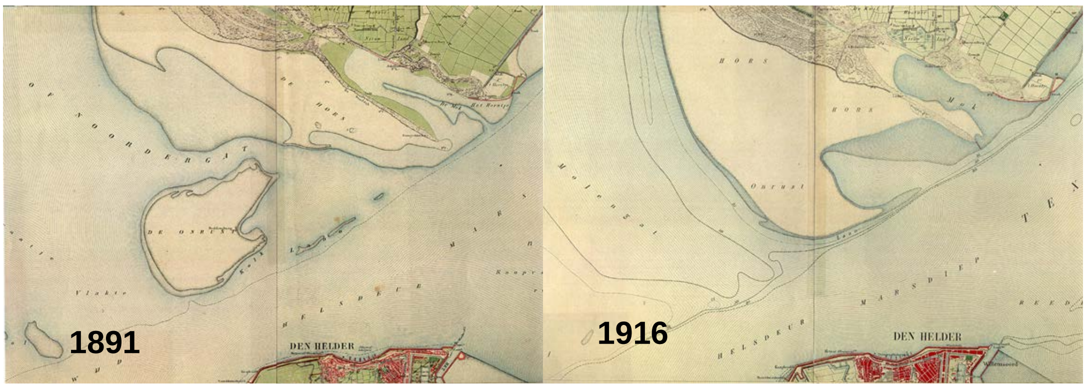


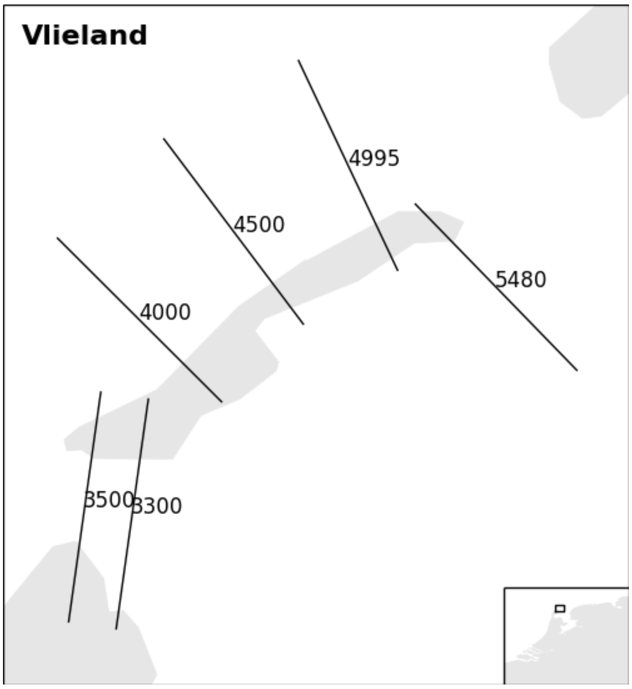
Figure 8.6 Historical maps of the southern tip of Texel. On the left hand side, map of the year 1891, on the right hand side map of the year 1916.

8.2.2.2 Vlieland

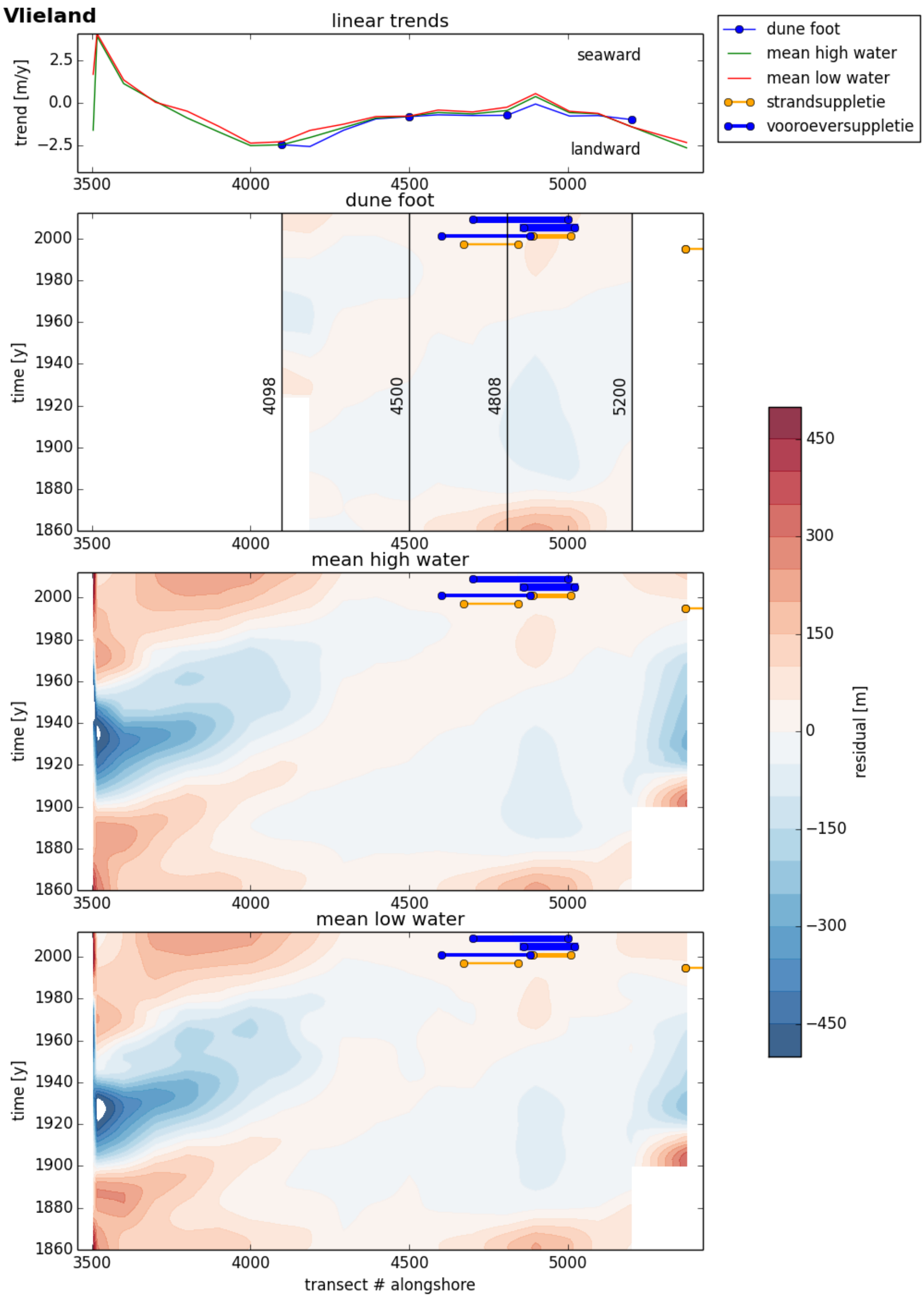
At Vlieland, a clear and regular sand wave pattern can be observed in Figure 8.7(b). Also the linear trends, underlying the residual pattern, are nearly equal for all three contour lines. Note that historical data on dune foot position are more limited at this island and therefore some information on dune foot position changes is missing for a part of the island. The amplitude is maximal, for mean high water and mean low water, at the South Western tip (transect 3500)

and quickly reduces in north eastern direction along the coast. There is no obvious phase difference visible between alongshore morphological changes in mean high- and mean low-water position, while a small phase shift can be observed sometimes in the response of the dune foot position indicator.
In the transect range 4800-5000 during the period 1860 to 1870, a larger peak in sand wave is observed, which is much more pronounced compared to the peak which appears around the year 2000 (one sand wave cycle later). This might be explained considering that this area is close to the north eastern island tip, where the morphodynamics are influenced by different mechanisms with respect to the north-west side of the island facing the north sea (e.g. island migration, large scale delta dynamics) rather than alongshore transport mechanisms.

The nourishments that have been carried out at Vlieland are all located in the region between transect 4600 and 5000. It is interesting to see that the nourishments are all carried out in a decade right after the peak in the residuals of dune foot, mean high water and mean low water position, when the coastline starts a natural retreat. The third row of plots (related to transect 4808) in Figure 8.8 nicely illustrates that situation in that nourished area. Around the year 1980, a local maximum is found for that transect (left hand panel). From then onwards, the dune foot position starts to slightly move landward. Since the nourishments take place, the dune foot position is approximately stable; a few local peaks are visible that most likely relate to individual nourishments.



(a)



(b)

Figure 8.7 (a) Map of Vlieland with the positions of transects used as ticks in (b).(b)Contour plots of residuals (absolute values – trend) of dune foot, mean high and mean low waterline positions of Vlieland. The respective linear trends for the entire period are in the top panel.

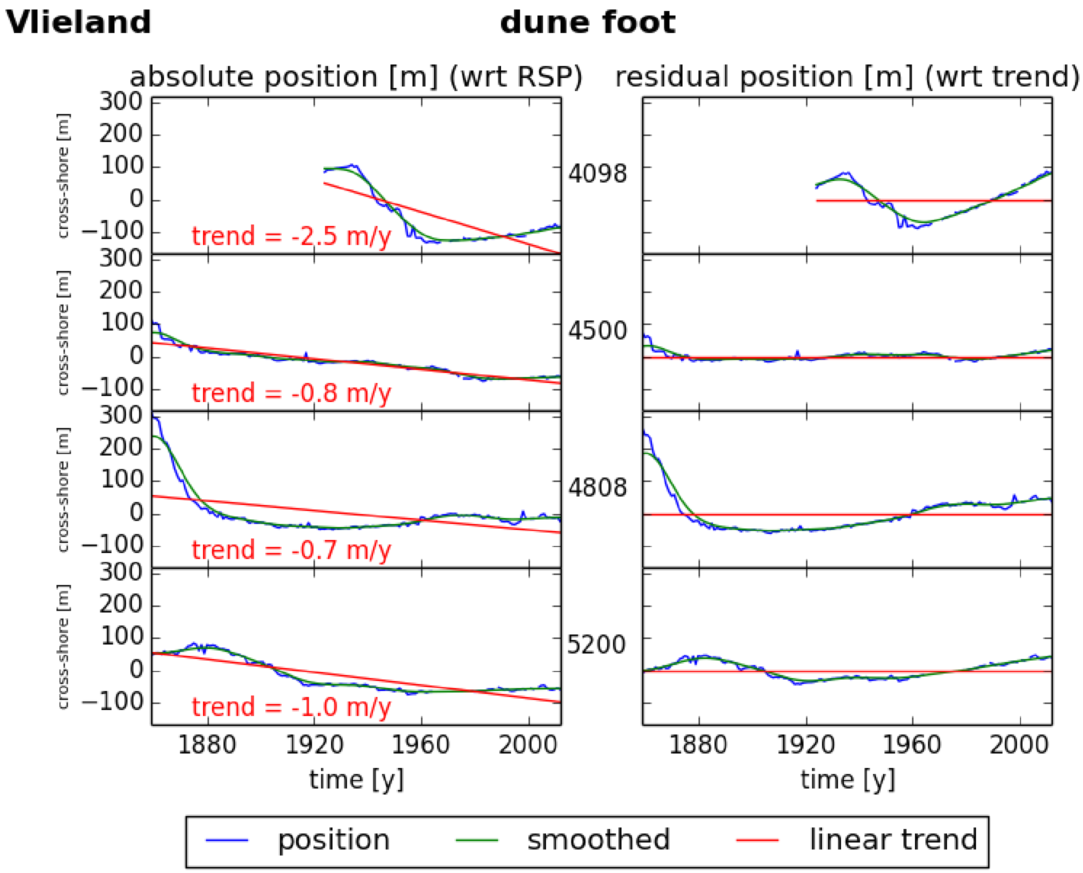
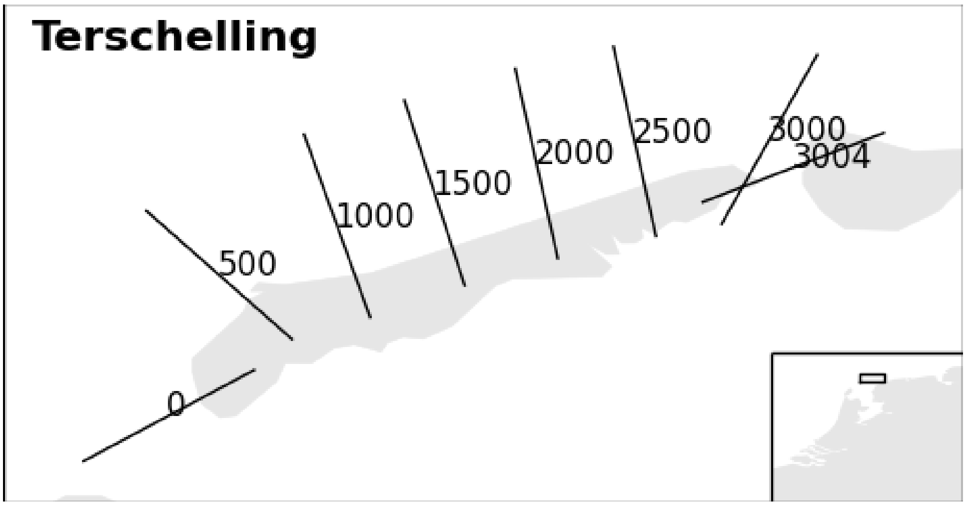


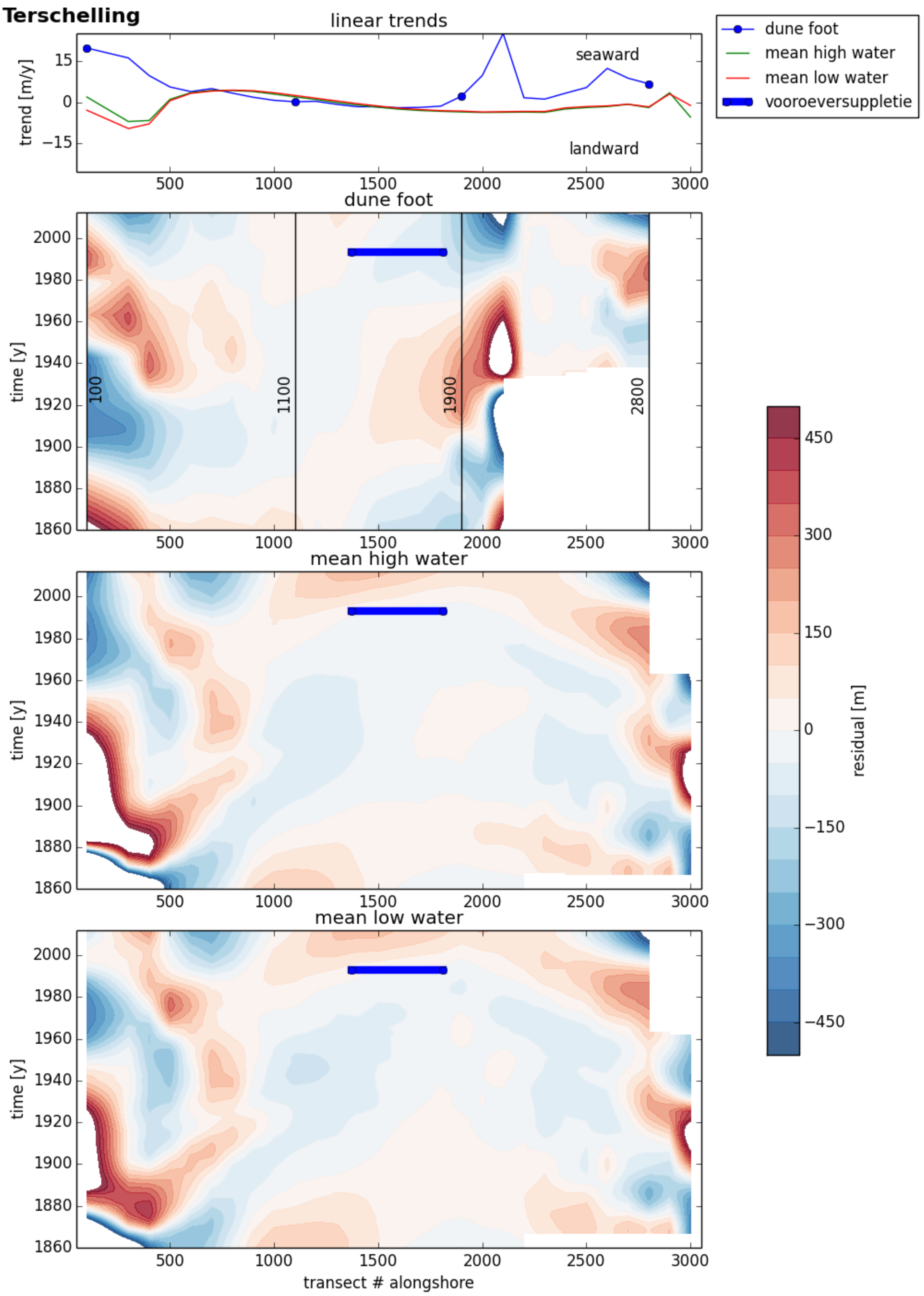
Figure 8.8 Dune foot position for four transects at Vlieland. The blue line represents the actual dune foot position changes, the green line the smoothed dune foot position after applying a low-pass filter, and the red line the linear trend. The figures in the left panel show the absolute values, while the figures in the right panel show the values relative to the linear trends.

8.2.2.3 Terschelling

The sand wave pattern at Terschelling is very irregular, as can be observed in Figure 8.9(b). At both island tips, until about transect 700 and from transect 2000 upwards, the waves travel in western direction (south-west at the island head), and the amplitudes are large, up to 500 m. In the area in between, the travel direction of the sand waves is eastward. This suggests that the morphodynamic development of the sand waves is mainly influenced by the local angle between coastline orientation and direction of wave approach.
At transect 2100, the dune foot residual as well as the linear trend significantly differ from the adjacent area. The reason is that between the years 1920 and 1940 there are two major seaward changes in the dune foot position (O(100) m).Those changes might be related to attempts to establish sand dikes around that period. As a result, the linear trend in dune foot changes is significantly positive (about 17 m/year) and the residual is negative before 1930, positive between 1930 and 1980 and then again negative.
There is only one shoreface nourishment which was built on the island in 1993 and with a volume of 2 million m^3 (NOURTEC project). The effectiveness of this nourishment can be clearly seen in Figure 8.9 (b) in the plots of mean high water and mean low water residual. After the nourishment a clear positive residual can be seen, which is however partly due to the natural sand wave like behaviour.



(a)



(b)

Figure 8.9 (a) Map of Terschelling with the positions of transects used as ticks in (b).(b)Contour plots of residuals (absolute values – trend) of dune foot, mean high and mean low waterline positions of Terschelling. The respective linear trends for the entire period are in the top panel.

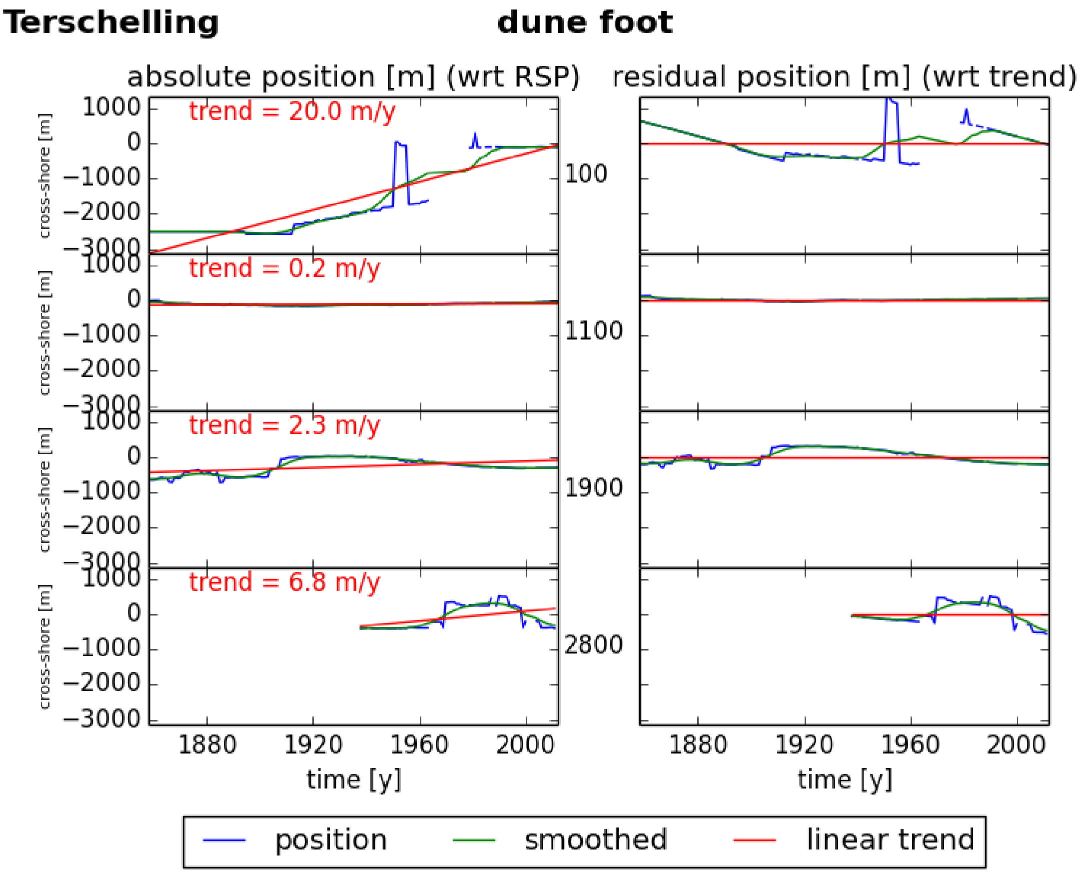
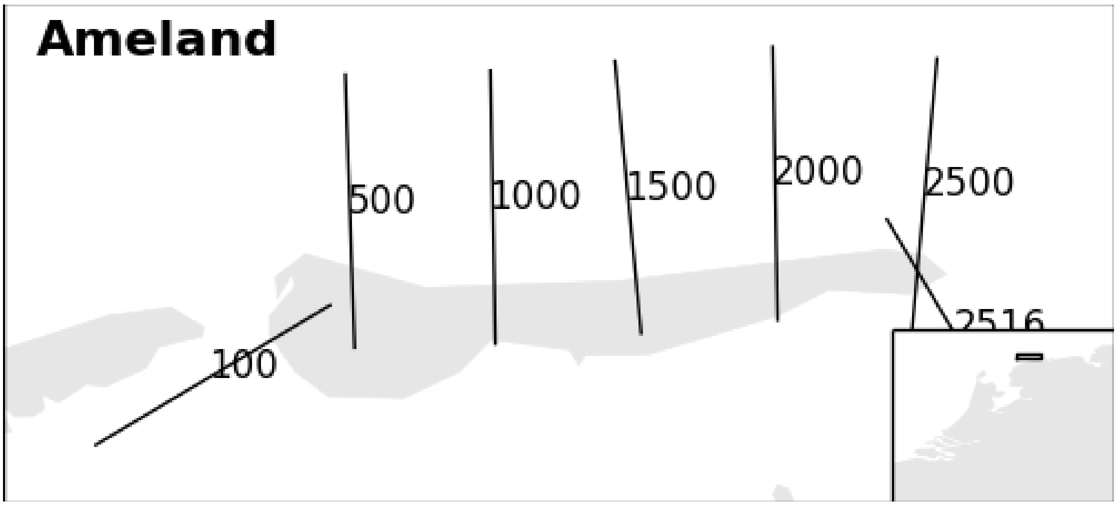


Figure 8.10 Dune foot position for four transects at Terschelling. The blue line represents the actual dune foot position changes, the green line the smoothed dune foot position after applying a low-pass filter, and the red line the linear trend. The figures in the left panel show the absolute values, while the figures in the right panel show the values relative to the linear trends.

8.2.2.4 Ameland

At Ameland, the dune foot does not show a clear sand wave pattern, but the mean high water and mean low water line do show this behaviour (Figure 8.11). The sand waves are in particular visible in the western region of the island, up to transect 1500. The large residuals near the western tip, up to transect 500, are due to the merging of the ‘Bornrif’ with the island. The Bornrif is a sandbar that periodically moves towards the coast and attaches to the south-west coast of Ameland. This cyclic behaviour has a period of approximately 50 years. Figure 8.11 shows two events at which the Bornrif moved towards the shore and attached to the beach, first in the 40s and then in the 90s. Especially after 1980 this merged Bornrif clearly travels in eastward direction, approximately until transect 1000. The nourishments that are carried out nicely follow the tails of this wave in eastward direction.



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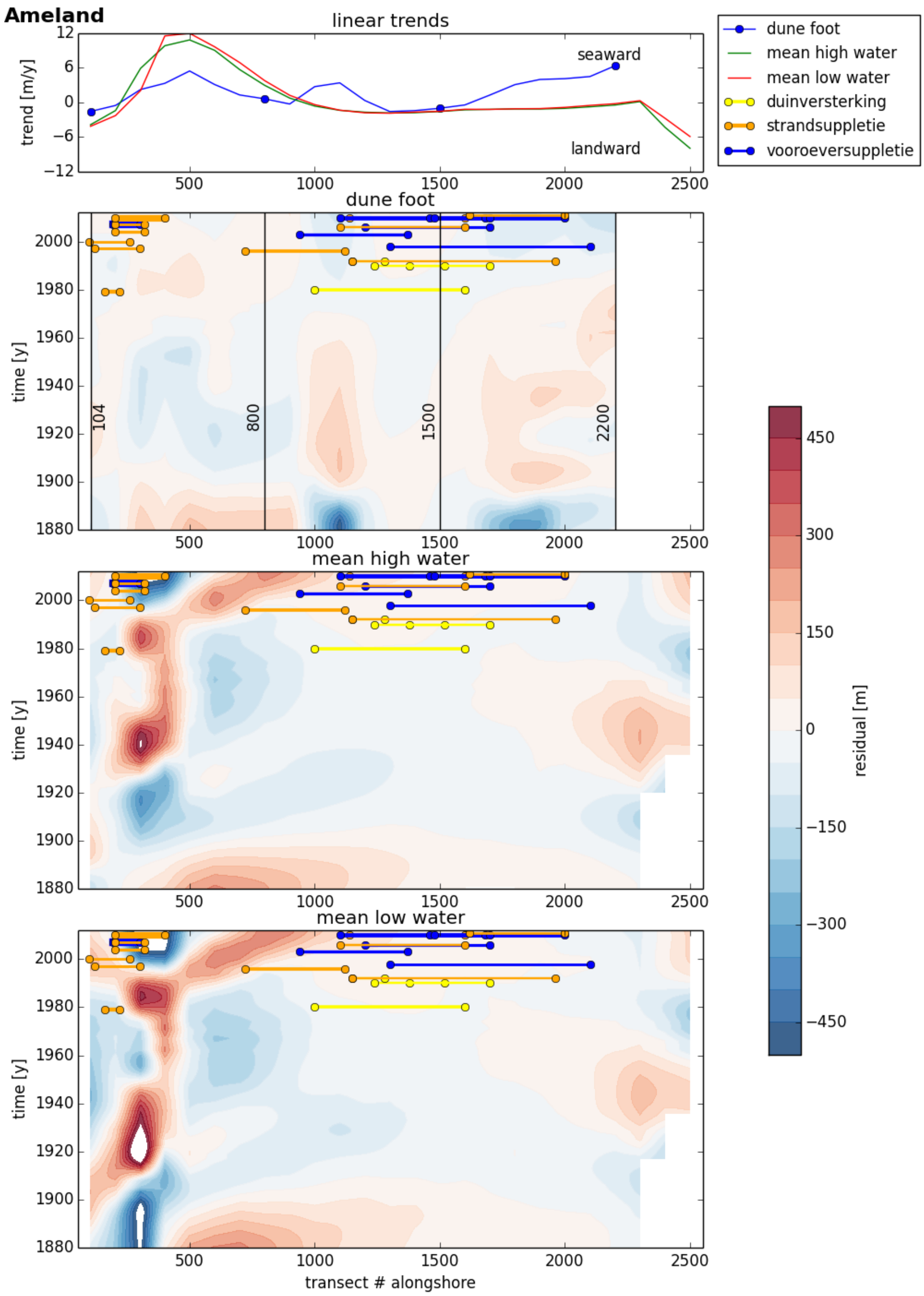


(b)

Figure 8.11 (a) Map of Ameland with the positions of transects used as ticks in (b).(b)Contour plots of residuals (absolute values – trend) of dune foot, mean high and mean low waterline positions of Ameland. The respective linear trends for the entire period are in the top panel.

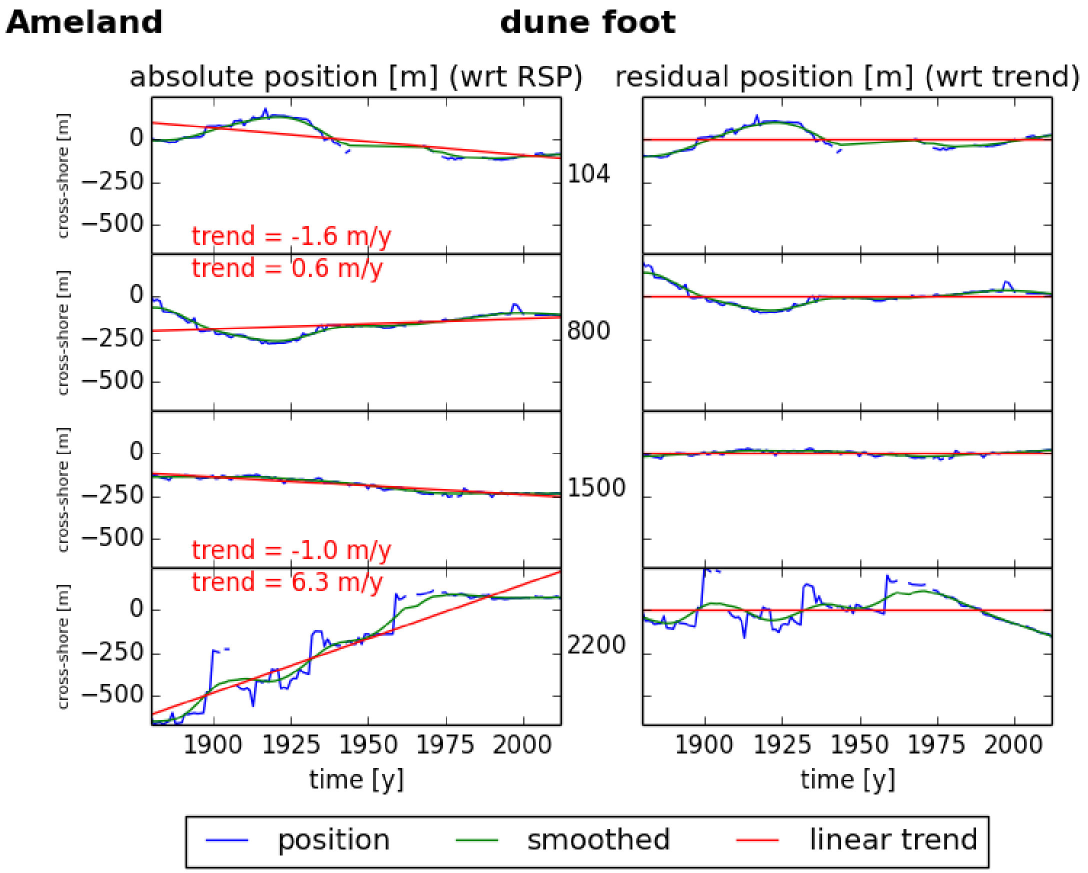
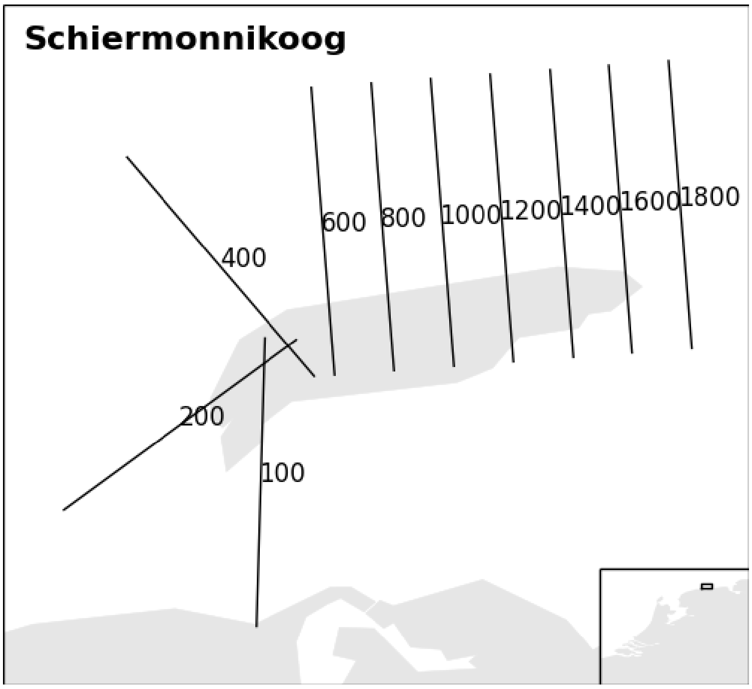


Figure 8.12 Dune foot position for four transects at Ameland. The blue line represents the actual dune foot position changes, the green line the smoothed dune foot position after applying a low-pass filter, and the red line the linear trend. The figures in the left panel show the absolute values, while the figures in the right panel show the values relative to the linear trends.

8.2.2.5 Schiermonnikoog

The situation at Schiermonnikoog looks similar to Terschelling. At both island tips, the sand waves travel in westward direction (south-west at the island head), whereas in the area in between (transect 500 to 1400) the direction is eastward. However, differently from Terschelling, the dune foot does not show a clear wave pattern. In addition, the linear trends of the dune foot do not agree with mean high and mean low water (Figure 8.13 top panel) and the amplitudes of the residuals are relatively small.
At this island, no nourishments have ever been carried out.


Schiermonnikoog
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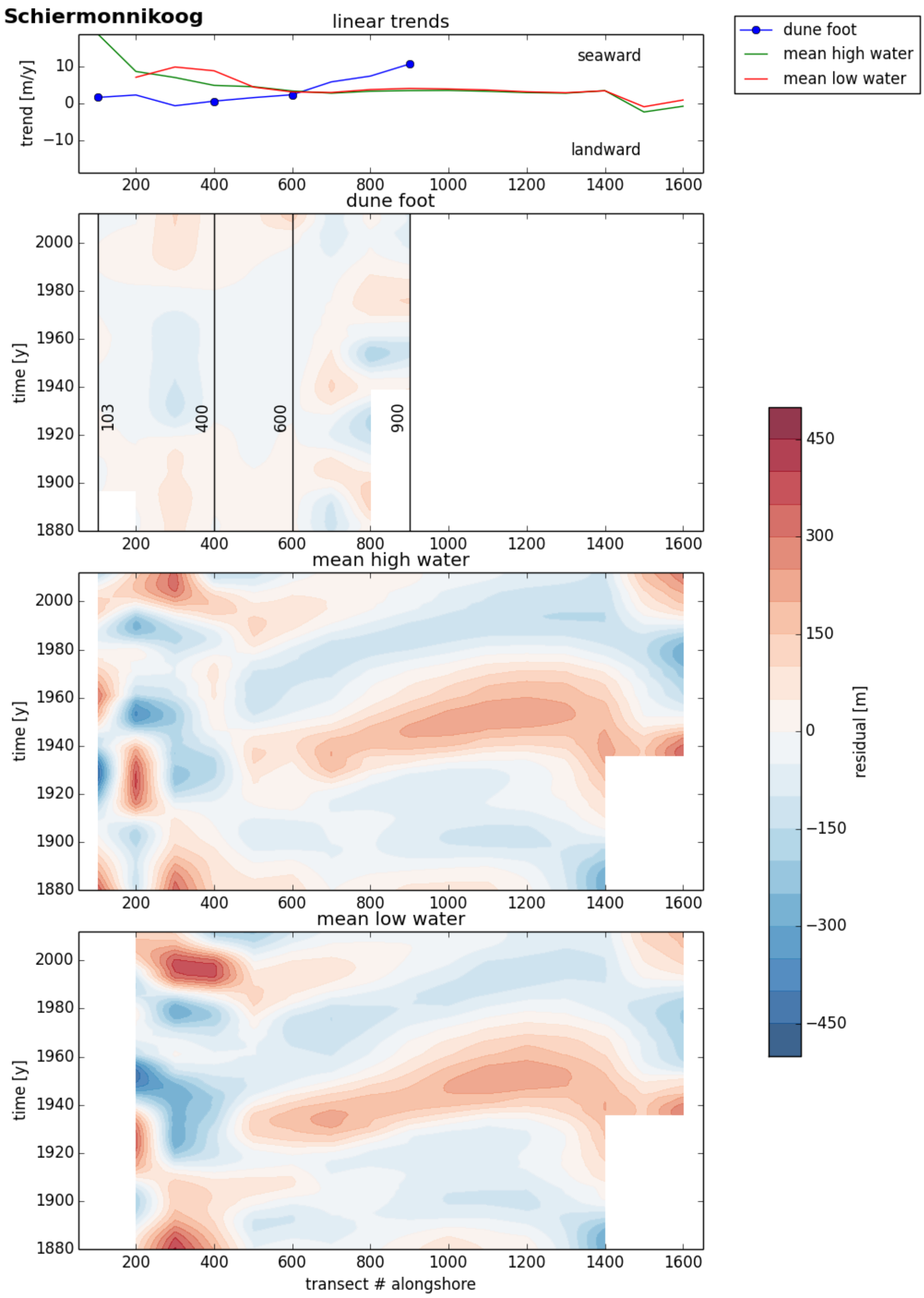
(a)



(b)

Figure 8.13 (a) Map of Schiermonnikoog with the positions of transects used as ticks in (b).(b)Contour plots of residuals (absolute values – trend) of dune foot, mean high and mean low waterline positions of Schiermonnikoog. The respective linear trends for the entire period are in the top panel.

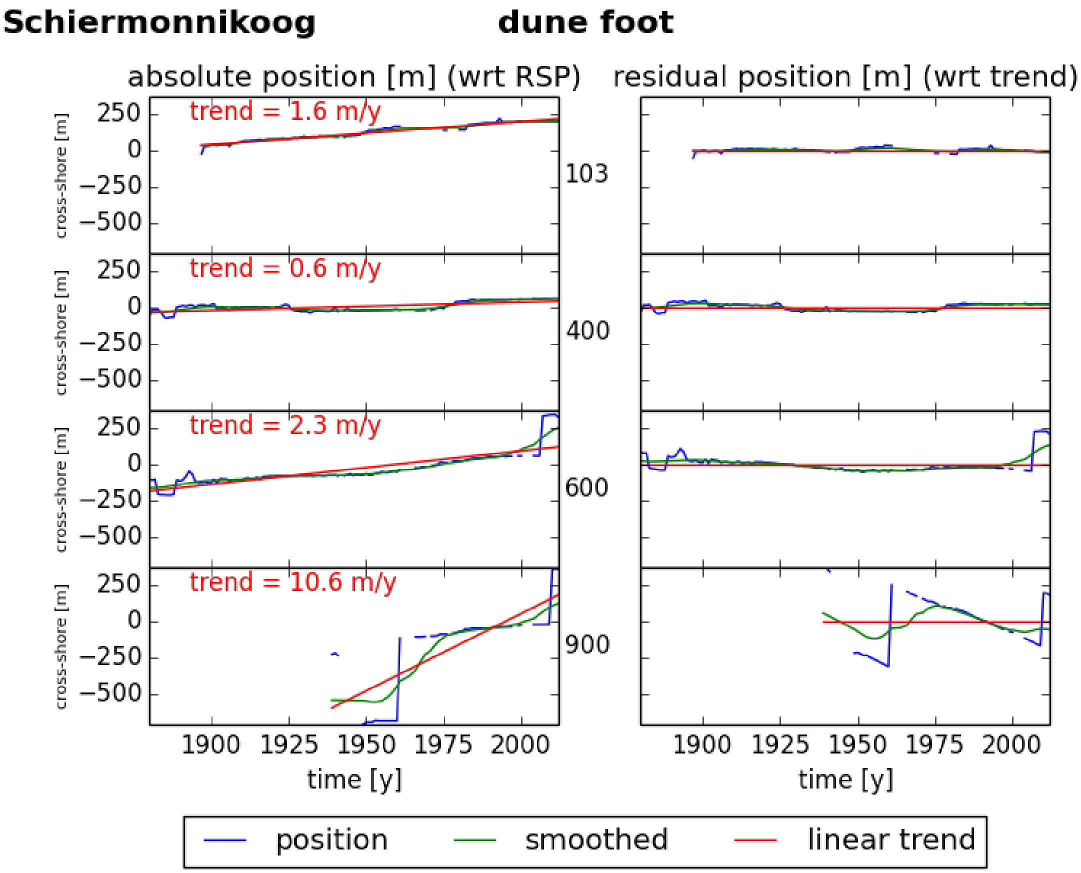


Figure 8.14 Dune foot position for four transects at Schiermonnikoog. The blue line represents the actual dune foot position changes, the green line the smoothed dune foot position after applying a low-pass filter, and the red line the linear trend. The figures in the left panel show the absolute values, while the figures in the right panel show the values relative to the linear trends.

8.2.3 Relation between sand waves and nourishments

Figure 8.4, Figure 8.7, Figure 8.9, Figure 8.11 and Figure 8.13 are very illustrative to depict alongshore morphological changes due to sand waves type of features and the possible interaction with nourishments. Figure 8.11 (Ameland), for example, clearly show that the nourishments have been built following the landing and consequent migration of the Bornrif along the coast.

For a proper and efficient planning and evaluation of the nourishments is definitely essential to account for the presence and migration of sand waves types of features, as already noticed for the South Westerly Delta (Giardino et al., 2014b). The evaluation of a nourishment superimposed to a sand wave with positive phase might lead to an overestimation of the effects of the nourishment, when the sand wave are not properly taken into account. On the other hand, the estimation of a nourishment superimposed to a sand wave with negative phase might lead to an underestimation of the effects of the nourishments.

For example, in the evaluation of the shoreface nourishment which was carried out at Terschelling (NOURTEC project), it is essential to account for the presence of cyclic features because they have most likely had an important contribution to the seaward migration of the coastline after the construction of the nourishment.

This could be done by including in the standard coastal nourishment procedure (comparison TKL vs. BKL position) the effects of alongshore migration of sand wave type of features, by using a predictive model. Methodologies to evaluate the future development of coastal positions accounting for sand waves have been implemented for example in Reinders et al., 2013.

8.3 Effects of tidal channels and nourishments on morphological indicators

The Wadden Sea bathymetry is characterized by deep meandering channels. The morphodynamic evolution of the area has changed largely during the last century, due to local artificial interventions and important works such as the construction of the Afsluitdijk and the closure of the Lauwerszee.
Large changes have in particular taken place within the tidal inlets inside the channels. Change in position (and size) of those channels can have an effect on the coastal indicators.
In particular, as shown on Figure 8.15, this analysis has focused on the following tidal channels:

- Helsdeur and Molengat (Texel inlet, between North Holland and Texel)
- Robbengat (Eierlandse Gat Inlet, between Texel and Vlieland)
- Vlietstroom and Zuiderstortemelk (Vlie Inlet, between Vlieland and Terschelling)
- Borndiep and Boschgat (Ameland Inlet, between Terschelling and Ameland)
- Oostgat of Borndiep
- Pinkegat and Zoutkamperlaag (Frisian Inlet, between Ameland and Schiermonnikoog)

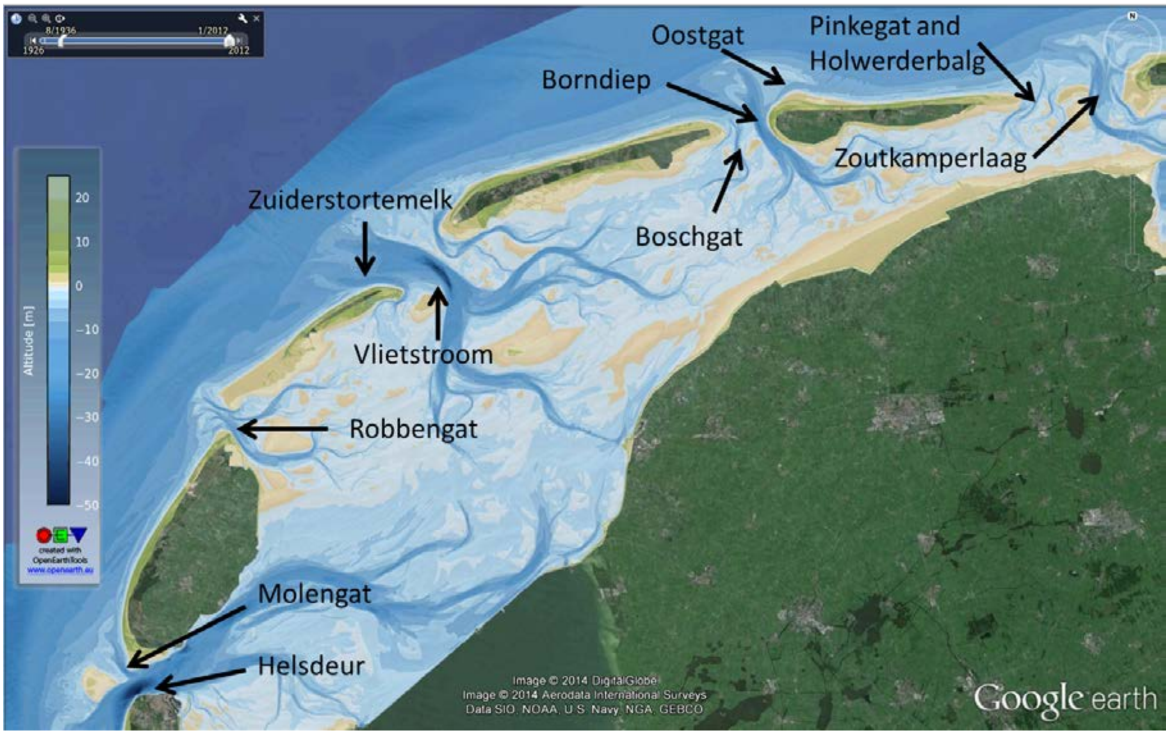


Figure 8.15 Location of the studied channels in the Wadden Sea area.

In this study, the evolution of the channels is analysed by looking at the evolution of the bathymetry based on vaklodingen data, below a contour line around the channel, arbitrary defined at -10 m. The only exception is the channel Oostgat which, since it is very shallow, was analysed choosing an arbitrary line at -5 m.

In this regard, two variables are analysed. The first is the evolution over time of the volume of water under the depth contour; the second is the horizontal migration of the centre of mass (centroid) of the area defined by the -10 m water depth line.

Time series of volume changes and 2D maps with spatial evolution of centroids are derived. Only years for which the bathymetry covers the entire area inside the contour line around the channels are used for the analysis.

The possible effects on morphological indicators are analysed by looking at changes in probability of failure, MKL, dune foot position, mean high- and mean low- water line at transects located in correspondence of the tidal channels. At the same transects, also cross-shore profiles are plotted for a better visualization of cross-shore morphological changes.

8.3.1 Helsdeur and Molengat

The Helsdeur is a deep old channel between North-Holland and Texel Island. Nowadays it reaches a depth of over 50 m in its deeper part and a minimum width of 2.5 km. A polygon around the channel was defined, partly located in the outer- and partly in the inner-delta (Figure 8.16). The polygons which are used to define the tidal channels throughout this chapter are usually larger than the tidal channels themself in order to include within the polygon possible time developments of the channels.

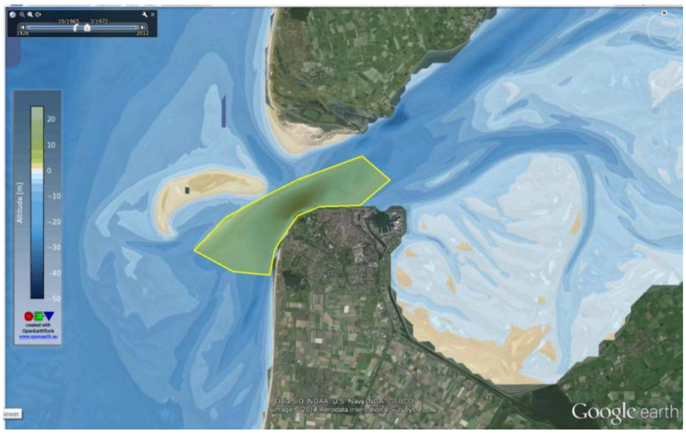


Figure 8.16 Limit of the region defining the Helsdeur.

The volume of water under the -10 m contour line (Figure 8.17) inside the polygon increased with ~6.5 $*10^7$ m^3 until 2001, then it nearly stabilized afterwards. The increase in water volume, corresponding to a lowering of the seabed or widening of the channel, is related to an increase in tidal volume through this channel and a decrease through the other channels. The sign minus in front of the volumes is related to the fact that the z-axis is directed upwards.
Minor horizontal shift of the centroid of that volume is observed, indicating the rather stable position of the channel (Figure 8.18). This is related to the presence of the Helderse Zeewering, a stone seawall protecting the tip of North Holland.

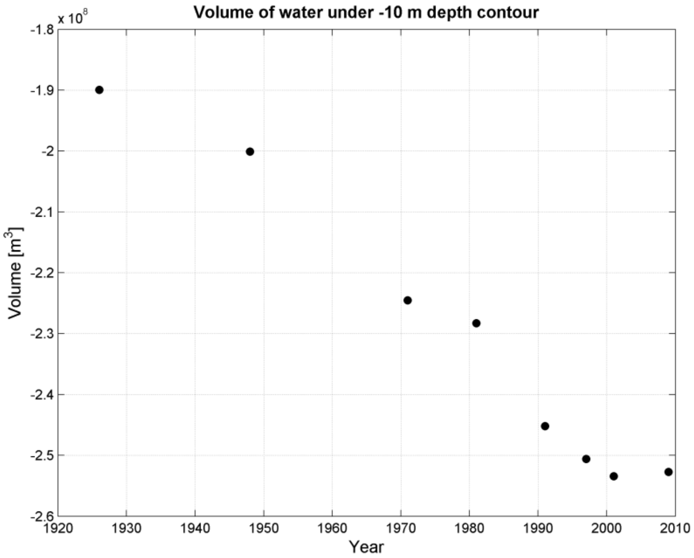


Figure 8.17 Helsdeur. Evolution over time of the volume of water delimited by the channel bed and -10 m contour line (from Vaklodingen data).

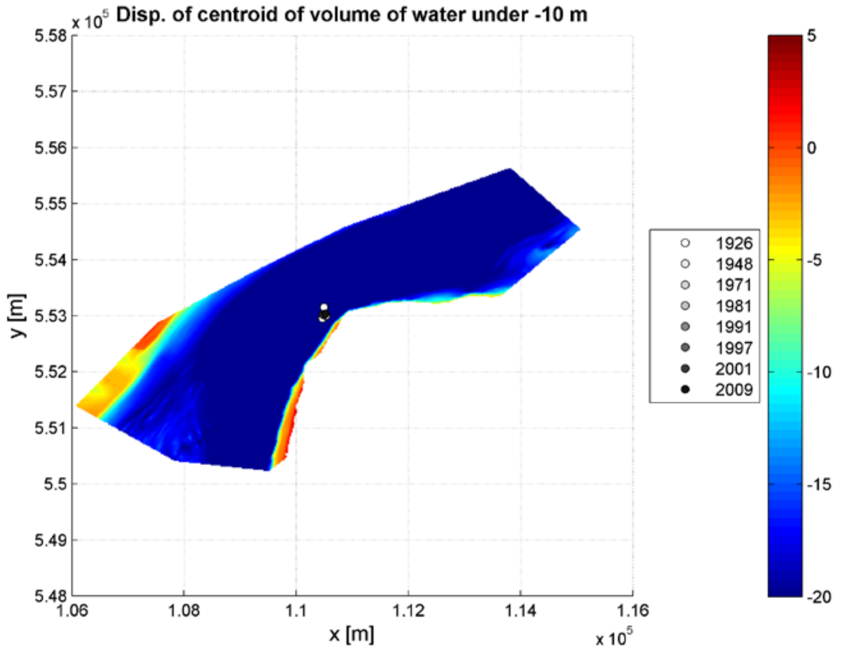


Figure 8.18 Displacement of the centre of mass of water defined by the -10 m contour line for the Helsdeur channel.

Coastal indicators are analysed for transect 7000150, crossing the Helsdeur at the North Holland coast (Table 8.3). The transect has been nourished with several beach nourishments for a total volume of ~760 m^3/m between 1992 and 2003 and a shoreface nourishment of ~900 m^3/m of sand in 2007. The nourishment policy has been effective, leading to a clear seaward shift of about 20 m of MKL, mean low water, mean high water line and dune foot position, from 1992 to 2007 (Table 8.3 b, c). The probability of breaching only shows a slight decrease (Table 8.3 a). Also interesting to notice is that, in the time between two nourishments, the coastline quickly tends to erode again with a landward trend up of about 4 m/year, making it necessary to repeat the intervention on a regular base.

Figure 8.19 Detail of the Helsdeur. Coastal indicators for the highlighted transect (7000150) are investigated.

Table 8.3 Coastal indicators for transect 7000150 (left panel) and transect 6000900 (right panel). Figures a., d.: Probability of failure. Figures b., e.: MKL, TKL, BKL. Figures c., f.: Mean High Water, Mean Low Water, Dune Foot.

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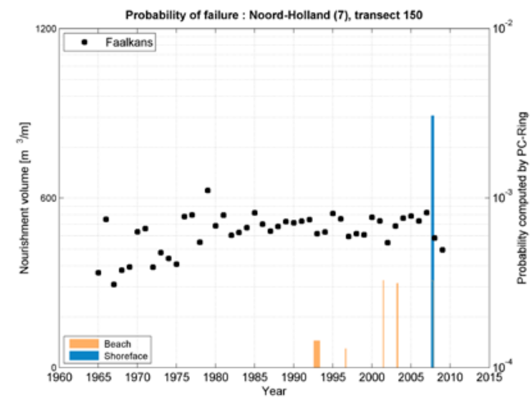

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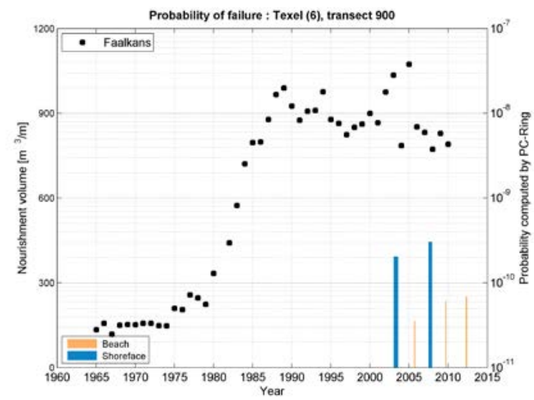

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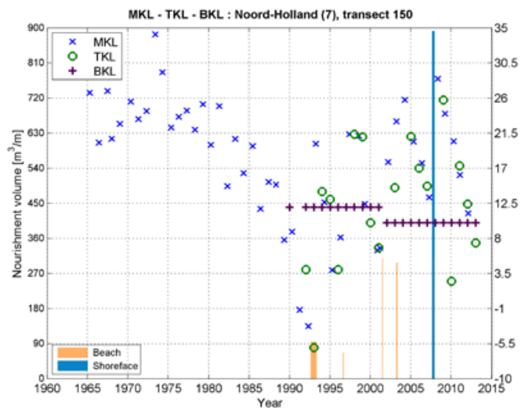

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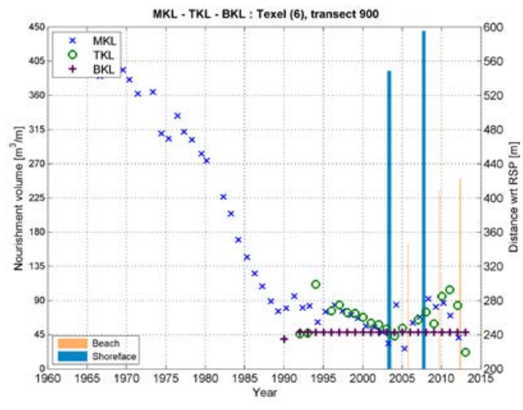

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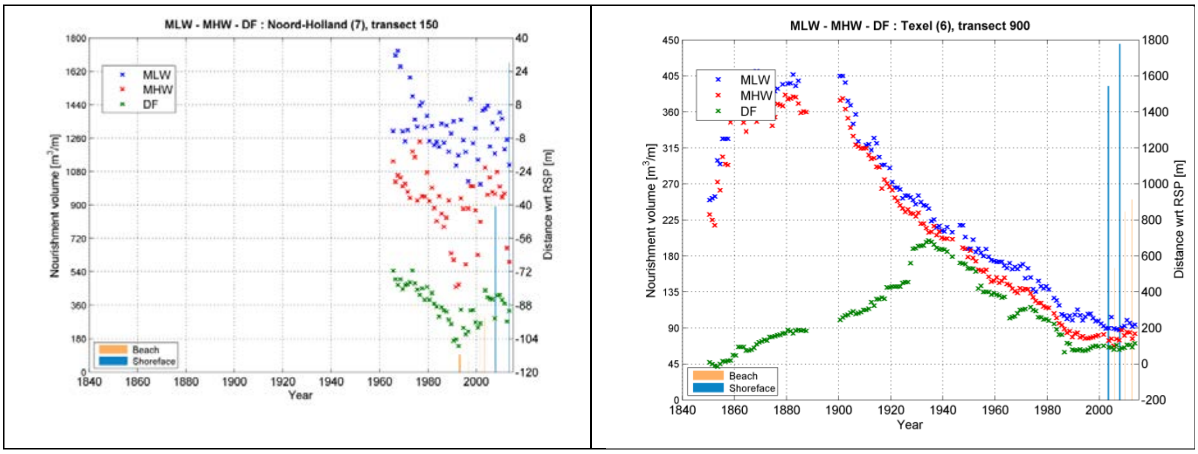

In correspondence to the transect 7000150, a cross-shore profile has also been extracted based both on vaklodingen data (Figure 8.20, left) and Jarkus data (Figure 8.20, right). Vaklodingen data have the advantage of further extending offshore covering the entire width of the channel; moreover, they also have a larger temporal extension. On the other hand, Jarkus profiles have a higher spatial resolution nearshore. The figure confirms the previous observation of a channel which approximately maintained its position but has been deepening during time as anticipated by Figure 8.17 and Figure 8.18.

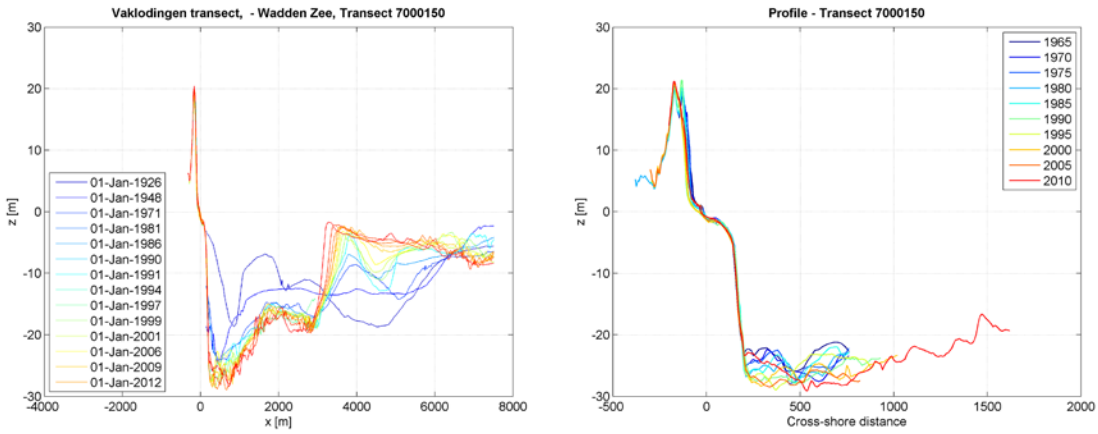

Figure 8.20 Profiles from Transect 7000150, based on vaklodingen data (left) and Jarkus data (right).

Along Texel island, a smaller and shallower channel is located called the Molengat. This channel is located ~500 m off the coastline of Texel. A polygon defining the area around the Molengat is shown in Figure 8.21.

Figure 8.21 Limit of the region defining the Molengat.

The volume of water under the -10 m contour line (Figure 8.22) and within the polygon showed first a tendency towards an increase in water volumes (erosion) before the beginning of the year 80s and then to a decrease (deposition) afterwards. The increase in volume mainly relates to the deepening of the deepest part of the channel. This process happened at the same time with an eastward shift of the channels and shoals located on the western side of the channel (Noorderhaaks and Noordelijke Uitlopers Noorderhaaks) and was mainly related to a relative increase in wave related transport towards the coast (Elias et al., 2014). This is clearly shown by Figure 8.23, which shows a movement of the centroid with a speed of ~20 m/year. The movement of the centroid indicates a movement of the deeper part of this channel towards this direction. This movement appears to have stabilized during the last years.

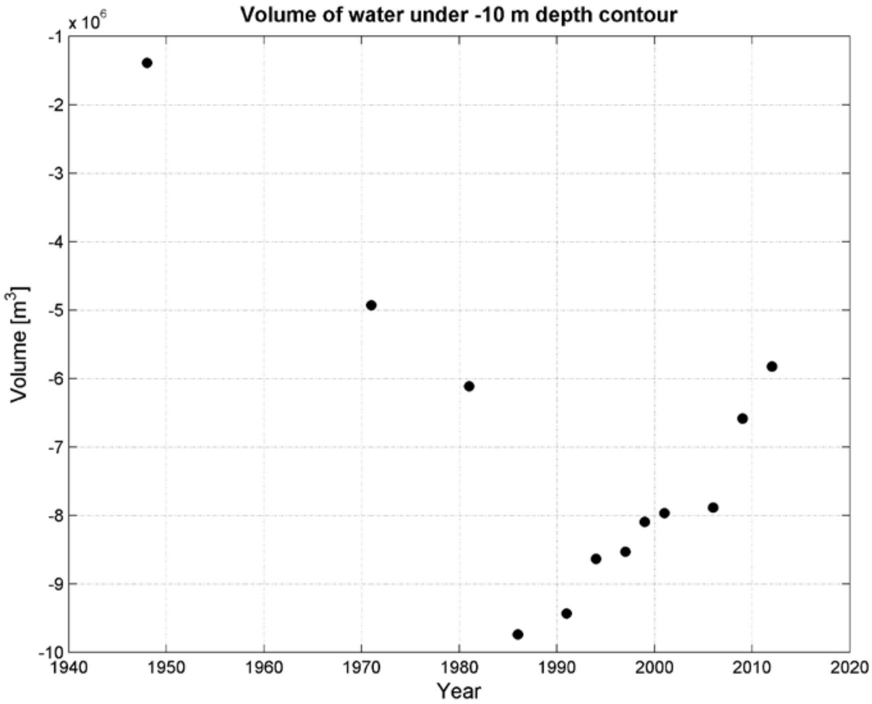

Figure 8.22 Molengat. Evolution over time of the volume of water delimited by the channel bed and -10m contour line (from Vaklodingen data).

A representative transect has been selected (6000900 in Figure 8.24) to study the evolution of the coastal indicators (Table 8.3d, e, f). For transect 6000900, two shoreface nourishments with volumes which sum up to 850 m^3/m have been applied after 2003. The transect has also been nourished with three beach nourishments for a total volume of ~640 m^3/m between 2005 and 2013. All the indicators show a clear change in trend from erosive to stable before and after year 1990. It is also interesting to point out the change in trend in dune foot position from accretive to erosive and which occurred in the year '30s. The erosive trend in indicators are mainly related to the landward shift of the Molengat and its deepening. Once again, nourishments have been successful in stabilizing the coastline.

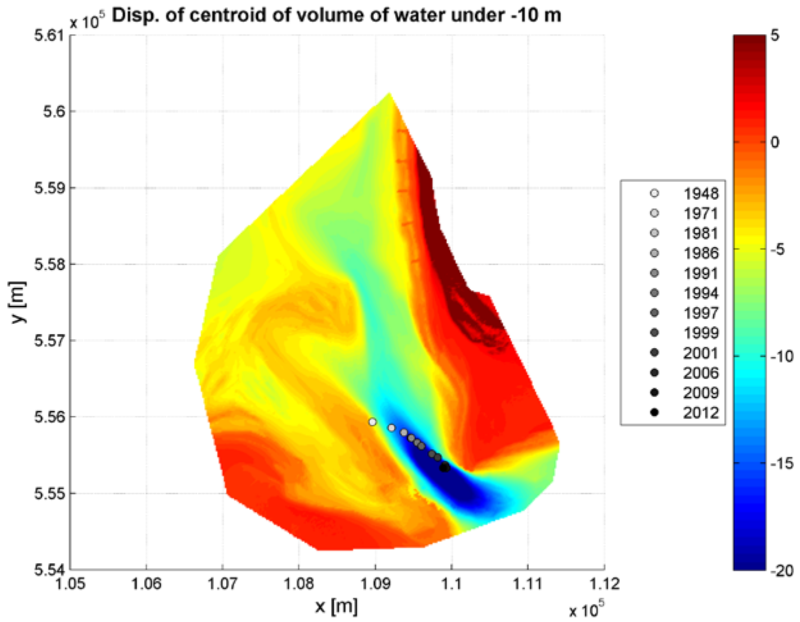

Figure 8.23 Displacement of the centre of mass of water defined by the -10 m contour line for the Molengat channel.

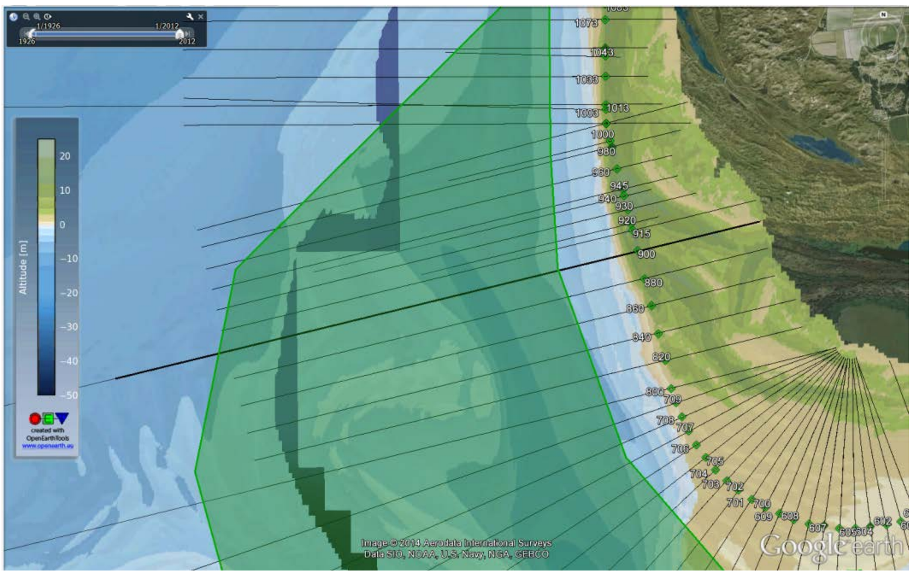

Figure 8.24 Detail of the Molengat. Coastal indicators for the highlighted transect (6000900) are investigated.

A cross-shore profile at transect 6000900 derived from vaklodingen data and Jarkus data is shown in Figure 8.25. The figure confirms the previous observation of a tidal channel which is migrating with a landward direction component as already shown in Figure 8.23 and with a channel depth which is slowly decreasing (Figure 8.22).

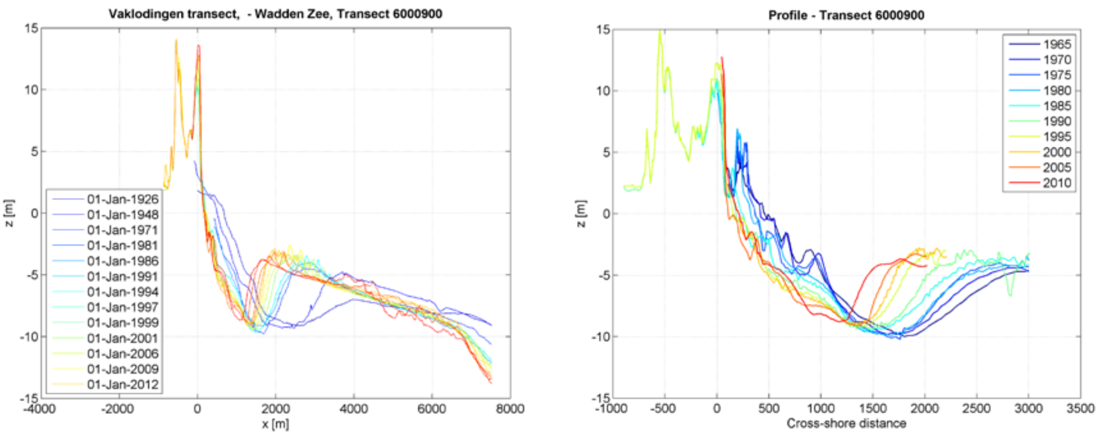

Figure 8.25 Profiles from Transect 6000900, based on vaklodingen data (left) and Jarkus data (right).

8.3.2 Robbengat

The Robbengat channel is situated in the Eierlandse Gat inlet, between Texel and Vlieland islands. This channel has a maximum depth of about 15 m. The polygon around the channel is shown in Figure 8.26. Bathymetries are available within the polygon for the period between 1970 and 2012.

Figure 8.26 Limit of the region defining the Robbengat.

The volume of water within the polygon under -10 m contour line increased (deepening) with ~1.3 Mm^3 in 30 years until today, as shown in Figure 8.27.

The centroid moved back and forth along the main direction of the Robbengat during the last 40 years (Figure 8.28), partly as a result of the different anthropogenic interventions which took place in the area and partly due the highly dynamic behaviour of this tidal channel. In 1995 for example an 800 m long shore-normal stone dam (the Eierlandse Dam) was constructed south of the inlet to reduce maintenance costs at the coastline of Texel.

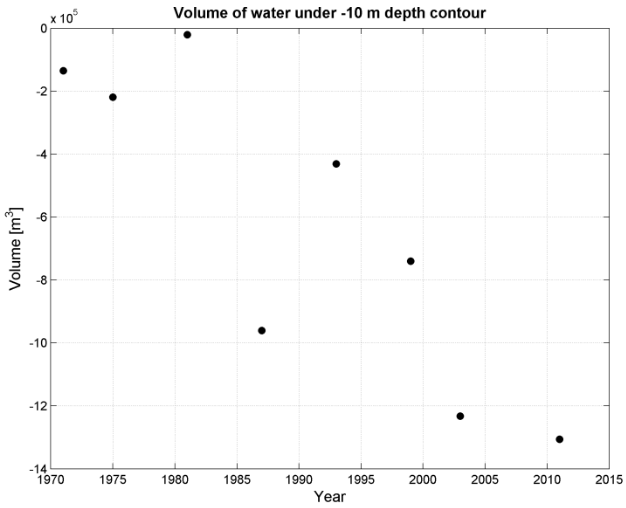

Figure 8.27 Robbengat. Evolution over time of the volume of water delimited by the channel bed and -10 m contour line (from Vaklodingen data).

Two transects crossing the region have been analysed in Figure 8.29 (6003081 and 6003200). Unfortunately, no MKL and probability of failure is available for the inner part of the Texel island (facing the Wadden Sea) and in front of the Robbengat. The available indicators at transect 3081 (probability of breaching and MKL) clearly show that the only beach nourishment which was implemented in 1979 (≈ 550 m^3/m) was effective in reducing the probability of failure and leading to a seaward shift of the MKL. Moreover, the effect of the construction of the Eierlandse Dam is also clearly visible starting from 1995, with a large seaward shift of the entire coastline (Table 8.4 - a and -b). The changes in mean low-water, mean high-water and dune foot position at transect 6003200 (Table 8.4 - f) show two large seaward changes which took place in 1900 and 1965 and related to the landing of large shoals.

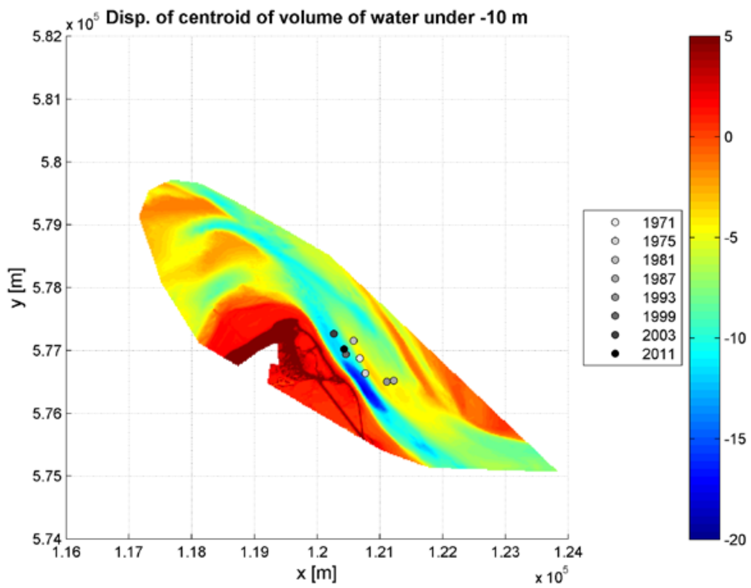

Figure 8.28 Displacement of the centre of mass of water defined by the -10 m contour line for the Robbengat channel.

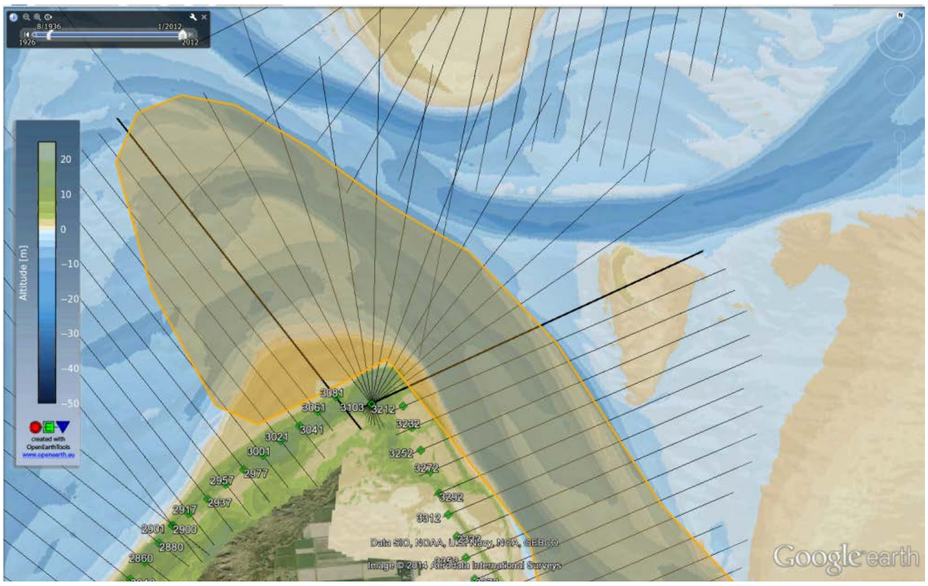

Figure 8.29 Detail of the Robbengat. Coastal indicators for the highlighted transects (6003081, 6003200) are investigated.

Table 8.4 Coastal indicators for transect 6003081 (left panel) and transect 6003200 (right panel). Figure a.: Probability of failure. Figure b: MKL, TKL, BKL. Figure f.: Mean High Water, Mean Low Water, Dune Foot position. Data for figures c, d, and e are missing.

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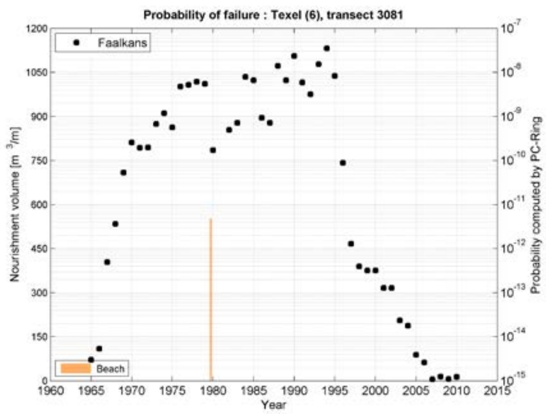
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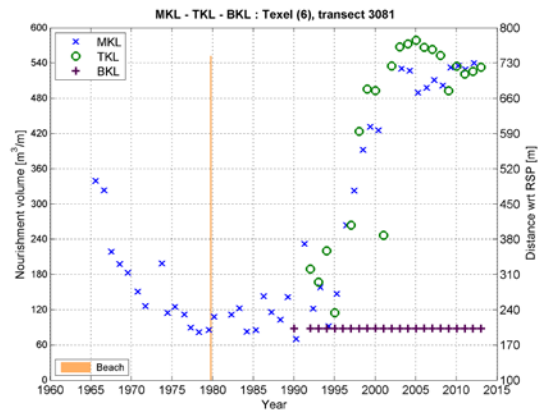
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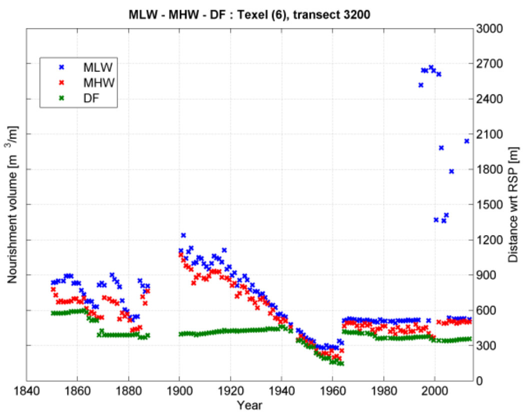
	

Two cross-shore profiles at transects 6003081 and 6003200 obtained from vaklodingen data and Jarkus data are shown in Figure 8.30 and Figure 8.31. Figure 8.30 clearly shows the effects of the Eierlandse Dam with large accumulation of sand volumes in front of the coast after 1995. Figure 8.31, located in front of the channel, confirms the high dynamicity of the channel as also shown by the movement of the centroid in Figure 8.28.

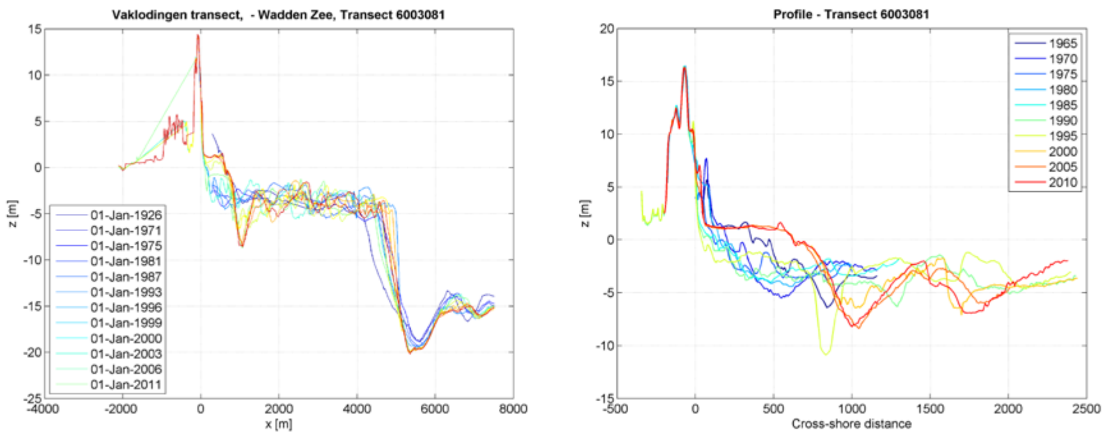


Figure 8.30 Profiles from Transect 6003081, based on vaklodingen data (left) and Jarkus data (right).

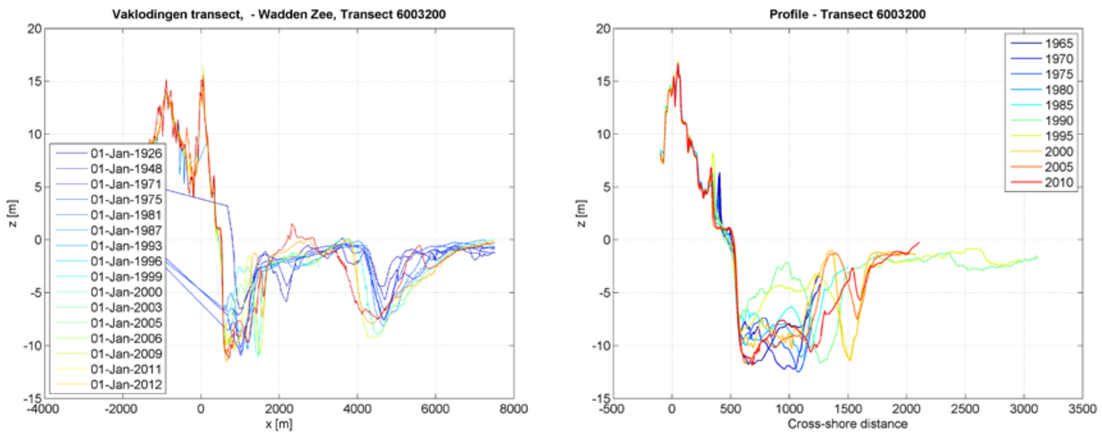


Figure 8.31 Profiles from Transect 6003200, based on vaklodingen data (left) and Jarkus data (right).

8.3.3 Vliestroom and Zuiderstortemelk

The Vliestroom is the largest and deepest gully between Vlieland and Terschelling. The polygon used to define the area of the analysis is shown in Figure 8.32.

Figure 8.32 Limit of the region defining the Vliestroom.

Bathymetries changes from 1927 to 2010 are studied within this polygon. The volume of water under the -10 m contour line (Figure 8.33) increased of about $0.9{*}10^8$ m^3 in 83 years, as a result of a deepening and extension of the channel. The sediment was transported partly into the Wadden Sea tidal basin after the closure of the Zuiderzee and partly stored on the West side of Vlieland above MLW.

The centroid of the channel moved along its axis in north-west direction, towards the outer delta, with a speed of ~16 m/year (Figure 8.34). This is due to the seaward extension of the tidal channel after the closure, with consequent erosion of the outer delta.

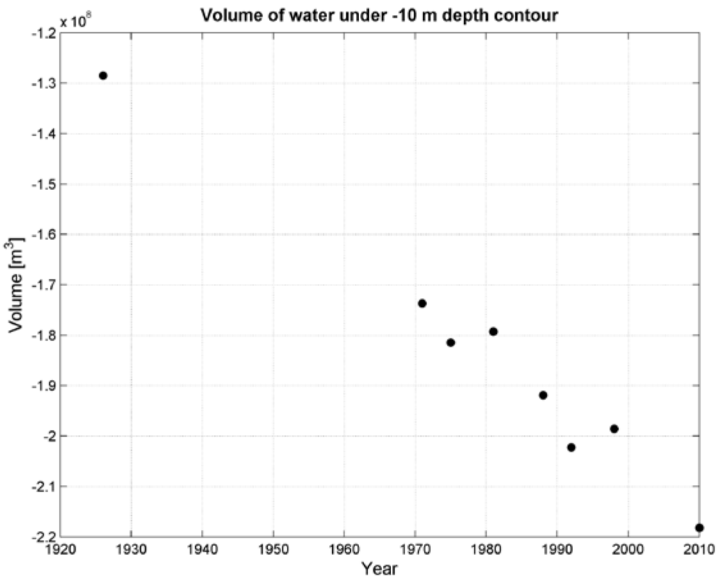


Figure 8.33 Vliestroom. Evolution over time of the volume of water delimited by the channel bed and -10m contour line (from Vaklodingen data).

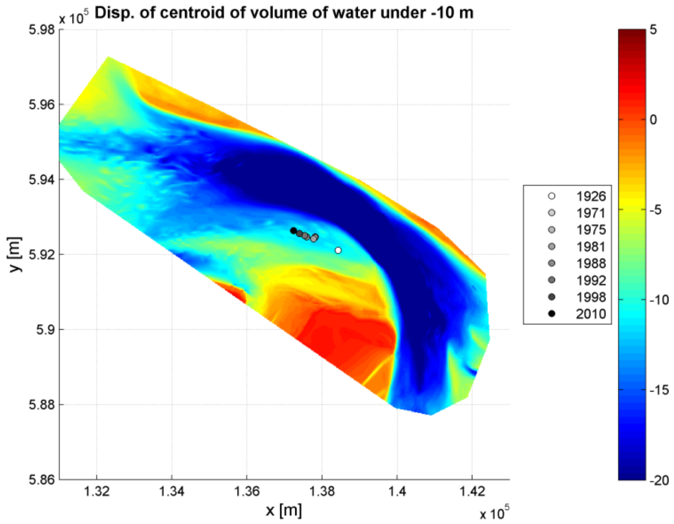


Figure 8.34 Displacement of the centre of mass of water defined by the -10 m contour line for the Vliestroom channel.

Two transects in this region have been analysed to assess the possible correlations between changes to the tidal channel and the coastal indicators: transects 5005360 and 5005374, located on the Vlieland Island (Figure 8.35). The channel is situated relatively far from the coast, which makes it more difficult to find correlations with the coastal indicators.
A beach nourishment plus a dune reinforcement for a total of 190,000 m^3 were constructed in 1995. Moreover, another beach nourishment with a volume of 20,000 m^3 was constructed in 2001 just south of those transects.
Although no clear correlation with the dynamics of the Vliestroom channel can be seen, the effect of the nourishment at transect 5005374 are clear: after the construction of the nourishment in 1995, MKL shifted seaward of about 30 m (Table 8.5 e). Remarkable are also the erosive trends which characterized the tip of the island in the 19th century (Table 8.5 f) for which also a groyne field was built.

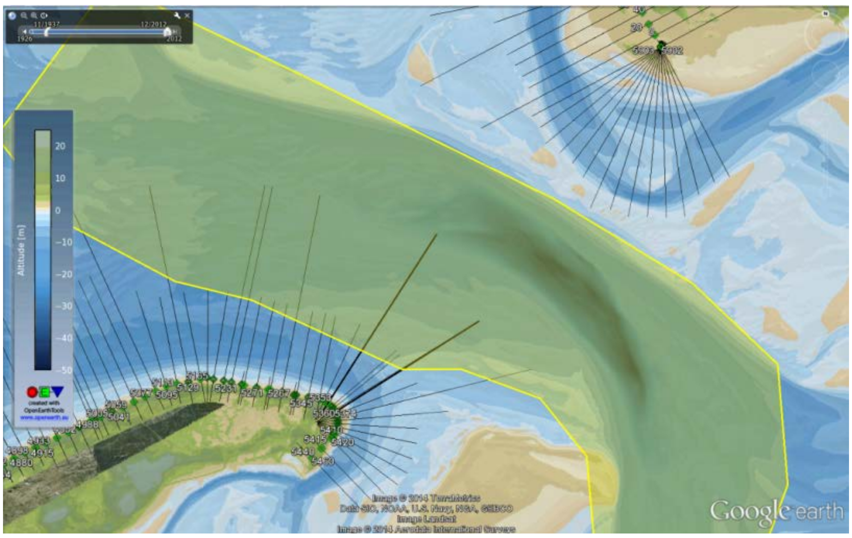
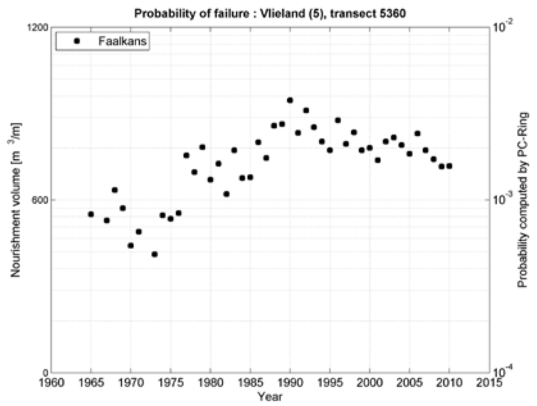


Figure 8.35 Detail of the Vliestroom. Coastal indicators for the highlighted transects (5005360, 5005374) are investigated.

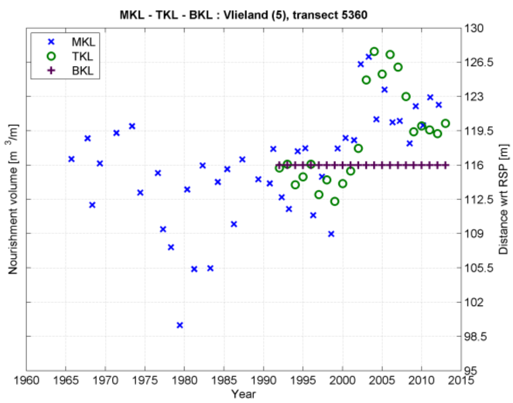
Table 8.5 Coastal indicators for transect 5005360 (left panel) and transect 5005374 (right panel). Figures a., d.: Probability of failure. Figures b., e.: MKL, TKL, BKL. Figures c., f.: Mean High Water, Mean Low Water, Dune Foot.

a.

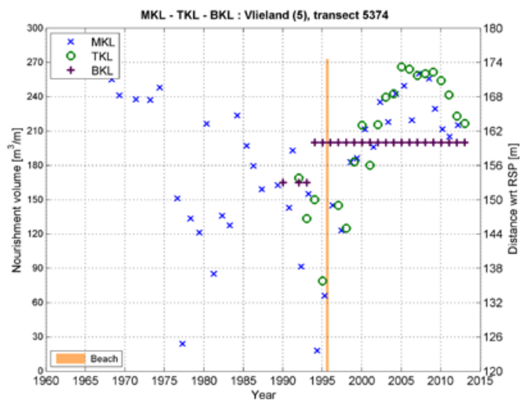


d.

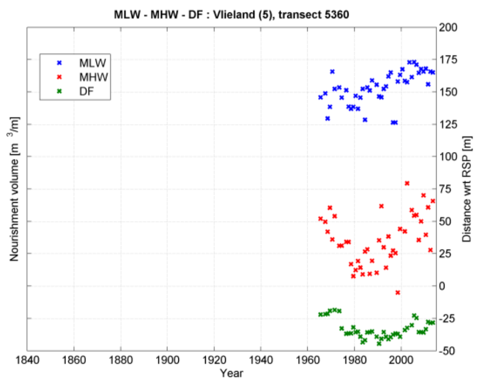
b.



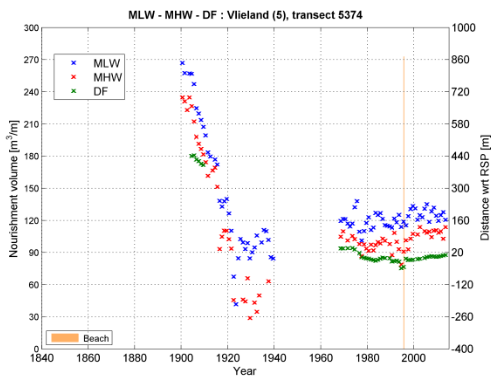
e.



c.



f.



Two cross-shore profiles at transect 5005360 and 5005374 obtained from vaklodingen data and Jarkus data are shown in Figure 8.36 and Figure 8.37. The figures confirm the previous observation of a tidal channel with a tendency towards deepening as shown by the increase in volume in Figure 8.33.

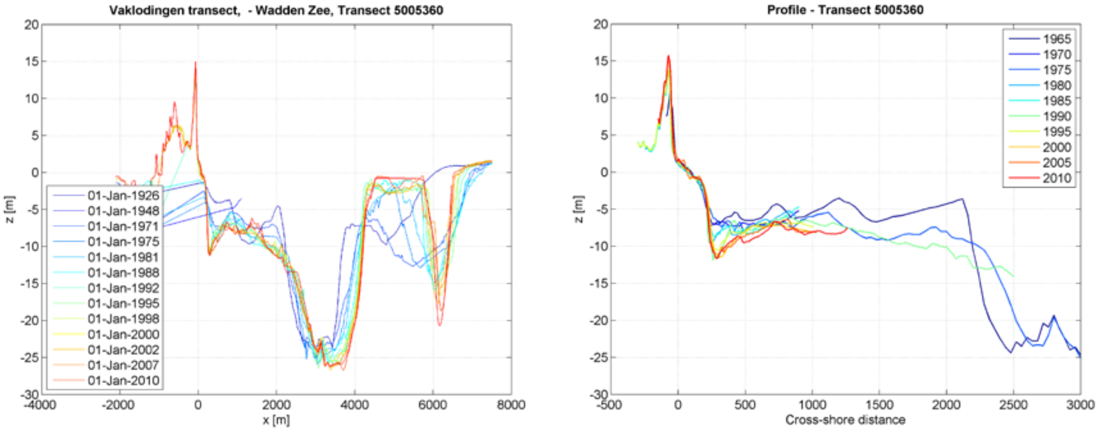


Figure 8.36 Profiles from Transect 5005360, based on vaklodingen data (left) and Jarkus data (right).

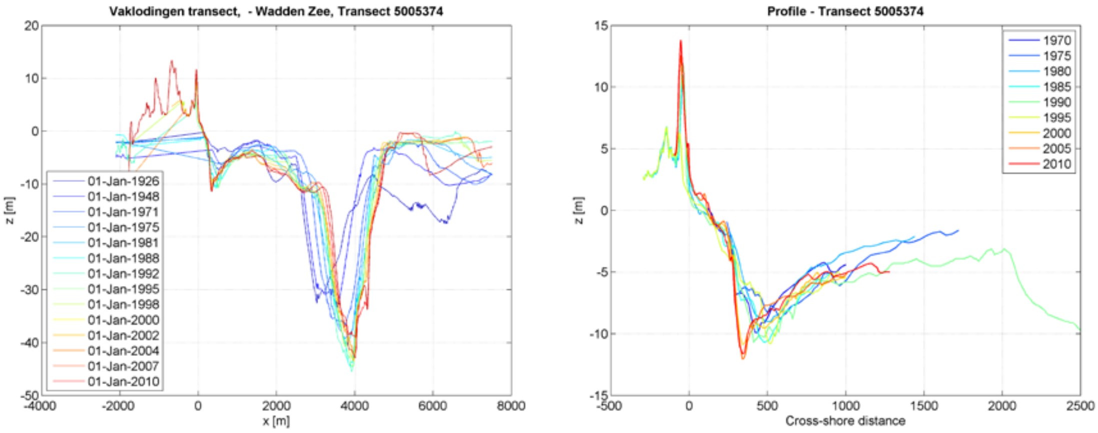


Figure 8.37 Profiles from Transect 5005374, based on vaklodingen data (left) and Jarkus data (right).

The Zuiderstortemelk channel is located next to the Vliestroom, along the northern tip of Vlieland island. The polygon around the channel, used to define the area for the analysis, is shown in Figure 8.38.

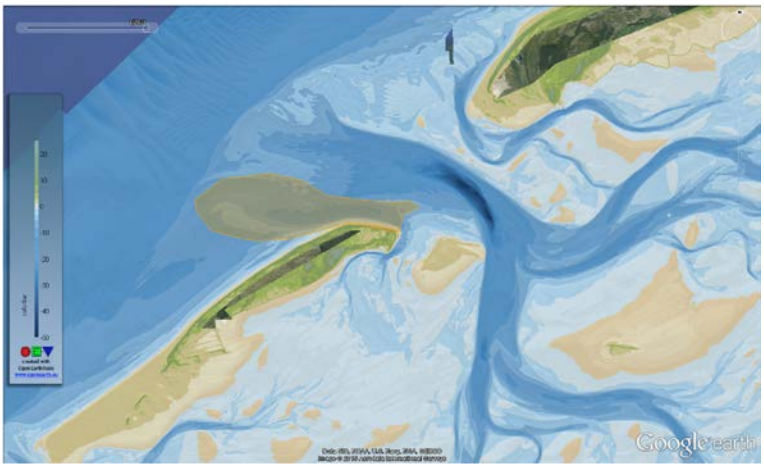


Figure 8.38 Limit of the region defining the Zuiderstortemelk.

Bathymetric changes between 1926 and 2010 are studied within this polygon. Similarly to the Vliestroom, the volume of water under the -10 m contour line (Figure 8.39) increased overall from 1926, although this trend reversed in 1992 and the channel is now decreasing its volume. The changes are partly due to a variation in extension of the channel (Figure 8.40) and partly due to changes in depth in the deeper part of the channel (Figure 8.42 and Figure 8.43).

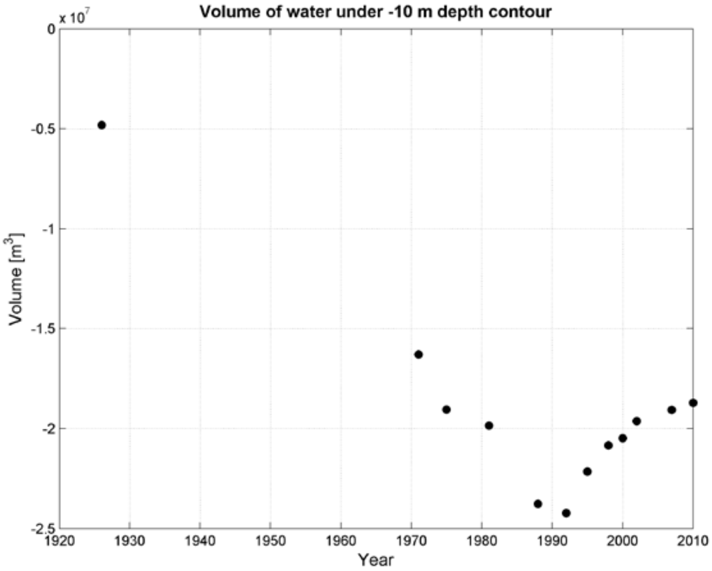


Figure 8.39 Zuiderstortemelk. Evolution over time of the volume of water delimited by the channel bed and -10m contour line (from Vaklodingen data).

The centroid of the channel moved along its axis in west direction with a speed of ~24 m/year from 1926 to 1992 suggesting a seaward extension of the channel, while it has been moving back in eastward direction with a speed of ~38 m/year after that year, suggesting a reduction in extension of the channel (Figure 8.40).

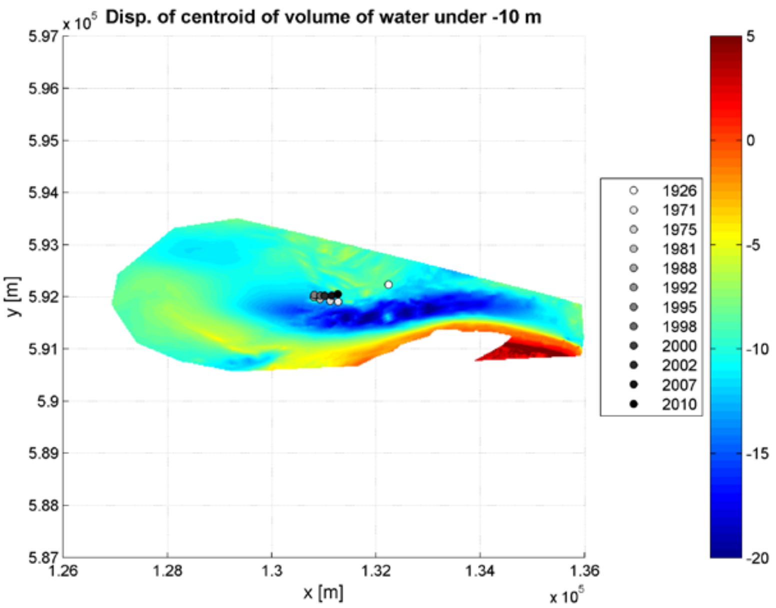


Figure 8.40 Displacement of the centre of mass of water defined by the -10 m contour line for the Zuiderstortemelk channel.

Two transects in this region have been analysed to assess the possible correlations between changes to the tidal channel, the effect of the nourishments and the coastal indicators: transects 5005005 and 5005200, located on the Vlieland Island, respectively in the middle of Zuiderstortemelk channel and near the eastern tip of the channel (Figure 8.41).

Transect 5005005 (Table 8.6 a, b, c) shows that the area is characterized by the presence of periodical changes due to sand waves type of features travelling along the coast (see also analysis of sand waves at Vlieland in Figure 8.7). Few nourishments were constructed at the location of transect 5005005. In particular: beach nourishments of 500,000 m^3 and 1,000,000 m^3 were constructed respectively in 2001 and 2013. Moreover, a shoreface nourishment with a volume of 1,000,000 m^3 was constructed in 2005. Assessing the efficiency of those nourishments is not trivial due to the co-presence of background periodical morphological changes and the nourishments.

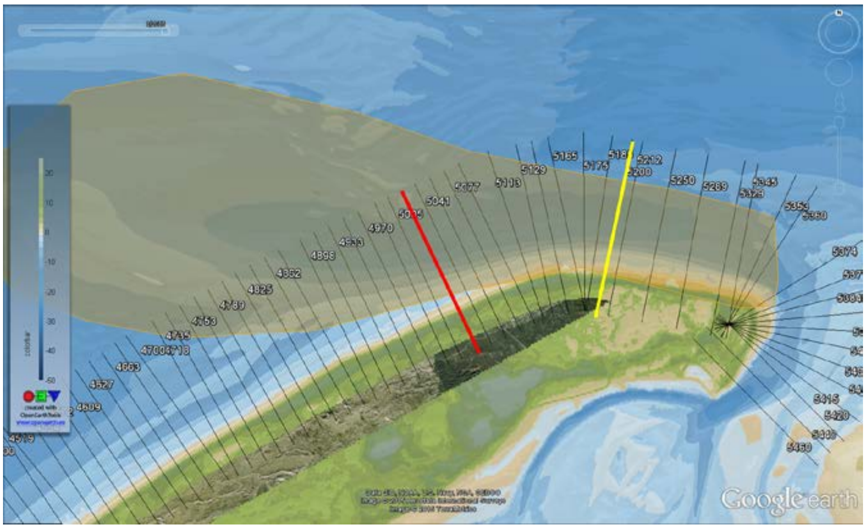


Figure 8.41 Detail of the Zuiderstortemelk. Coastal indicators for the highlighted transects (5005005, 5005200) are investigated.

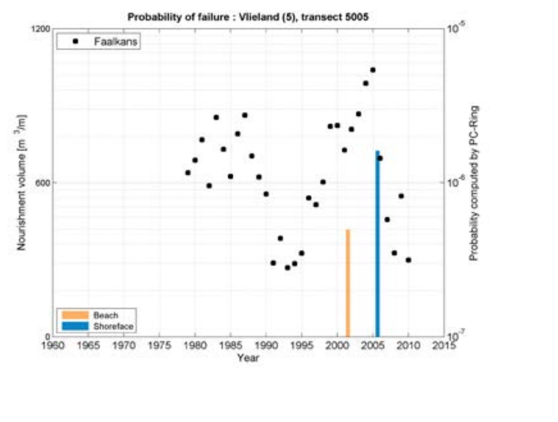
Although less strong, a periodical behaviour can also be recognized for transect 5200. No nourishments at this transects have been carried out.

A correlation with the morphological changes at Zuiderstortemelk is not found as the changes at this channel mainly occur along its axis, parallel to the coastline.

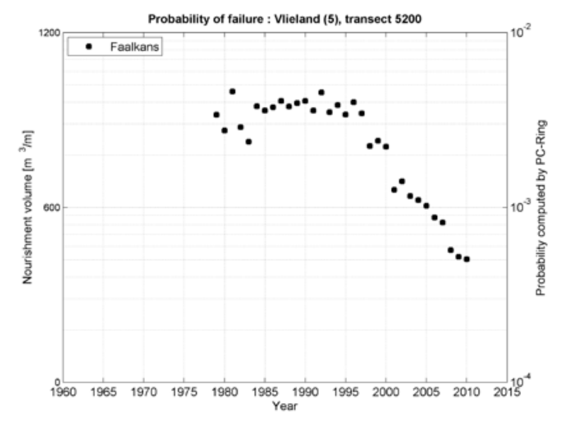
Remarkable are also the erosive trends which characterized the tip of the island during the 19th and beginning of the 20th century (Table 8.6 c, f).

Table 8.6 Coastal indicators for transect 5005005 (left panel) and transect 5005200 (right panel). Figures a., d.: Probability of failure. Figures b., e.: MKL, TKL, BKL. Figures c., f.: Mean High Water, Mean Low Water, Dune Foot.

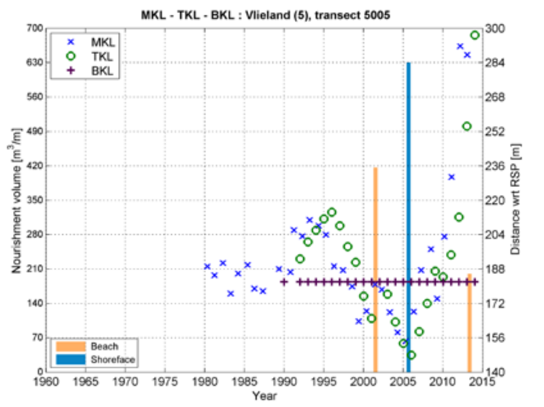
a.



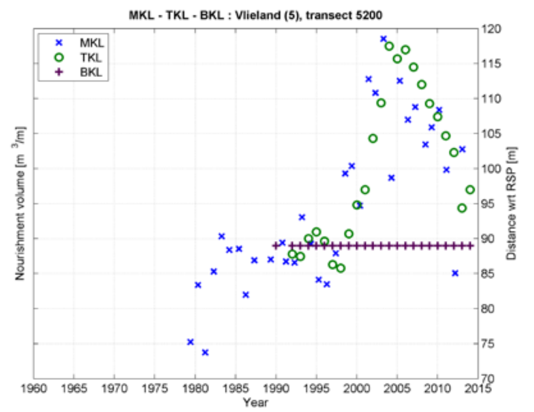
d.



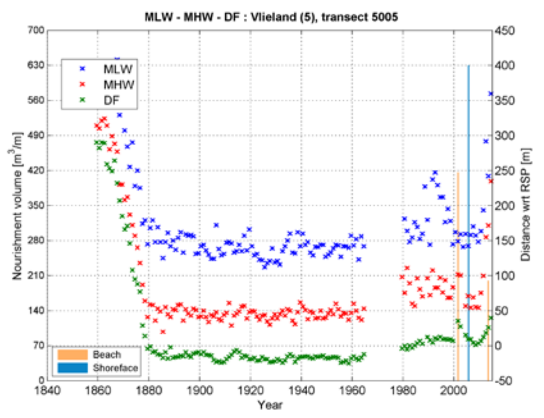
b.



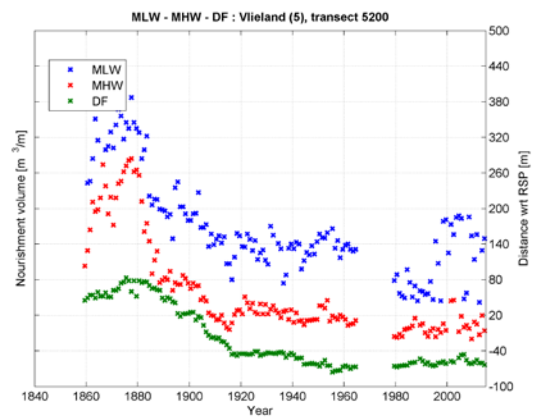
e.



c.



f.



Two cross-shore profiles at transect 5005005 and 5005200 obtained from vaklodingen data and Jarkus data are shown in Figure 8.42 and Figure 8.43. The figures seem to confirm the observation already suggested in Figure 8.39 of a channel with a volume which has been slightly decreasing in its deeper part after approximately 1990.

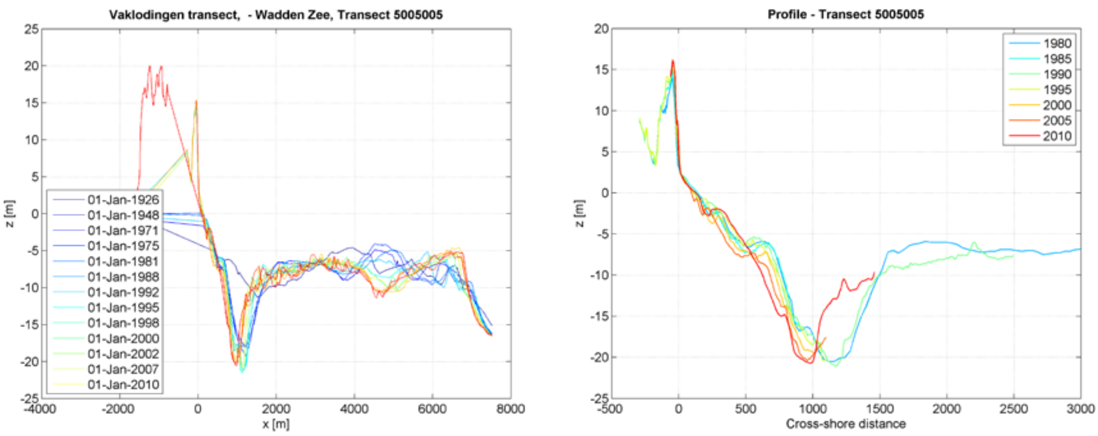


Figure 8.42 Profiles from Transect 5005005, based on vaklodingen data (left) and Jarkus data (right).

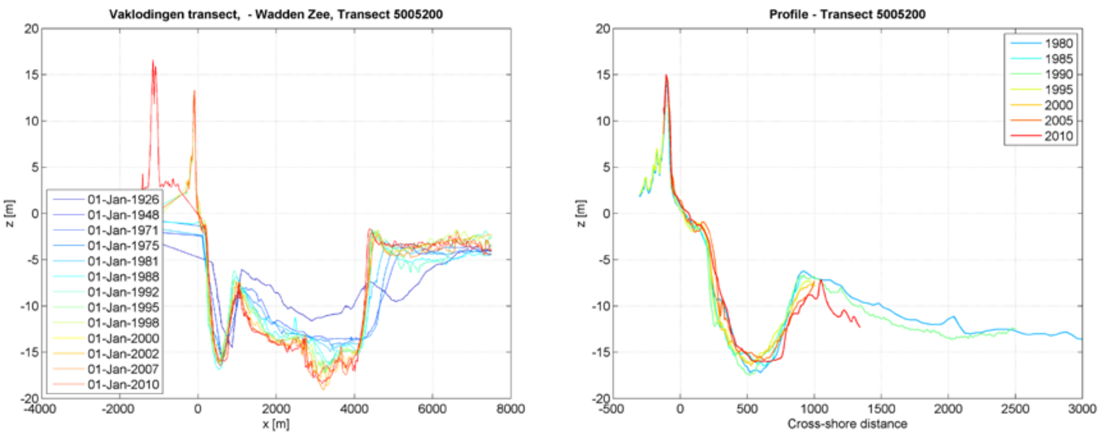


Figure 8.43 Profiles from Transect 5005200, based on vaklodingen data (left) and Jarkus data (right).

8.3.4 Borndiep and Boschgat

The Borndiep channel is the deepest channel of the Ameland inlet, between Terschelling and Ameland. The polygon around the channel used to define the area for the analysis is shown in Figure 8.44.

Figure 8.44 Limit of the region defining the Borndiep.

The bathymetry data below the -10 m contour show first an increase in water volume (erosion) approximately before 1970, followed by a decrease in water volume (deposition) afterwards (Figure 8.45) with a total net sedimentation of about 25 Mm^3 of sand. Those movements are related to a cyclic evolution of the channels and shoals on the ebb-tidal delta, with a period of 50 to 60 years (see also Section 8.2.2.4).This cyclic behaviour can also be recognized in the movement of the centroid of the channel, which was moving northward before 1975 and then start moving in south-east direction afterwards (Figure 8.46). Those shift led to a large wave-built bar migrate onshore forming a spit system called Bornrif.

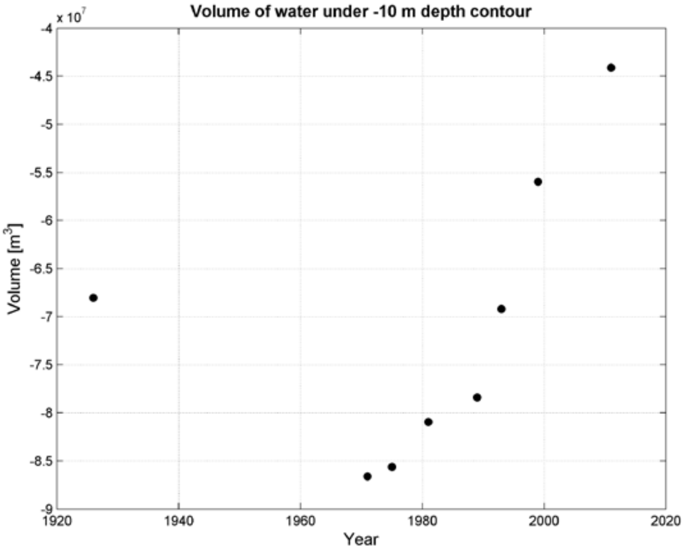


Figure 8.45 Borndiep. Evolution over time of the volume of water delimited by the channel bed and -10m contour line (from Vaklodingen data).

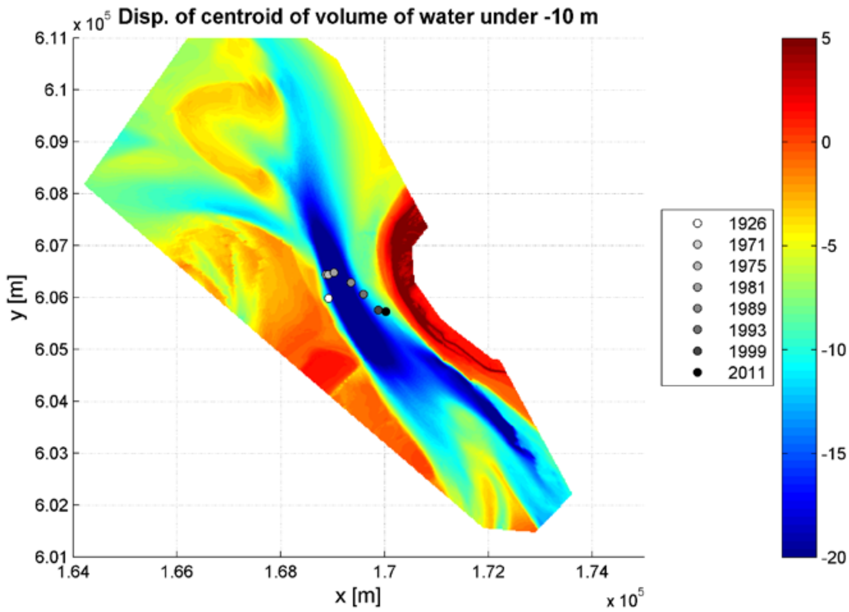


Figure 8.46 Displacement of the centre of mass of water defined by the -10 m contour line for the Borndiep channel.

One transect at Ameland located in front of the channel (transect 3004928) has been considered for the analysis of the indicators. The location of the transect is shown in Figure 8.47.

The evolution of the coastal indicators shows how the inlet is partly influenced by the cyclic morphdynamic changes of the entire inlet which also induce the migration of the tidal channels and shoals (Table 8.7c). However, next to this, the effect of a beach nourishment of 190 m^3/m in 1994 had a clear effect on the indicators: for example the MKL shifted seaward and the probability of breaching decreased at once of about one order of magnitude (Table 8.7a, b).

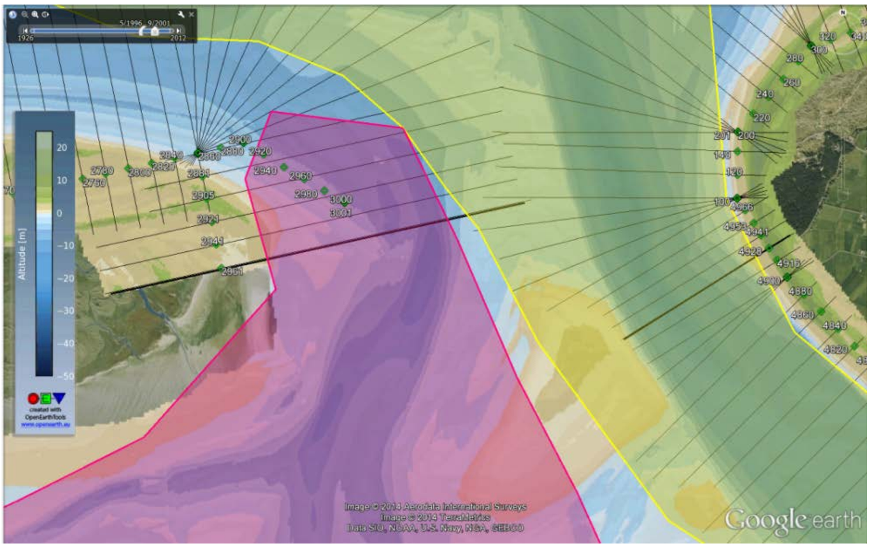
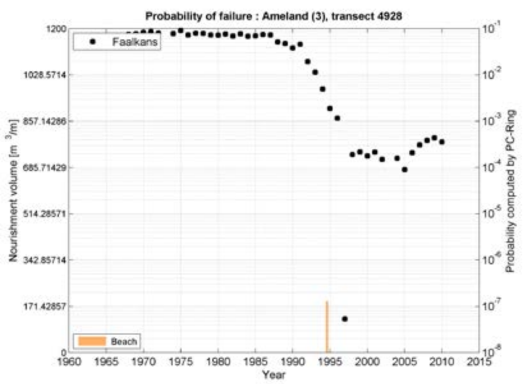
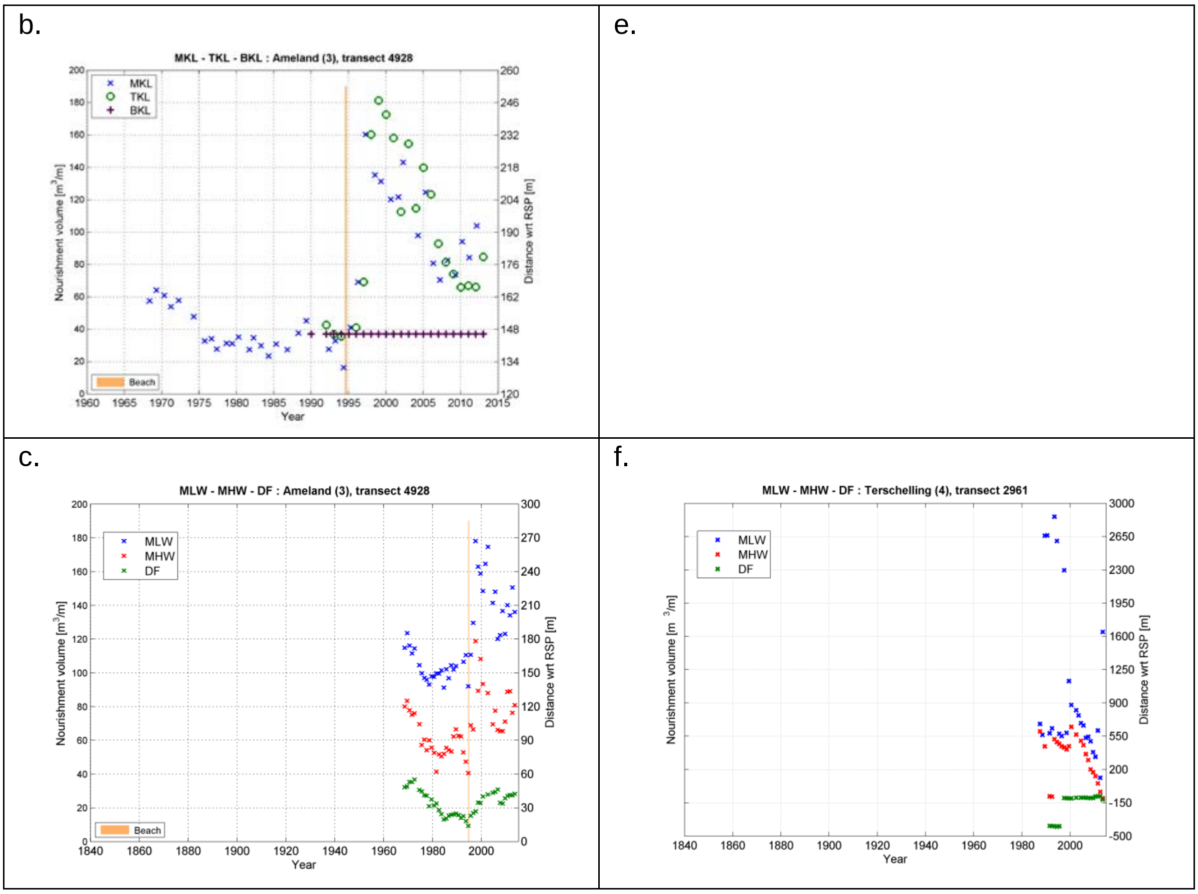


Figure 8.47 Detail of the Borndiep (yellow) and the Boschgat (purple). Coastal indicators for the highlighted transects (3004928, 4002961, for the Borndiep and the Boschgat, respectively) are investigated.

Table 8.7 Coastal indicators for transect 3004928 and 3004902 (left panel) and transect 4002961 (right panel). Figures a., d.: Probability of failure. Figures b., e.: MKL, TKL, BKL. Figures c., f.: Mean High Water, Mean Low Water, Dune Foot.

a.	d.
	



The cross-shore profiles of transect 3004928 obtained from Vaklodingen data and Jarkus data are shown respectively in Figure 8.48 (left and right). The figure confirms the shift of the channel towards the eastern direction (Figure 8.46). Moreover, the channel becomes less deep, as shown already in Figure 8.45.

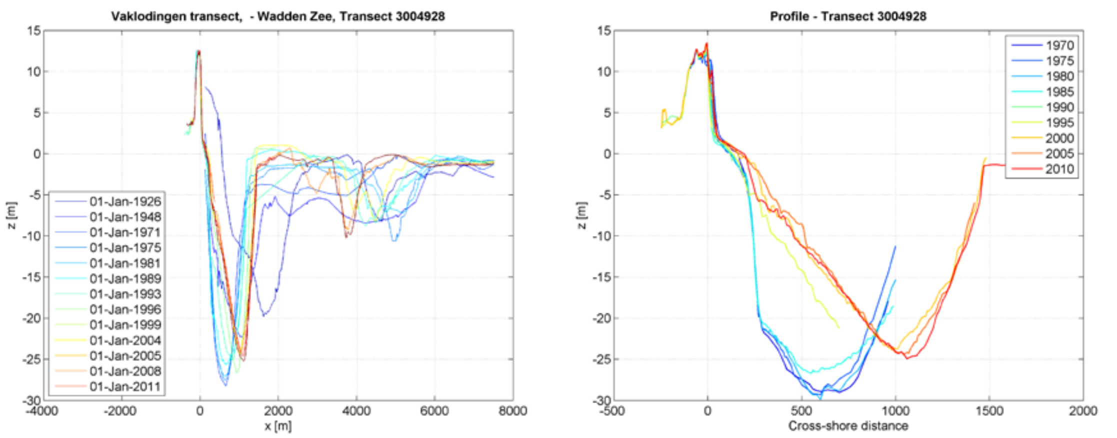


Figure 8.48 Profiles from Transect 3004928, based on vaklodingen data (left) and Jarkus data (right).

The other channel located in the Ameland inlet is the Boschgat. Also this channel is very dynamic and influenced by the periodic changes which have occurred within the entire inlet. The polygon around the channel is shown in Figure 8.49. Since the channel is very dynamic in time, the polygon around this channel is very wide so that can follow the time development of the channel system.

Figure 8.49 Limit of the region defining the Boschgat.

Figure 8.50 shows the volume development in time of the deeper part of this channel system (below the -10 m water line). The figure shows that the volume of the channel system remained quite stable. The channel system is on average shallower than the Borndiep channel, therefore the volumes in this figure are very small. One outlier is visible in the figure at year 2000, which stands out because all the volumes are very small. This is related to a local deepening of the channel at this year, as shown also by the JARKUS measurement (Figure 8.52 – right).

The centroid of the deeper part of the channel showed a shift towards the south-east, while a new channel has been forming close to Terschelling island during the last years (Figure 8.51).

The absence of Jarkus data in the southern part of Terschelling makes it hard to analyse any possible relation between shifts in the tidal channel and the coastal indicators. One transect has been selected for this analysis (transect 4002961) located on the eastern tip of the island, as shown in Figure 8.47. The few available data (Table 8.7 f) suggest that an erosive trend has taken place during the last 20 years at the tip of the island, and which was indeed the case.

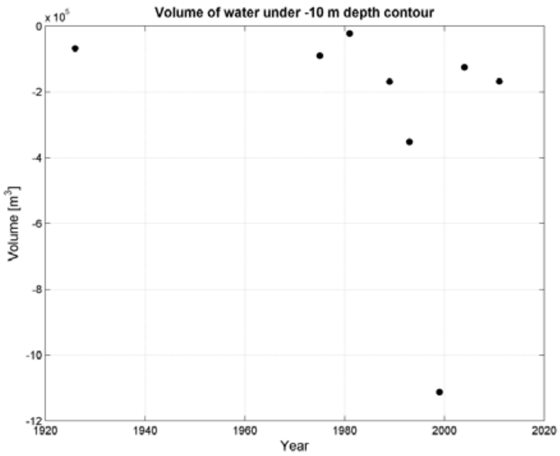


Figure 8.50 Boschgat. Evolution over time of the volume of water delimited by the channel bed and -10 m contour line (from Vaklodingen data).

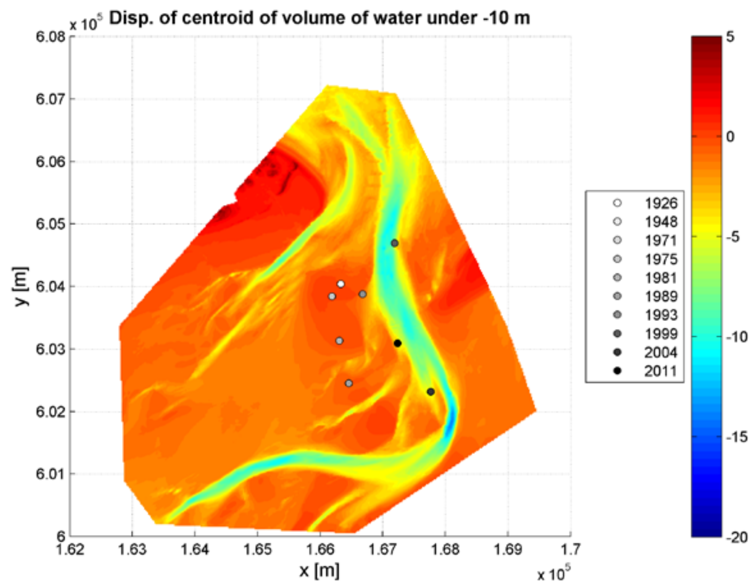


Figure 8.51 Displacement of the centre of mass of water defined by the -10 m contour line for the Boschgat channel.

The cross-shore profiles of transect 4002961 obtained from Vaklodingen data and Jarkus data is shown in Figure 8.52 (left and right). Figure 8.52 (right) confirms that the coastline is eroding.

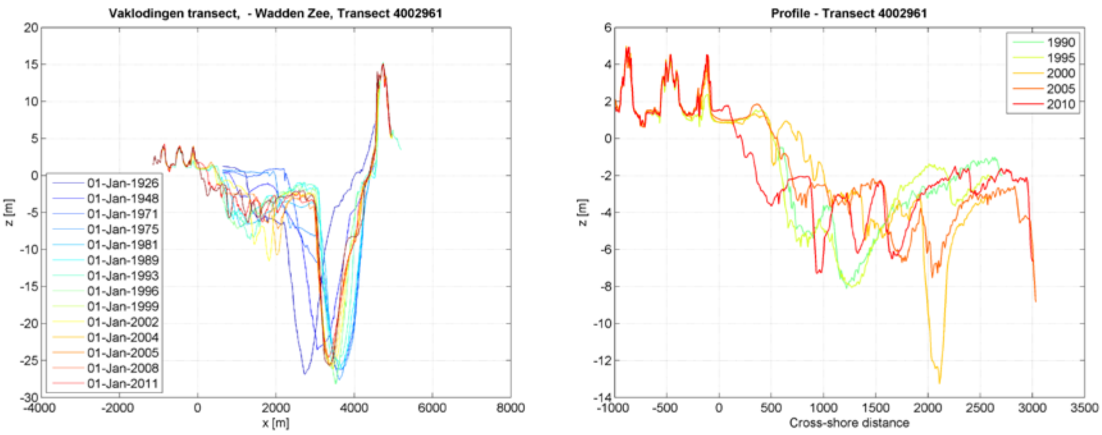


Figure 8.52 Profiles from Transect 4002961, based on vaklodingen data (left) and Jarkus data (right).

8.3.5 Oostgat

The Oostgat channel is situated in the inlet between the islands of Terschelling and Ameland, south of the Bornrif shoal. It is part of a highly dynamic system, including channels and flats (Israel, 1998). The morphological development of the channel follows a cyclic behaviour with a period of about 50 to 60 years, determined by the wave-dominated movement of the Bornrif shoal. For this reason, the channel does not behave like a typical tidal channel.

The channel has a maximum depth of about 7 m. The polygon around the area with the channel is shown in Figure 8.53. Bathymetry data is available within the polygon for the period between 1926 and 2011. Figure 8.54 shows the volume development in time of the deeper part of this channel system. As this channel is shallower than the others investigated in this report, volumes are computed between the sea bed and the -5 m water level (instead of -10 m as for the other channels). Volume changes in the last 40 years are in general quite limited. More important are the periodic shifts in time of this channel, and which have a direct consequence on the development of the coastline indicators. Figure 8.55 shows the development in time of the centre of mass, for the area defined by the -5 m contour line. The figure clearly indicates the progressive shift of the channel towards the south-east approximately during the last 20 years and with a speed of about 150 m/year.

Figure 8.53 Limit of the region defining the Oostgat.

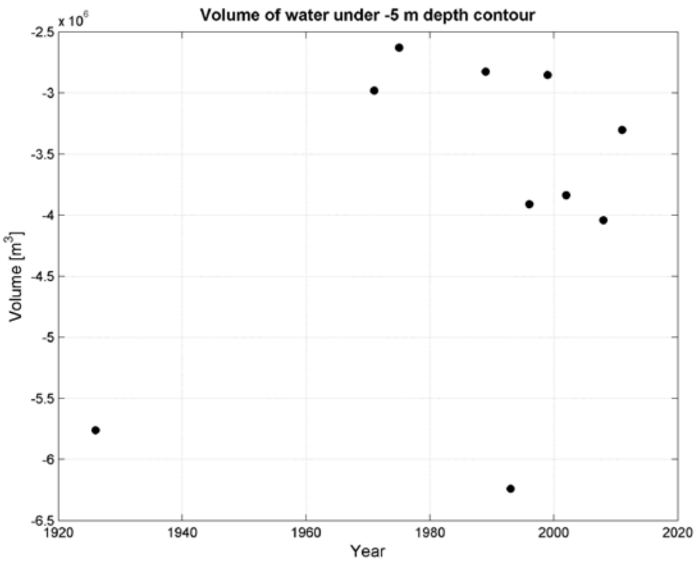


Figure 8.54 Oostgat. Evolution over time of the volume of water delimited by the channel bed and the -5 m contour line (from Vaklodingen data).

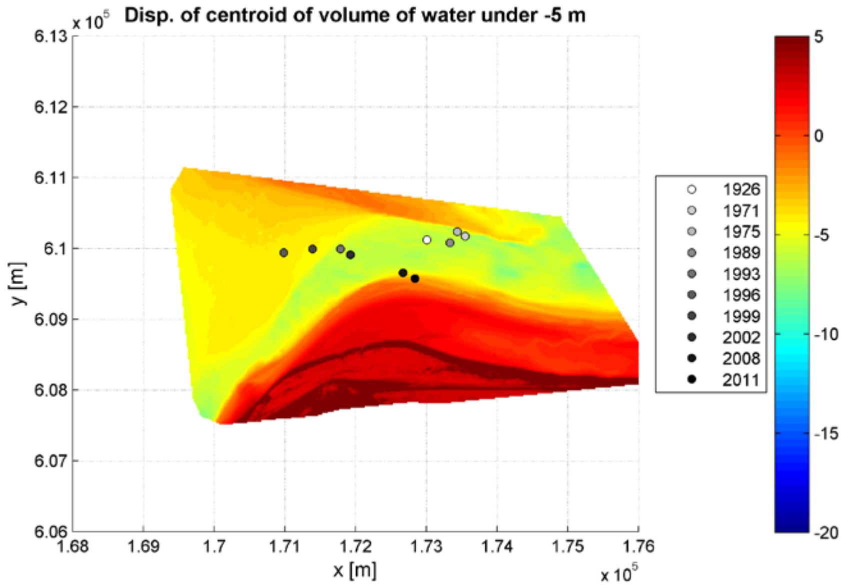


Figure 8.55 Displacement of the centre of mass of water defined by the -5 m contour line for the Oostgat channel.

Two transects (respectively 3000304 and 3000401) crossing the area of interest as shown in Figure 8.56 have been analysed to derive possible relations with the morphological development of the channel and the effects of nourishments.

Transect 3000304 has been clearly subject to periodic morphological changes, with an alternation of periods characterized by erosion and deposition (see for example Table 8.8c).
At present, the transect is subject to general erosion with a rate of about 25 m/year and related to the landward movement of the channel. As a result, the BKL is now located seaward of the MKL position since year 2005. Three beach nourishments have been implemented in the period 2004-2012. The beach nourishments have been effective in stopping the erosion trends as shown by Table 8.8 b and c. Seaward trends are observed after the implementation of the nourishments, followed by erosion in the periods in between the nourishments, suggesting that nourishments are necessary to maintain the coastline at its position. The probability of breaching stabilized during the last years, but did not really show a change in trend (Table 8.8 a).

No nourishment has been applied at transect 3000401 (Table 8.8 d, e, f). This transect is however subject to very similar erosion trends as transect 3000304 caused by the shifts of the Oostgat channel. Therefore, it is expected that nourishments will be required in the near future as the MKL position has almost reached the BKL position at this transect.

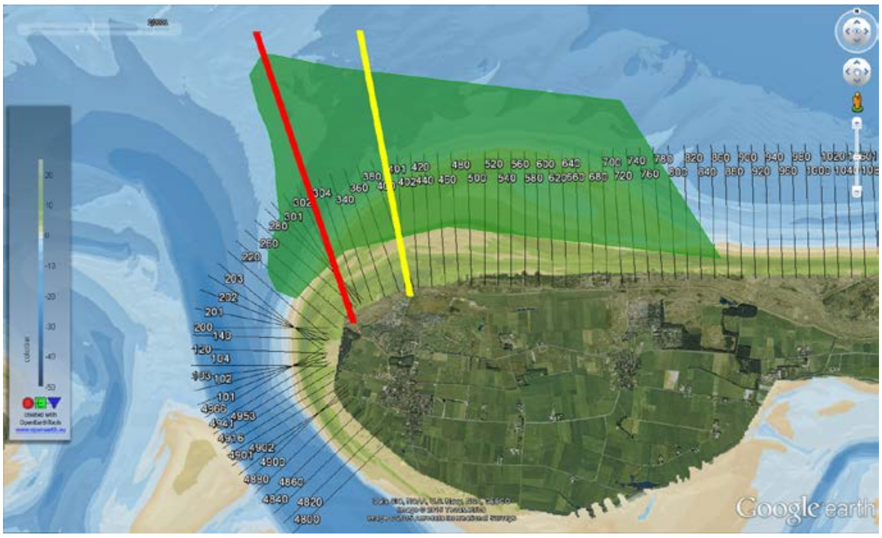
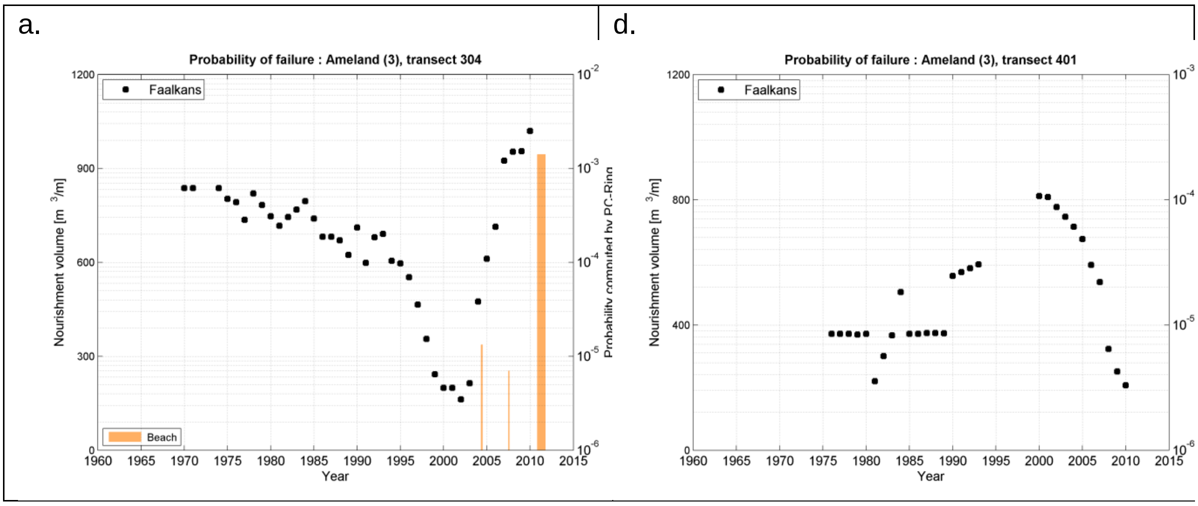
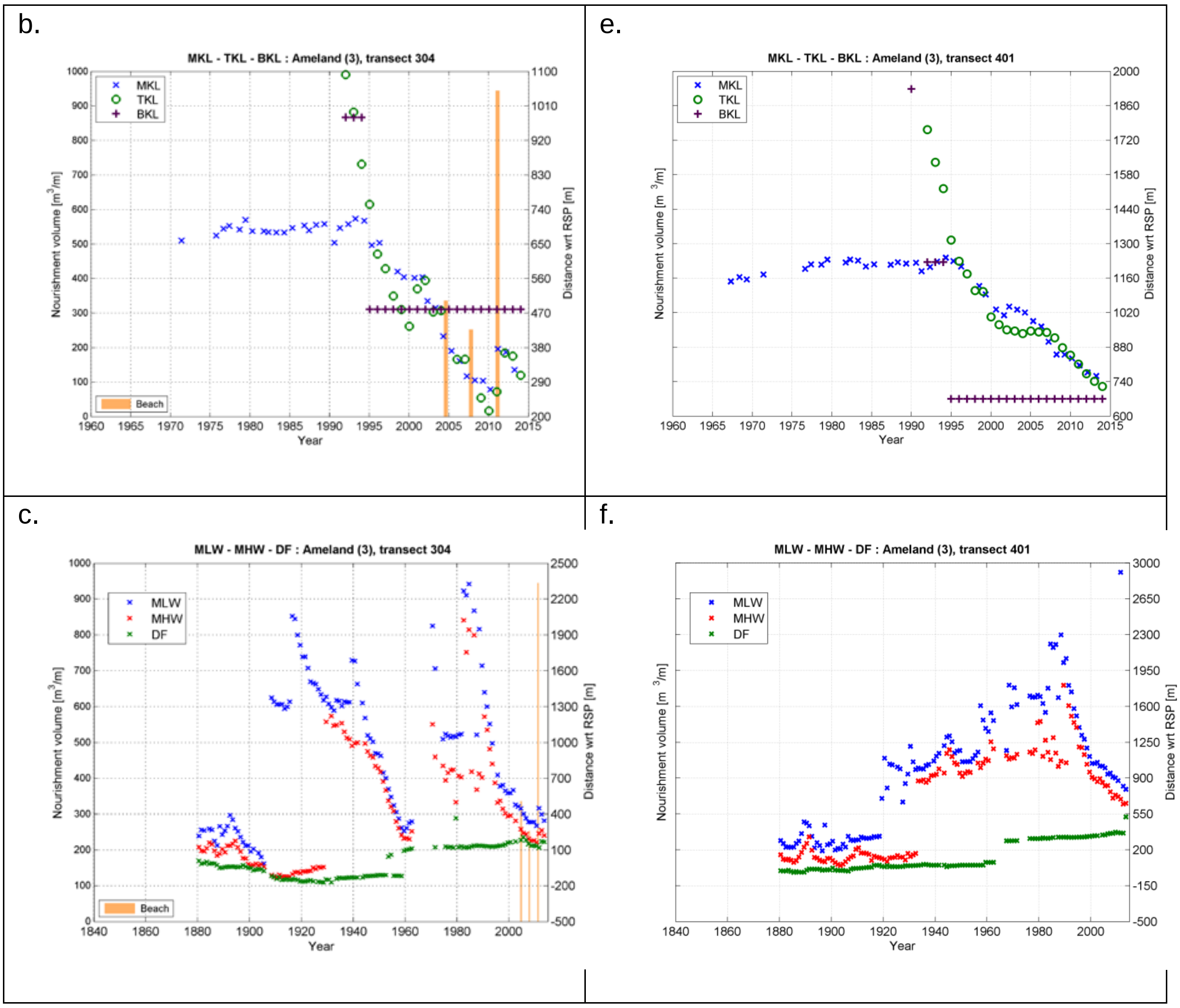


Figure 8.56 Detail of the Oostgat channel. Coastal indicators for the highlighted transects (3000304 in red, 3000401 in yellow) are investigated.

Table 8.8 Coastal indicators for transect 3000304 (left panel) and transect 3000401 (right panel). Figures a., d.: Probability of failure. Figures b., e.: MKL, TKL, BKL. Figures c., f.: Mean High Water, Mean Low Water, Dune Foot.





Two cross-shore profiles of transect 3000304 and transect 3000401 derived from vaklodingen data and Jarkus data are shown respectively in Figure 8.57 and Figure 8.58. The figures confirm the high dynamics in the channel and the general erosive trend which has taken place during the last 40 years.

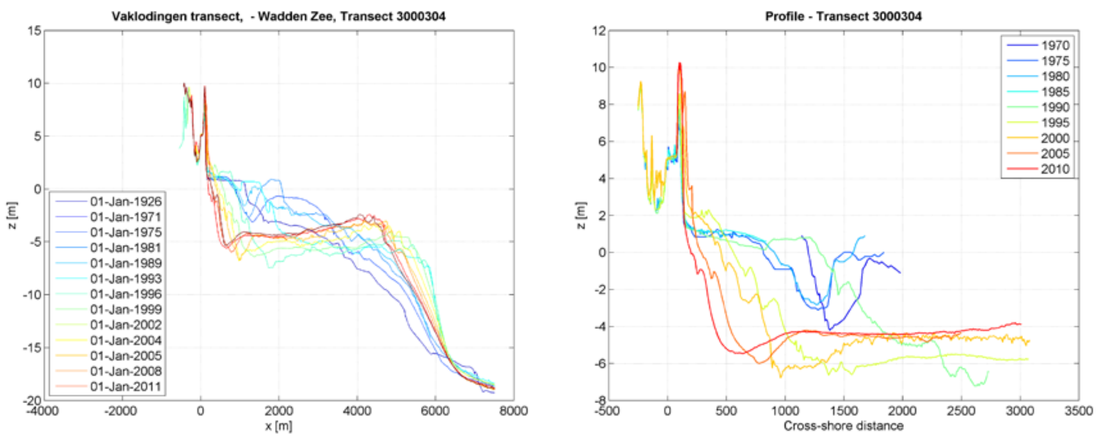


Figure 8.57 Profiles from Transect 3000304, based on vaklodingen data (left) and Jarkus data (right).

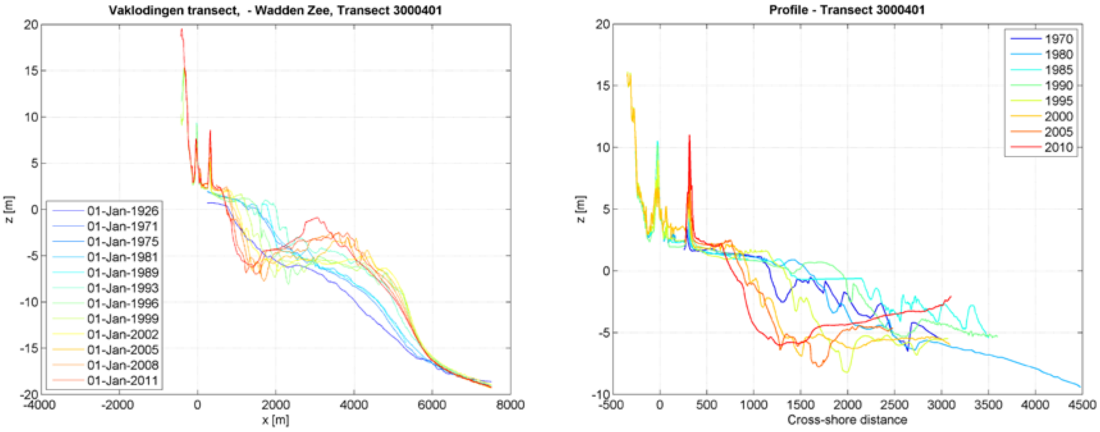


Figure 8.58 Profiles from Transect 3000401, based on vaklodingen data (left) and Jarkus data (right).

8.3.6 Pinkegat and Zoutkamperlaag

The Frisian Inlet (Friesche Zeegat) comprises two main inlet channels: the Pinkegat (Figure 8.59, green area) and the Zoutkamperlaag (Figure 8.59, yellow area). The two channel systems are separated by the supra-tidal shoal called Engelmansplaat. Before the closure of the Lauwerszee in 1969, both Pinkegat and Zoutkamperlaag displayed cyclic morphological changes between single and double channel configuration (Oost, 1995). The closure caused a considerable reduction in tidal prism, which induced major morphological changes both in the basin and at the ebb-tidal delta as the inlet started to evolve to a new state of dynamic equilibrium (Elias et al., 2012). Wave-driven onshore transport induced erosion on the ebb-tidal delta front, contributing to sediment transport onto the coast and into the inlet channel and back barrier basin.

The Pinkegat shows a cyclic development from a single main channel to multiple channels and back, with a period varying between 20 to 40 years. After the closure the cyclic development continued. Figure 8.60 shows the time development of the water volume under the -10 m contour line. The time series confirms a cyclic behaviour of erosion and deposition, with deposition trends taking place in the ‘40s and from the ‘80s until today; the period of the entire cycle is about 50 years. The time changes of the centroid of that volume also shows nicely the periodic morphological development of the channel system, which first moved in north-west direction (approximately before 1949) and then towards the south-east direction.

Figure 8.59 Polygons defining the Pinkegat (green) and Zoutkamperlaag (yellow) channel systems.

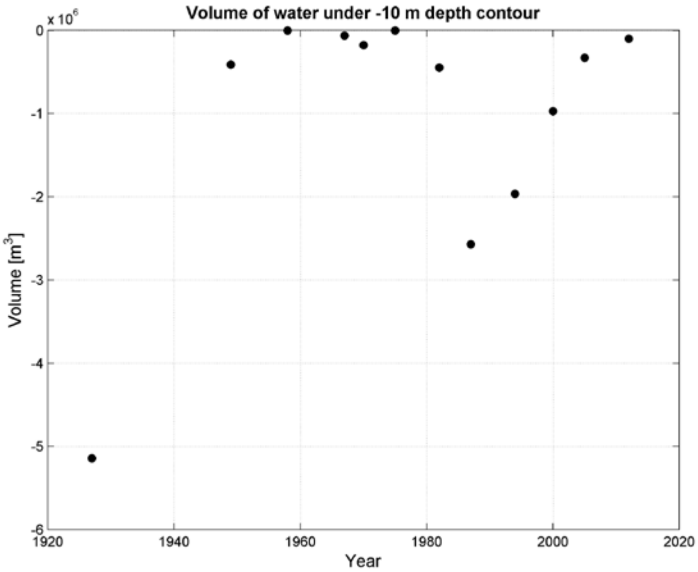


Figure 8.60 Pinkegat. Evolution over time of the volume of water delimited by the channel bed and -10m contour line (from Vaklodingen data).

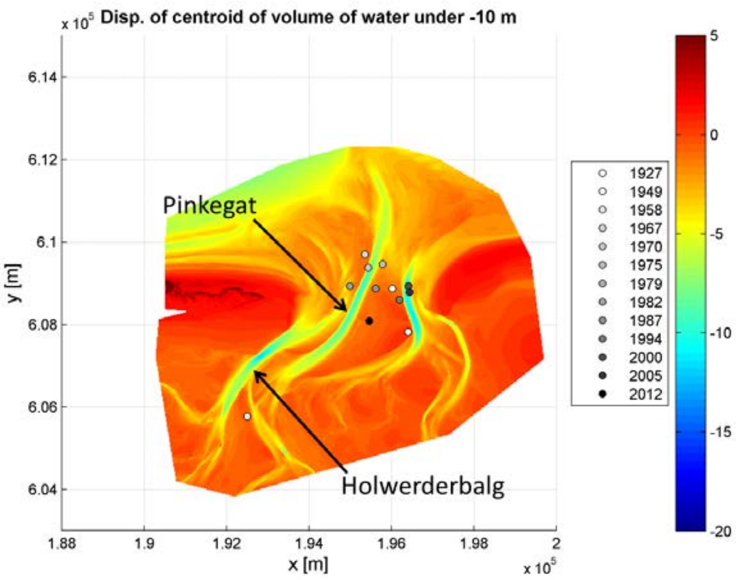


Figure 8.61 Displacement of the centre of mass of water defined by the -10 m contour line for the Pinkegat and Holwerderbalg channel.

Transect 3002500, located at the north-east of Ameland has been selected to find possible correlation with the coastal indicators (Figure 8.62, green area). Unfortunately, data available from indicators is limited. Table 8.9 c, shows that the long-term variations which are also observed in the evolution of the tidal channels are also found back in the trends of mean high water and mean low water position, with erosion taking place before 1980, then accretion until year 2000 and then again erosion. No nourishment has been applied at this location.

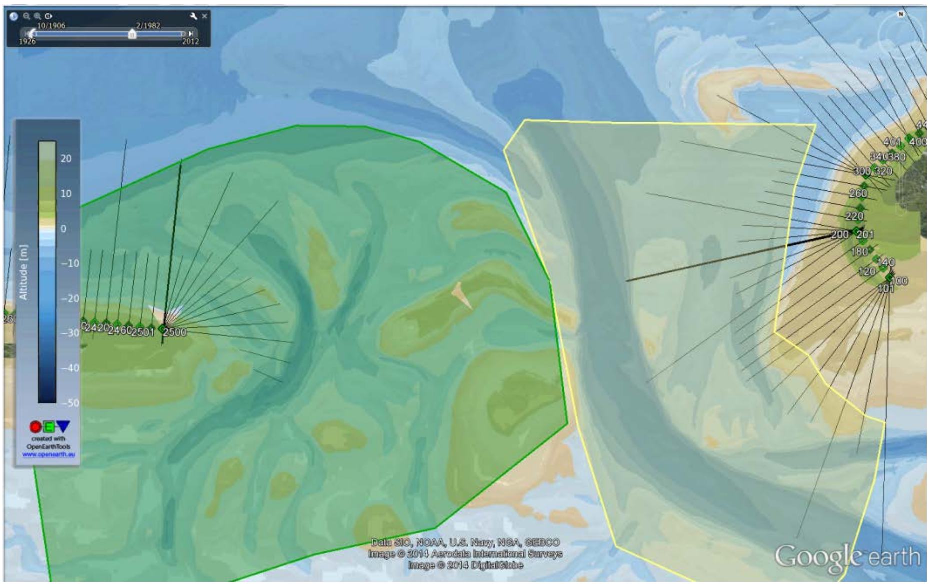


Figure 8.62 Detail of the Pinkegat and Holwerderbalg (green area) and the Zoutkamperlaag (yellow area). Coastal indicators for the highlighted transects (3002500, 2000200) are investigated.

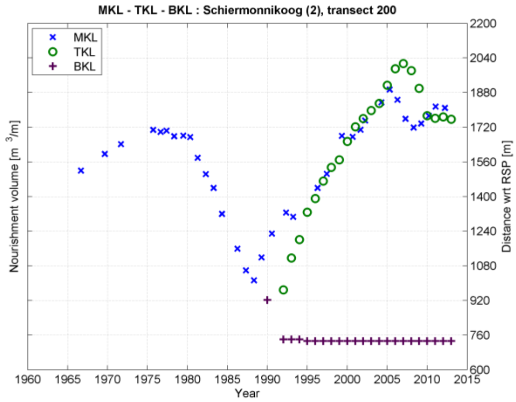
Table 8.9 Coastal indicators for transect 3002500 (left panel) and transect 2000200 (right panel). Figures a., d.: Probability of failure. Figure e.: MKL, TKL, BKL. Figures c., f.: Mean High Water, Mean Low Water, Dune Foot.

a.

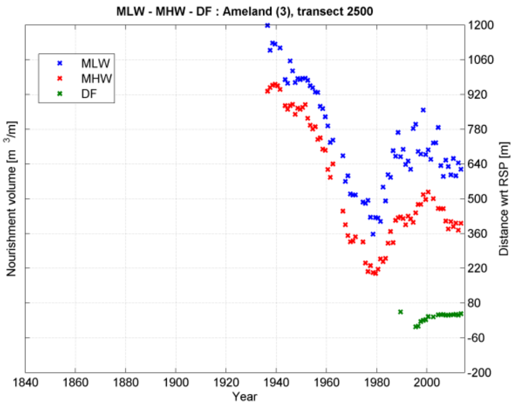
d.

b.

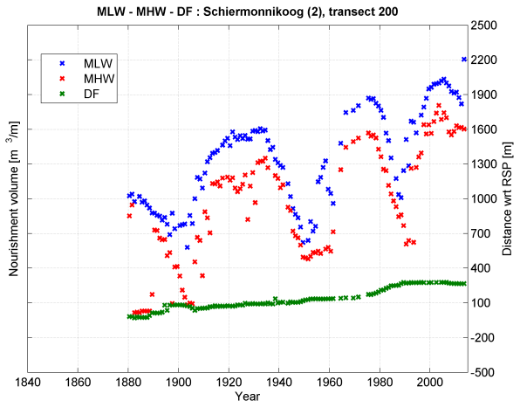
e.



c.



f.



A cross-shore profile at transect 3002500 derived from vaklodingen data and Jarkus data is shown in Figure 8.63. The figure confirms the erosive and accretive trends during the years also shown in Figure 8.60 and Table 8.9 (erosion before 1980, accretion between 1980 and 2000 and then again erosion).

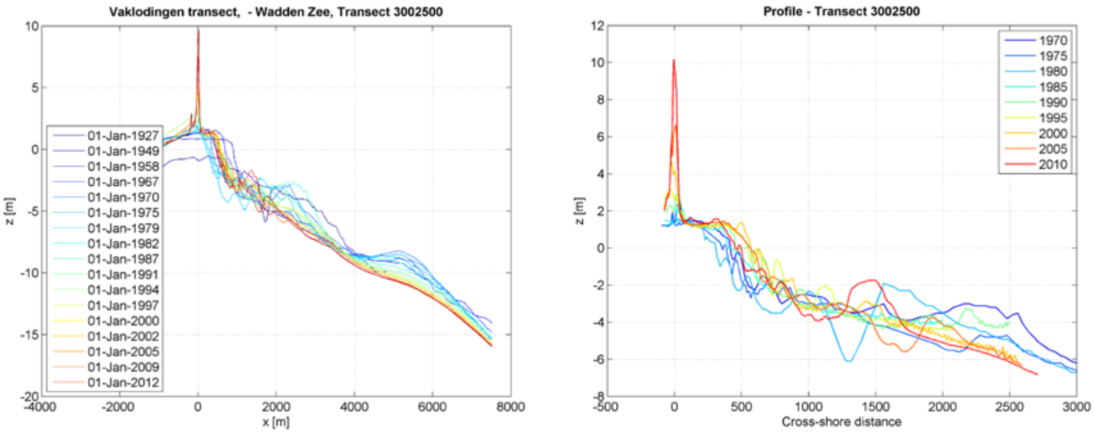


Figure 8.63 Profiles from Transect 3002500, based on vaklodingen data (left) and Jarkus data (right).

Prior to closure of the Lauwerszee in 1969, basin and inlet portions of Zoutkamperlaag were fairly stable in depth (Elias et al., 2012). Figure 8.64 shows the volume changes for the deeper part of this channel below the -10 m contour line. Starting from the ‘60s it is clear how the channel has been undergoing sedimentation resulting from the reworking of the excess volume of ebb-tidal delta deposits. This trend resulted into a considerable reduction in size and seaward extension of the channel. This trend can be also visualized by the migration of the centroid of the channel, which has migrated clearly in south-east direction during the last 30 years (Figure 8.65).

Transect 2000200, located on the western tip of Schiermonnikoog, has been selected to study the relation between tidal channel and coastal indicators (Figure 8.62, yellow area). Table 8.9-f clearly shows the long-term cyclic variation with a period of about 40 years on the indicators mean-low water, mean-high water and dune foot position. Those variations are also observed on the trends of MKL for the last decades (Table 8.9-e). The steep seaward migration during the years ’70 is also influenced by effects of the closure of the Lauwerszee, when sand from the ebb tidal delta was brought to the coast in the form of a shoal which finally attached to the land. The indicator probability of breaching shows that in general safety has improved since 1965 when Jarkus measurements are available (Table 8.9-d). No nourishment has been applied at this location.

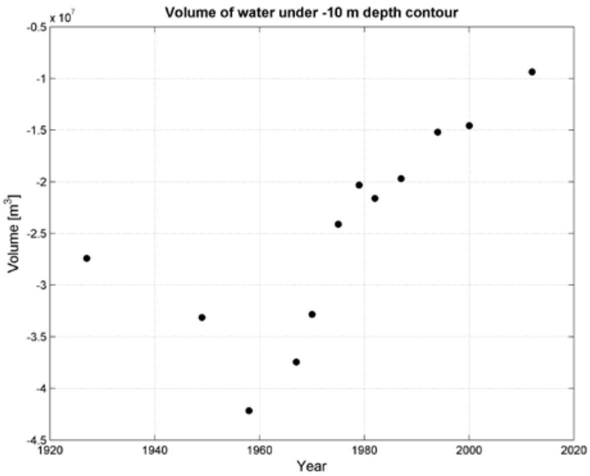


Figure 8.64 Zoutkamperlaag. Evolution over time of the volume of water delimited by the channel bed and -10m contour line (from Vaklodingen data).

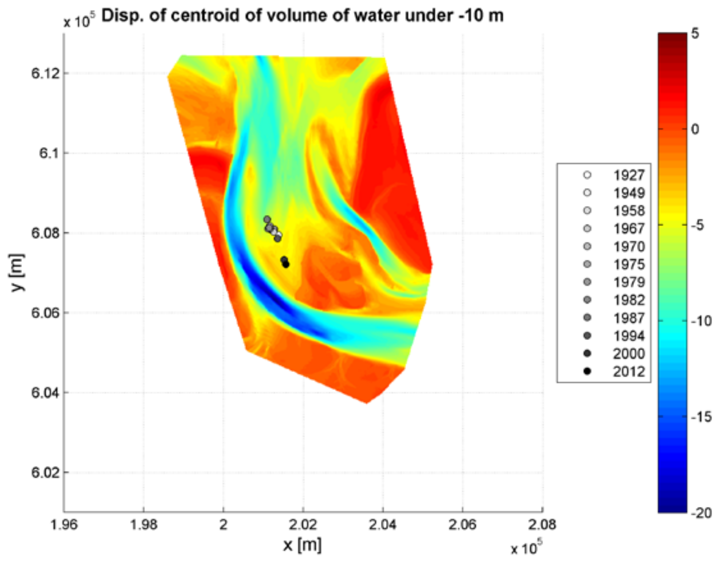


Figure 8.65 Displacement of the centre of mass of water defined by the -10 m contour line for the Zoutkamperlaag channel.

A cross-shore profile at transect 2000200 derived from vaklodingen data and Jarkus data is shown in Figure 8.66. The figure confirms the narrowing of the channel after 1960 as also shown by the reduction in volume in Figure 8.64.

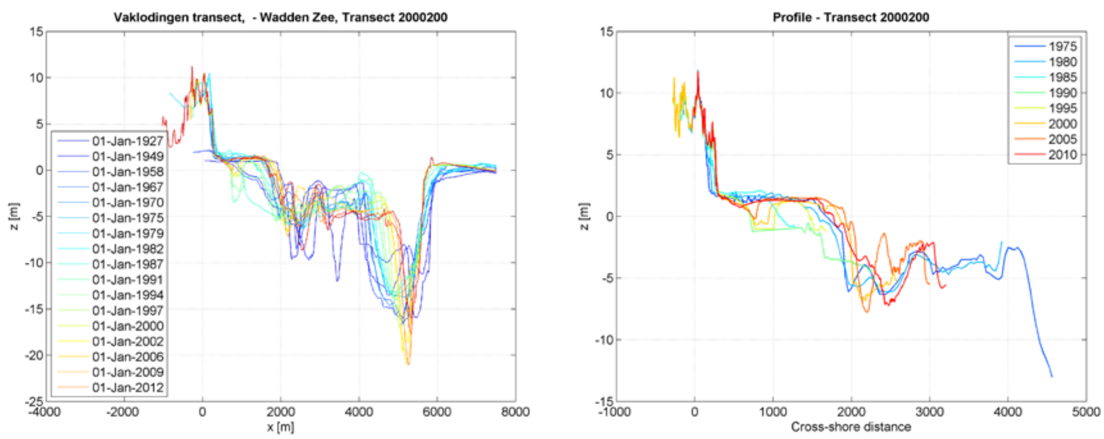


Figure 8.66 Profiles from Transect 2000200, based on vaklodingen data (left) and Jarkus data (right).

9 Discussions

Two hypotheses have been presented and assessed within this report (Chapter 2):

1) The nourishment strategy of the past years has led to a positive development of a number of "indicators" along the Wadden coast.
2) As a consequence, nourishments contribute to an increase of the safety level through a seaward shift of the erosion point.

In general, the study has shown that, given the large number of factors which have influenced the morphological development of the Wadden islands, it is very difficult to assess the effect of nourishments at the regional scale and draw conclusions on the effectiveness of different nourishment strategies at this scale. However, the positive effect of the nourishments can still be recognized clearly at the local scale at locations where large nourishments are implemented (e.g. at Ameland and Texel – hypothesis 1, in Chapter 2).
In general, this is different from what can be observed at North- and South- Holland where the effects of nourishments is much more evident (i.e. due to larger nourishment volumes and more limited influence of external factors) and where relations can be derived between nourishment volumes and the effects on coastal indicators even at larger scale (Giardino et al., 2014a).

At locations which showed a general seaward shift in MKL, mean-low and mean-high water line (e.g. due to a nourishment) a consequent reduction or stabilization in the indicator probability of breaching was generally also observed (e.g. see for example Table 8.7). This confirms hypothesis 2.

Without any doubt, at the Wadden Islands the largest changes in coastal indicators are induced by periodic changes in the ebb tidal delta (i.e. movements of tidal channels), presence of sand waves, both also influenced by the closures of the Zuiderzee and Lauwerszee, and finally the construction of coastal defences. This also implies that to advice WVL on where to nourish and on the most efficient nourishment strategy at the Wadden islands (objectives in Chapter 2), it is crucial to have a good understanding of the morphological changes happening in the background of the coastal system, and which might completely overrule the effects of the nourishments. The assessment of the morphological changes induced by sand waves and tidal channel migration on coastal indicators, should therefore be included to the standard coastline maintenance evaluation procedure (i.e. by predicting future trends using a predictive model calibrated on past data).
Next to data analysis, the numerical modelling of the morphodynamics of the outer Delta it is also crucial as it allows assessing future scenarios which might differ from the past observed trends.

10 Conclusions

The morphological development of the Wadden island has been assessed by looking at the time evolution of a number of coastal state indicators. In particular, as the focus of this study is on coastline care, only the stretches of coast of those islands facing the North Sea, as well as the tidal inlets, are included in this analysis. Possible changes in the following indicators were assessed: dune foot position, mean high water and mean low water position, MKL and probability of breaching. Several factors, which have influenced their development, have been depicted and their effect was assessed. Among those factors, a number of man-made interventions (i.e. closure of the Zuiderzee and Lauwerszee, other hard structures for coastal protection and sand nourishments) natural long-term natural trends, dynamic movement of morphological features (i.e. sand waves and tidal channels) and storminess.

The main conclusions from this study are grouped below under different themes as analysed in this research.

10.1 General (large scale) observations

- Given the large number of factors which have influenced the morphological development of the Wadden islands, it is very difficult to assess the effect of nourishments at the regional scale and draw conclusions on the effectiveness of different nourishment strategies, as given in the underlying objectives of the project (Chapter 2). However, the positive effect of nourishments can still be recognized at the local scale.

- At locations which showed a general seaward shift in MKL, mean-low and mean-high water line (e.g. due to a nourishment) a consequent reduction or stabilization in the indicator probability of breaching was also observed. This confirms hypothesis 2 (Chapter 2).

- Different islands show very different morphological developments from each other.

- The largest morphological changes in trend generally occur at the tips of the islands. In particular, the heads of the islands are generally characterized by a much wavier pattern, with rapid morphological changes. The tails of the islands are mainly characterized by slow alternating trends of accretion and retreat (see e.g. Terschelling, Ameland and Schiermonnikoog) (Section 7.2).

- The analysis of the trends in coastal indicators suggests that the largest negative trends (erosion) during the last two decades are observed at Terschelling. On the other hand, the largest accretion is suggested at Schiermonnikoog, and which followed from the closure of the Lauwerszee.

- The effect of natural forcing (i.e. storminess) was discussed based in the previous works from Vuik et al. (2012) and Giardino et al. (2014a). Increase in yearly wave energy or yearly maximum water level leads to a general increase in probability of failure and a landward migration of MKL and dune foot position. However, those correlations show often a lot of scatter due to the presence of many other factors responsible for the morphological developments of the indicators.

10.2 Sand waves and tidal channels

- Sand waves type of features can be observed at most of the islands, influencing the time and spatial development of the coastal indicators. Sand waves are defined in this study as time fluctuations of the coastal lines around the average value. The origins of those fluctuations are not investigated in details within this report. Values of amplitude, celerity and period for the sand waves were also derived. Some of the values are in the same order of magnitude as shown by Verhagen (1989), but differences were also found. In particular, the values computed by Verhagen show in general larger celerities and smaller periods, which are somewhat difficult to justify based on our analysis.

- The effect of sand waves on different coastal indicators (mean high- and mean low-water and dune foot position) is similar. However, locally a phase shift between dune foot migration and mean high- and mean-low water line can be observed.

- The morphodynamic development of the sand waves is mainly influenced by the local angle between coastline orientation and direction of wave approach (Section 8.2.2.3).

- The morphological development of several tidal channels has been assessed by looking at their volume development as well as their migration rate (Section 8.3). In particular, the migration rate was assessed by looking at the shifts of the centroid of those channels. The quantification of the migration rates of those channels can help predicting the future coastal development of the region around the channel and indicate possible future problems. Morphological changes in the tidal channels were partly attributed to cyclic morphological behaviours of the tidal inlets (e.g. Oostgat, Pinkegat, Zoutkamperlaag, Borndiep), and partly to the effects of the closures of the Zuiderzee and Lauwerszee (e.g. Molengat, Vliestroom, Zoutkamperlaag). Relations can be found between shifts in tidal channels and the effects on coastal indicators (e.g. Molengat, Oostgat).

10.3 Nourishments and coastal indicators

- The large nourishment volumes implemented at Texel (Section 5.5) are necessary to maintain the coastline close to stable.

- Despite the fact that several nourishments have been built recently on top of the sand waves, sand waves still exist in the background and they develop in time. Coastal managers should account for the development of sand wave type of features when planning future nourishments and when evaluating the effectiveness of past nourishments (e.g. see Nourtec project example; Section 8.2.2.3). 2D maps showing the indicator development in time for each region and including the past nourishment works have been produced to point out the presence of those features and support coastal mangers in the planning of the future nourishments. A nice example of the implementation of nourishments accounting for the alongshore migration of morphological features is the case of the Bornrif at Ameland (Section 8.2.2.4). Methodologies to evaluate the future development of coastal positions accounting for sand waves have also been implemented within other studies (e.g. Reinders et al., 2013).

- Nourishments are required at stretches of coasts characterized by tidal channels approaching the coast. This analysis has also pointed out transects which have not been nourished so far but which are likely to need nourishments in the near future when tidal channels will get closer (e.g. in front of the Oostgat; Section 8.3.5).

10.4 Coastline protection structures and coastal indicators

- The effect of the main coastline protection structures on the indicator developments is well recognizable even at the large scale. As an example, the effects of the construction of the Eierlandse Gat dam at Texel in 2005 is shown in Section 7.2.

- As observed for the nourishments, protection structures can lead to changes in medium-term safety indicators (e.g. MKL) and which can in turn affect short-term safety indicators (e.g. probability of breaching) (see for example Table 8.4).

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A The indicator database

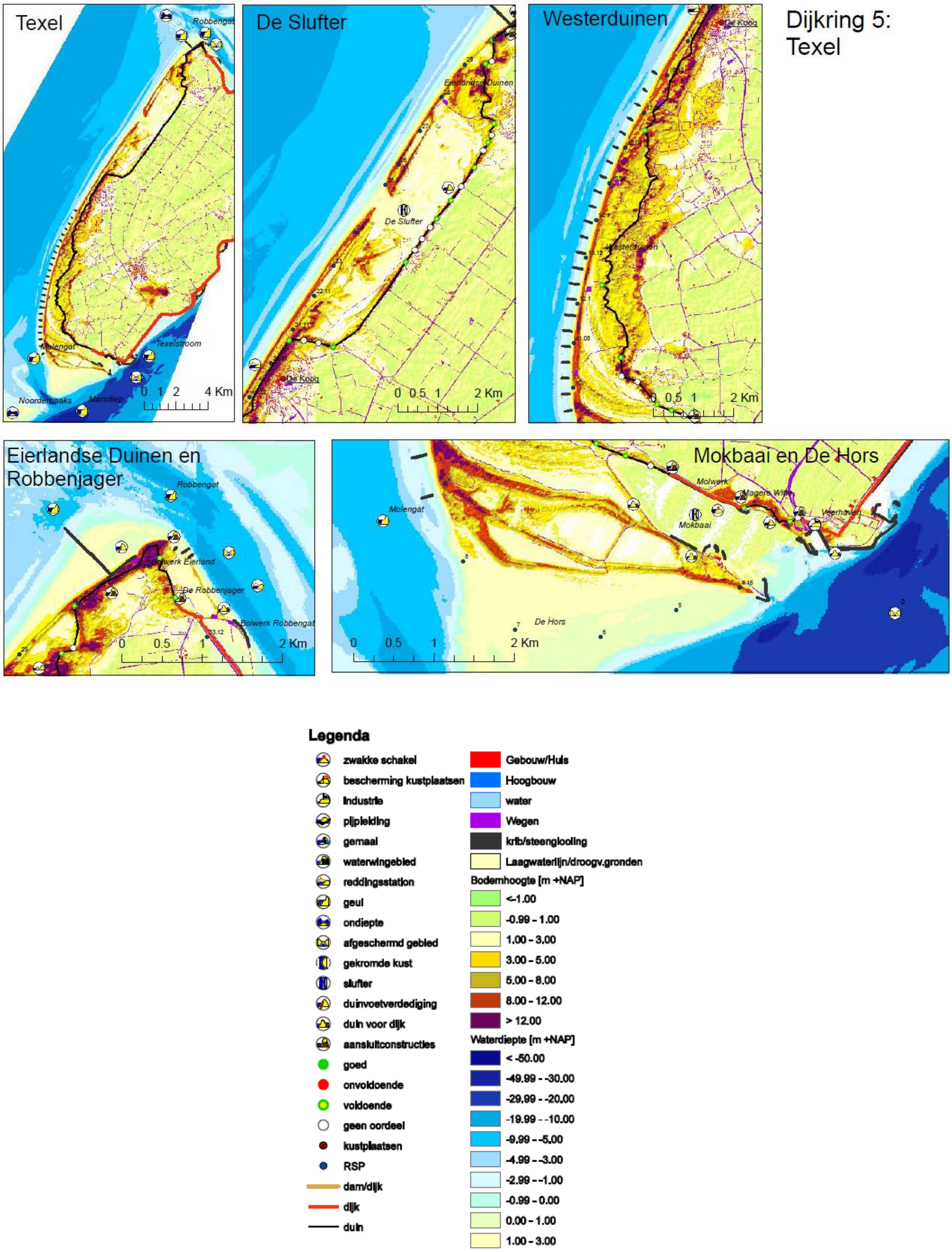
A complete database with the different indicators has been developed within this study. These data are freely available in NetCDF format through the Open Earth system (https://publicwiki.deltares.nl/display/OET/OpenEarth). Table A.1 gives the full list of indicators, accompanied by the URL link from which the data can be downloaded.

Table A.1 List of indicators with URL from which the dataset can be downloaded

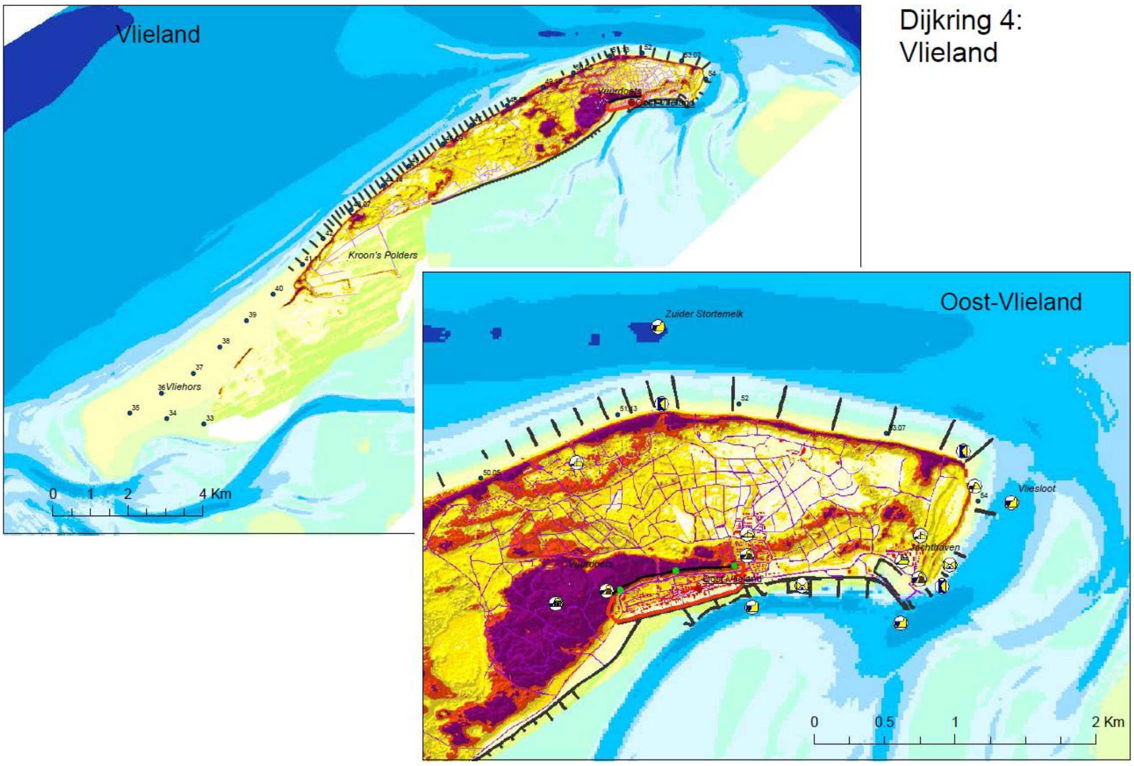
Indicator	URL Link
Nourishments	http://opendap.deltares.nl/thredds/dodsC/opendap/rijkswaterstaat/suppleties/suppleties.nc
Probability of breaching	http://opendap.deltares.nl/thredds/dodsC/opendap/rijkswaterstaat/faalkans_PC-Ring/faalkans.nc
Erosion length, MDL	http://opendap.deltares.nl/thredds/dodsC/opendap/rijkswaterstaat/safetyIndicators_Arcadis/kustlijnindicatoren_netCDF_nov2011_v2.nc
MKL	http://opendap.deltares.nl/thredds/catalog/opendap/rijkswaterstaat/BKL_TKL_MKL/catalog.html?dataset=varopendap/rijkswaterstaat/BKL_TKL_MKL/MKL.nc
BKL, TKL	http://opendap.deltares.nl/thredds/catalog/opendap/rijkswaterstaat/BKL_TKL_MKL/catalog.html?dataset=varopendap/rijkswaterstaat/BKL_TKL_MKL/BKL_TKL_TND.nc
Beach Width	http://opendap.deltares.nl/thredds/dodsC/opendap/rijkswaterstaat/strandbreedte/strandbreedte.nc
Dune Foot	http://opendap.deltares.nl/thredds/dodsC/opendap/rijkswaterstaat/DuneFoot/DF.nc
Sand volumes	http://opendap.deltares.nl/thredds/dodsC/opendap/rijkswaterstaat/sandVolumes_Alterra/DWI.nc

B Overview hard structures (Boers, 2008)

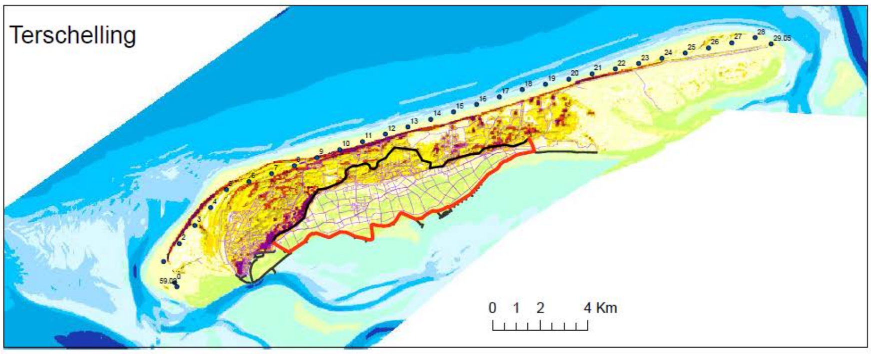
B.1 Texel



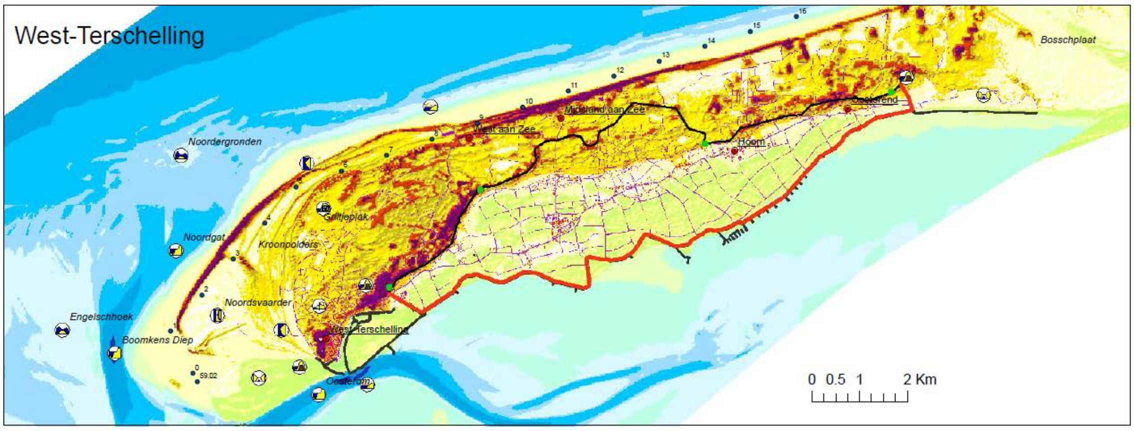
B.2 Vlieland


Dijkring 4:
Vlieland
Vlieland
Kroon's Polders
Vliehors
0 1 2 4 Km
Oost-Vlieland
Zuider Stortemelk
Vliesloot
0 0.5 1 2 Km

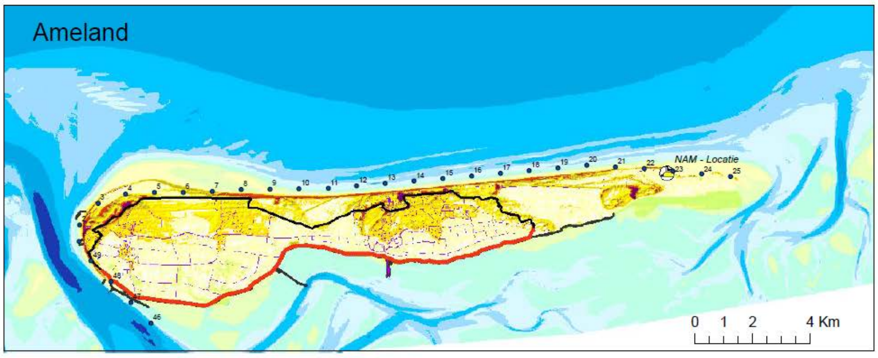
B.3 Terschelling



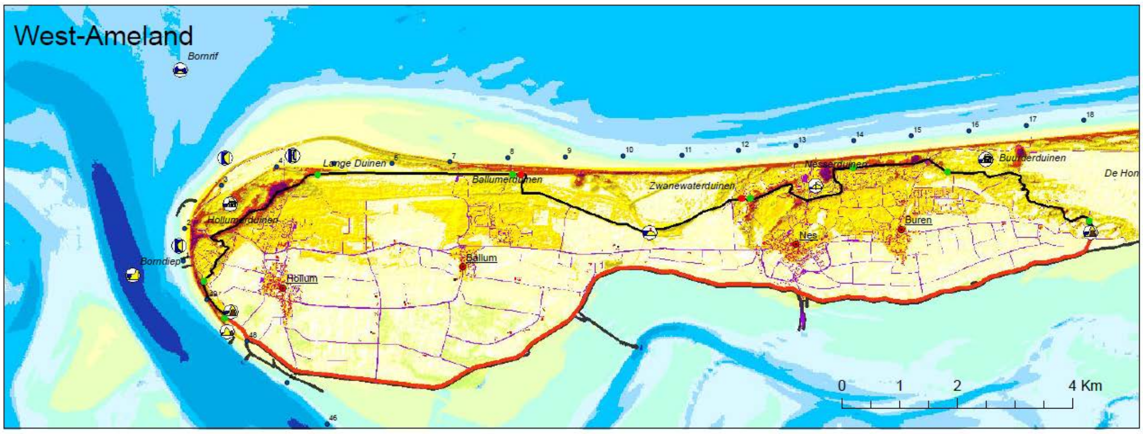
Dijkring 3:
Terschelling



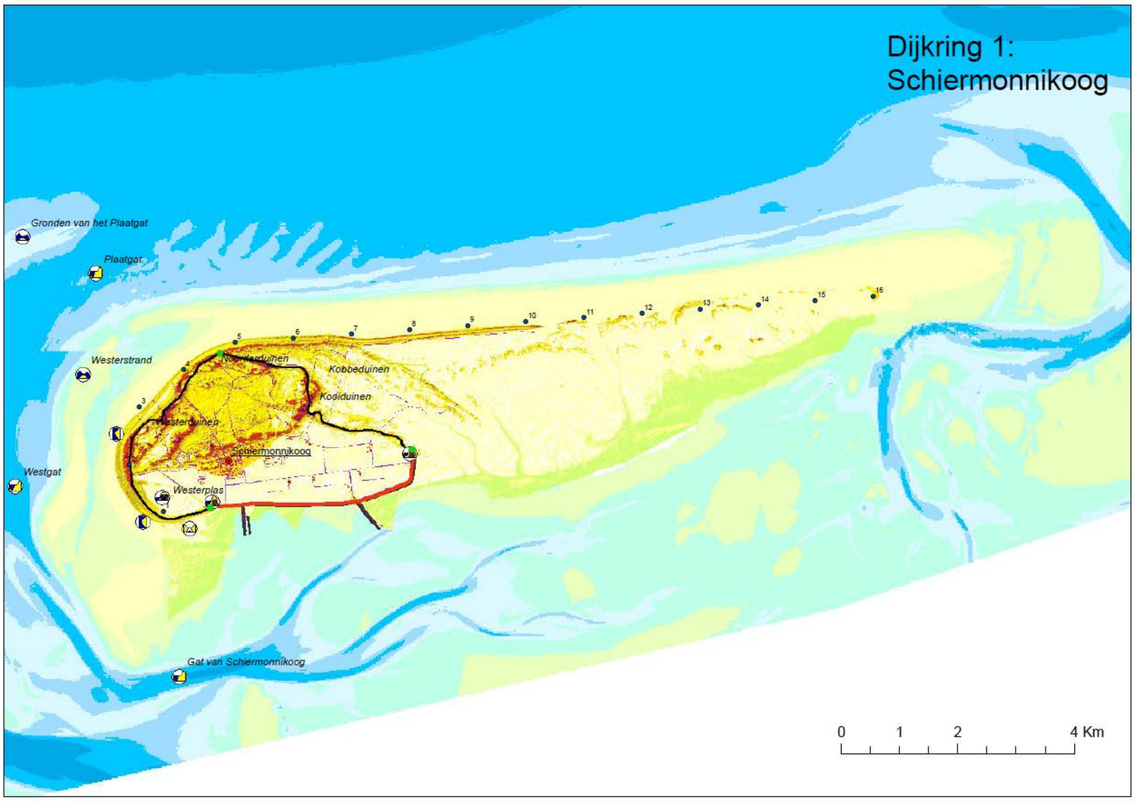
B.4 Ameland



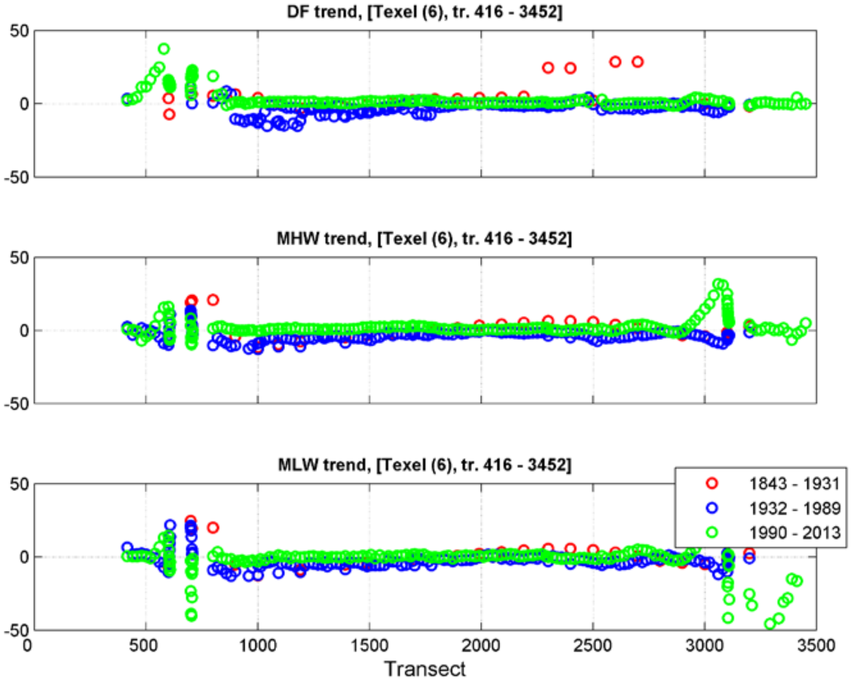
Dijkring 2:
Ameland

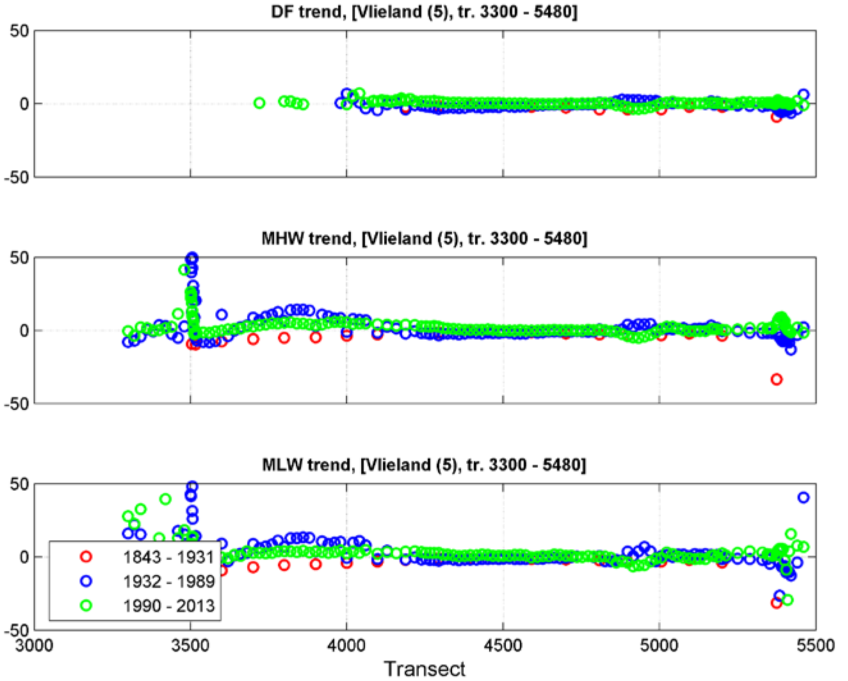


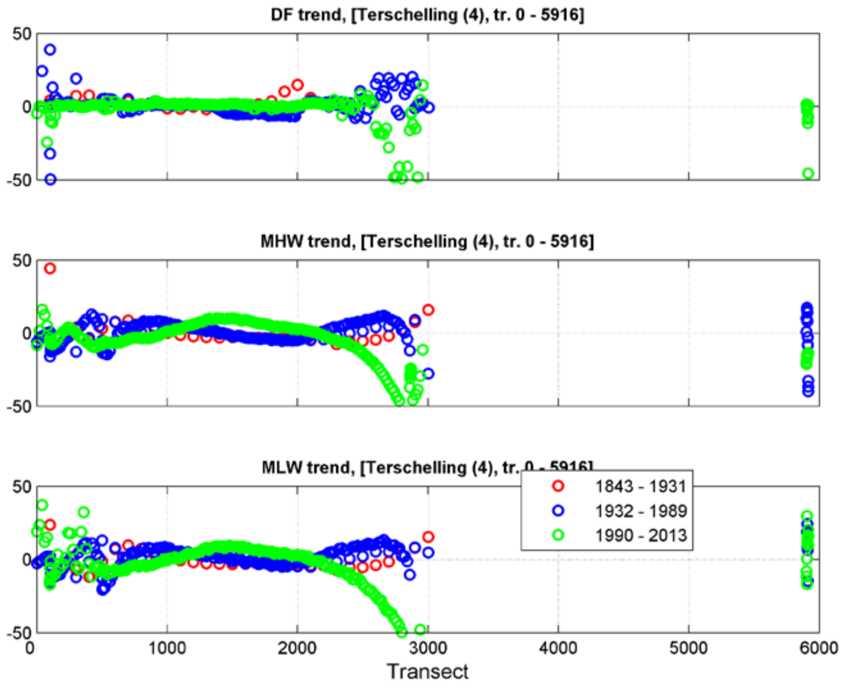
B.5 Schiermonnikoog

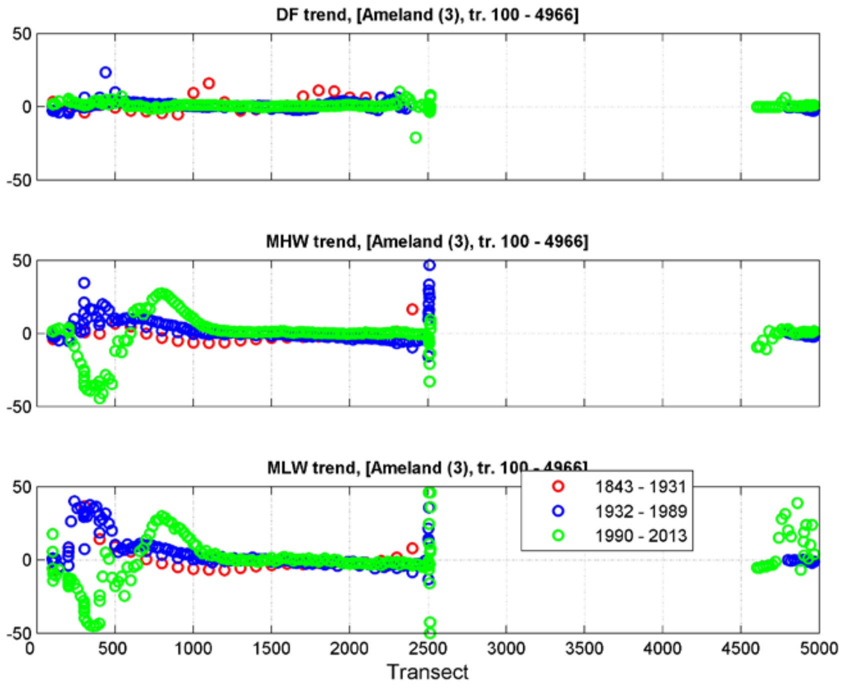


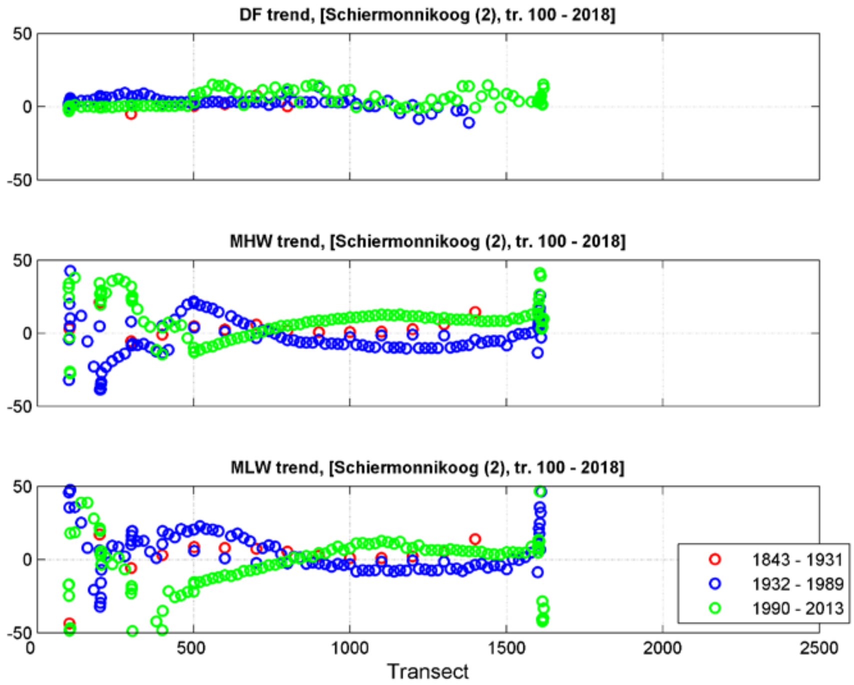
C Trends of indicators [m/year] for different regions






DF trend, [Terschelling (4), tr. 0 - 5916]
MHW trend, [Terschelling (4), tr. 0 - 5916]
MLW trend, [Terschelling (4), tr. 0 - 5916]
1843 - 1931
1932 - 1989
1990 - 2013
Transect


DF trend, [Ameland (3), tr. 100 - 4966]
MHW trend, [Ameland (3), tr. 100 - 4966]
MLW trend, [Ameland (3), tr. 100 - 4966]
1843 - 1931
1932 - 1989
1990 - 2013
Transect


DF trend, [Schiermonnikoog (2), tr. 100 - 2018]
MHW trend, [Schiermonnikoog (2), tr. 100 - 2018]
MLW trend, [Schiermonnikoog (2), tr. 100 - 2018]
50
0
-50
0
500
1000
1500
2000
2500
Transect
1843 - 1931
1932 - 1989
1990 - 2013

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