Deltares

Enabling Delta Life

The state of the coast

Toestand van de Kust

Case study:

The South-Westerly Delta

The state of the coast
- Toestand van de Kust -

Case study: The South-Westerly Delta

Alessio Giardino
Kees den Heijer
Giorgio Santinelli

1209381-006

Deltares

Title
The state of the coast
- Toestand van de Kust -

Client	Project	Reference	Pages
Water, Verkeer en Leefomgeving	1209381-006	1209381-006-ZKS-0001	89

Keywords
South-Westerly Delta, coastal indicators, MKL, mean low water line, mean high water line, dune foot position, probability of breaching, tidal channels, sand waves, nourishments, Delta Works.

Summary
The South-Westerly Delta is the area within the Netherlands which has been subject to the larger and longest anthropogenic interventions during the history. The construction of polders started already in the 12th century. From the 17th century, hard structures have been built against coastal erosion, and then accompanied by sand nourishments during the last decades. Next to it, other major interventions were built: the Delta Works, the construction with subsequent extension of the Maasvlakte harbour, and the Slufter.

Due to the strong anthropogenic impact, the assessment of the morphological evolution of the region is a complex task. Next to it, a number of natural 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 South-Westerly Delta has been assessed using an indicator approach. In particular, the following indicators were used in the analysis: MKL, mean low and mean high water line, dune foot position, and probability of breaching. As part of this analysis, 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 impact of those features on the indicators has been assessed, in combination with the effects of sand nourishments and other anthropogenic interventions. By looking at the past morphological changes and the effects of past nourishments, useful information is derived as a basis for planning of the future nourishment works.

References
-

Version	Date	Author	Initials	Review	Initials	Approval	Initials
	Feb. 2014	Alessio Giardino	[signature]	John de Ronde	[signature]	Frank Hoozemans	[signature]
	May 2014	Kees den Heijer					[signature]
		Giorgio Santinelli					

State
final

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).
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. According to predicted sea level rise scenarios, higher volumes of sand will 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 this 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 the third year of the project, the analysis has focused on the Zeeland coast.

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 South-Westerly Delta 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 the main conclusions from this study.

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 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. This 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. In case financial state of affairs makes prioritizing urgent, the state of the coast can contribute to the prioritization process.
- *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 validated 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 is the South-Westerly Delta coast, while similar studies have already been completed for North and South Holland coast.

To be able to achieve the objectives and to verify the hypothesis, a number of indicators have been defined. These indicators are representative of 1) the morphological development of the Dutch coast at different temporal and spatial scale and 2) related 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 South-Westerly Delta, considerable effort has been put into the evaluation of the effects of other man-made interventions as well as natural forcings, next to the effects of the nourishments.

---

[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, 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 5):

- 1843 – 1969. During this time window, it is assumed that morphological changes were mainly driven by natural processes.
- 1970 – 1989. Most of the Delta Works are carried out during this period (Section 5.3), affecting the morphological development of the entire region.
- 1990 – 2012. During this time window, the effects on the Delta Works in terms of morphological development are still very relevant. On top of that, a large nourishment program has been implemented (Section 5.6).

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: MKL, 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.
Next to the choice of the indicators, a further assumption relates to the procedure chosen to compute those indicators. 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.
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 along the coast. 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 beween the profile and the +3 m NAP. This is an assumption, generally adopted; however the dune foot so determined might differ from the real dune foot position.

4 Description of the study area

4.1 Morphological characterization of the study area

The South-Westerly Delta is located in the southern part of The Netherlands. The total length of its coastline is about 100 km, excluding the dams built during the Delta works, and divided in six different regions ("Kustvakken"), as given in Table 4.1. The South-Westerly Delta is officially located partly in the province of South-Holland and partly in Zeeland.

Table 4.1 Names of kustvakken with their respective lengths

Kustvakken	Length (km)	Province
Voorne	14	South-Holland
Goeree	17	South-Holland
Schouwen	17	Zeeland
Noord-Beveland	5	Zeeland
Walcheren	32	Zeeland
Zeeuws-Vlaanderen	15	Zeeland
TOTAL	**100**	

The South-Westerly Delta has seen large changes over the last few decades. Before 1970, four main estuaries existed in the Delta area. These estuaries are, from south to north: the Western Scheldt, the Eastern Scheldt, the Grevelingen and the Haringvliet (De Jongste et al., 2013, Figure 4.1). At present, only the Western Scheldt and Eastern Scheldt (partly closed) remain as tidal estuaries; the other two estuaries have been closed.

Figure 4.1 Bathymetry of the South-Westerly Delta. In yellow. the different regions (kustvakken) are given with their respective numbering. In red, the names of the different estuaries are shown.

As a consequence of those projects the outer delta was subjected to major morphological developments, which turned the Delta from a tidal dominated system into a more wave dominated system (Cleveringa, 2008). Sedimentation of the major tidal channels, which were dammed, has been observed. In particular, the most pronounced changes have been observed as a result of the closure of the Grevelingen and Haringvliet (3 and 6 in Figure 4.2). The closure of the Eastern Scheldt has resulted in minor and more localized changes in the proximity of the storm-surge barriers, as this tidal inlet is still connected to the outer delta and only closed during extreme storm surge events (9 in Figure 4.2), with, in the outer delta, some shoaling of the tidal channels (8 in Figure 4.2).

In the outer delta, the relative increase of wave forcing with respect to the tidal forcing, which were responsible for feeding the shoreface with sediments from the estuary, has resulted into shoreface erosion (2 and 5 in Figure 4.2). The erosion took place approximately between NAP -9 m and NAP -4 m (De Jongste et al., 2013).

Next to the Delta works other major projects were carried out just North of Voorne, impacting the morphological development of the South-Westerly Delta. In particular, the construction of the Sea Harbour of Rotterdam (Maasvlakte 1), realized in the sixtieths and its extension (Maasvlakte 2, realized between 2010 and 2013), and the Slufter, realized between 1986 and 1987 (Chapter 5).

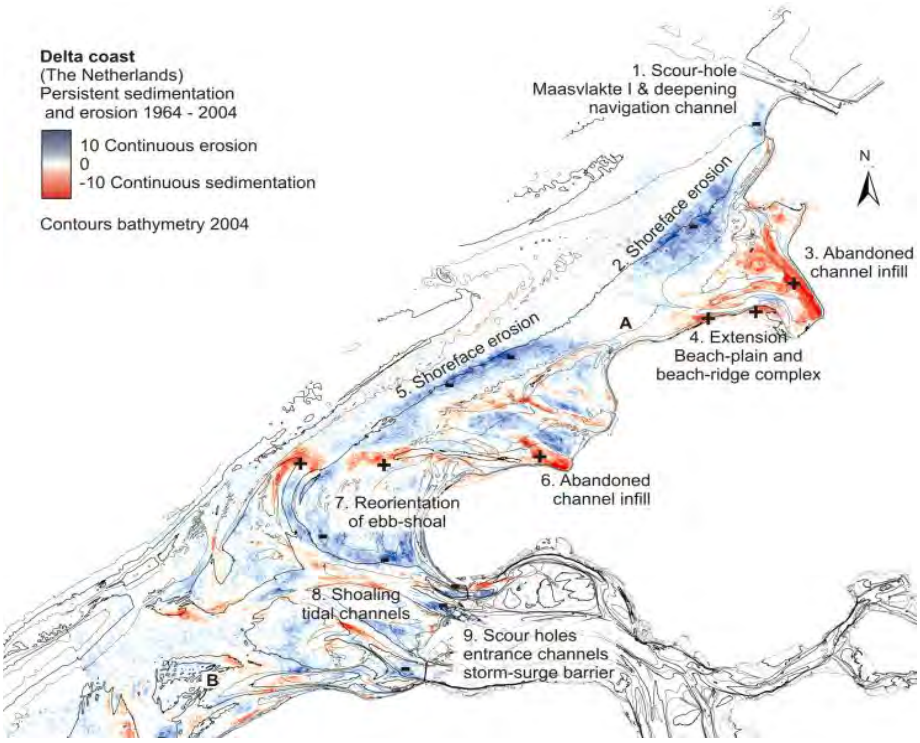


Figure 4.2 Sedimentation (red) and erosion (blue) plot in the Outer Delta in the period 1964-2004 (Cleveringa, 2008).

4.2 Tides and waves

The area is characterized by a mesotidal regime with a tidal range decreasing from South to North from about 5 m to about 3 m. Due to the closure of the Grevelingen and Haringvliet the current velocities at those locations decreased in terms of tidal velocities and changed towards a direction sub-parallel to the coast. Figure 4.3 shows for example the changes in tidal velocities and direction at the delta of the Grevelingen.

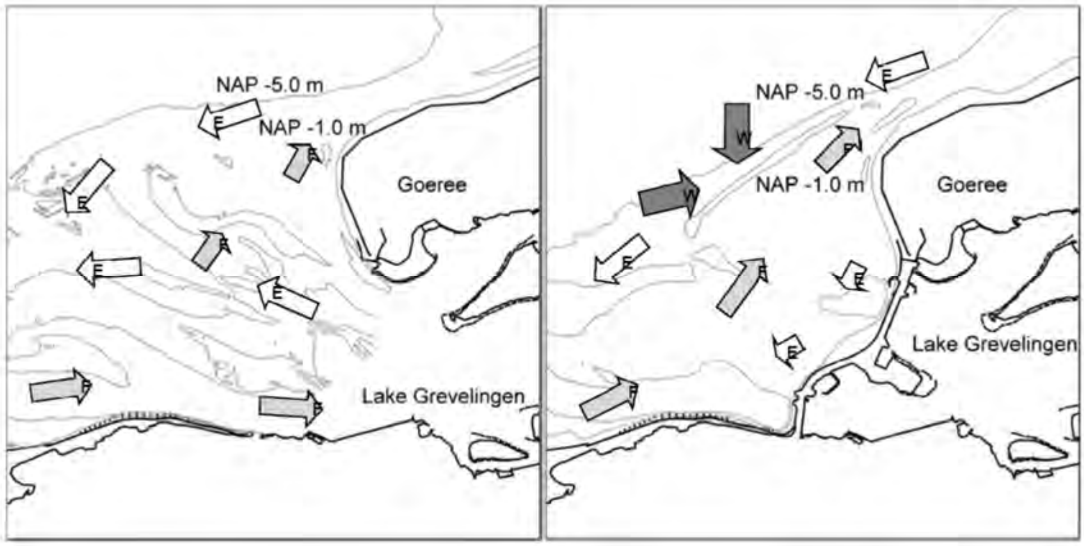


Figure 4.3 Ebb-tidal delta of Lake Grevelingen in 1964 (left) and 2010 (right) after construction of the Brouwersdam. Depth contour lines of NAP -1 m and NAP -5 m and dominant tidal velocities are shown. (E)= Ebb-dominated flow. (F) = Flood-dominated flow. (W) = Dominant wave load. (Nipsius, 1998).

The wave climate of the outer delta is shown in Figure 4.4. The Figure shows two dominant wave directions: from the North and from the South-West, with a wave height which usually ranges between 0 and 2 m, and that during occasional storm is above 5 m.

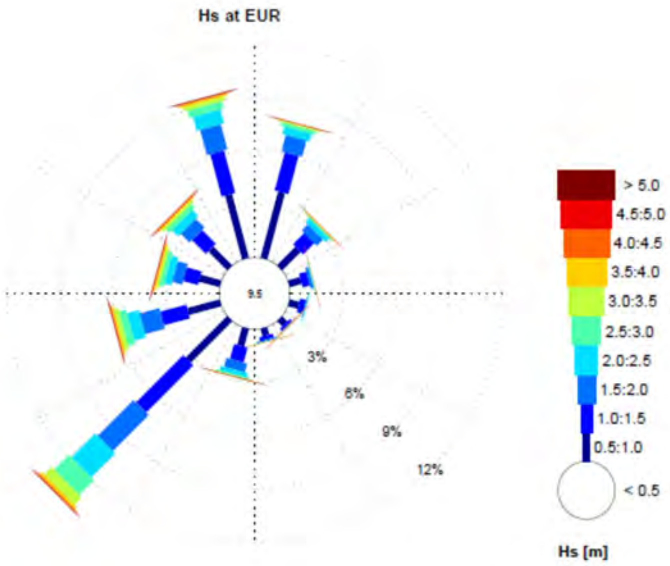


Figure 4.4 Wave climate at Europlatform station

4.3 Sediment characteristics

The median grain size (D50) on the foreshore ranges approximately between 160 μm and 320 μm as shown in Figure 4.5 (TAW, 1984). The alongshore grain size in the 80's, when the last measurements were collected, show coarser sediments at Walcheren and finer at Voorne.

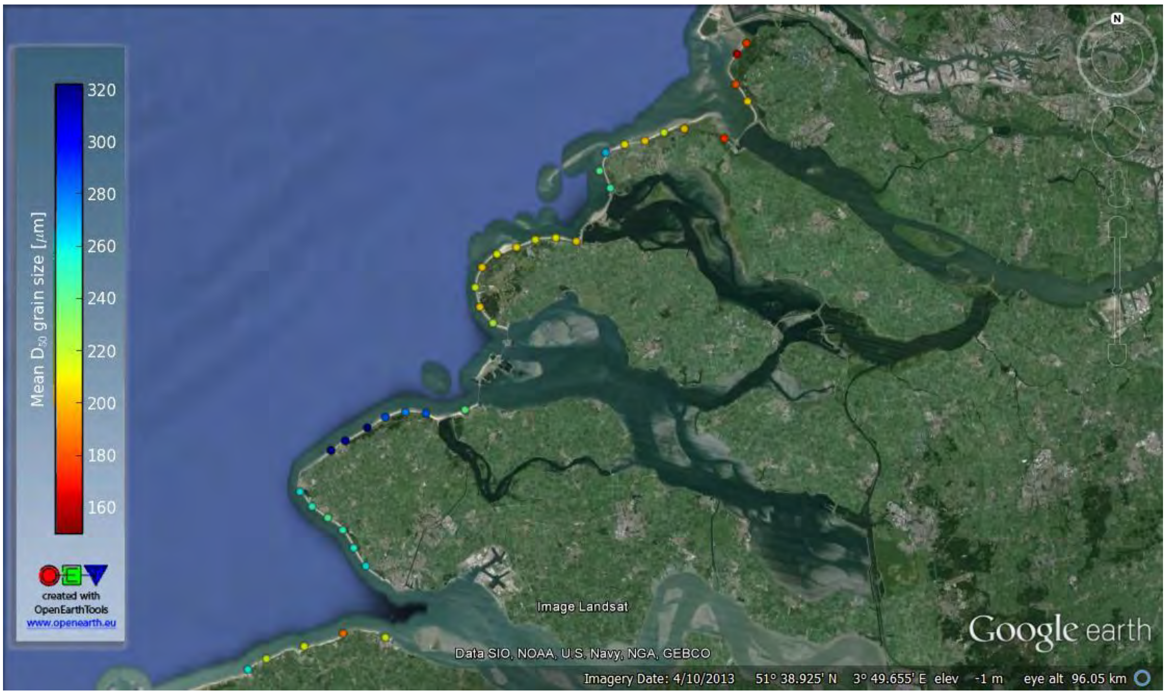


Figure 4.5 Median grain size (in μm) along the Holland coast (TAW, 1984).

5 Man-made interventions

5.1 Introduction

The South-Westerly Delta is the area within the Netherlands which has been subjected to the larger and longest anthropogenic interventions during the history.The construction of polders started already in the 12th century, as shown in Figure 5.1. The coastline, which had to be protected by the structural erosion, was then shielded by constructing different types of hard structures (Section 5.2), and in the later years using soft measurements as nourishments (Section 5.6) and a more efficient dune management (Section 5.7).
Next to it, other major interventions were built: the Delta Works (Section 5.3), the construction with subsequent extension of the Maasvlakte harbour (Section 5.4), and the Slufter (Section 5.5).

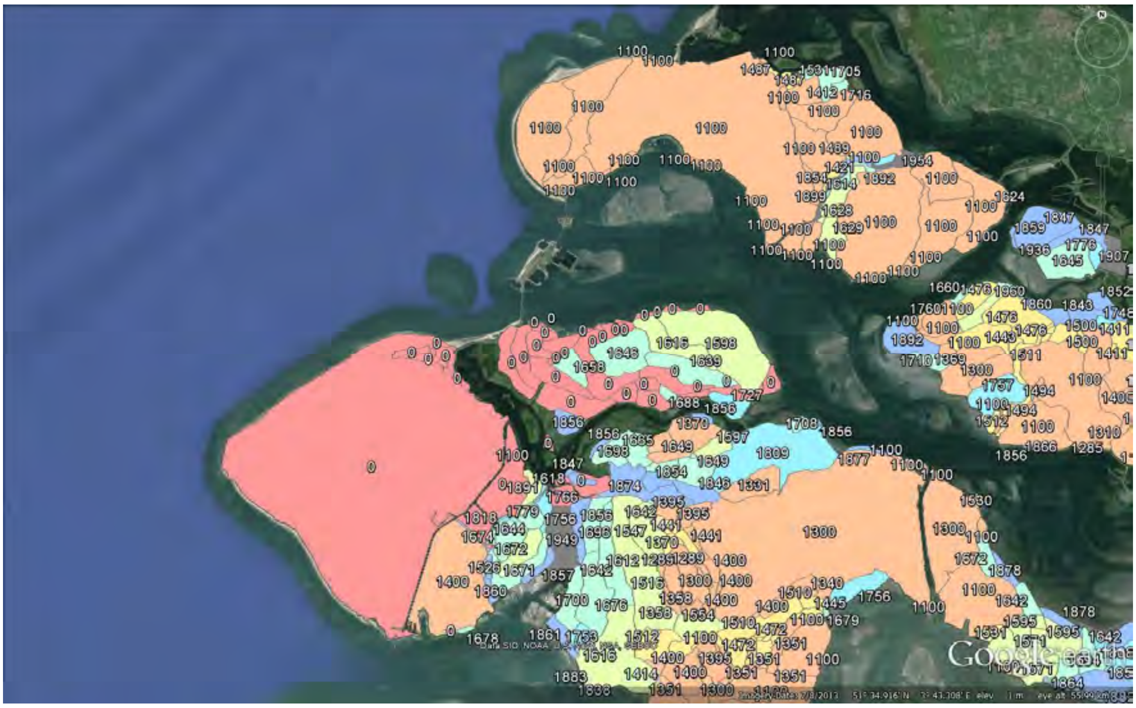


Figure 5.1 History of polder construction. The years indicate the approximate time when the polder was constructed.

5.2 Hard structures for coastal protection

Several types of hard structure have been constructed to counteract the chronic erosion. An overview of those structures can be found in Eversdijk (1989) and Verhagen (1989b).

Sea dikes were the first form of coastal protection against erosion. The most important are:
in Walcheren, the seadikes at Westkapelle, at Zoutelande and Vlissingen, and at Zeeuws-Vlaanderen the seadikes between Breskens and Nieuwvliet. The oldest seadike at Vlissingen already exists since 1326 (Verhagen, 1989b).

Several groins were also built in the past. In Schouwen, groins started being built in 1834. The erosion trend, which between 1750 and 1865 ranged approximately between 1 and 5 m per year, was replaced by a nearly stable coastline (Verhagen, 1989b). Figure 5.2 shows an overview of the changes in morphological development from the 17th century until the end of the 20th century.

The North-West of the coast of Walcheren had eroded for about 1 km in a few centuries, with a trend up to about 3 m per year. Groynes started being built in the 17th century, with a general stabilization of the coastline. Nevertheless, large temporal variations were still clearly visible due to the presence of big sand waves. Also in the South-West part of the island erosion trends were largely reduced by the groynes from about 4 m/year to a nearly stable coastline. On the other hand, the southern part of the island (north of Vlissingen) has always been rather stable, also due to the presence of the seadike, since 1326 (see Figure 5.2).

In Zeeuws-Vlaanderen the erosion trend has also been largely reduced by the groins, from about 3 m/year to a nearly stable coastline (see Figure 5.3). An overview of the structures along the entire coast is given in Figure 5.4. A detailed overview of the structures for single stretches of coast can be found in Appendix B.

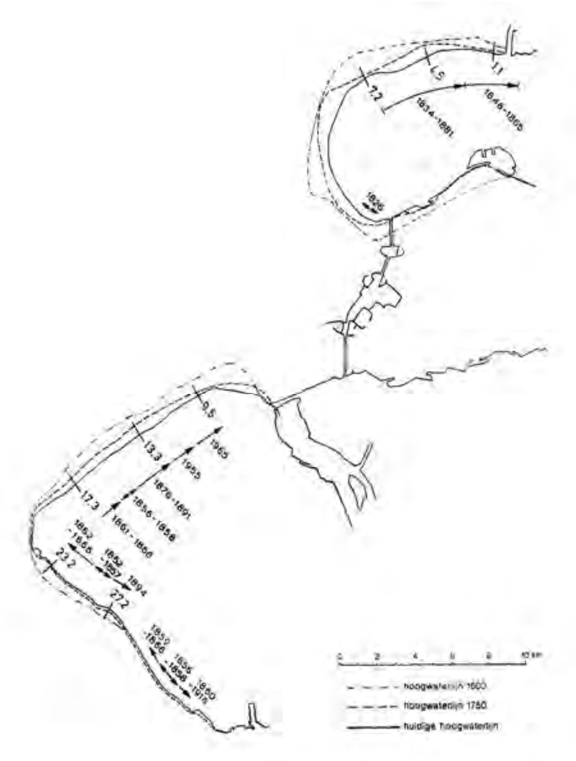


Figure 5.2 Morphological development of the coastline of Schouwen and Walcheren from the 17th century until the end of the 20th century (Verhagen, 1989b).

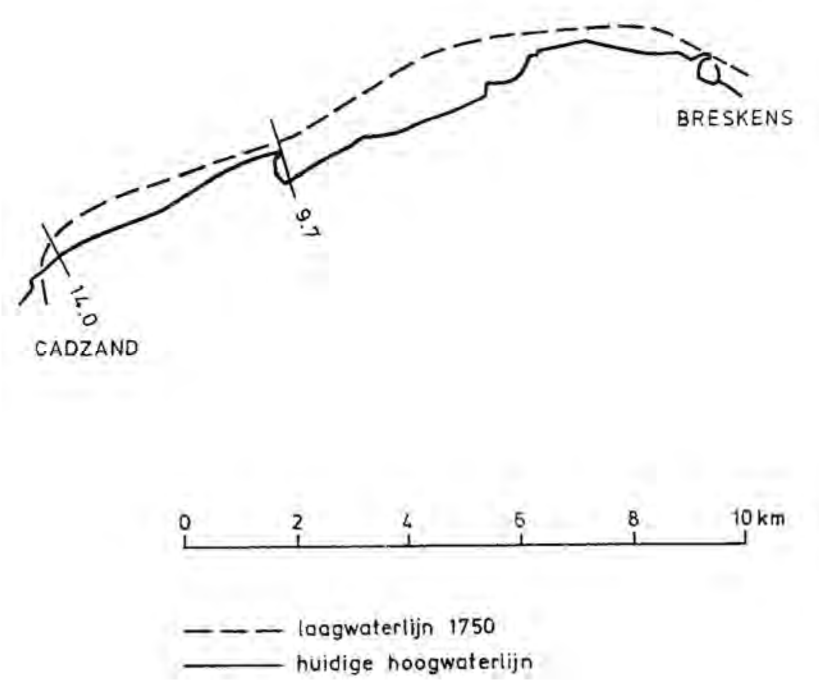


Figure 5.3 Morphological development of the coastline of Zeeuws-Vlanderen between 1750 and the end of the 20th century (Verhagen, 1989b).

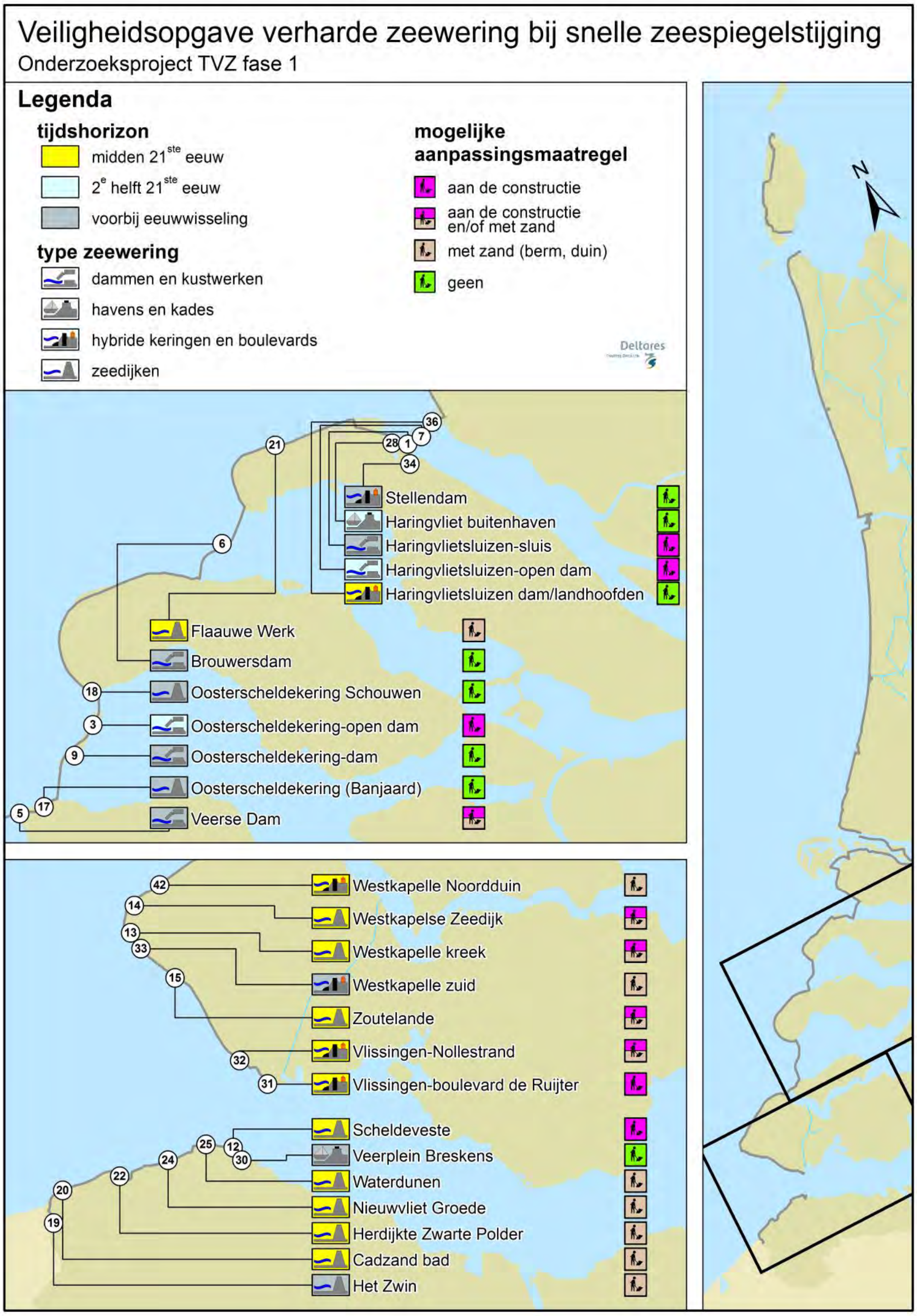


Figure 5.4 Overview of hard structures in Zeeland (Stronkhorst and Lagendijk, 2012).

5.3 The Delta Works

After the flood in 1953, the Delta works were constructed for flood protection and land reclamation purposes in the south-west part of The Netherlands. The Eastern Scheldt is maintained as a tidal embayment protected by a storm surge barrier whose works started in 1967 and which were completed in 1986. The Grevelingen is closed by the Brouwersdam and turned into a fresh water lake from 1971 to 1978 and a saline lake afterwards. The Haringvliet was closed in 1970 becoming a fresh water basin (Figure 5.5). The Western Scheldt was left open and regularly deepened to maintain the access of vessels to the harbour of Antwerpen and other minor harbours inside the estuary.

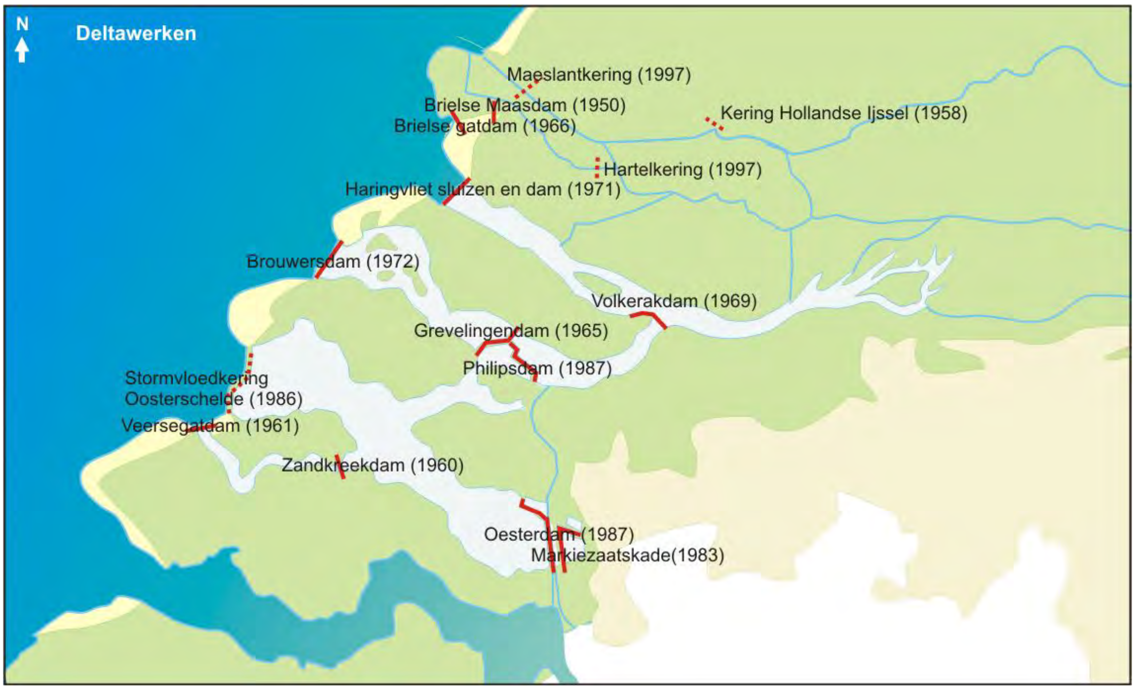


Figure 5.5 Overview of the Deltaworks and other major projects in the South-Westerly Delta. The year when the project was completed is given in brackets.

5.4 Maasvlakte 1 and 2

The Maasvlakte is a harbour and industrial area, which was created in the 1960s by reclaiming land from the North Sea through dykes and sand nourishment.

In September 2008, work has started on the "Second Maasvlakte" or Maasvlakte 2: the existing area has been expanded and in 2013 the new harbour of the Maasvlakte 2 was opened for commercial use. Between 2008 and 2013, 240 million m^3 of sand have been deposited from which 210 million m^3 is dredged from a sand extraction area in the North Sea and around 30 million m^3 comes from dredging the port basins and the Yangtzehaven.

Figure 5.6 Aerial view of the Maasvlakte harbour and the Slufter

5.5 The Slufter

The Slufter is a deposit for polluted sediments built in 1985 and with a surface area of 260 ha (Figure 5.6). The polluted sediments come from the maintenance of the harbour of Rotterdam.

5.6 Nourishments

Starting from the Fiftieth, large volumes of sand were nourished along the South-Westerly Delta coast. One of the characteristics of the nourishments along this region, with respect to the rest of the Dutch coast, is that nourishments are mainly built on the beach and not on the shoreface.
This is related to the relative steeper profile of the foreshore, which makes it more complicated to realize standard shoreface nourishments. To give an indication, the ratio beach/shoreface nourishment for the different regions along the Dutch coast, for the period 1990 – 2012 (value in millions of m^3), was: 26.6/37.6 for the Wadden coast, 33.8/49.2 for the Holland coast, and 46.2/13.7 for the Delta area (Vermaas and Van Oevereen, 2013). For reference, the steepness of the coastal area, computed between the dune foot position and the seaward boundary of the MKL, for different regions of the South-Westerly Delta is given in Appendix E. On the other hand, typical values of steepness for the Holland coast are in average around 0.025 (steepness of 1:40).
The total volume of nourishments for the South-Westerly Delta is given in Figure 5.7, with sub-division per region ("kustvak") and type. The nourishment volumes for each region and subdivided for each Jarkus transect are given in Figure 5.8 - Figure 5.13. Among others, the nourishment volumes at Walcheren stand out, with linearly volumes reaching almost 4500 m^3/m.

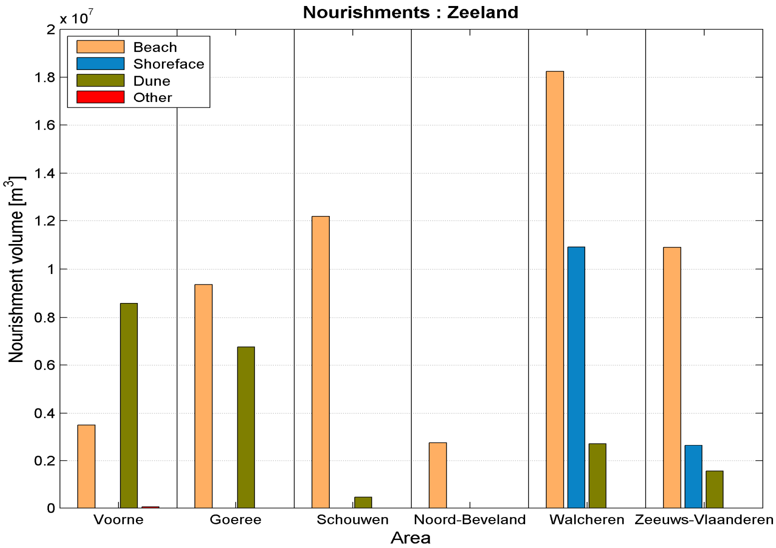


Figure 5.7 Total volume of nourishments applied in the South-Westerly Delta.Sub-division per region and type.

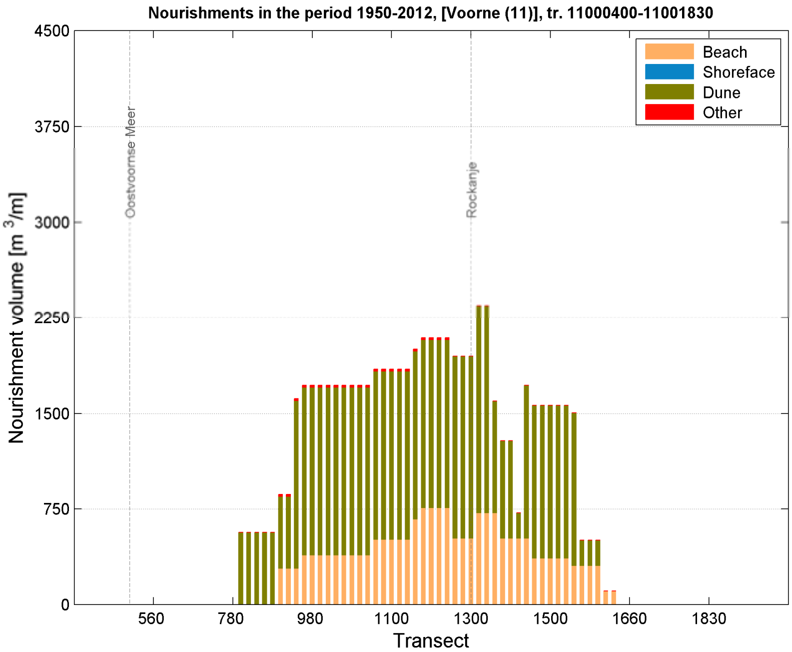


Figure 5.8 Total volume of nourishments in Voorne (Kustvak 11) for the period 1950-2012.

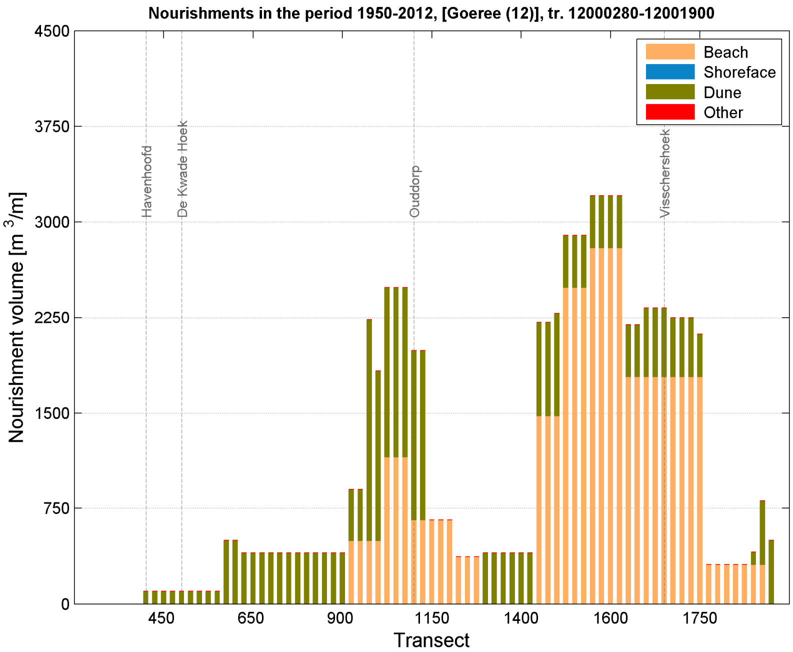


Figure 5.9 Total volume of nourishments in Goeree (Kustvak 12) for the period 1950-2012.

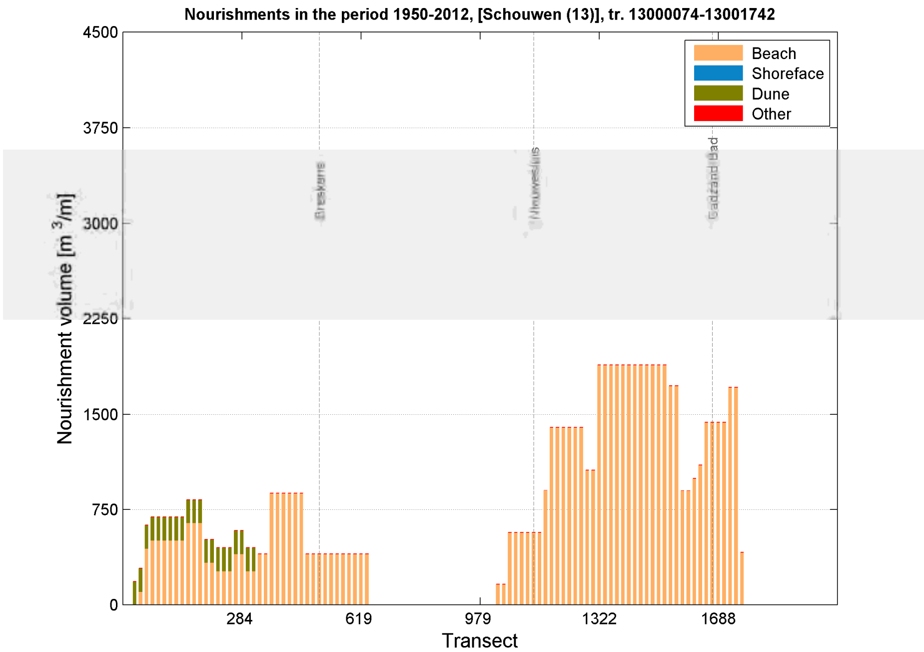


Figure 5.10 Total volume of nourishments in Schouwen (Kustvak 13) for the period 1950-2012.

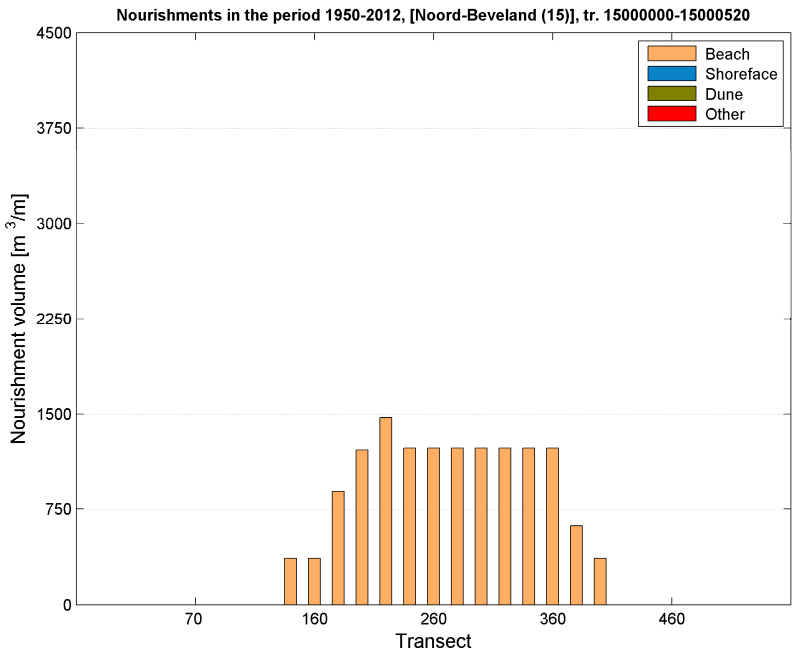


Figure 5.11 Total volume of nourishments in Noord-Beveland (Kustvak 15) for the period 1950-2012.

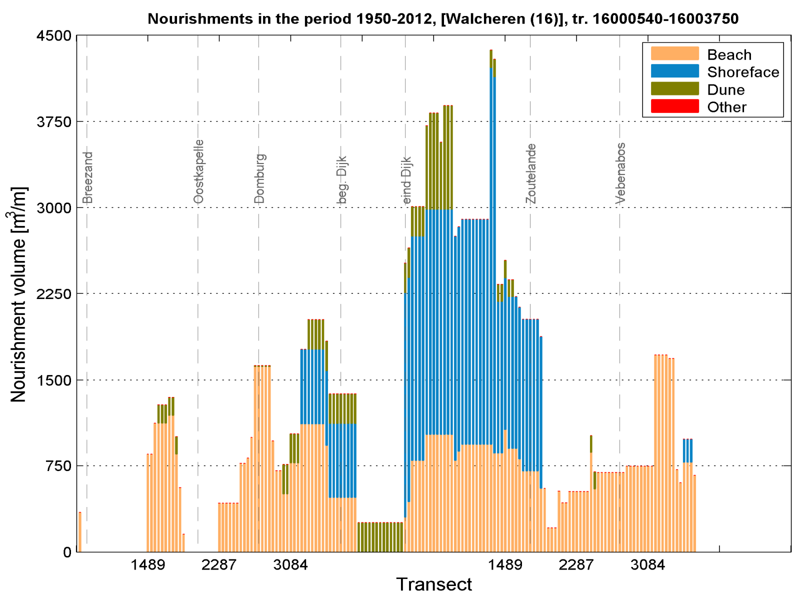


Figure 5.12 Total volume of nourishments in Walcheren (Kustvak 16) for the period 1950-2012.

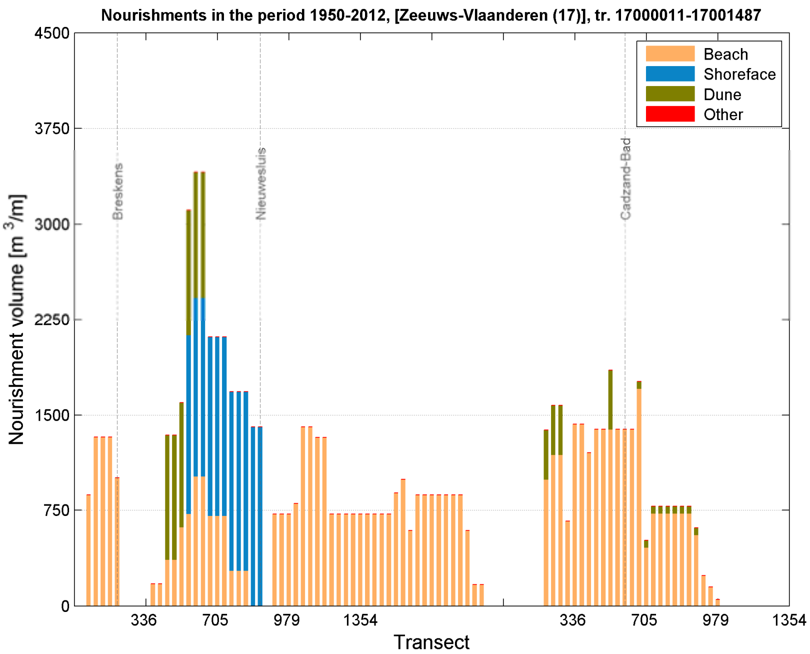


Figure 5.13 Total volume of nourishments in Zeeuws-Vlaanderen (Kustvak 17) for the period 1950-2012.

A typical nourishment design for this stretch of coast is the “gully-shift” (“geulverlegging”) type of intervention. This intervention consists of dredging the seaward side of the gully, and nourishing the landward side. The aim is shifting the gully further from land whenever it gets too close. This intervention was carried out twice at the Krabbengat (Figure 8.15) for a total volume of 5,1 millions of m^3 (Figure 5.14)[3]. In 1987 the intervention was implemented between RSP 13,35 and 15,25, and in 1991 between RSP 11,44 and RSP 13,35) (Maranus, 1996; Cleveringa, 2013).

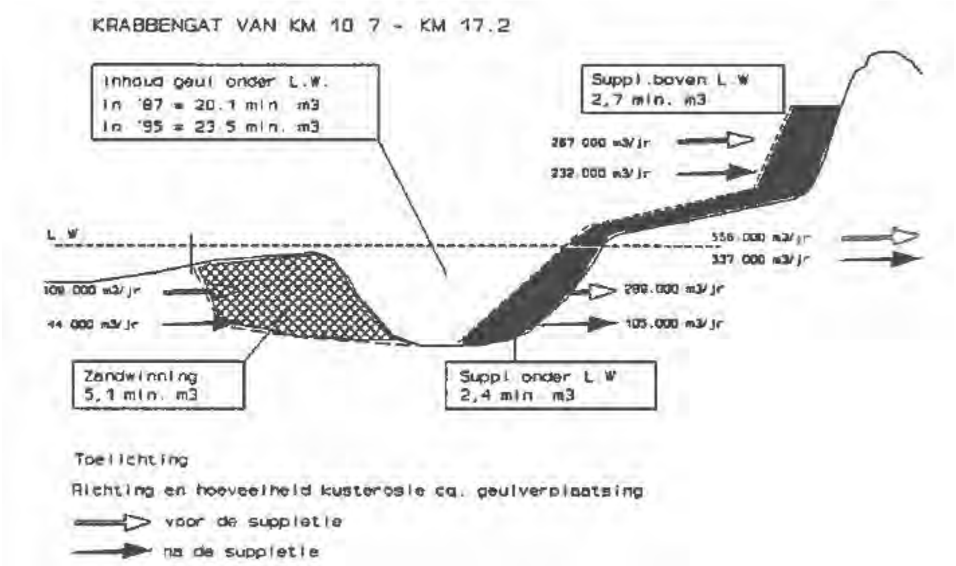


Figure 5.14 Schematization of the “gully-shift” interventions realized in the Krabbengat (Maranus, 1996).

[3] *The nourishment volume given by Maranus (1996) of 5.1 millions of m^3 is slightly larger than what is reported in the nourishment database (RWS) and equal to about 4.6 millions of m^3.*

Similarly to the "gully-shift" intervention is the nourishment at the gully-side ("geulwandsuppletie"), where the sand is put on the landward side of the gully and taken elsewhere. This intervention was realized twice in the Oostgat gully (Figure 8.15): 2.77 million m^3 of sand were placed in 2005 and 6.25 million m^3 in 2009 (Vermaas and Van Oevereen-Theeuwes, 2013). A 3D visualization of this type of intervention is shown in Figure 5.15.

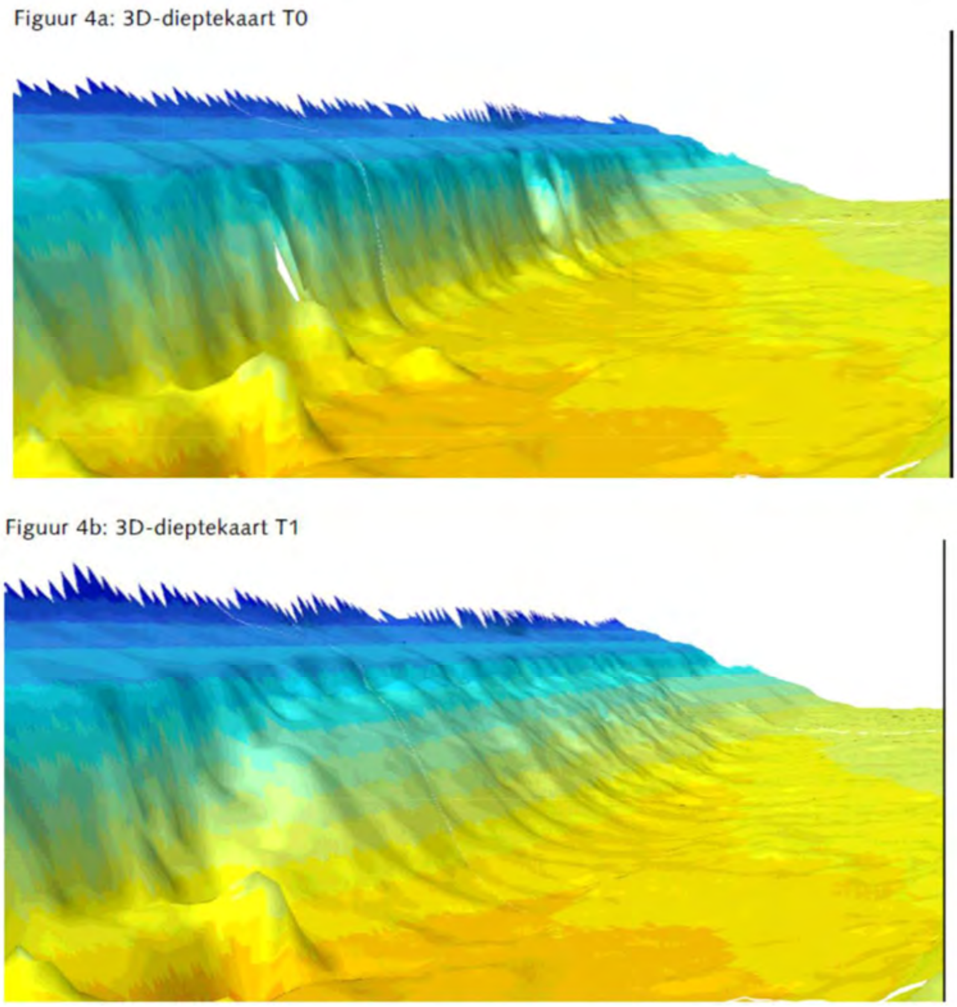


Figure 5.15 Oostgat tidal gully before (figure above) and after construction of the gully nourishment (2005, source Rijkswaterstaat - M.Lazar).

The effects of those nourishments on the morphological developments of the gullies and of the coastal indicators is further analysed in Section 8.3.

5.7 Dune management

The management of the coastal dunes is an old practice in The Netherlands, originally for flood protection 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.

During the last fifty years large volumes of sand were used to nourish the coastal area and also the dunes (Figure 5.7). As a result of those interventions, the volumes of the coastal dunes have been growing consistently over time (Arens et al., 2010). On the other side, the dynamism of those dunes appears to have largely decreased in recent years. On-going projects aim at restoring this dynamism in a number of pilot areas by removing the vegetation at selected locations (Van der Valk et al., 2013; Arens et al., 2012) as part of the project Programmatische Aanpak Stikstof (PAS).

6 Natural forcing and effects on coastal indicators

6.1 Climatological forcing

The effect of storms on morphological indicators along the South Holland coast was investigated in details in Vuik et al. (2012). Long term natural trends 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 South-Westerly Delta, the following stations have been used: “Hoek van Holland”, “Westkapelle”, “Vlissingen” and “Cadzand” for the water levels and “IJmuiden munitiestortplaats” and “Europlatform” 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 station (in yellow) and buoy (in red) used for the analysis (Vuik et al., 2012).

6.1.1 Impact of storms on probability of breaching

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 (Figure 6.2).

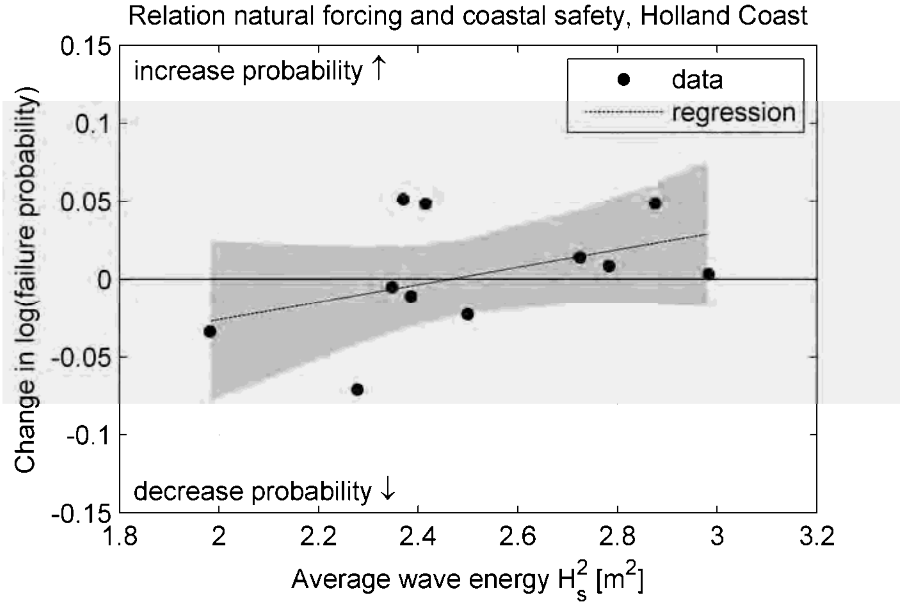


Figure 6.2 Changes in probability of breaching as a function of the yearly averaged wave energy for the Holland coast (Giardino et al., 2014).

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 Schouwen of a factor 0.16 (in logarithmic scale) or, in the words, a change for example from 10^{-5} to 0.16 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 (Giardino et al., 2014).

The general larger *m* value computed for the South-Westerly Delta coast with respect to the Holland coast (Figure 6.2) suggests that storminess and cross-shore transport processes have at this part of the coast a larger influence due to the general larger steepness of the coastal profile. Remarkable is the very large *m* value computed for Noord-Beveland, which most likely, can be explained by the small number of transects (5) used for the computation, making this value not very representative of the actual trend.

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)
Voorne	0.17
Goeree	0.14
Schouwen	0.16
Noord-Beveland	0.57
Walcheren	0.13
Zeeuws-Vlaanderen	0.14

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).

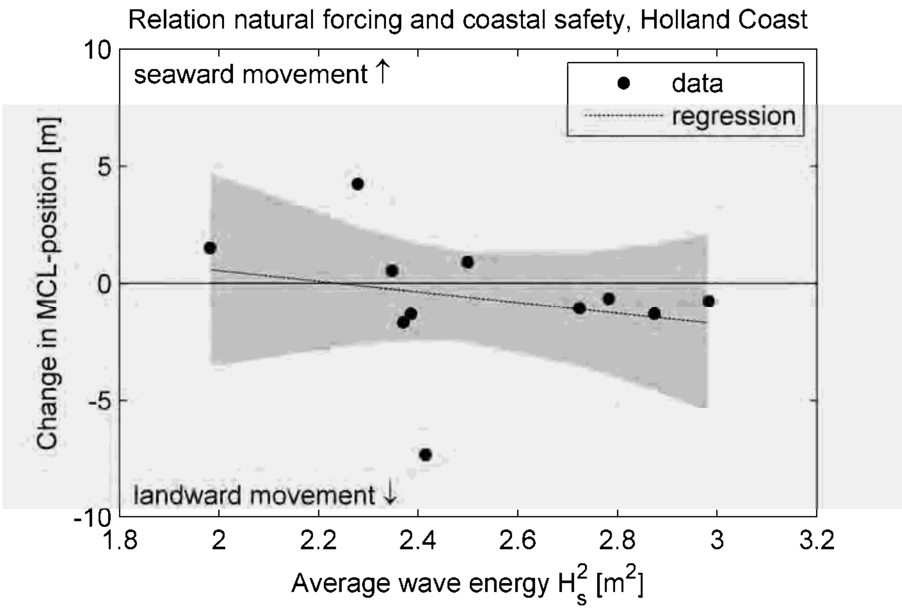


Figure 6.3 Changes in MKL position as a function of the yearly averaged wave energy for the Holland coast (Giardino et al., 2014).

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 the effect of nourishments or other anthropogenic interventions (e.g. Delta works). As a reference, the average value of *m* for the Holland coast was equal to -2.

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)
Voorne	1.9
Goeree	-4.5
Schouwen	-2.2
Noord-Beveland	-9.2
Walcheren	-2.7
Zeeuws-Vlaanderen	-5.8

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 yearly 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).

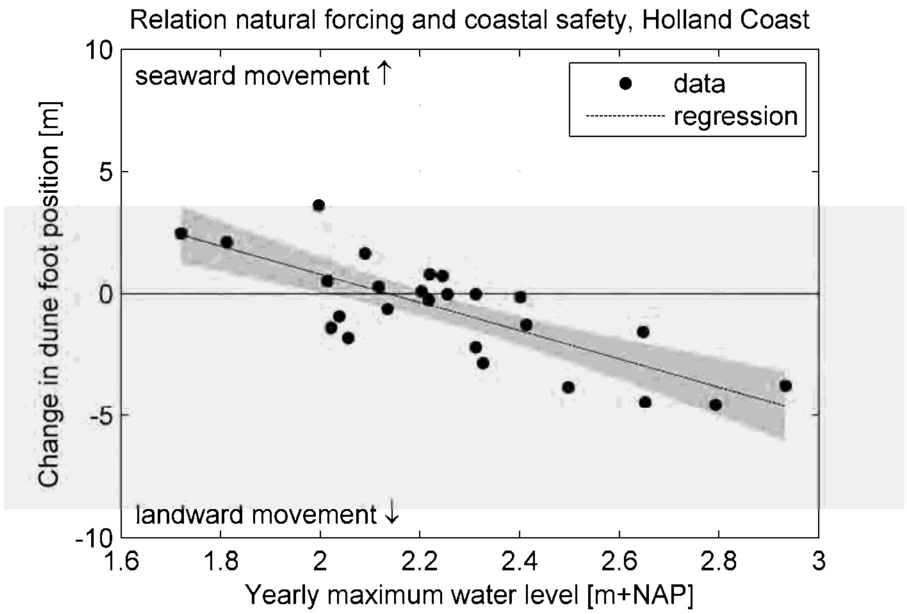


Figure 6.4 Changes in dune foot position as a function of the maximum yearly water level for Holland coast (Giardino et al., 2014).

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 nearly 7 m can be expected at Schouwen. As a reference, the average value of *m* for the Holland coast was equal to -6.
Changes in dune foot position are in any case lower than the ones identified as a consequence of the nourishment interventions or other anthropogenic interventions (e.g. Delta works) (Giardino et al., 2014).

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 =(ΔDF) / (ΔWL)
Voorne	-4.0
Goeree	-4.8
Schouwen	-6.9
Noord-Beveland	-2.8
Walcheren	-3.5
Zeeuws-Vlaanderen	-0.3

6.2 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 South-Westerly Delta coast: the sea level rise and the subsidence. In 2006, the KNMI published four climate scenarios for the Netherlands, known as the KNMI'06 scenarios (KNMI, 2006). These scenarios estimate Sea Level Rise along the Dutch coast between 15-35 cm by 2050 and 35-85 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 system.

A map showing the possible predicted subsidence by year 2050 is shown in Figure 6.5. 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 up to 40 cm by year 2050 at Walcheren. This value will be most likely much lower at the location of the primary defences and along the coast than in the hinterland where subsidence and soil compaction were caused by ground water extraction and compaction of the peat layer.

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.

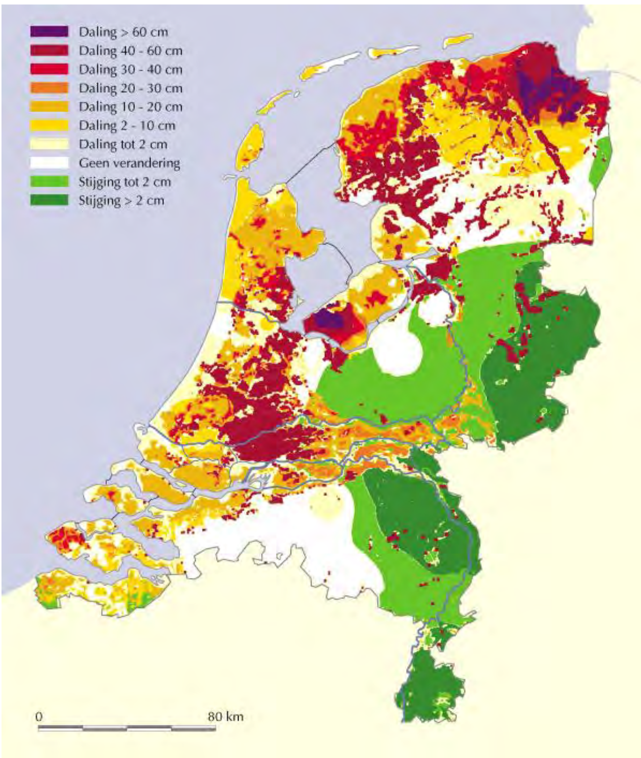


Figure 6.5 Expected subsidence and uplift for the all Netherlands by year 2050 (Rijkswaterstaat, NAM).

7 Large scale development of the coast of the South-Westerly Delta 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 this 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 the most recent anthropogenic changes (e.g. Delta Works).

As we are looking into the effects of changes considering a large temporal scale, the variation of the indicators are assessed based on regions (“kustvakken”). Moreover, the complex and dynamic morphology of the coast of Zeeland does not allow performing a trend analysis based on subdivision in smaller areas. More detailed information on changes of the different indicators within each region can be found in the Beheerbibliotheek.

7.2 Morphological development

The human impact during the last century has radically contributed to the development of this stretch of coast and has largely affected the morphological evolution of the area (Chapter 5). For this reason, the analysis has been performed based on three different time windows:

- 1843 – 1969. During this time window, it is assumed that morphological changes were mainly driven by natural processes.

- 1970 – 1989. Most of the Delta Works are carried out during this period (Section 5.3), affecting the morphological development of the entire region.

- 1990 – 2012. During this time window, the effects of the Delta Works in terms of morphological development are still very relevant. On top of that, large nourishments have been implemented (Section 5.6).

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 areas in Zeeland, 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 six coastal areas in Zeeland. 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.

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 show that the entire South-westerly Delta coast was subject to a slightly erosive trend before 1969, as shown by the consistent negative trends during the first time window. The picture has changed completely after the human interventions of the last 40 years (Chapter 5). All the trends have been replaced by positive trends, with the average of the absolute values during the last time window, consistently above (more seaward) with respect to the first time window.
- The largest changes have been observed in regions 12 (Goeree) with total average changes in mean low water and mean high water line position of more than 50 m. This is due to the permanent closures of the Grevelingen and Haringvliet, which largely influenced this region.
- The relative effects of nourishments and Delta Works on the coastal indicators during the last time window are superimposed and difficult to separate. However, looking at the changes in trend, it is safe to assume that for region 11 (Voorne), 12 (Goeree), 13 (Schouwen), and 15 (Noord Beveland) those changes are mainly influenced by the effects of the Delta Works as the larger changes occurred between time window 1843-1969 and 1970-1989. For regions 16 (Walcheren) and 17 (Zeeuws-Vlaanderen) the main changes are due to the nourishments.
- The high values in dune foot position (absolute value) for the period 1990-2012 observed at Voorne are related to the Zwakke Schakel intervention carried out in 2010.

Next to those indicators, the probability of breaching of the first dune row was computed by HKV by means of the PC-ring model, as described in Van Balen et al. (2011). The output of these calculations for kustvak 11, 12, 13, 16 and 17 are shown in Appendix C. The output is shown for the periods 1965-1990, 1991-2000, and 2001-2010 when Jarkus measurements, required for the calculations, were available.

The figures show a general trend toward a decrease of the probability of failure (safer situation) as a consequence of the general increase in sand volumes, also shown by the other indicators. In particular, it is very visible at Schouwen and Walcheren, where the trend in probability of failure changes from increasing towards decreasing. As shown in Giardino et al. (2014) there is in fact a close relation between increase for example in MKL or seaward shift in dune foot position and a decrease in probability of failure.

In Appendix D, the trends in indicators at each transect used to compute the average values as reported in Figure 7.1 are also given. Next to the observations mentioned above, those plots also show the presence of sand waves migrating along the coastline (see for example at Schouwen).

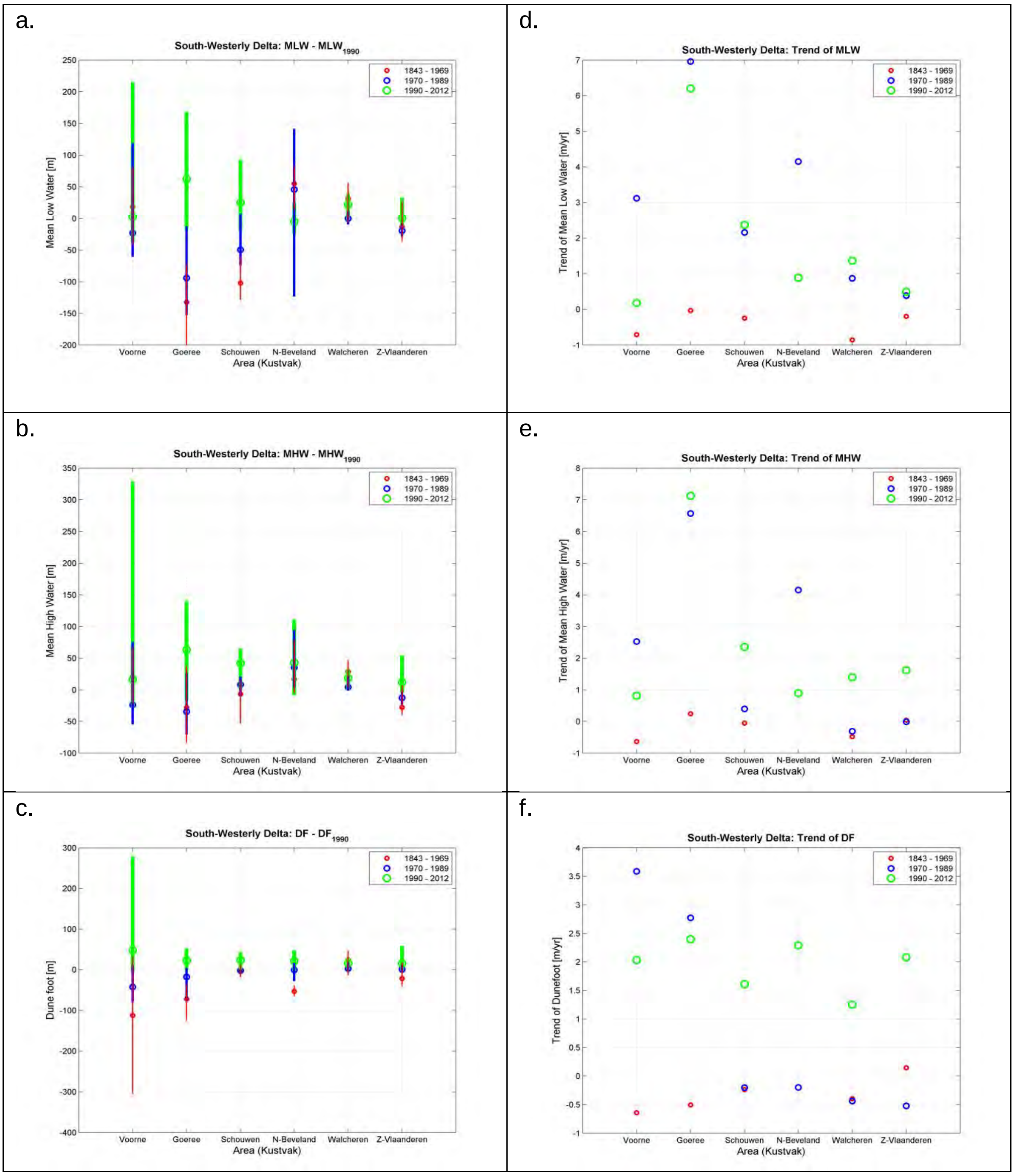


Figure 7.1 MHW, MLW, DF w.r.t. values in 1990 (a., b., c.) and linear trends of MHW, MLW, DF within the three periods 1843-1969, 1970-1989, 1990-2012 (d., e., f.). Negative values mean onshore shift, while positive values offshore migration. Due to lack of data, there is no value for Noord-Beveland for the time-window 1843-1969.

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

Voorne	Period 1843-1969	Period 1970-1989	Period 1990-2012
MLW - MLW_{1990}	19	-23	2.5
MHW - MHW_{1990}	21	-24	16
DF – DF_{1990}	-112	-42	48
MLW trend	-0.71	3.1	0.18
MHW trend	-0.63	2.5	0.81
DF trend	-0.64	3.6	2

Goeree	Period 1843-1969	Period 1970-1989	Period 1990-2012
MLW - MLW_{1990}	-132	-94	62
MHW - MHW_{1990}	-28	-35	63
DF – DF_{1990}	-72	-17	23
MLW trend	-0.032	7.0	6.2
MHW trend	0.24	6.6	7.1
DF trend	-0.5	2.8	2.4

Schouwen	Period 1843-1969	Period 1970-1989	Period 1990-2012
MLW - MLW_{1990}	-102	-49	25
MHW - MHW_{1990}	-6.6	8.1	41
DF – DF_{1990}	-2.1	-1.6	24
MLW trend	-0.25	2.2	2.4
MHW trend	-0.050	0.39	2.4
DF trend	-0.24	-0.2	1.6

Noord-Beveland	Period 1843-1969	Period 1970-1989	Period 1990-2012
MLW - MLW_{1990}	55	46	-5.3
MHW - MHW_{1990}	17	35	43
DF – DF_{1990}	-53	-0.5	22
MLW trend	-	4.1	0.89
MHW trend	-	-2.8	5.2
DF trend	-	-0.19	2.3

Walcheren	Period 1843-1969	Period 1970-1989	Period 1990-2012
MLW - MLW_{1990}	31	-0.1	22
MHW - MHW_{1990}	29	4.2	18
DF – DF_{1990}	25	2.9	16
MLW trend	-0.85	0.87	1.37
MHW trend	-0.48	-0.31	1.4
DF trend	-0.39	-0.44	1.3

Zeeuws-Vlaanderen	Period 1843-1969	Period 1970-1989	Period 1990-2012
MLW - MLW_{1990}	-13	-20	0.3
MHW - MHW_{1990}	-28	-13	12
DF – DF_{1990}	-22	0.8	16
MLW trend	-0.19	0.39	0.50
MHW trend	0.042	-0.010	1.61
DF trend	0.15	-0.52	2.1

8 Effect 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 different spatial and temporal scales. This chapter specifically focusses on the morphological development of sand waves and tidal channels in the South-Westerly Delta in relation to 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.

8.2 Effects of sand waves and nourishments on morphological indicators

Horizontal sand waves, defined as shoreline fluctuations that move wave-like alongshore, are described by Verhagen (1989a) along several parts of the Dutch coast. With a wave period of 50 – 150 years and an amplitude of tens to hundreds of meters, these waves can significantly influence the effectiveness of nourishments and thus the required nourishment frequency at certain locations (Maranus and Verhagen, 1987). During the positive phase of the sand wave, the seaward movement of the shoreline results into a very high apparent effectiveness of the nourishment volumes, where during the negative phase of the sand wave, this measure of nourishment effectiveness can be low or even negative. When using the experience of nourishment effectiveness over the past decades to develop a nourishment strategy for the future, omission of sand waves in the analysis can lead to wrong expectations.

This section deals with the sand waves at dune foot, mean high water and mean low water level. First the steps taken to derive and visualize the sand waves are described. Based on that, the relation to the nourishments is discussed.

8.2.1 Visualization of sand waves

This section describes the sand waves and the way of visualizing them for 4 transects at the coastal area Schouwen. Figure 8.1 shows at the left hand side the dune foot position (w.r.t. RSP“Rijks“S”trand”P”aal) in blue. The locations of the four transects is shown in Figure 8.2. In green, the smoothed dune foot position, after applying a moving average low-pass filter, is presented. In this way, only the signal on a longer time scale is highlighted and yearly oscillations are filtered out. The red lines give the linear trends per transect through the dune foot positions for the whole time series. On the right hand side of Figure 8.1, similar lines are presented, but in this case relative to the linear trend line, thus showing the residual. The smoothed residual together with the gradient give 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 presenting makes it easier to show a larger coastal area (e.g. whole *kustvak*) and to show not only the information on the dune foot position, but also the mean high water and mean low water lines.

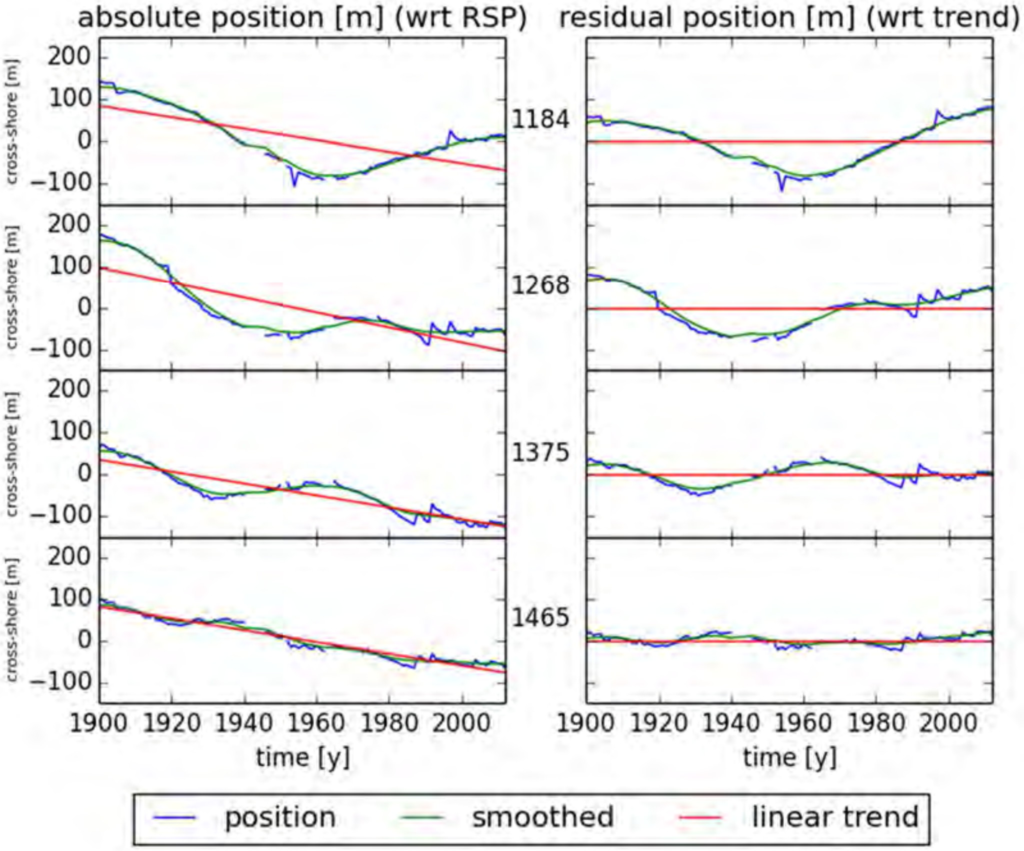


Figure 8.1 Dune foot position for four transects at Schouwen. The blue line represents the actual dune foot position changes, the green line the smoothed dune foot position after applying a low-pass filter, and the red line the linear trend. The figures in the left panel show the absolute values, while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

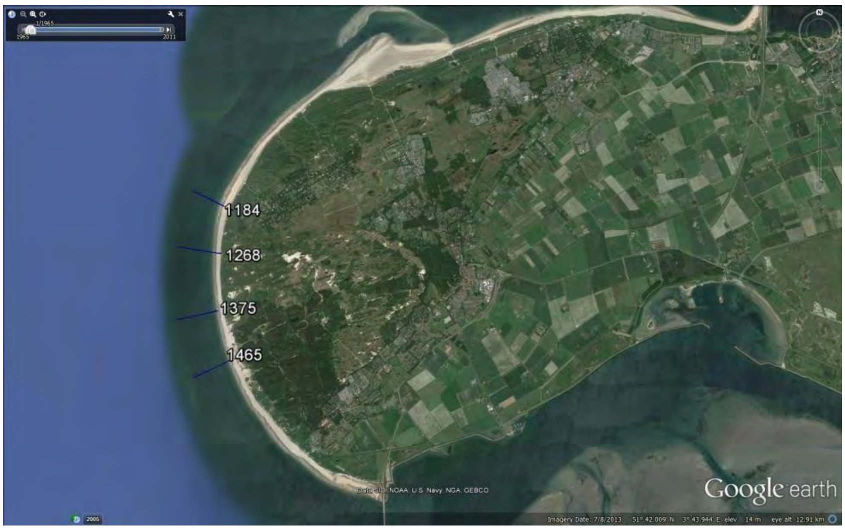


Figure 8.2 Location of the 4 transects analysed in Figure 8.1.

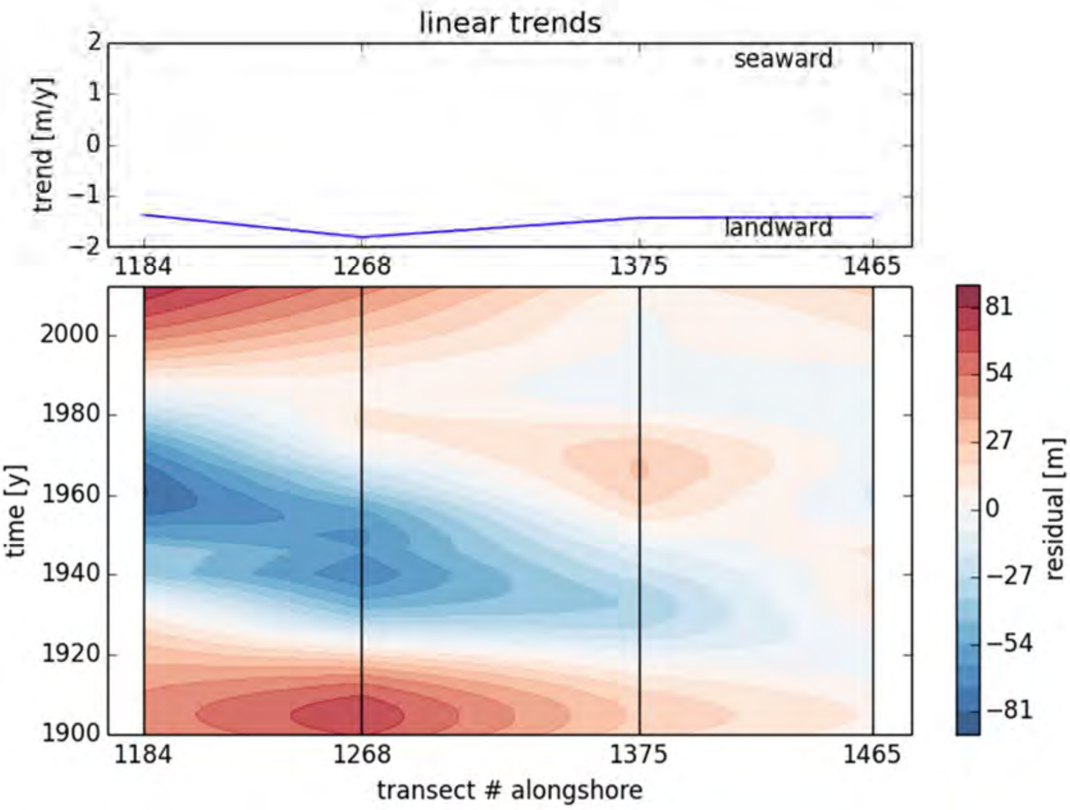


Figure 8.3 Linear trend of dune foot position (top) and contour plot of residual sand wave (below) of a part of Schouwen. See Figure 8.8 for the location.

Figure 8.4, Figure 8.6, Figure 8.8, 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 in time and space, for all Zeeland coastal areas (*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 and time as constructed. 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, but with a time lag. Also the underlying trends are almost equal for most areas. An exception can be found at Schouwen (kustvak 13) between transect 600 and 900, where the mean low water line moves in offshore direction (with max. about 8 m/y around transect 800) whereas the dune foot is rather stable or moves slightly onshore (around transect 800). This can be explained by the alongshore movement and accretion of the shoal in front of the coast ("Relict Schaar van Renesse"), as visible in Figure 8.10.

8.2.2 Sand wave characteristics

Verhagen (1989a) made an inventory of the sand wave along the whole Dutch coast. In the South-Westerly Delta, he only studied in details the areas Schouwen and Walcheren, but he provided indicative figures of amplitude, celerity and period on all coast areas. The figures as given by Verhagen, are presented in Table 8.1. It should be noted that Verhagen derived this figures from the shoreline position, defined as a volume based position between mean high and mean low water.

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

Area	Amplitude [m]	Celerity [m/y]	Period [y]
Voorne	50-150	65	75-100
Goeree	50-350	220-300	100
Schouwen	50-450	90	40-60
Walcheren	80-400	45	120-150
Zeeuws-Vlaanderen	50-200	100	60

The investigation underlying this report, as visualised in Figure 8.4, Figure 8.6, Figure 8.8, Figure 8.11, and Figure 8.13, show that sand wave patterns are most clearly visible at Schouwen (kustvak 13, specifically between transect 600 and 1400) and Walcheren (kustvak 16, most pronounced between transect 600 and 1300). For comparison with Verhagen (1989a), Table 8.2 gives amplitude, celerity and period for five coastal areas in the South-Westerly Delta based on manual interpretation of Figure 8.4, Figure 8.6, Figure 8.8, Figure 8.11, and Figure 8.13. It should be noted that the figures are based combining qualitatively information on how crests and troughs visible in the figures of dune foot position, mean high and mean low water lines shift in time. Except for the celerity for Goeree, most figures show the same order of magnitude, but not necessarily equal, as estimated by Verhagen. The differences can be attributed to several reasons: at first, the way of computing the sand wave characteristics is different as Verhagen used volumes while in this report different coastal indicators were used. Moreover, for this study more than 20 years of recent data were available during which sand wave characteristics were not necessarily the same.

Table 8.2 Sand wave characteristics along the Zeeland coast as derived in this study.

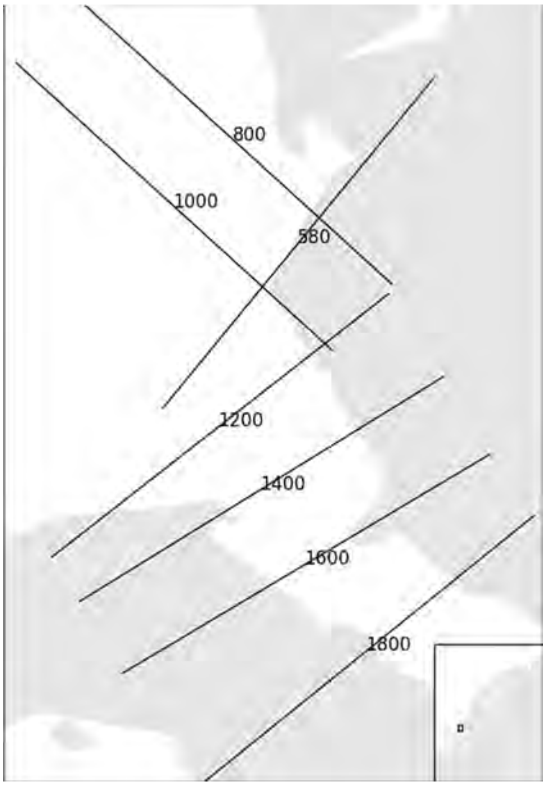
Area	Amplitude [m]	Celerity [m/y]	Period [y]
Voorne	50-200	35	75-100
Goeree	50-500	50	100
Schouwen	50-300	60	40-60
Walcheren	50-150	90	120
Zeeuws-Vlaanderen	30-40	80	60

8.2.2.1 *Voorne*

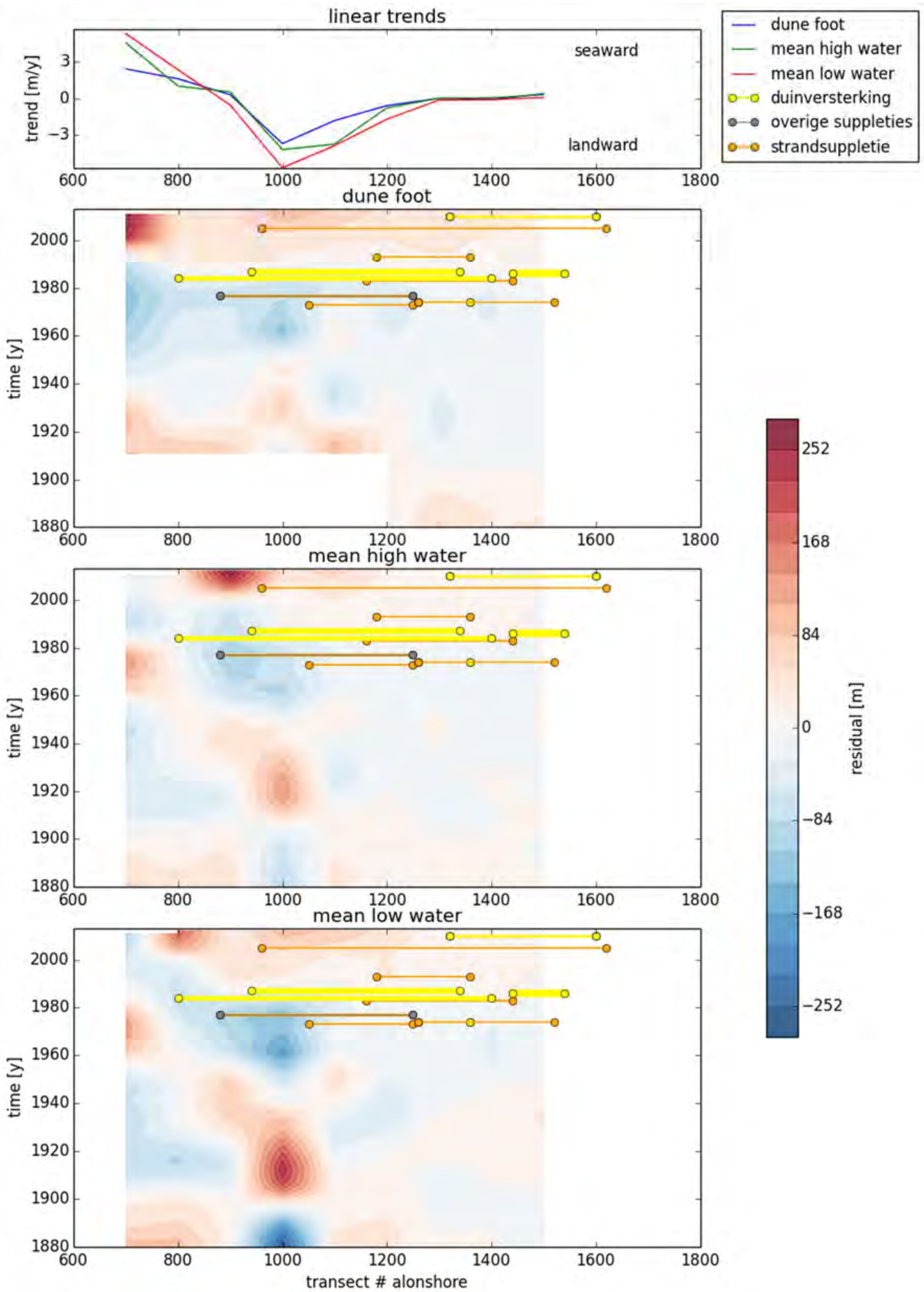
At the Voorne area (kustvak 11), the dune foot data before 1910 has been omitted for part of the transects, as visible in Figure 8.4 (b). The reason is that the dune foot data shows a change of more than 300 m in seaward direction between 1910 and 1911, being related to a newly grown dune that started to appear at that time on the broad beachplain (Adriani and Van der Maarel, 1968). Transect 1000 has also for the mean high and mean low water lines some unclear features that might relate to the same.

The sand wave pattern is not clearly visible in this coastal area. Between transect 700 and 1100, there are some wave alike features. This could be related to the orientation, which is in this area comparable to other areas at Schouwen and Walcheren that show very clear sand wave patterns.

The same type of information is also given in Figure 8.5 for four different transects (transect 700, 1000, 1200, and 1500). The time series confirm that, except for the northern part (transect 700 and 1000), the other transects show minor oscillations in time.



(a)



(b)

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

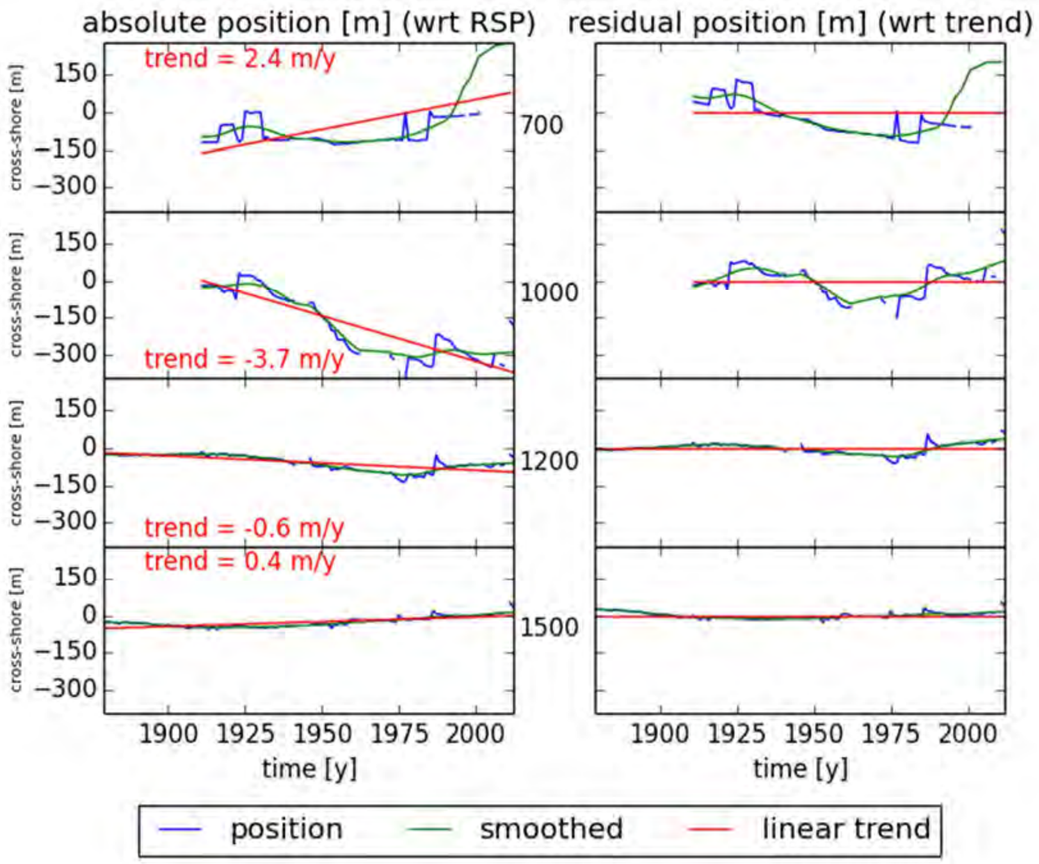
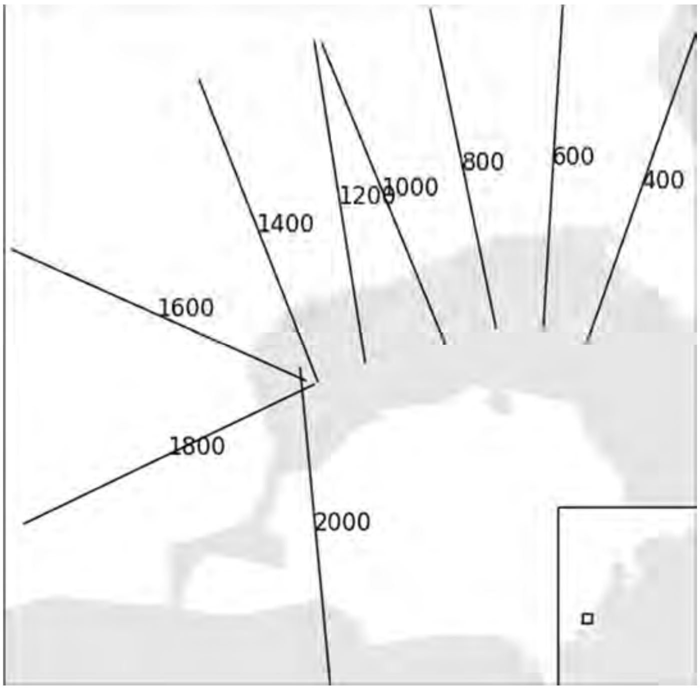


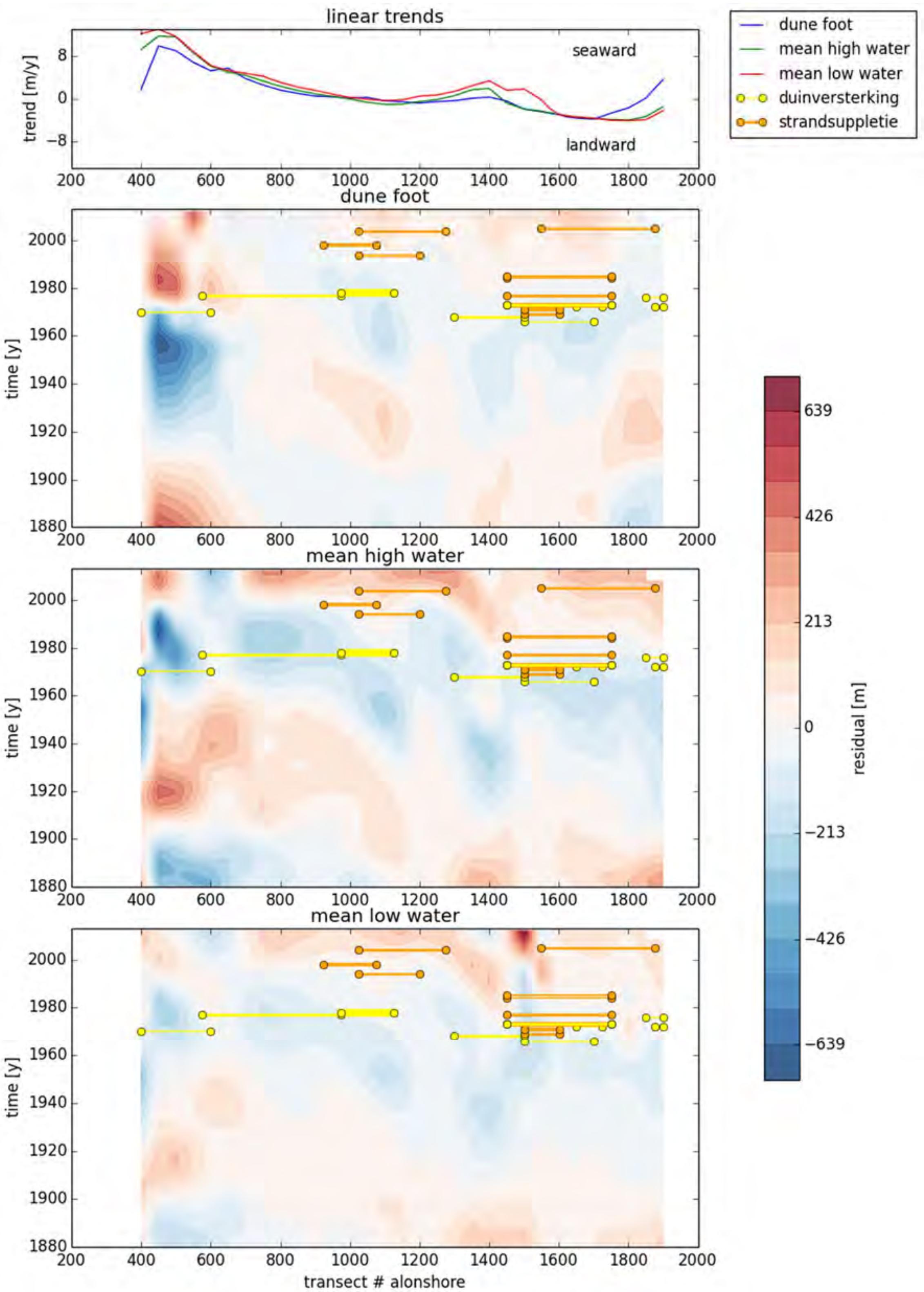
Figure 8.5 Dune foot position for four transects at Voorne. The blue line represents the actual dune foot position changes, the green line the smoothed dune foot position after applying a low-pass filter, and the red line the linear trend. The figures in the left panel show the absolute values, while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

8.2.2.2 Goeree

At Goeree, the sand wave patterns are still difficult to recognize, but they are more clear than at Voorne (Figure 8.6). The reason could be that the Goeree coast has a longer stretch that is mainly northerly oriented. The waves migrate from about transect 1500 in eastward direction. Between transect 1500 and 1900, they behave more like a standing wave. The presence of sand wave type of features is also confirmed by Figure 8.7, which shows this morphological behaviour for all the four transects chosen for the analysis (transect 400, 950, 1450, and 1900).



(a)



(b)

Figure 8.6 (a)Map of Goeree with the positions of transects used as ticks in (b).(b)Contour plots of residuals of dune foot, mean high and mean low waterline positions of Goeree. The respective linear trends for the entire period are in the top panel.

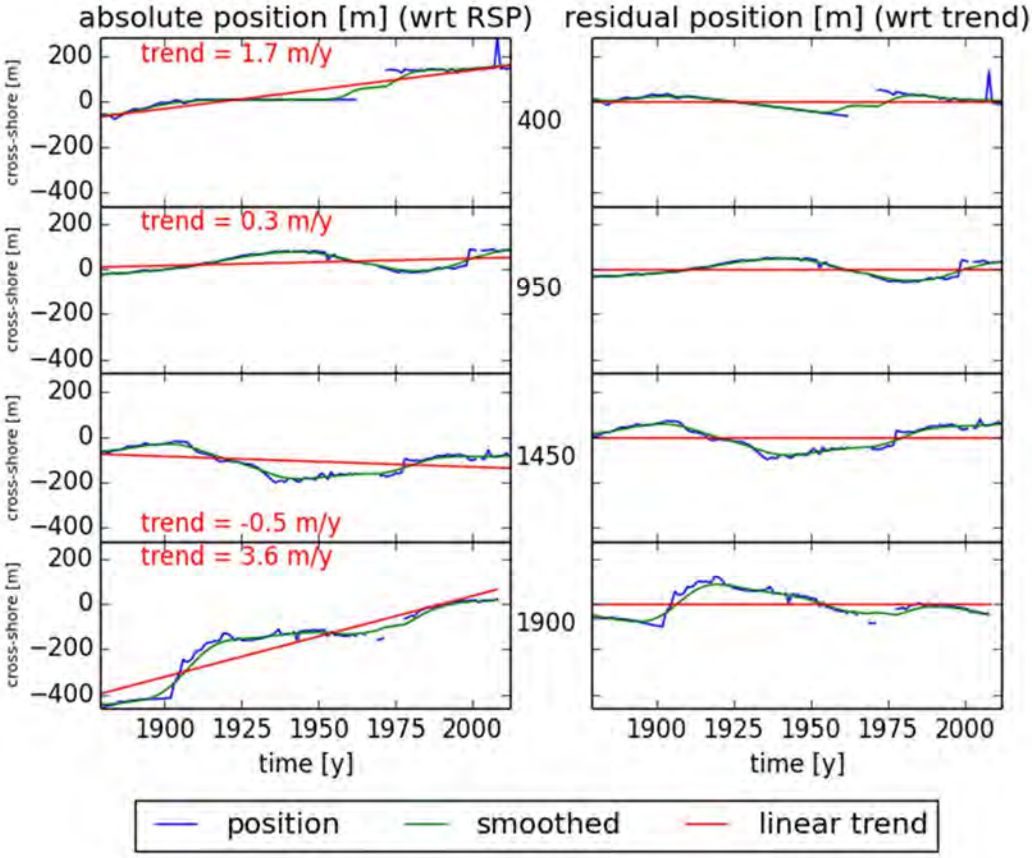
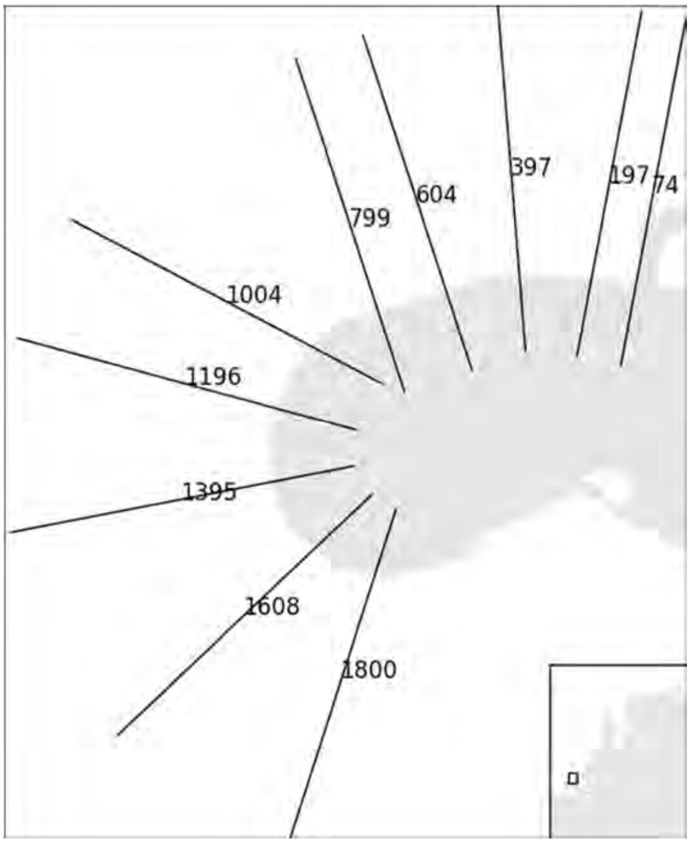


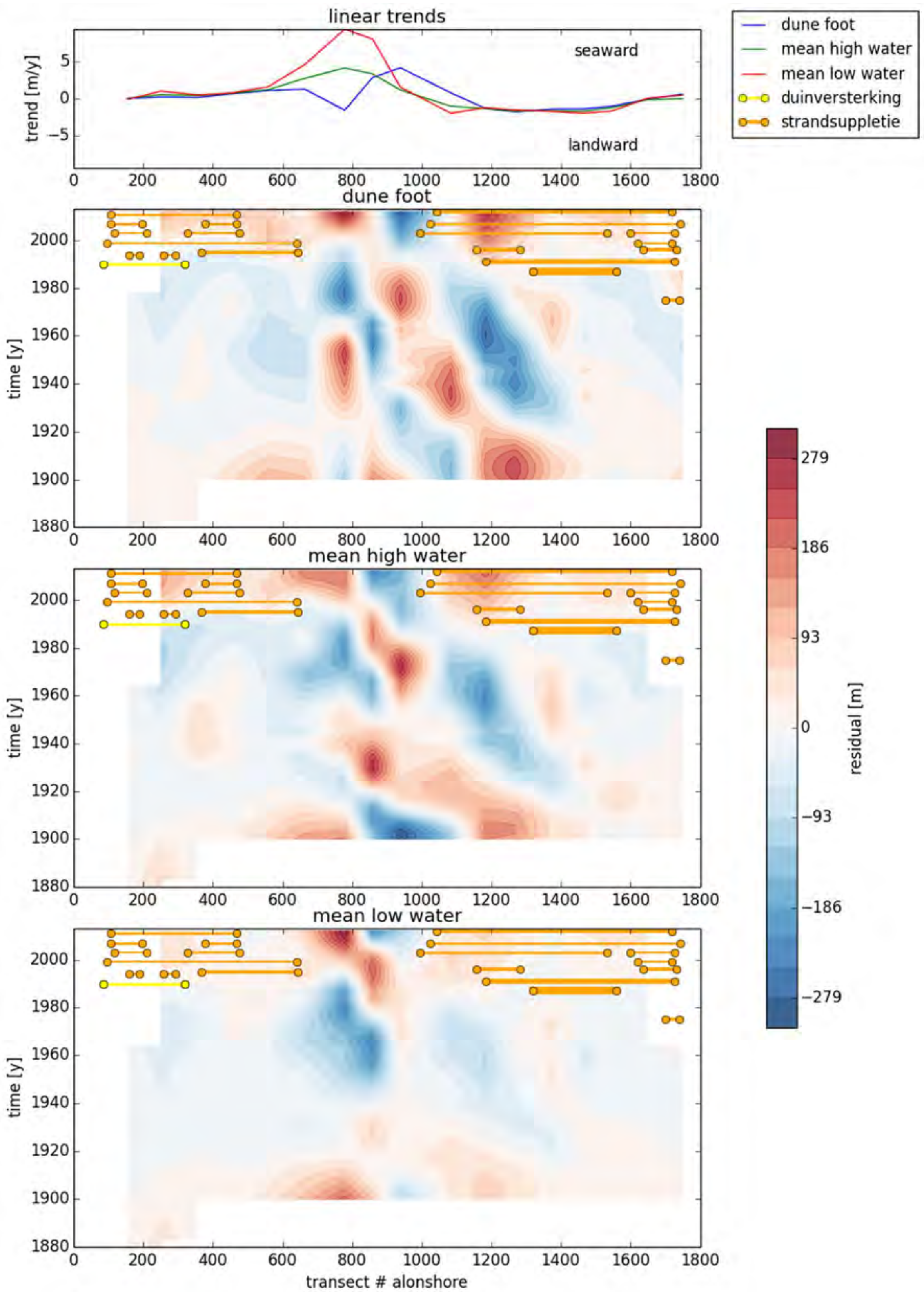
Figure 8.7 Dune foot position for four transects at Goeree. The blue line represents the actual dune foot position changes, the green line the smoothed dune foot position after applying a low-pass filter, and the red line the linear trend. The figures in the left panel show the absolute values, while the figures in the right panel show the values relative to the linear trends.

8.2.2.3 Schouwen

At Schouwen, sand wave patterns are visible at almost the whole area, but most clearly between transects 600 and 1400 (Figure 8.8). Also here, the waves are propagating towards the (north) east. In this area, approximately one and half sand wave cycle it is visible since 1900. This is confirmed also by Figure 8.9, showing the time variation in dune foot position at four different transects (transect 155, 664, 1268, 1750). In particular, sand wave type of features are visible for the two central transects (transect 664 and 1268). The origin of these morphological features in Schouwen and of their migration, are not further investigated within this report. Next to respond to the local hydrodynamic conditions, they are likely to be influenced by the northern migration of the Krabbengat in front of it, which has a very similar migration rate (≈ 60 m/year; Section 8.3.1).



(a)



(b)

Figure 8.8 (a) Map of Schouwen with the positions of transects used as ticks in (b).(b) Contour plots of residuals of dune foot, mean high and mean low waterline positions of Schouwen. The respective linear trends for the entire period are in the top panel.

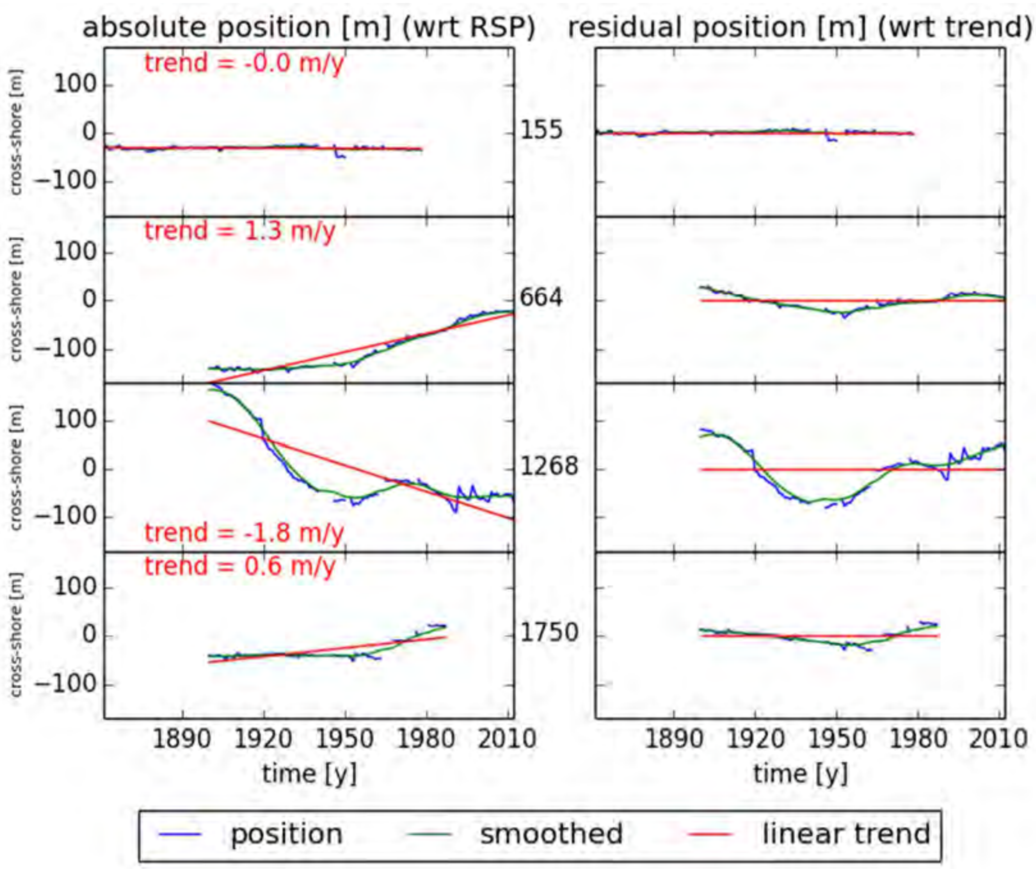
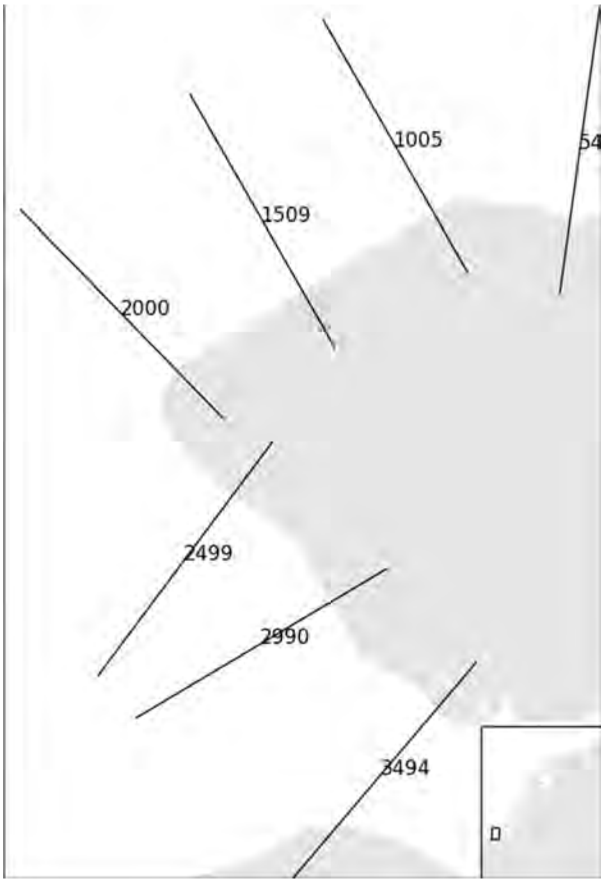


Figure 8.9 Dune foot position for four transects at Schouwen. The blue line represents the actual dune foot position changes, the green line the smoothed dune foot position after applying a low-pass filter, and the red line the linear trend. The figures in the left panel show the absolute values, while the figures in the right panel show the values relative to the linear trends.

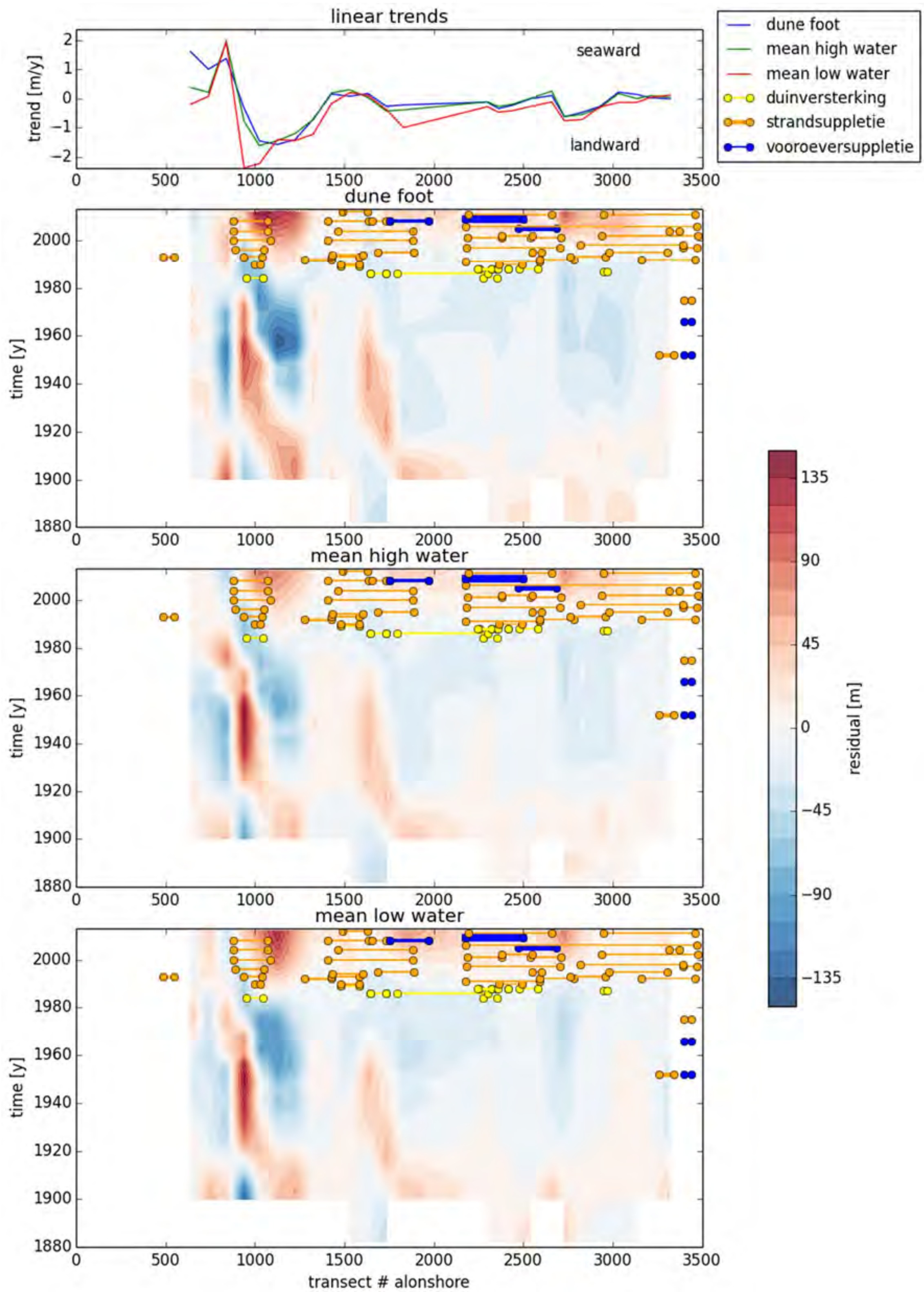
Figure 8.10 Aerial photo of Northern Schouwen with zoom on the shoal "Relict Schaar van Renesse".

8.2.2.4 *Walcheren*

At Walcheren, the sand waves are mainly visible at the north western part of the island (Figure 8.11). The waves propagate from transect 2000 in north eastern direction along the coast. The largest amplitude (amplitude ≈ 140 m) is found between transect 1300 and 800. Outside this area the sand wave amplitude is negligible as confirmed by the time series for four different transects (transect 640, 1428, 2541, 3320) in Figure 8.12.



(a)



(b)

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

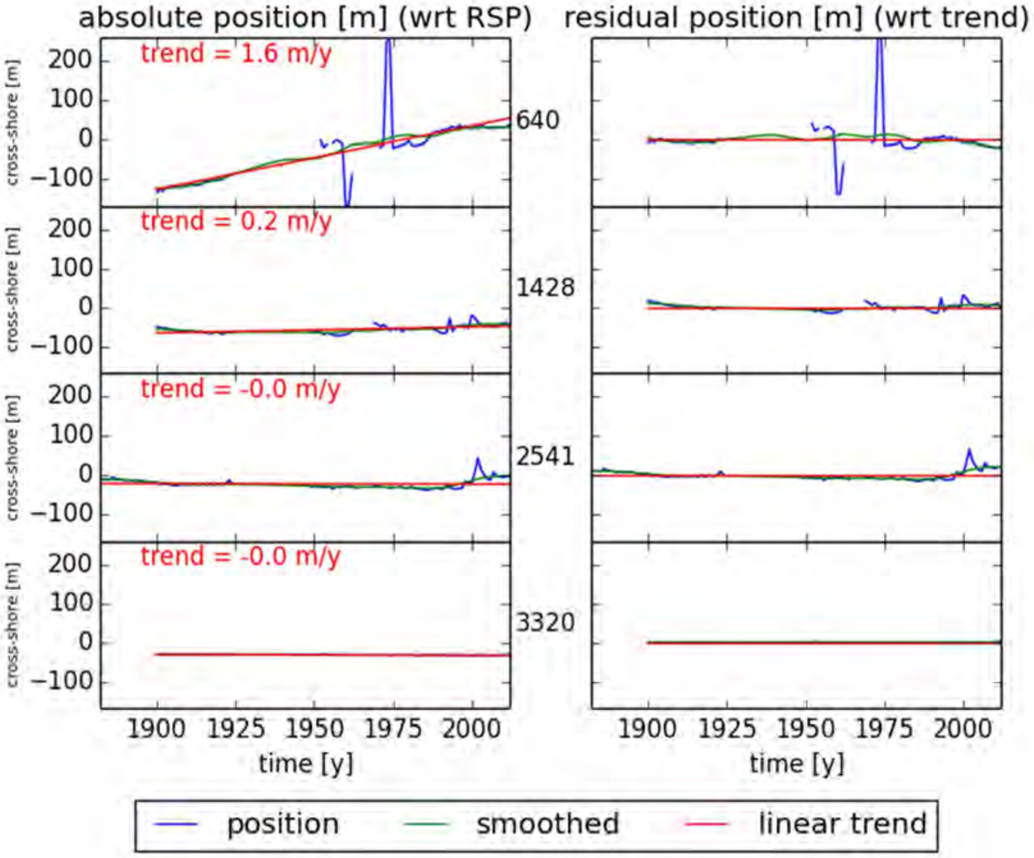
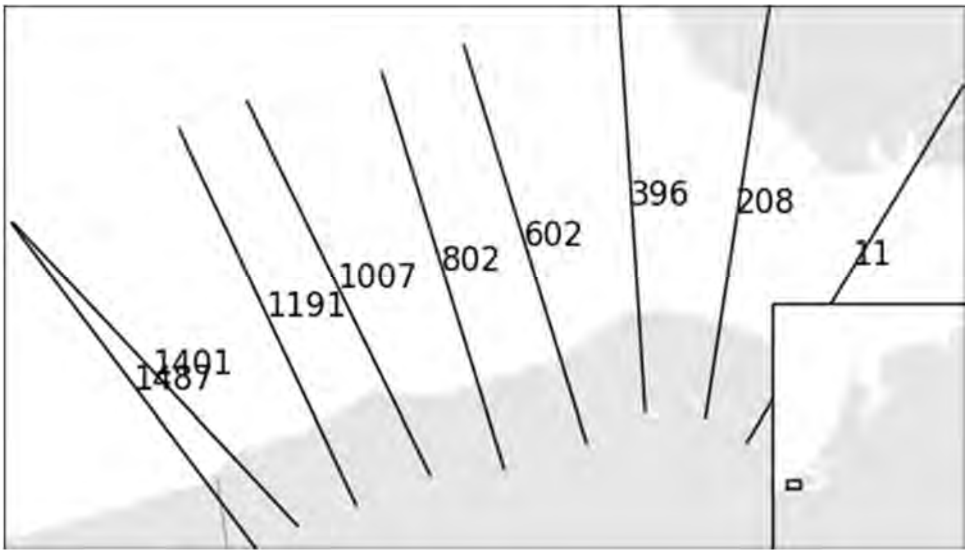


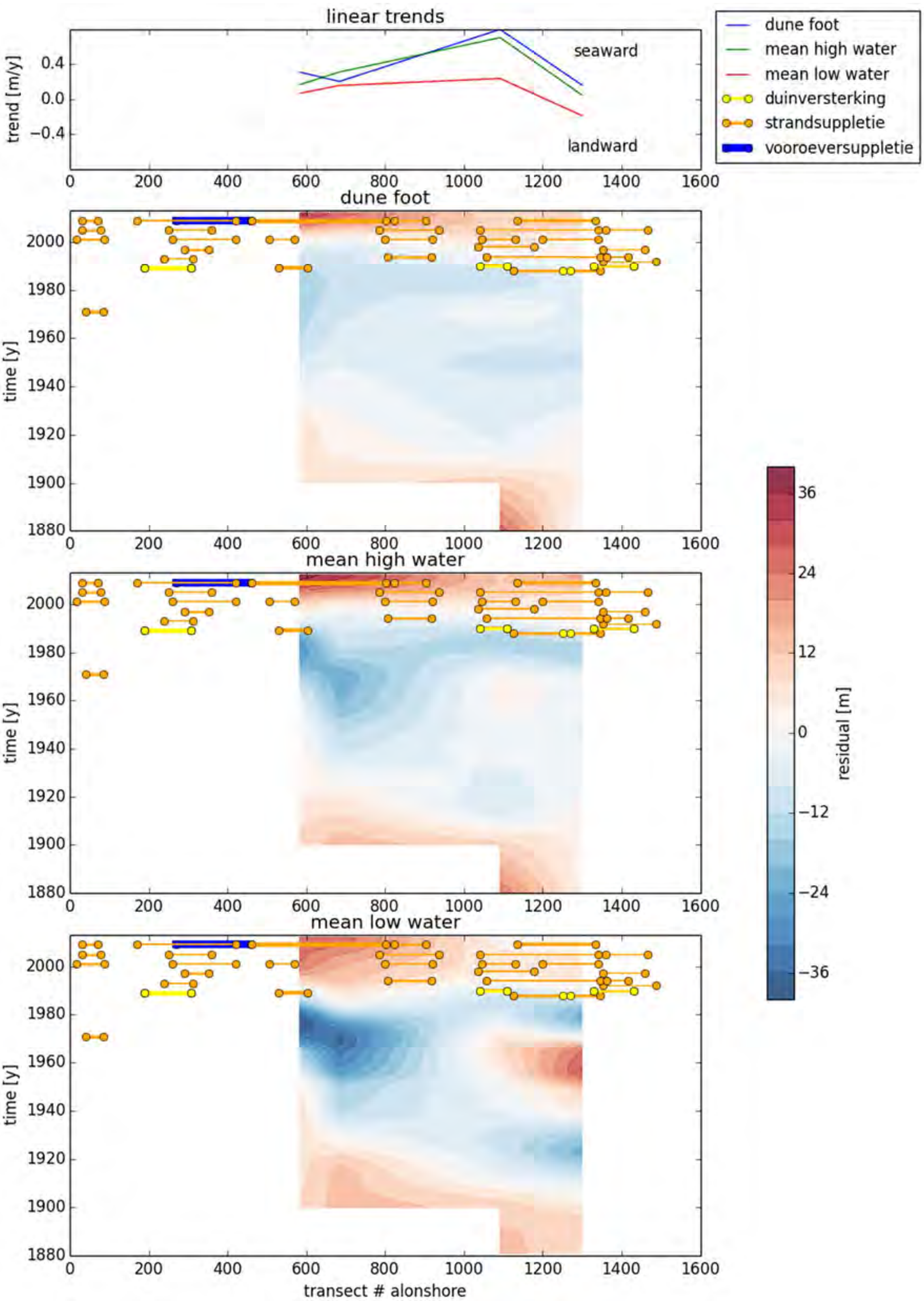
Figure 8.12 Dune foot position for four transects at Walcheren. The blue line represents the actual dune foot position changes, the green line the smoothed dune foot position after applying a low-pass filter, and the red line the linear trend. The figures in the left panel show the absolute values, while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

8.2.2.5 Zeeuws-Vlaanderen

Zeeuws-Vlaanderen is only a small area at the mouth of the Western Scheldt. Long-term data is only available in the western part, from transect 600 to 1300. In that area, the mean high and mean low water lines show a slight wave pattern with a small amplitude (compared to the other Zeeland areas) (Figure 8.13). Like in all the other areas, the wave propagates in north easterly direction. Sand waves features can hardly be distinguished looking at the dune foot, as also shown in Figure 8.14 for four different transects (transect 584, 684, 1092 and 1300).



(a)



(b)

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

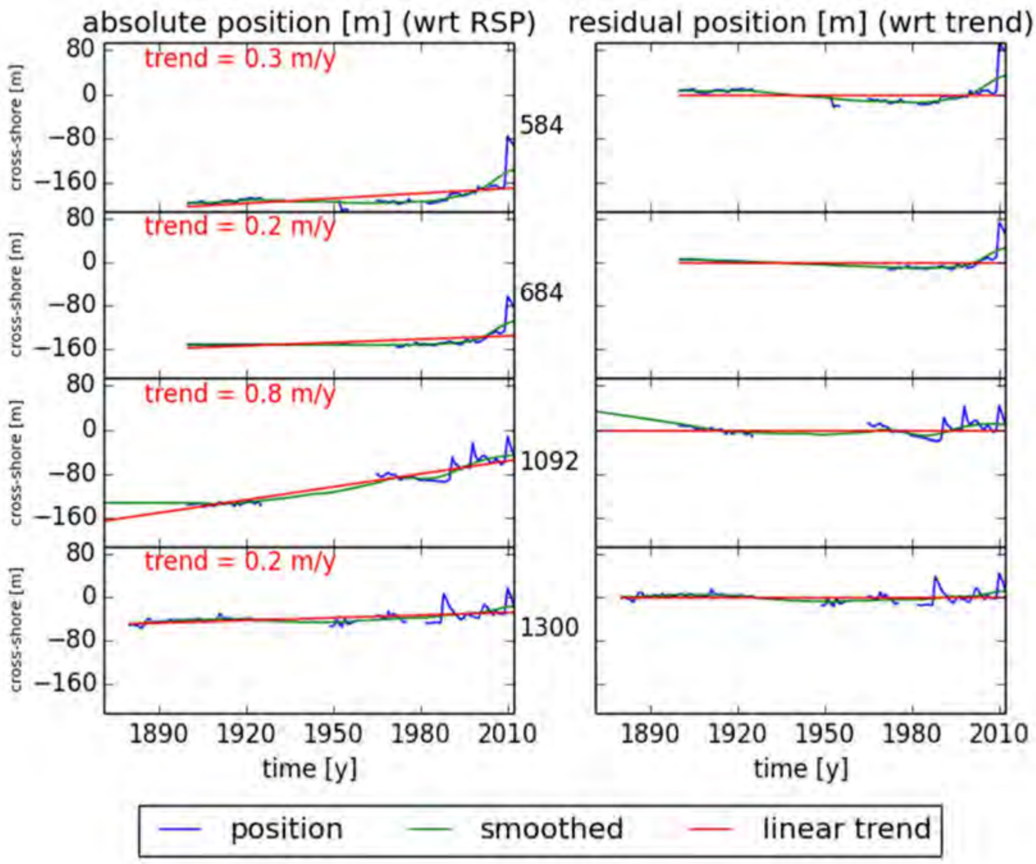


Figure 8.14 Dune foot position for four transects at Zeeuws-Vlaanderen. The blue line represents the actual dune foot position changes, the green line the smoothed dune foot position after applying a low-pass filter, and the red line the linear trend. The figures in the left panel show the absolute values,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

8.2.3 Relation between sand waves and nourishments

The figures with the smoothed residuals (Figure 8.4, Figure 8.6, Figure 8.8, Figure 8.11, and Figure 8.13) do in general not show a clear relation between sand waves and nourishments. At Schouwen, for instance, the sand wave patterns (Figure 8.8) seem to continue undisturbed also in the recent decades when several nourishments have taken place. If we look in more detail to the individual transects that are presented in Figure 8.1, it could be argued that the pattern has changed from the 1980s onwards. This can be attributed to the Delta works and the start of the regular nourishments; it is difficult to distinguish between the two. Even if the sand wave pattern is slightly disturbed by human intervention, that does not mean that the sand waves have disappeared as a background signal. A nourishment is expected to be more effective in the up going period of the sand wave and less effective in the down going period. Consequently, the effectiveness of the nourishments in a certain area over the past decades is not always representative for the expected effectiveness in the near future. This is especially the case around the troughs and crests of the sand waves. A complicating factor is the present human intervention, which makes further analysis difficult even when more data becomes available over time. Depending on the way of maintaining the coastline, on a longer time scale (50 to 100 years), the sand wave pattern might appear in the effectiveness indicator of the nourishments.

8.3 Effects of tidal channels and nourishments on morphological indicators

The Delta bathymetry is composed by deep channels and flats that evolve in time. The morphodynamic changes of those features have a direct effect on the evolution of the coastal indicators describing the state of the coast.

Whenever channels get too close to the coastline, sand nourishments are generally carried out (Section 5.6). Predicting the natural evolution of those channels is therefore essential to predict when and how much nourishment will be needed. Moreover, this has also relevant effects on the migration of sand waves like type of features (Section 8.2).

Five channels in the South-Westerly Delta have been studied in the context of this research (Figure 8.15):

- Krabbengat (Schouwen)
- Oude Roompot (Noord Beveland)
- Oostgat (Walcheren)
- Sardijngeul (Walcheren)
- Roompot and Schaar van de Onrust (Walcheren)

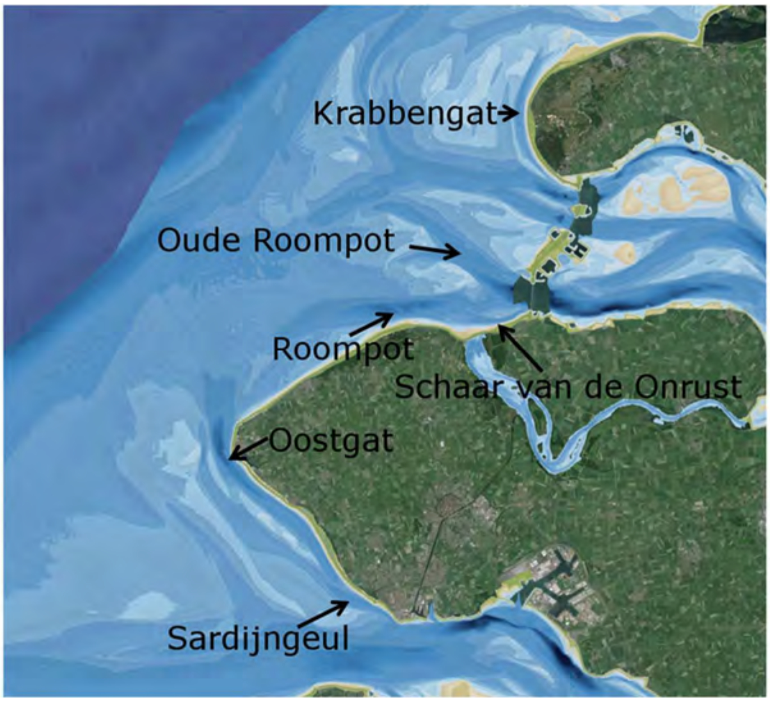


Figure 8.15 Location of the channels analysed in the South-Westerly Delta.

In this study, the evolution of the channels is analysed by looking at the evolution of the bathymetry below a contour line around the channel, arbitrary defined at -10 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 evolution of the centre of mass (centroid) of that volume. The centre of mass is approximated as the centre of mass of the area defined by the -10 m water depth line.

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

8.3.1 Krabbengat (Schouwen)

Figure 8.16 shows the location of the Krabbengat and the region around the channel used for the analysis.

Figure 8.16 Limit of the area defining the Krabbengat.

Within that region, the volume of water delimited by the channel bed and the -10 m contour line is plotted over time (Figure 8.17). Volumes are negative as a result of the z-axis directed upwards; hence negative values represent a widening/deepening of that volume. In other terms, the plot shows that the area of the Krabbengat under a depth of 10 m loses $3*10^6$ m^3 of sediments. The zero value at the start of the analysed period, indicates that the tidal channel in 1960 was shallower than -10 m.

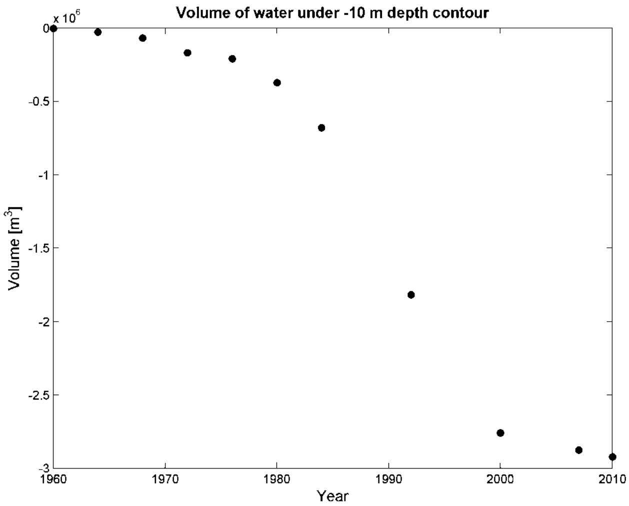


Figure 8.17 Krabbengat. Evolution over time of the volume of water delimited by the channel bed and -10m contour line (from Vaklodingen data).

Figure 8.18 shows the displacement of the centroid of the channel. The centroid of the channel has moved over 3 km towards the North in 50 years, at an average speed of ~60 m/year. As a consequence of the shift of the channel towards the north, erosion has to be expected in the future for transects which are now north of the channel, assuming that this trend would continue in the future. Nevertheless, it is important to point out that this trend appears to have been slowing down during the last years. The centroid of the channel also has migrated slightly in cross-shore direction. Before 1972, it moved more than 100 m in offshore direction, and then it shifted with nearly 200 m in onshore direction, stabilizing during the last 10 years.

The results obtained are related to the evolution of the coastal indicators, also considering the effects of the nourishments. Two transects are considered for Krabbengat: 13001004, 13001268 (Figure 8.19).

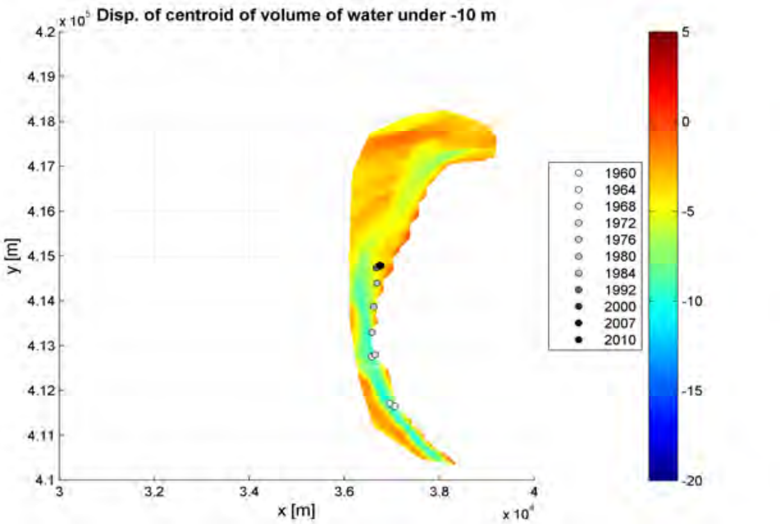
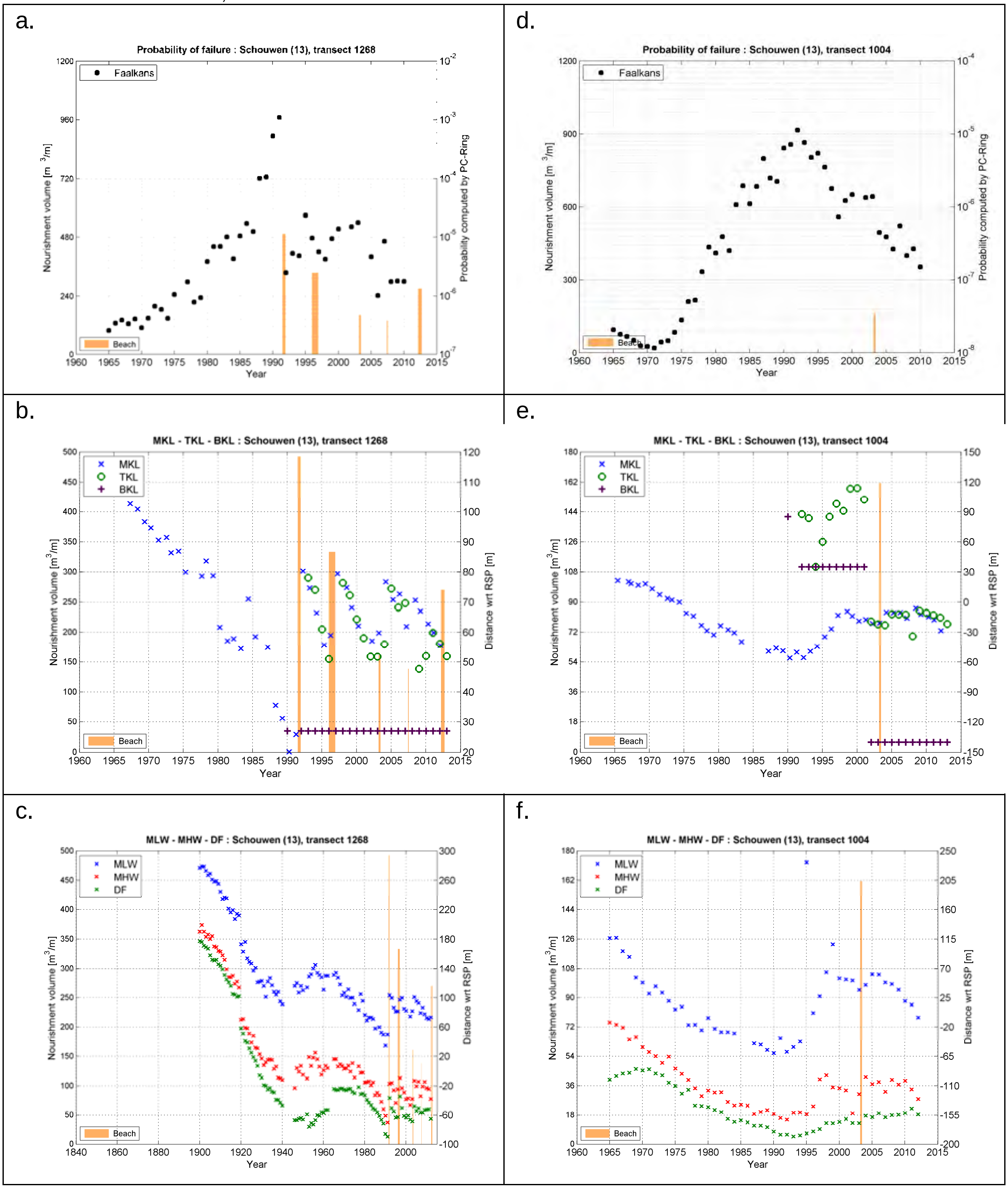


Figure 8.18 Displacement of centre of mass of water between the -10 m contour and the Krabbengat seabed.

Figure 8.19 Detail of the Krabbengat. Coastal indicators for the highlighted transects (13001004, 13001268) are investigated.

Table 8.3 Coastal indicators for transect 13001268 (left panel) and transect 13001004 (right panel). Figures a., d.: Probability of failure of the first dune row. Figures b., e.: MKL, TKL, BKL. Figures c., f.: Mean High Water, Mean Low Water, Dune Foot.



Several nourishments have been carried out in the region of the Krabbengat.

In the area between km 13.20 and 15.60 of Schouwen (south of the analysed transects), ~5.1 Mm^3 of sand have been nourished from 1987 to 1991. This was a “gully-shift” (“geulverlegging”) type of intervention (Section 5.6) with a nourishment volume of about 2.7 Mm^3 of sand above the low water line and 2.4 Mm^3 of sand below the low water line.

Next to it, in the area between km 9.94 and km 17.42, which includes the two transects selected for the analysis, ~4.3Mm^3 have been nourished between 1996 and 2012, during several nourishment interventions.

As a consequence of those interventions, at transect 13001268 the probability of failure decreases about ~3 orders of magnitude from the beginning of the 1990's. For clarity, 1:4000 year is the limit admitted by law for wave load during testing of the coastal defences in the South-Westerly Delta. The MKL, MHW, MLW and DF are kept in place with nourishment campaigns every ~4 years (Table 8.3 a, b, c).

Transect 13001004, located 2.5 km northern than 13001268, has been maintained with a single beach nourishment of 150 m^3/m in 2003 (Table 8.3d, e, f). Nevertheless the time evolution of MKL, mean low water and mean high water position suggests that a new nourishment will be needed in the future, both due to the approach of a trough of a sand wave (Section 8.2.2) as well as the extension towards the north of the centre of mass of the tidal channel.

8.3.2 Oude Roompot (Noord-Beveland)

The Oude Roompot has faced a shift in its evolution caused by the construction of the Delta Works (*"Oosterschelde Stormvloedkering"* and *"Veersegatdam"* – Section 5.2). A region of the channel in the outer Delta, right seaward of the storm surge barrier, is considered (Figure 8.20).

Figure 8.20 Limit of the area defining the Oude Roompot.

The volume of water under the -10 m contour line (Figure 8.21) inside the region decreased with ~5 *10^6 m^3 from 1960 to 1970, then it increased with ~30 *10^6 m^3 from 1970 to 1986, it decreased again with ~12 *10^6 m^3 from 1986 to 2000 (i.e. after the closure of the Easter Scheldt), and it nearly stabilized afterwards.

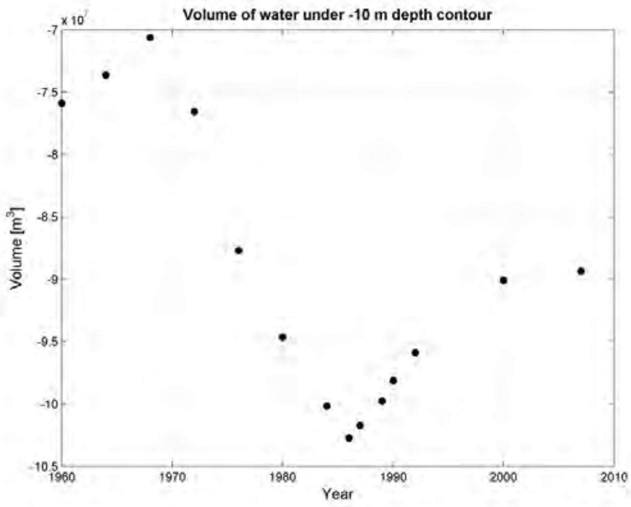


Figure 8.21 Oude Roompot. Evolution over time of the volume of water delimited by the channel bed and -10m contour line (from Vaklodingen data).

The centroid of that volume has moved ~800 m towards the North-West along the channel from 1960 to 1986, as a consequence of the extension of the channel towards the North-West. After 1986 the position of the centroid has stabilized (Figure 8.22).

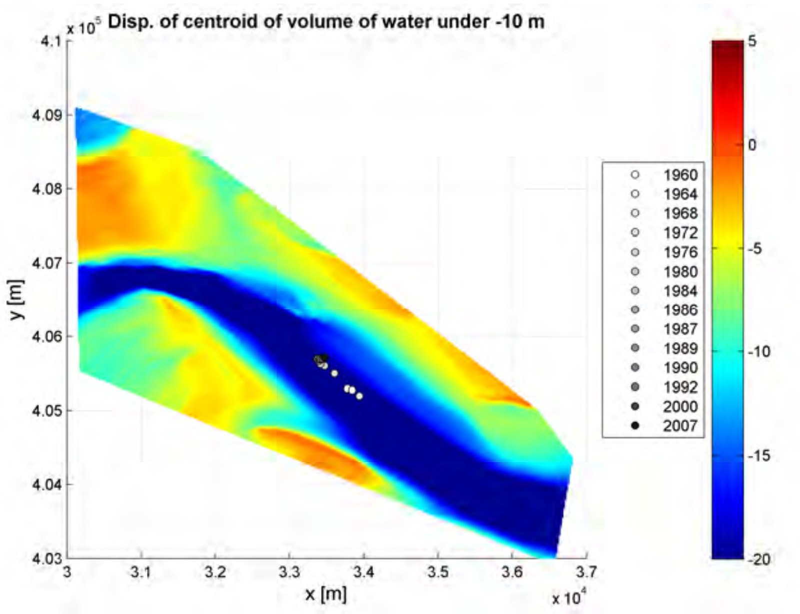
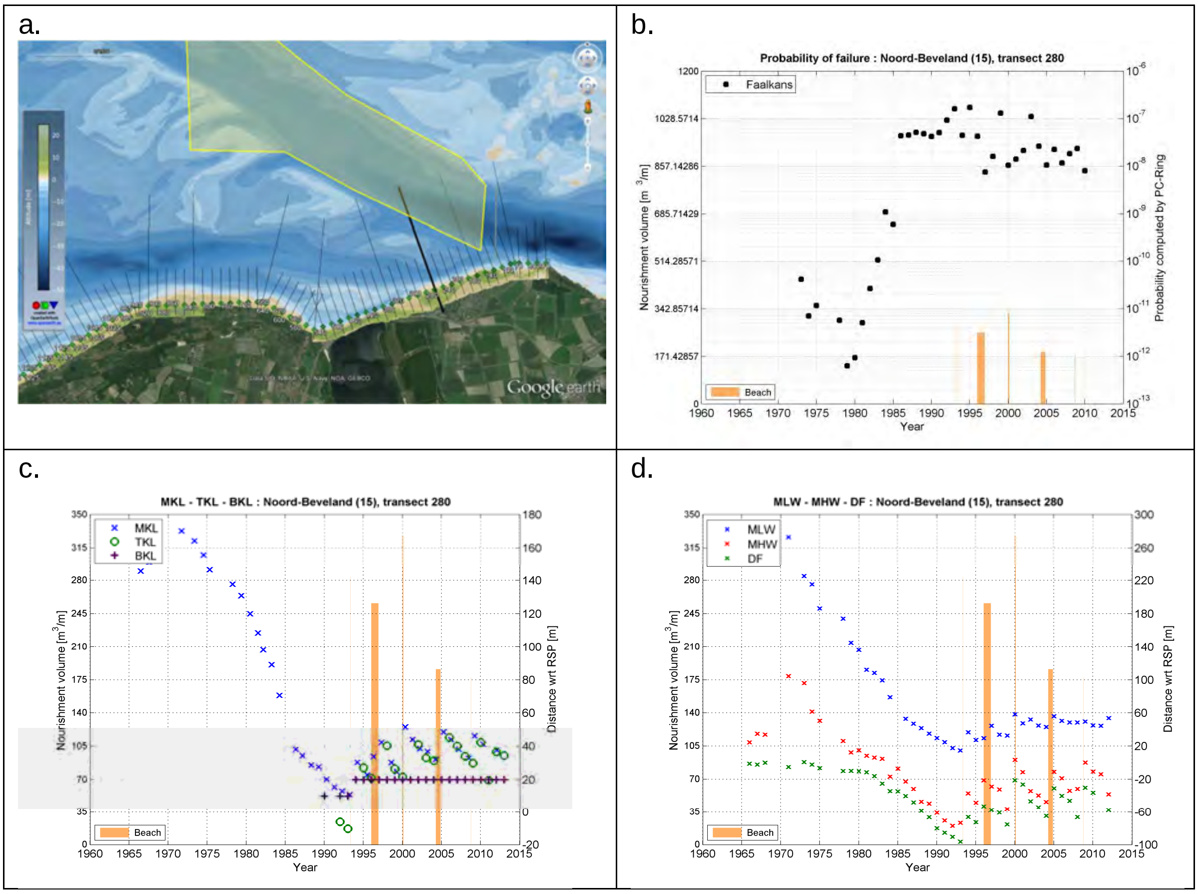


Figure 8.22 Displacement of centre of mass of water between the -10 m contour and the Oude Roompot seabed.

Coastal indicators are analysed for a single cross-shore transect in the Oude Roompot (Table 8.4 a). Transect at km 2.80 in Noord-Beveland has been nourished with a cumulative volume of ~1250 m^3/m of sand between 1994 and 2008. The positive effects of coastal management can be observed from the 1996, when nourishments started being applied on a 4 years base. As a result of the nourishments, the probability of failure is maintained on a safety level, as well as the MKL position (Table 8.4 b, c, d).

Table 8.4 Coastal indicators for transect 15000280. Figure. a.: Detail. Figure b.: Probability of failure. Figure c.: MKL, TKL, BKL. Figure d.: Mean High Water, Mean Low Water, Dune Foot.



8.3.3 Oostgat (Walcheren)

The area defining the Oostgat channel is shown in Figure 8.23.

Figure 8.23 Limit of the area defining the Oostgat.

The volume of water under -10 m contour line (Figure 8.24) within the region increased of ~$16*10^6$ m^3 in 45 years and its centroid moved ~200 m landwards (~4 m/year) (Figure 8.25). This might have effects on the stability of the Westkapelse Seawall. To counteract the shift and increase deepening of the Oostgat, two gully-side nourishments were carried out in 2005 and 2009 (Section 5.6). Those volumes are indicated in Figure 8.24 as blue lines, and easily recognizable as jumps in the water volumes. Those volumes have stopped the landward shift of the centroid (Figure 8.25).

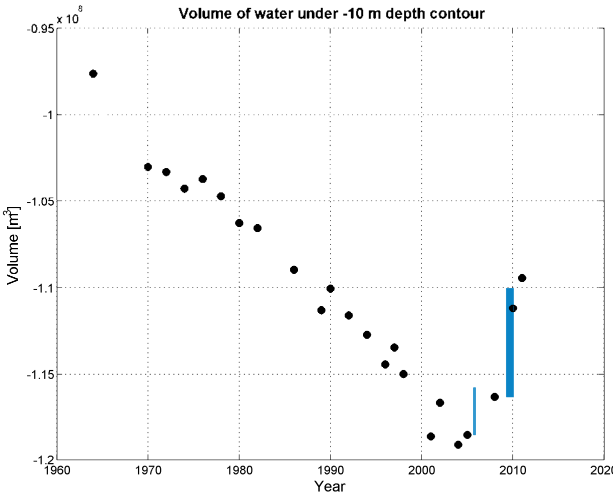


Figure 8.24 Oostgat. Evolution over time of the volume of water delimited by the channel bed and -10 m contour line (from Vaklodingen data).The blue lines indicates the volumes of the two gully-side nourishments carried out in 2005 and 2009.

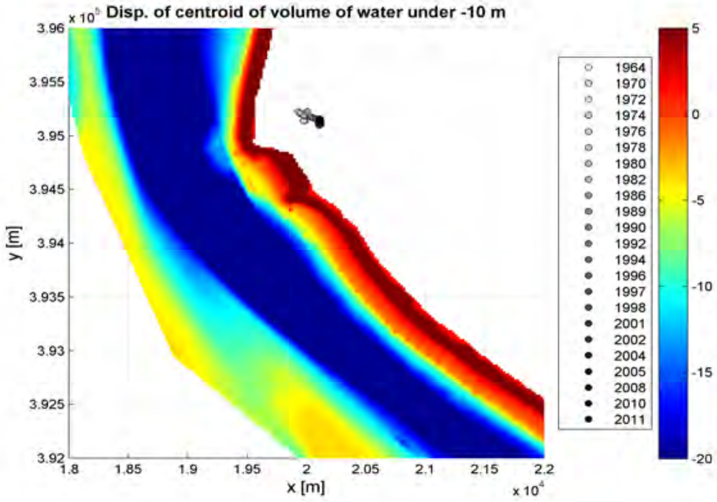


Figure 8.25 Displacement of the centre of mass of water between the -10 m contour and the Oostgat seabed.

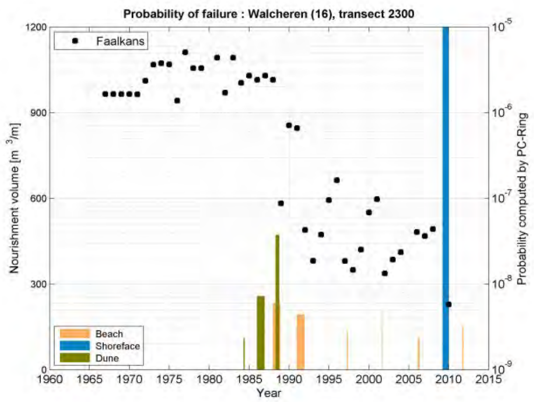
Coastal indicators are analysed for two cross-shore transects in the Oostgat (Figure 8.26). Transect at km 23.00 in Walcheren has been nourished with a total of ~2800 m^3/m of sand in the last 28 years. Half of the volume has been nourished underwater in 2009. The volume includes a gully-side (“geulwandsuppletie”) intervention carried out in 2009 (Section 5.6).

The positive effects of the coastal management can be observed already since the 1980s, when this coastal stretch started being nourished. Probability of failure decreased with about 2 orders of magnitude and a seaward shift of ~40 m in MKL position is observed (Table 8.5a, b, c).
Table 8.5b and e shows that, in between nourishments, the MKL moves landwards about~ 20 m in 5 years (~4 m/year). This result is comparable with the landward shift of the centroid which is likely to be the cause of the MKL landward movement (Figure 8.25).

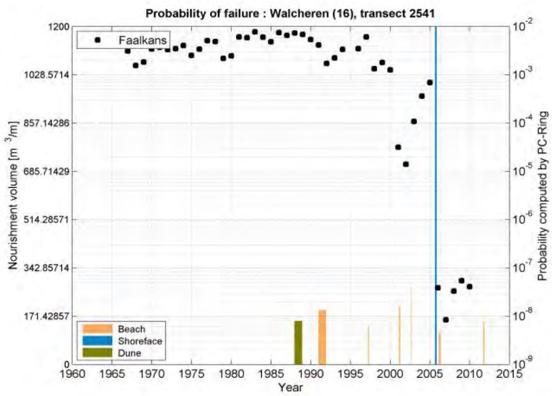
Figure 8.26 Detail of the Oostgat. Coastal indicators for the highlighted transects (16002300, 16002541) are investigated.

Table 8.5 Coastal indicators for transect 16002300 (left panel) and transect 16002541 (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.

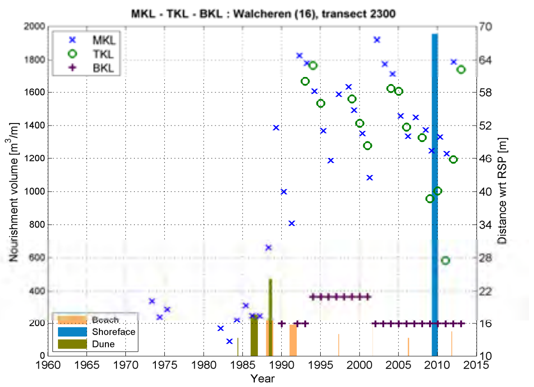
a.



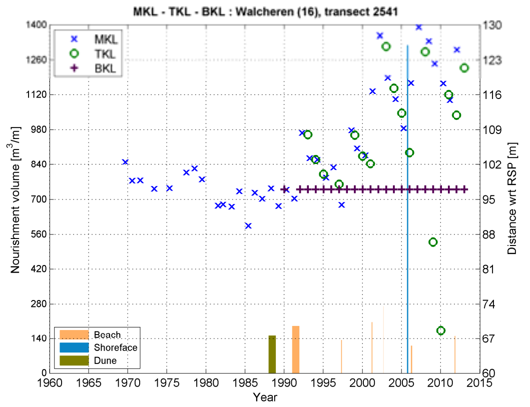
d.



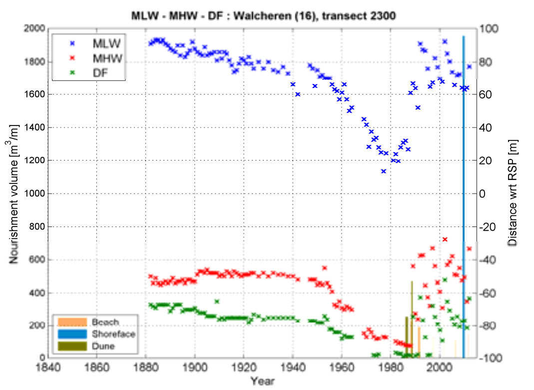
b.



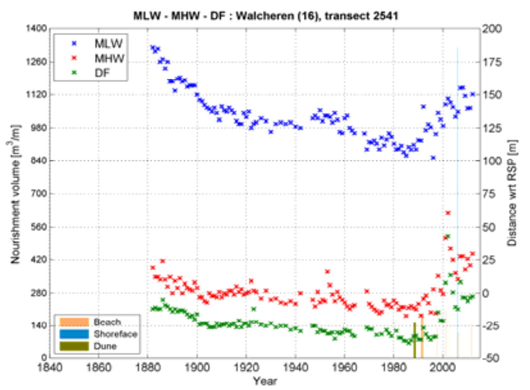
e.



c.



f.



The underwater nourishment decreased the probability of failure of transect 16002541 with ~4 orders of magnitude; nourishment policy from the 1980s' contributed to a MHW, MLW and DF shift of about 50 m in seaward direction (Table 4.1d., e., f.).

8.3.4 Sardijngeul (Walcheren)

The Sardijngeul is located in front of Vlissingen, and it is confined in the region shown in Figure 8.27. The channel has been kept at its depth through a number of dredging campaigns carried out since 1992. The dredged material was used as nourishments on the coast. The volume of water under the -10 m contour line did not face major changes (Figure 8.28). Minor horizontal shift of the centroid of that volume is observed, indicating a rather stable channel (Figure 8.29).

Coastal indicators are analysed for transect 16003360, crossing the Sardijngeul approximately in its central part (Table 8.6 a). The transect has been nourished with ~700 m^3/m of sand between 1993 and 2011. The nourishment policy has been effective, leading to a clear seaward shift of more than 30 m of MKL, mean low water and mean high water line, from the moment the nourishments started (Table 8.6 b, c, d).

Figure 8.27 Limit of the area defining the Sardijngeul.

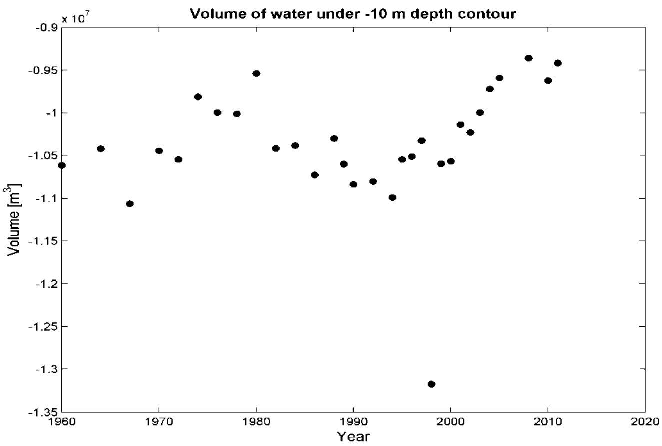


Figure 8.28 Sardijngeul. Evolution over time of the volume of water delimited by the channel bed and -10m contour line (from Vaklodingen data).

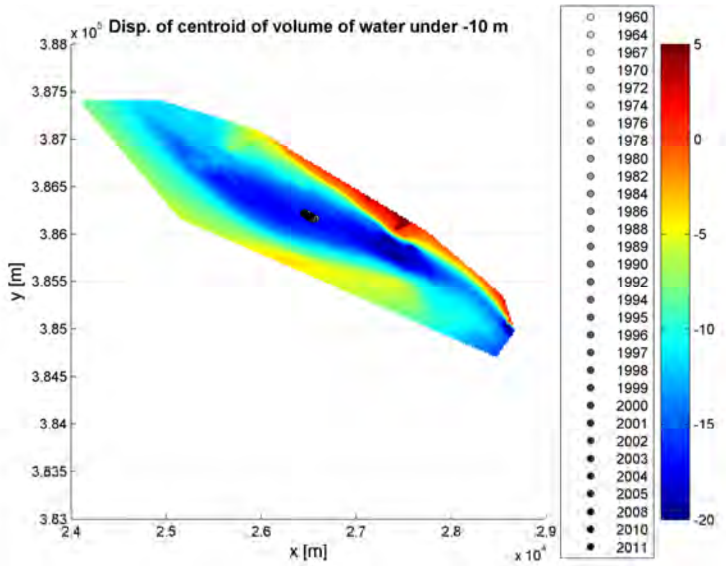
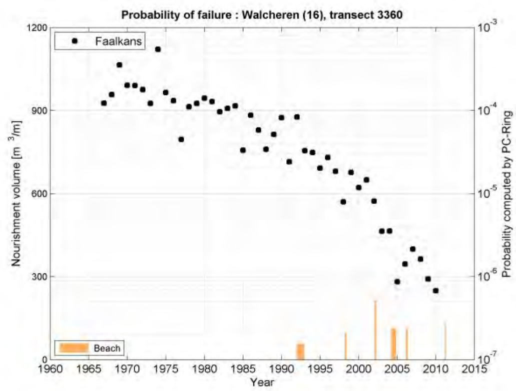


Figure 8.29 Displacement of centre of mass of water between the -10 m contour and the Sardijngeul seabed.

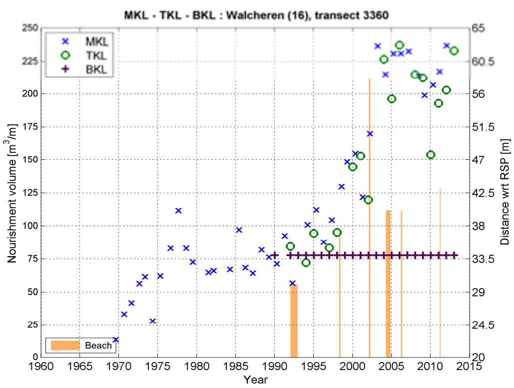
Table 8.6 Coastal indicators for transect 16003360. Figure. a.: Detail. Figure b.: Probability of failure. Figure c.: MKL, TKL, BKL. Figure d.: Mean High Water, Mean Low Water, Dune Foot.

a.

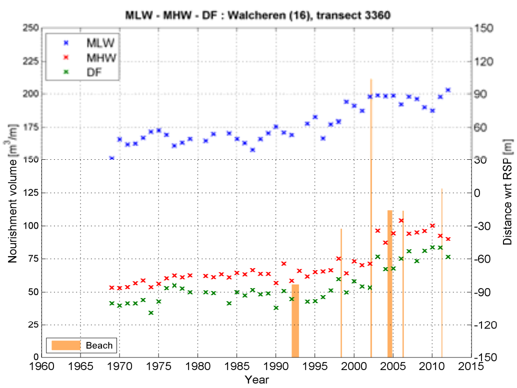
b.



c.



d.



8.3.5 Roompot and Schaar van de Onrust (Walcheren)

These channels are studied together because of the connection between the two. A snapshot of the region containing both channels is shown in Figure 8.30. The volume of water below the -10 m contour decreased with ~8*10^6 from 1968 to 1976 and then increased with ~9*10^6 until 2010 in relation to the construction of the storm surge barriers (Figure 8.31).

Figure 8.30 Limit of the area defining the Roompot and Schaar van de Onrust.

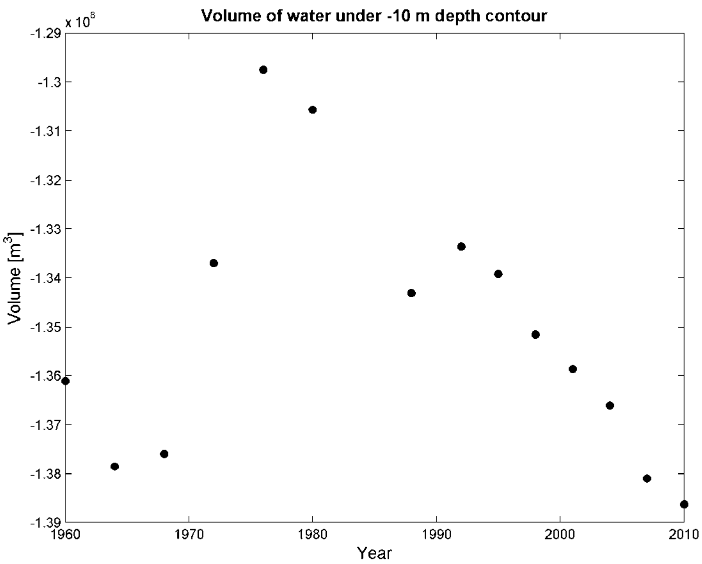


Figure 8.31 Roompot and Schaar van de Onrust. Evolution over time of the volume of water delimited by the channel bed and -10 m contour line (from Vaklodingen data).

Looking at vaklodingen data, the eastern part of the selected region is the most dynamic one, which is undergoing a deepening and extension towards the storm-surge barriers. As a result, the centroid of the channels has moved to the East with ~600 m in 50 years (Figure 8.32). Moreover, the centroid has also shifted with ~100 m in landward direction during the same period. This can most likely explain the erosive trends which are observed in this part of the coastline (i.e. between transect 16000880 and 16001085) and which have pushed towards the construction of a number of nourishments.
Coastal indicators are analysed for transects 16000740 and 16000900 (Figure 8.33). Transect at km 7.40 in Walcheren has never been nourished. Probability of failure is very low

in magnitude (~10^{-12}) and MKL has a buffer of ~80 m with respect to BKL (Table 8.7 a, b, c). Although the gully has deepened, MKL and probability of failure moved towards safer conditions. Transect at km 9 has been nourished with 850 m^3/m between 1996 and 2008, with a beach nourishment campaign every 4 years. The effects of the nourishments on coastal indicators are visible in Table 8.7 d, e, f, leading to a decrease in probability of breaching of almost three orders of magnitude, a seaward shift of MKL, mean high water, mean low water line and dune foot position of about 100 m.

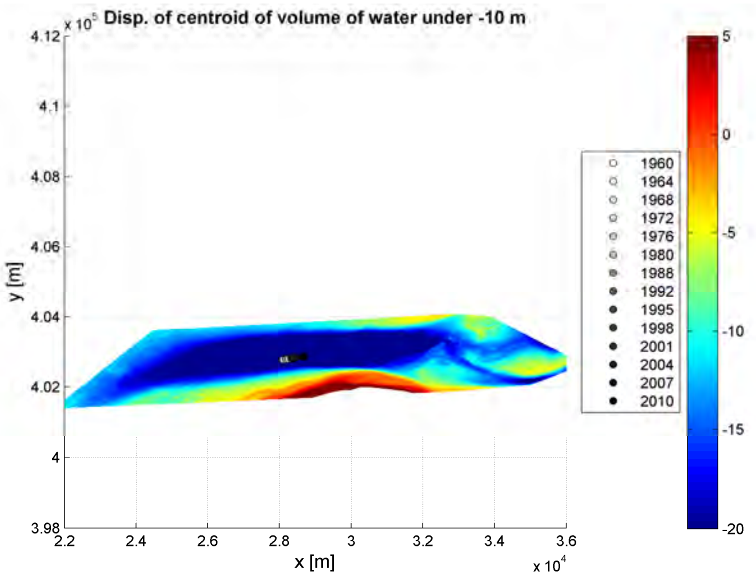


Figure 8.32 Displacement of centre of mass of water between the -10 m contour and the Roompot and Schaar van de Onrust seabed.

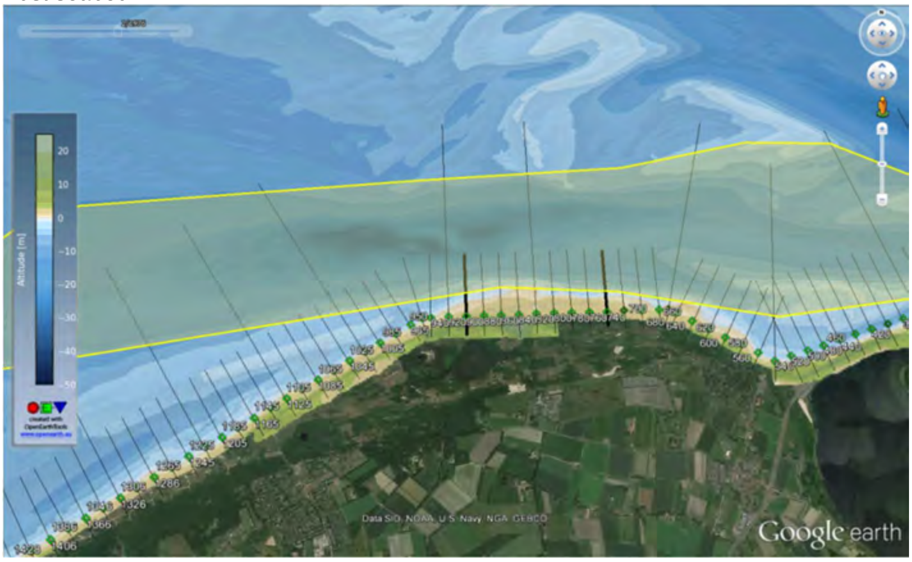
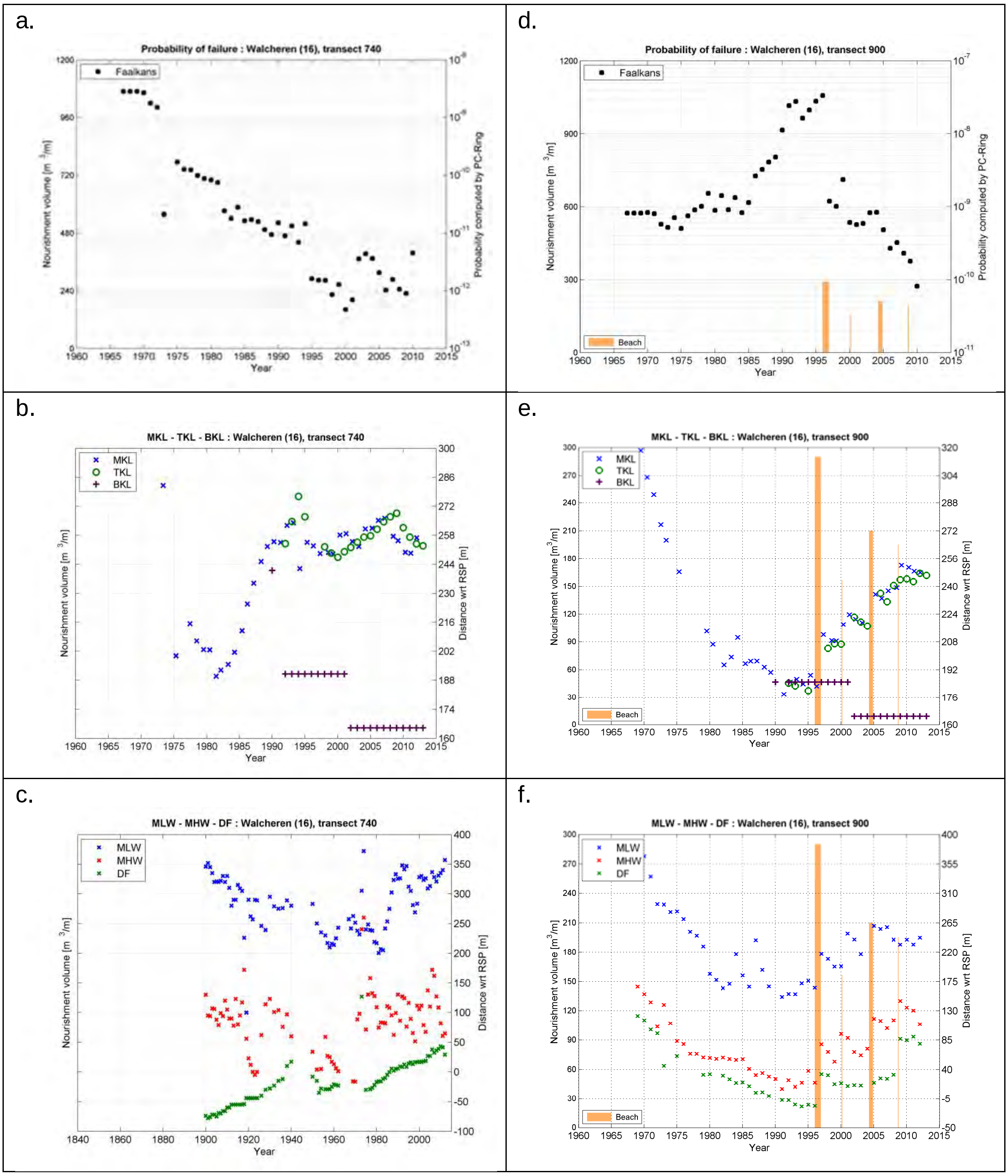


Figure 8.33 Detail of the Roompot and the Schaar van de Onrust (Walcheren). Coastal indicators for the highlighted transects (16000740, 16000900) are investigated.

Table 8.7 Coastal indicators for transect 16000740 (left panel) and transect 16000900 (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.



9 Summary and conclusions

The morphological development of the South-Westerly Delta has been assessed by looking at the time evolution of a number of coastal state indicators. In particular, the following indicators were studied: 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. construction of the Delta works and sand nourishments) natural long-term natural trends, dynamic movement of morphological features (i.e. sand waves and tidal channels) and yearly storminess.

Based on this analysis a number of conclusions can be drawn:

- In general, the indicators show that the entire South-westerly Delta coast was subject to a slightly erosive trend before 1969. The picture has changed completely after the anthropogenic interventions of the last 40 years. All the trends in indicators have been replaced by positive trends, with the average of the absolute values of the indicators during the last time window used in the analysis, consistently above (more seaward) with respect to the first time window (Chapter 7).
- The largest changes have been observed in regions 11 (Voorne) and 12 (Goeree) with total average changes of more than 100 m, and the changes decrease consistently moving from north to south. This is due to the permanent closures of the Grevelingen and Haringvliet, which largely influenced those first two regions (Chapter 7).
- The relative effects of nourishments and Delta Works on the coastal indicators during the last time window are superimposed and difficult to separate. However, looking at the changes in trend, it is safe to assume that for region 11 (Voorne), 12 (Goeree), 13 (Schouwen), and 15 (Noord-Beveland) those changes are mainly influenced by the effects of the Delta Works as the larger changes occurred between time window 1843-1969 and 1970-1989. For regions 16 (Walcheren) and 17 (Zeews-Vlaanderen) the main changes are due to the nourishments (Chapter 7).
- Looking at single transects (Chapter 8), the implementation of the nourishments has resulted into a general improvement or stabilization of the safety conditions, as shown by a general decrease of the probability of breaching of the first dune row and a seaward shift of the MKL position, mean high water and mean low water line. These conclusions prove the two hypotheses underlying this study to be correct (Chapter 2).
- Sand waves characteristics have been derived looking at the development of different indicators. Values of amplitude, celerity and period are in line with previous studies of Verhagen (1989a). 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. At some locations (e.g. Schowen), the presence and migration of tidal channels in front of the coast might affect the dynamics of those features as shown by similar migration rates of the tidal channel in front of the coastline and the sand wave. Next to it, local wave and hydrodynamic conditions, in relation to the coastline orientation, can explain the growth and migration rates of those features. Further research is recommended to investigate the link between the difference forcing parameters and the effects on the growth and migration of those features.

- The effect of sand waves on different coastal indicators (mean high and low water and dune foot position) is similar, with a time delay occurring sometimes between them.
- Sand waves, in the South Westerly Delta, have a very large effect into the local development of the coastal state indicators (locally larger than the nourishments itself). 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 therefore account for their development when planning future nourishments. 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 these sand waves and support coastal mangers in the planning of the future nourishments. 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).
- The morphological development of several tidal channels has been assessed by looking at their volume development as well as their migration rate. In particular, the migration rate was assessed by looking at the shifts of the centre of mass of those channels. The quantification of those migration rates also allow to link their morphological evolution to the evolution of the coastal indicators. Moreover, 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.
- The effect of natural forcing (i.e. storminess) was discussed based on the previous report from Vuik et al. (2012) and Giardino et al. (2014). 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 and the effect of the yearly storminess is much smaller than that one of the other anthropogenic interventions.
- Subsidence is also very relevant, with estimated values up to 40 cm by year 2050 in the hinterland of Walcheren, due to subsidence and compaction of the peat layers as a consequence of ground water extraction (Rijkswaterstaat, NAM). Those values are most likely much lower at the position of the primary defences and along the coast, as here ground water extraction did not take place.

10 References

Adriani, M.J., en Van der Maarel, E., 1968, Voorne in de branding, Stichting wetenschappelijk duinonderzoek.

Arens, S.M., Wiersma, J., 1994. The Dutch foredunes; inventory and classification. Journal of Coastal Research 10, 189-202 p.

Arens, B., de Vries, N., and Mulder, J., 2012. Herstelstrategieën Kop van Schouwen en Manteling Walcheren in ruimte en tijd concept. Arens BSDO Rapportnummer RAP2012.03.

Boers, M., 2008. Duinen als Waterkering. Inventarisatie van kennisvragen bij waterschappen, provincies en rijk. Deltares report H5019.10.

Cleveringa, J., 2008. Morphodynamics of the Delta Coast (south-west Netherlands): Quantitative analysis and phenomenology of the morphological evolution 1964-2004. Alkyonrapport A1881; ook WL| Delft Hydraulics & Rijkswaterstaat RIKZ.

Cleveringa, J., 2013. Beheer Bibliotheek Schouwen; Morfologie en Ingrepen. Arcadis report number C03041.003080. The Netherlands.

Damsma, T., 2009. Dune growth on natural and nourished beaches: “A new perspective”. M.Sc. Thesis, TUDelft, The Netherlands.

De Jongste, L., Dusseljee, D., Smit, M., Jansen, M., 2013. Morphological Impact on Ebb-Tidal Deltas of Reintroducing Tide in a Former Estuary. Proceedings of the Coastal Dynamics 2013 Conference. Bordeaux, France.

Eversdijk, P.J., 1989. Kustverdediging na 1990. Kustverdediging na 1990. Harde kustverdediging. Technisch rapport 12. Ministerie van verkeer en waterstaat (Rijkswaterstaat), The Netherlands.

Giardino, A., Santinelli, G., Vuik, V., 2014. Coastal state indicators to assess the morphological development of the Holland coast due to natural and anthropogenic pressure factors. Journal of Ocean & Coastal Management, 87, 93-101.

Maranus, J.W. and Verhagen, H.J., 1987. Zandgolven en kustverdediging in Zeeland. PT/Civiele techniek, 42 (2), 1987.

Maranus, J.W., 1996. Zandwinning suppleties Kop van Schouwen 1996/1997. Rijkswaterstaat directie Zeeland Memo NWL 96-40.

Nipsius,K.G., 1998.Dwarstranspoortmodellering m.b.v. Bailard, toegepast op de Voordelta Grevelingen-monding. MSc Thesis, Delft University of Technology.

Reinders, J., van der Valk, L., den Heijer, C., Giardino, A., Buma, J.T., and Arens, B., 2013. Voorhoedeproject: Slimmer omgaan met zand op Schouwen. Deltares report num. 1208510-000, The Netherlands.

Stronkhorst and Lagendijk, 2012. Toekomstbestendige Verharde Zeeweringen. Report 1206188-000. Deltares, The Netherlands.

TAW, 1984. Leidraad voor de beoordeling van de veiligheid van duinen als waterkering,Technische Adviescommissie voor de Waterkeringen, Den Haag, Nederland.

Van der Valk, B., Arens, S.M., Koomen, A., and Bakker, M.A.J., 2013. Verkenning herstelmogelijkheden duindynamiek Westduinen (Schouwen).

Van Konigsveld, M., and Mulder, J.P.M., 2004. Sustainable Coastal Policy Developments in The Netherlands. A Systematic Approach Revealed.Journal of Coastal Research, 20, 2, 375-385.

Verhagen, H.J., 1989a. Sand Waves along the Dutch Coast. Journal of Coastal Engineering, 13, 129-147.

Verhagen, H.J. 1989b. Kustverdediging na 1990. Strandhoofden en paalrijen. Technisch rapport 12. Ministerie van verkeer en waterstaat (Rijkswaterstaat), The Netherlands.

Vermaas, T. and Van Oeveren-Theeuwes, C., 2013. Beheerbibliotheek Walcheren. Deltares report, Delft, The Netherlands.

Van Balen, W., Vuik, V., Van Vuren, S., 2011. Indicatoren voor kustlijnzorg.Analysie van indicatoren voor veiligheid en recreatie. Project report (PR2063.20), HKV, The Netherlands.

Vuik, V., van Balen, W., Paarlberg, A., 2012. Indicatoren voor kustlijnzorg. Analyse van stormen, suppleties en kustveiligheid. HKV Lijn in Water.

A The indicator database

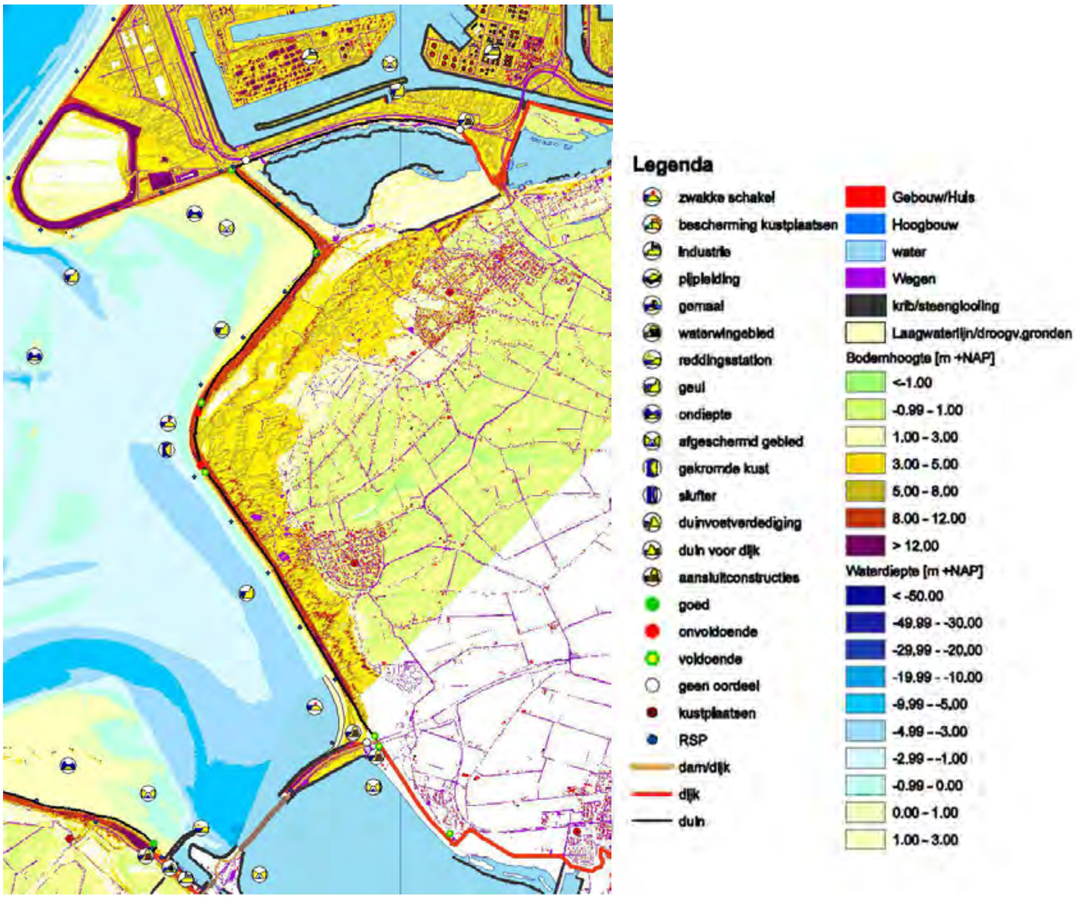
A complete database with the different indicators has been developed within this study. These data are freely available in NetCDF format through the Open Earth system (https://publicwiki.deltares.nl/display/OET/OpenEarth). Table A.1 gives the full list of indicators, accompanied by the URL link from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

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

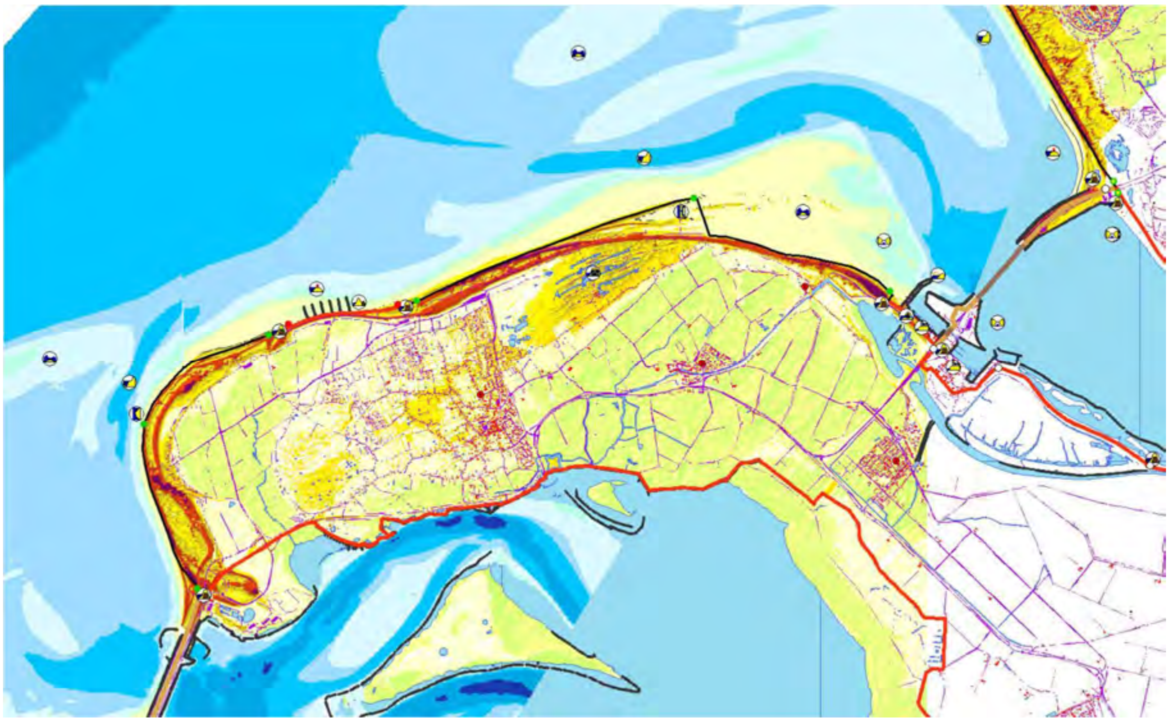
Indicator	URL Link
Nourishments	http://opendap.deltares.nl/thredds/dodsC/opendap/rijkswaterstaat/suppleties/suppleties.nc
Probability of breaching	http://opendap.deltares.nl/thredds/dodsC/opendap/rijkswaterstaat/faalkans_PC-Ring/faalkans.nc
Erosion length, MDL	http://opendap.deltares.nl/thredds/dodsC/opendap/rijkswaterstaat/safetyIndicators_Arcadis/kustlijnindicatoren_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)

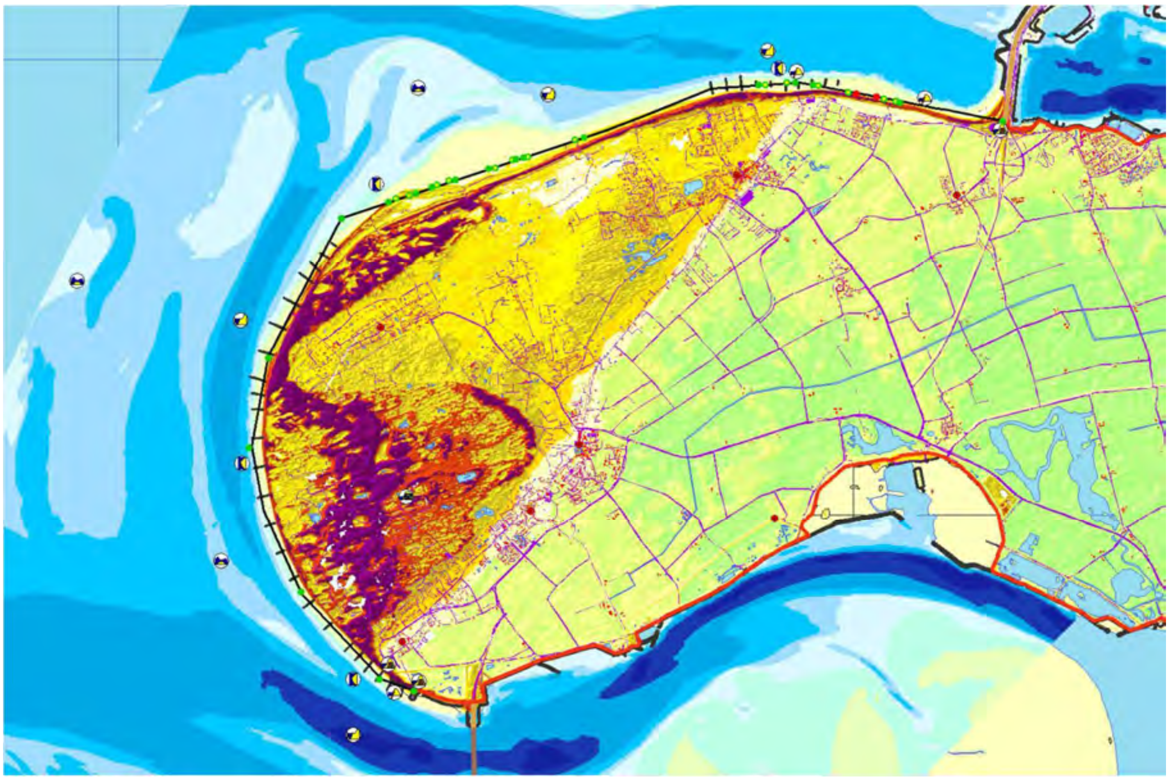
B.1 Voorne



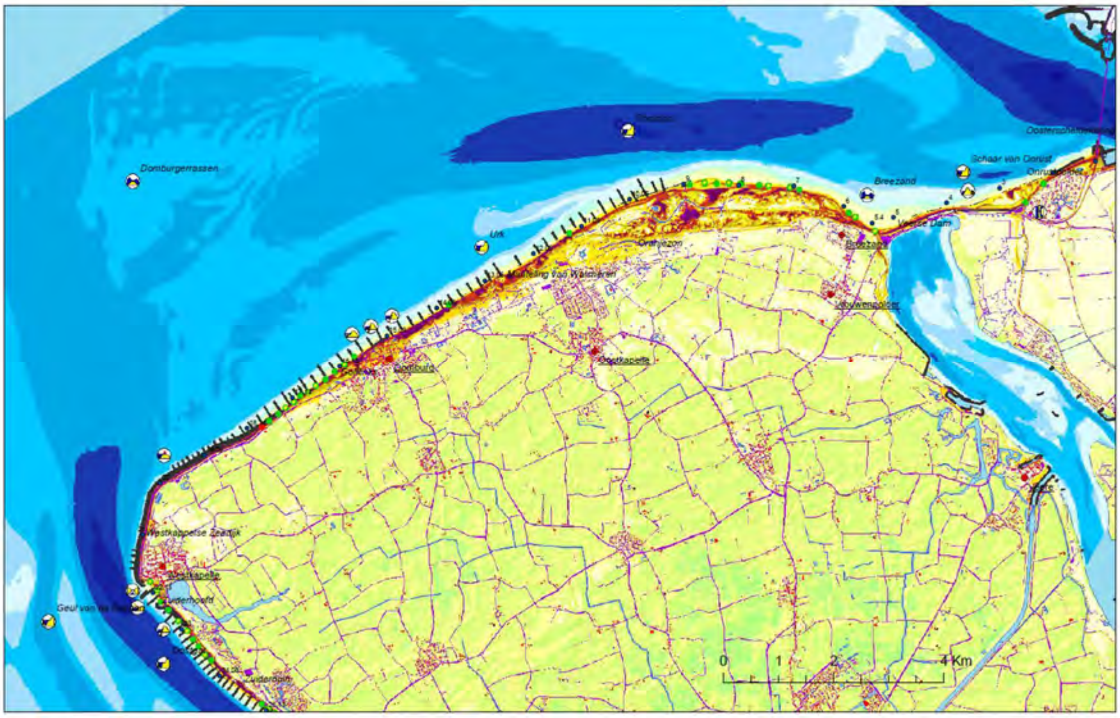
B.2 Goeree



B.3 Schouwen



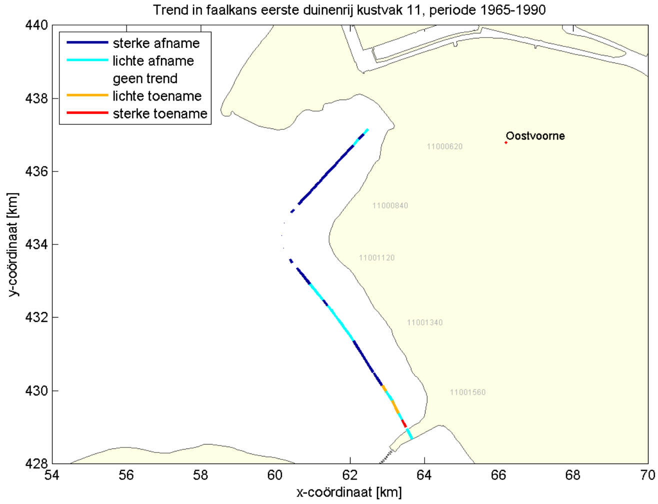
B.4 Noord Beveland – Walcheren

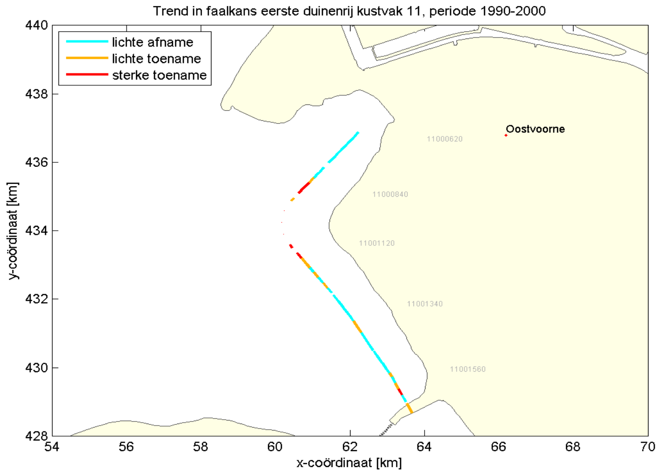


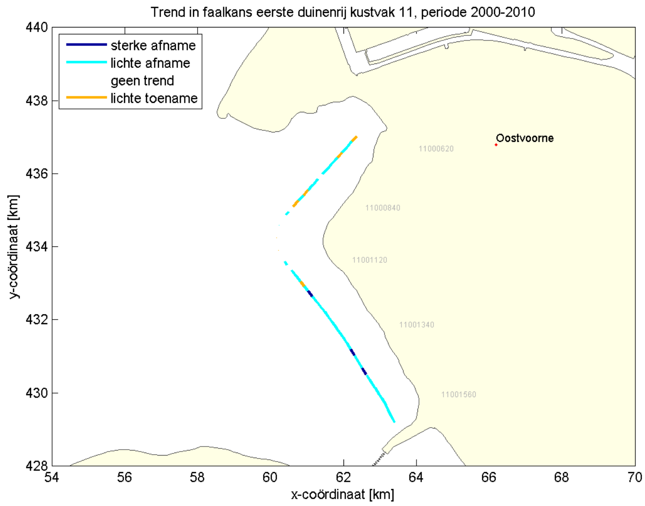
B.5 Zeeuws-Vlaanderen

C Probability of breaching of the first dune row

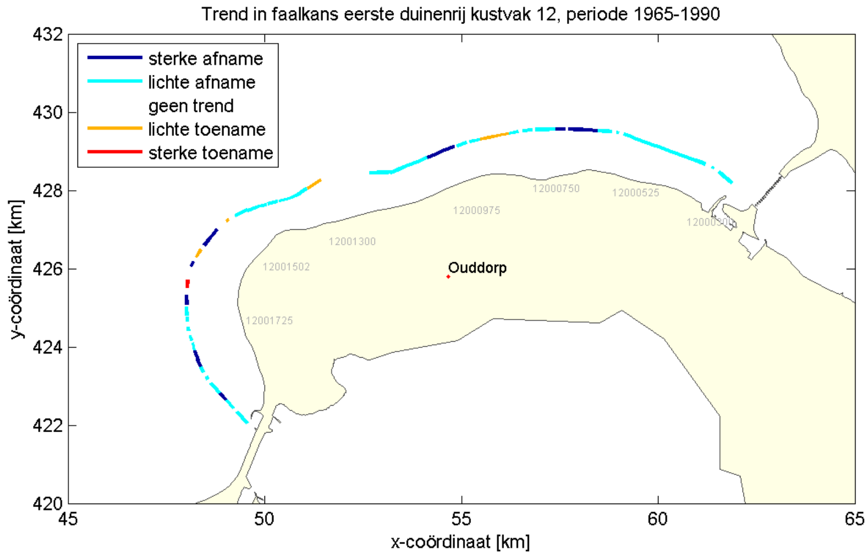
C.1 Kustvak 11: Voorne

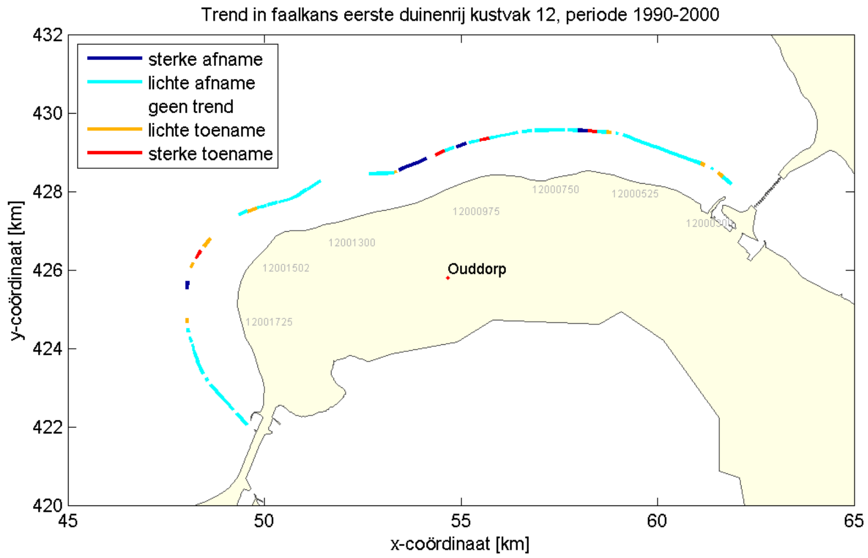


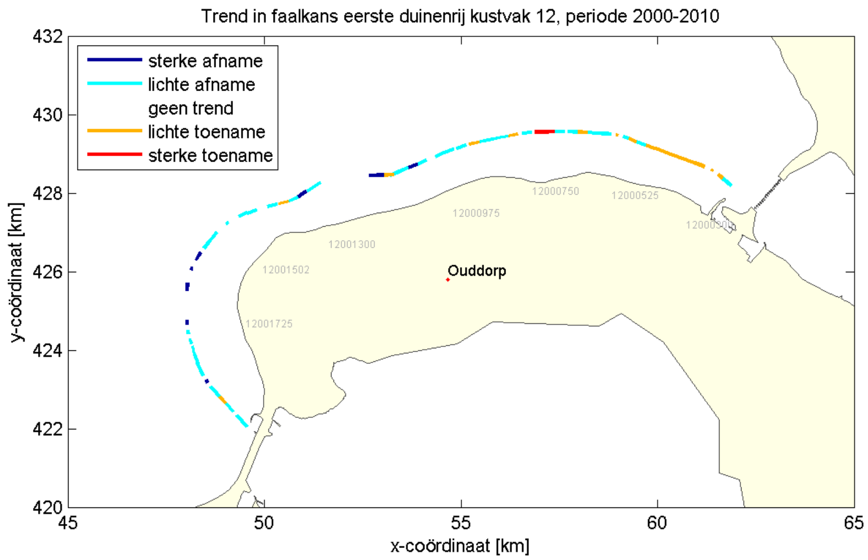




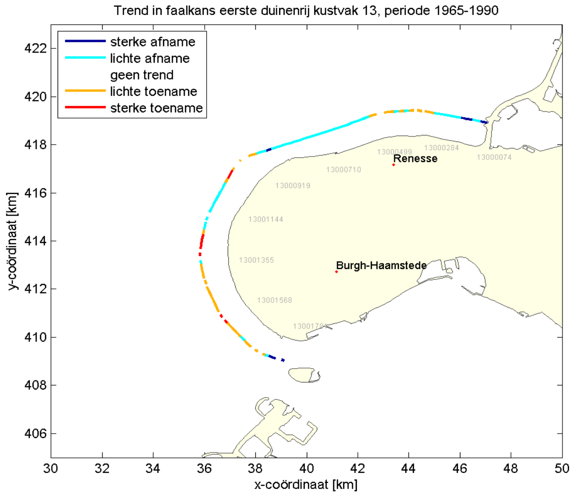
C.2 Kustvak 12: Goeree

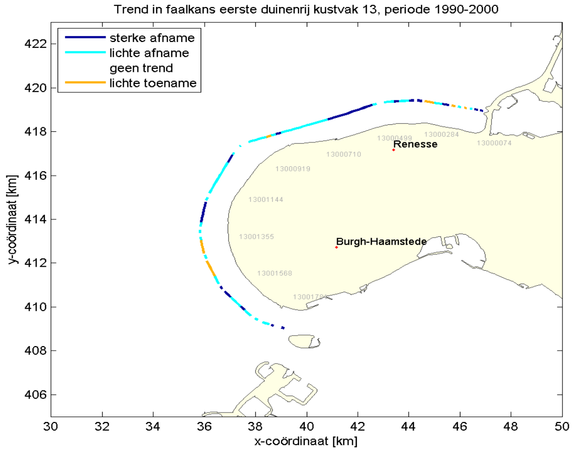


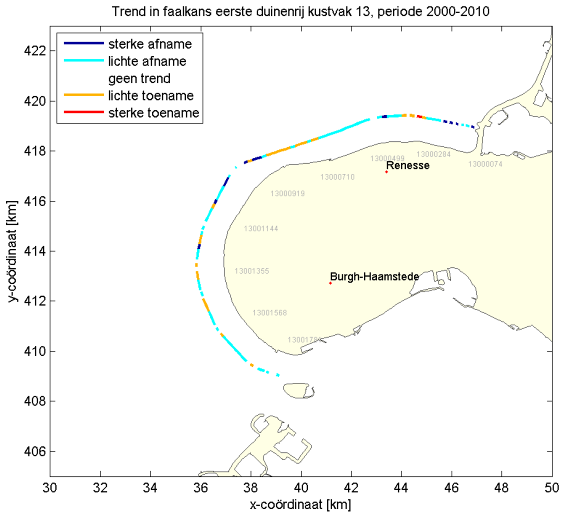




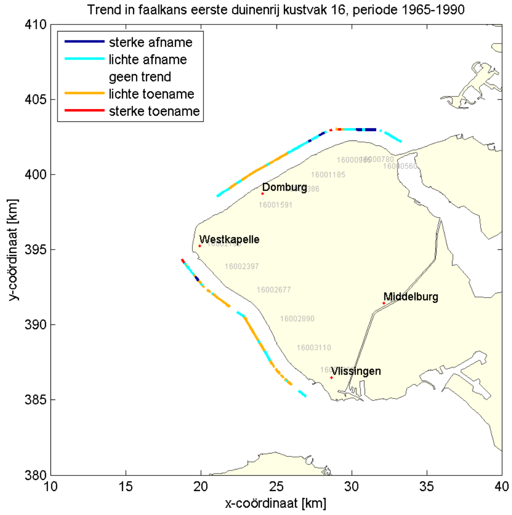
C.3 Kustvak 13: Schouwen

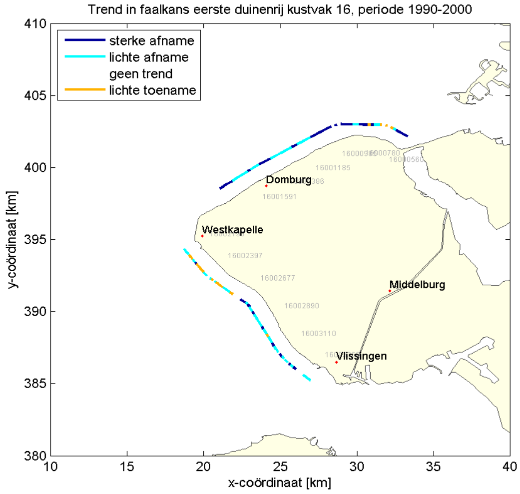


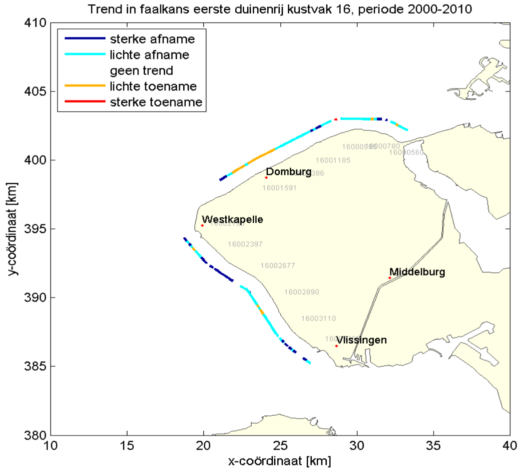




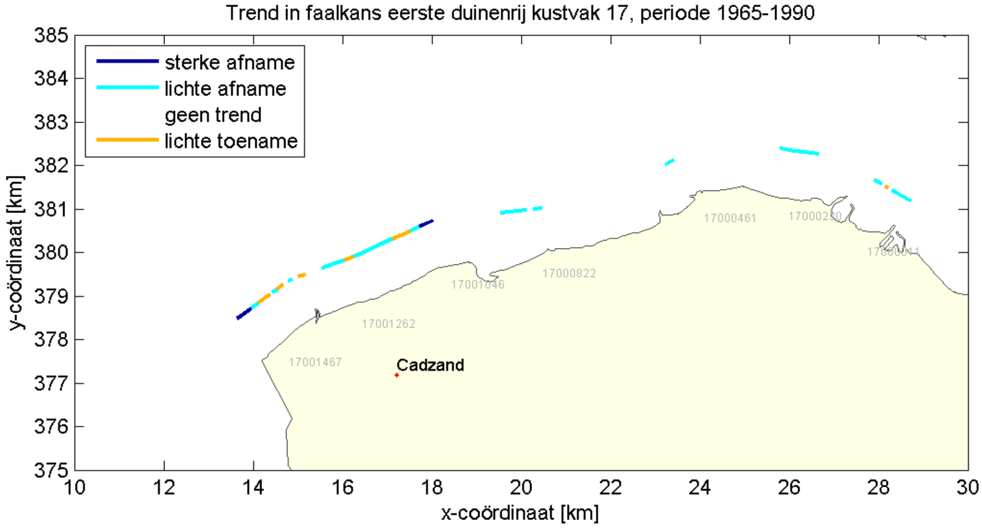
C.4 Kustvak 16: Walcheren

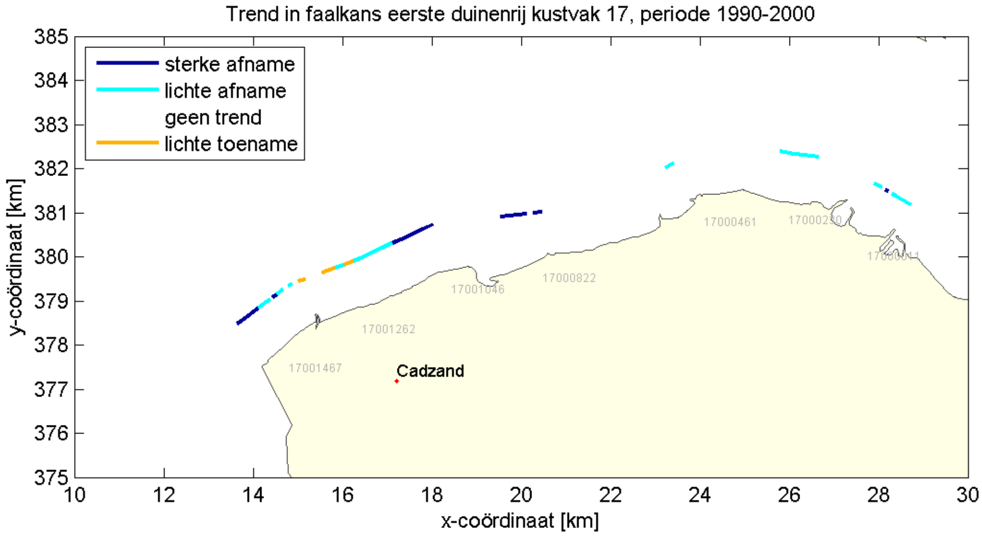


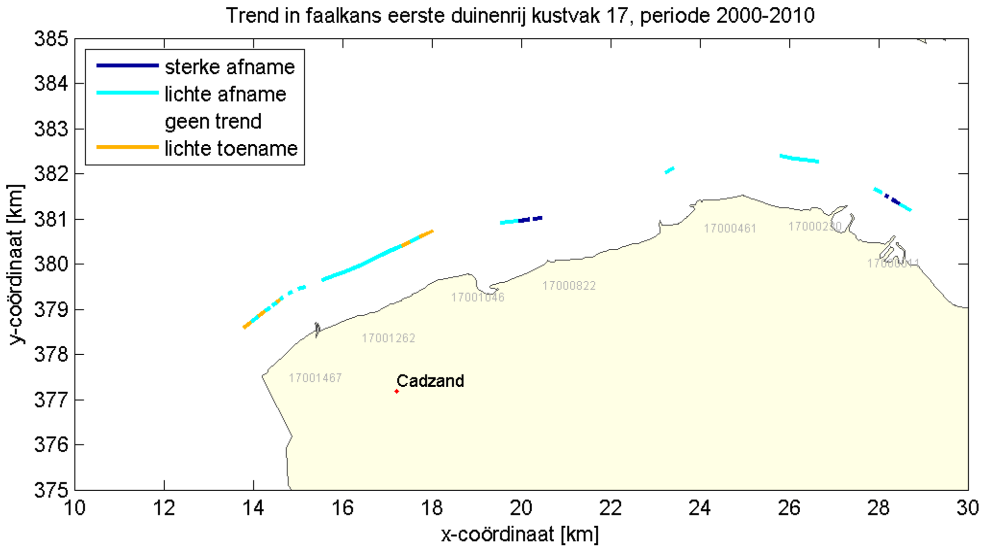




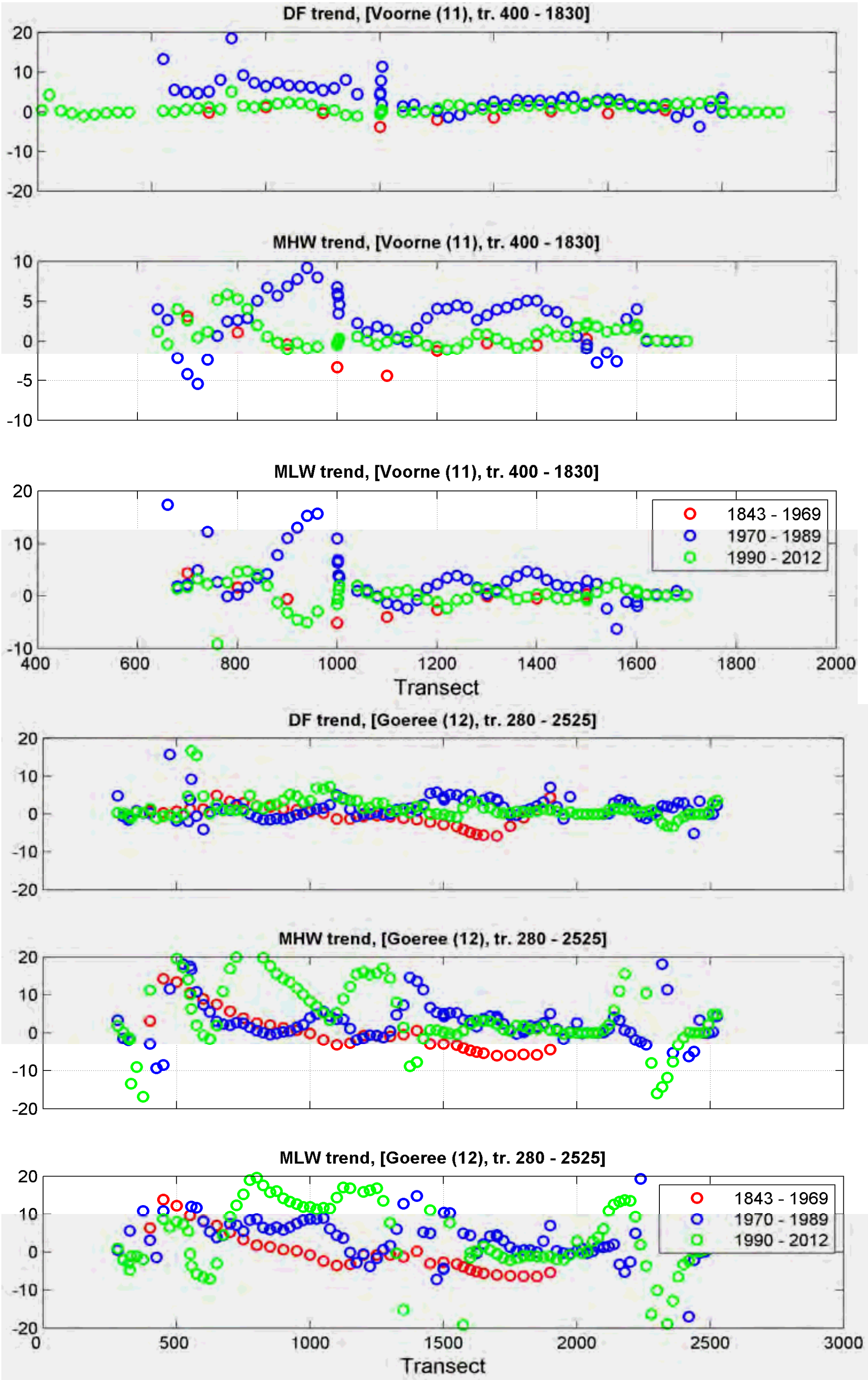
C.5 Kustvak 17: Zeeuws-Vlaanderen

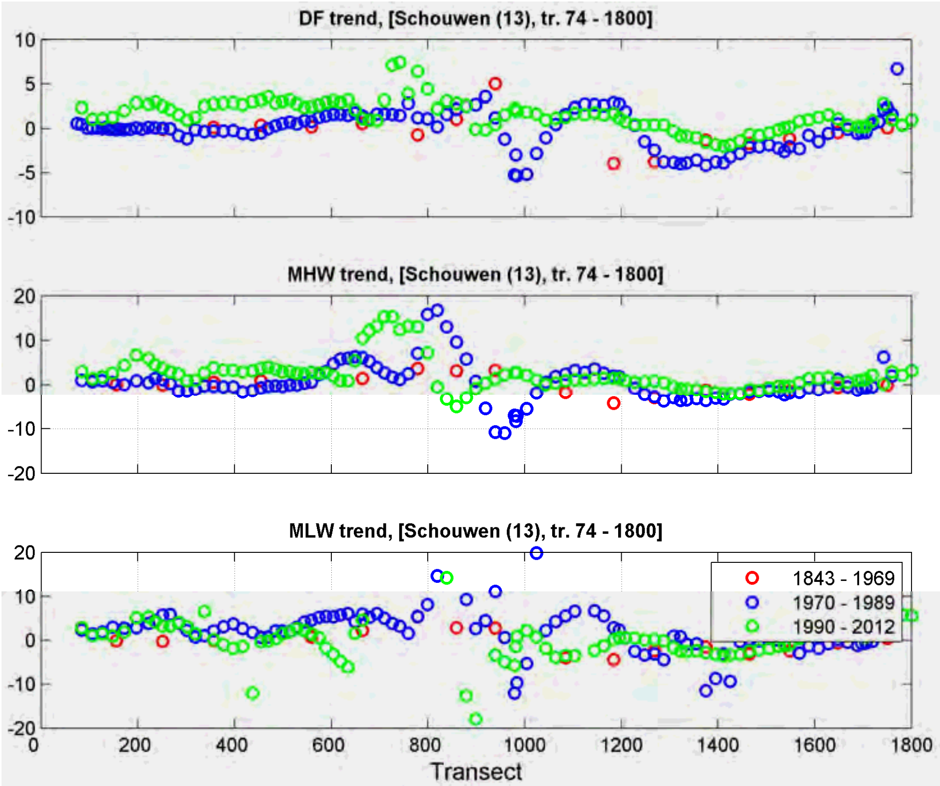


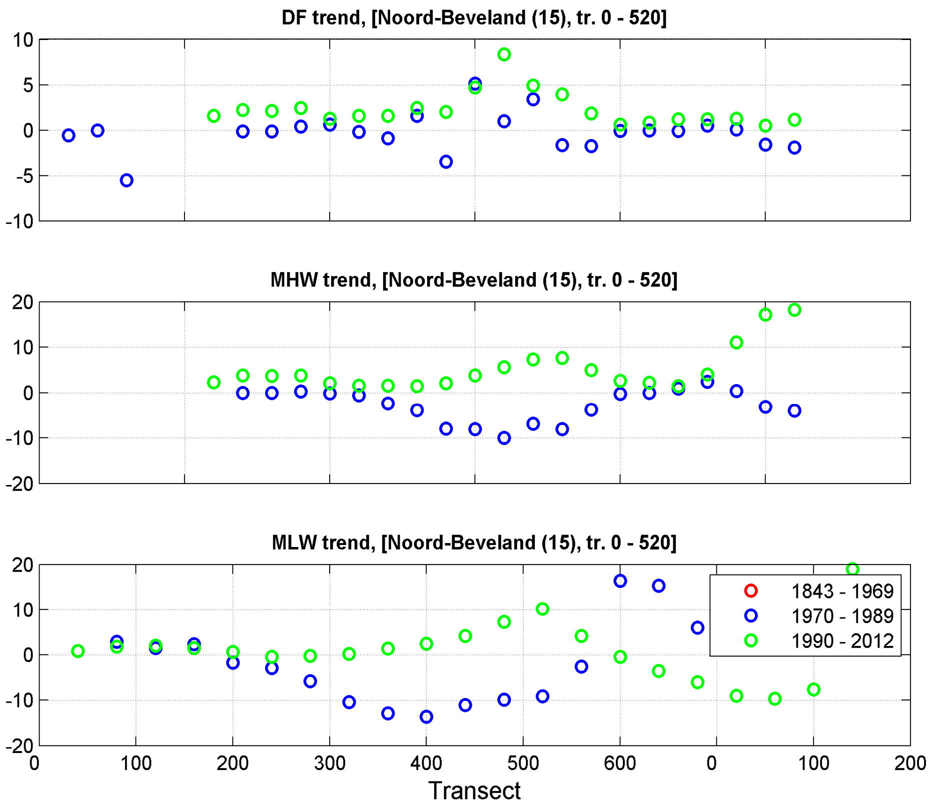


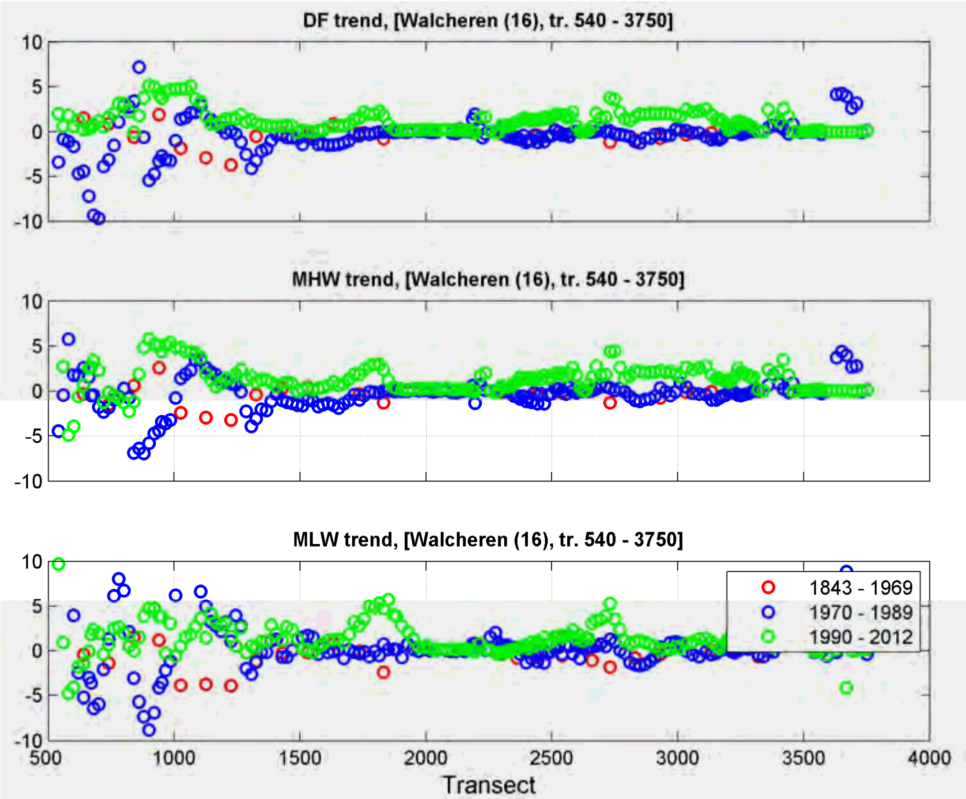


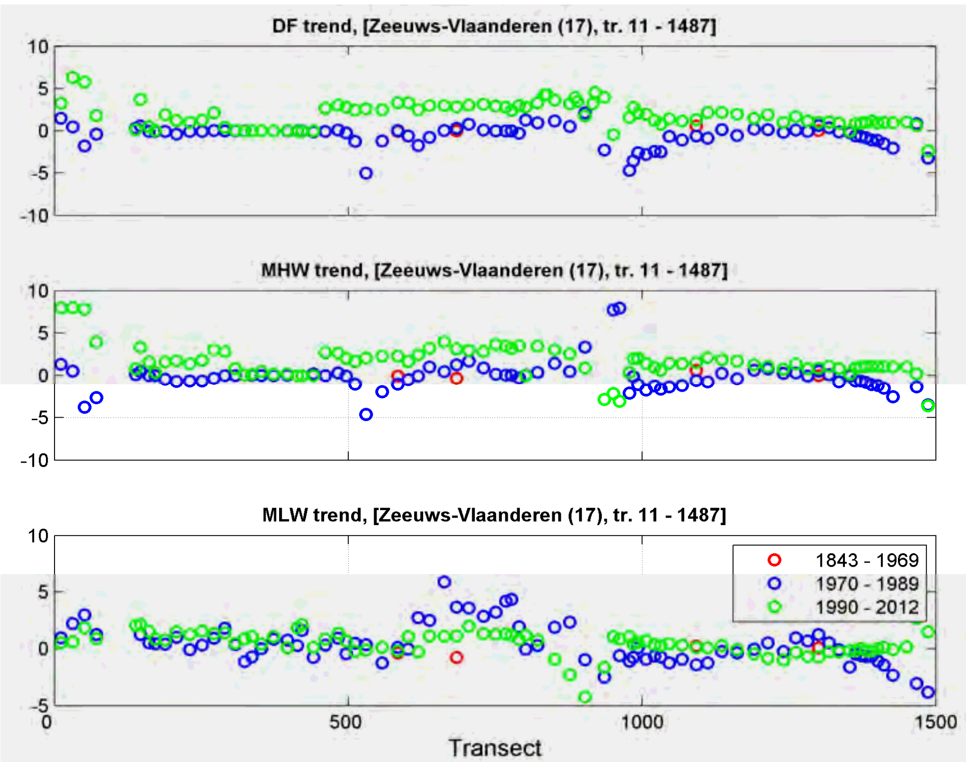
D Trends of indicators for different regions



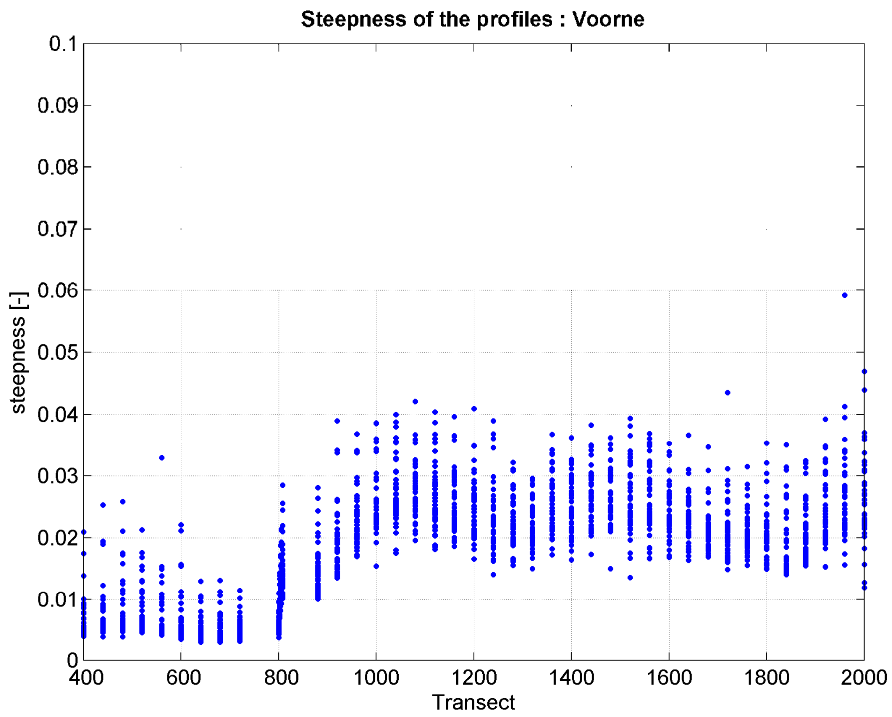

DF trend, [Schouwen (13), tr. 74 - 1800]
MHW trend, [Schouwen (13), tr. 74 - 1800]
MLW trend, [Schouwen (13), tr. 74 - 1800]
1843 - 1969
1970 - 1989
1990 - 2012
Transect

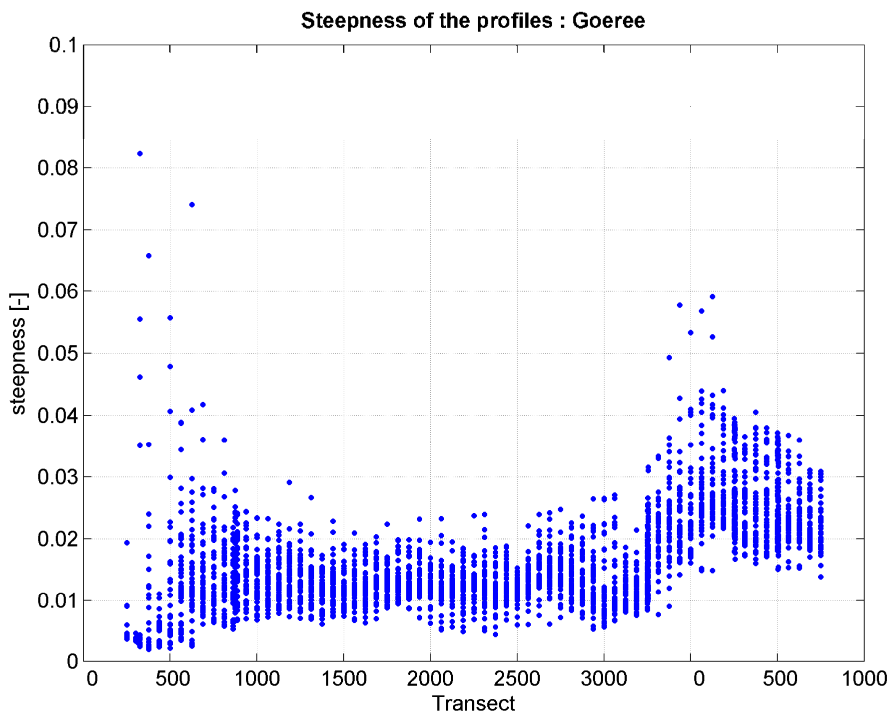

DF trend, [Noord-Beveland (15), tr. 0 - 520]
MHW trend, [Noord-Beveland (15), tr. 0 - 520]
MLW trend, [Noord-Beveland (15), tr. 0 - 520]
1843 - 1969
1970 - 1989
1990 - 2012
Transect

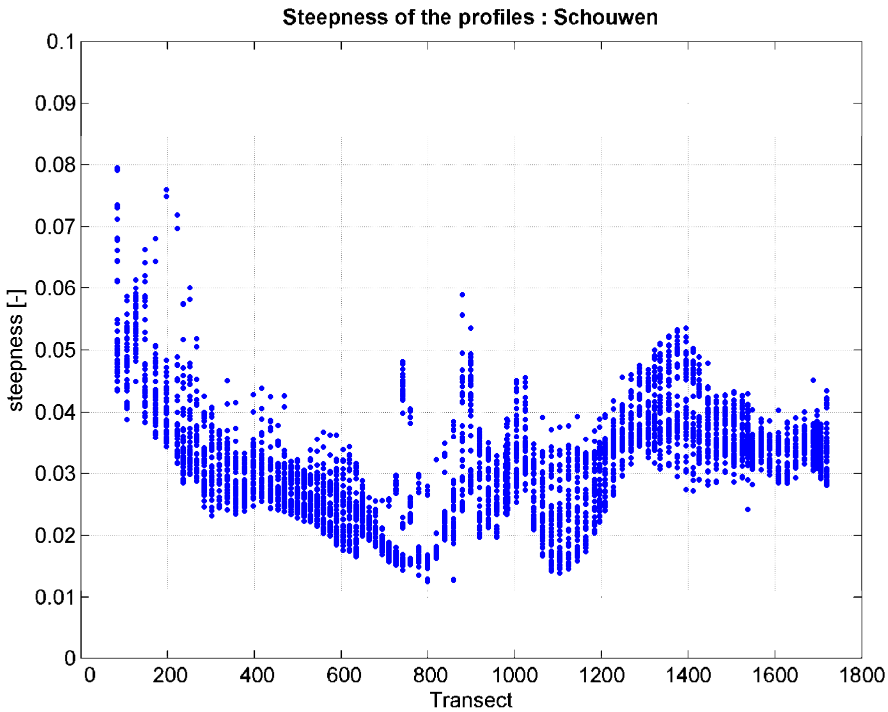

DF trend, [Walcheren (16), tr. 540 - 3750]
MHW trend, [Walcheren (16), tr. 540 - 3750]
MLW trend, [Walcheren (16), tr. 540 - 3750]
1843 - 1969
1970 - 1989
1990 - 2012
Transect

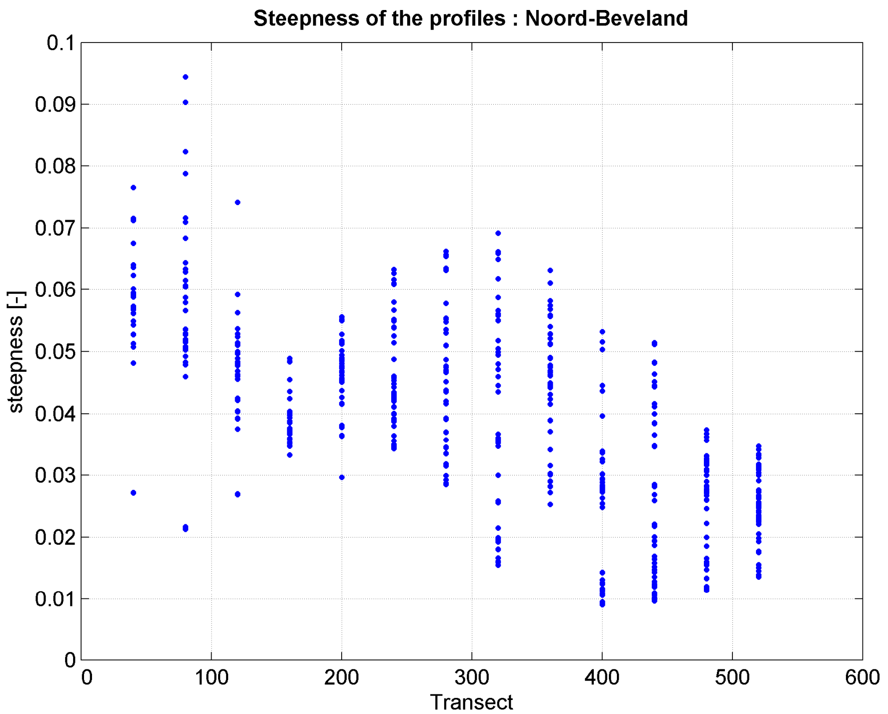

DF trend, [Zeeuws-Vlaanderen (17), tr. 11 - 1487]
MHW trend, [Zeeuws-Vlaanderen (17), tr. 11 - 1487]
MLW trend, [Zeeuws-Vlaanderen (17), tr. 11 - 1487]
1843 - 1969
1970 - 1989
1990 - 2012
Transect

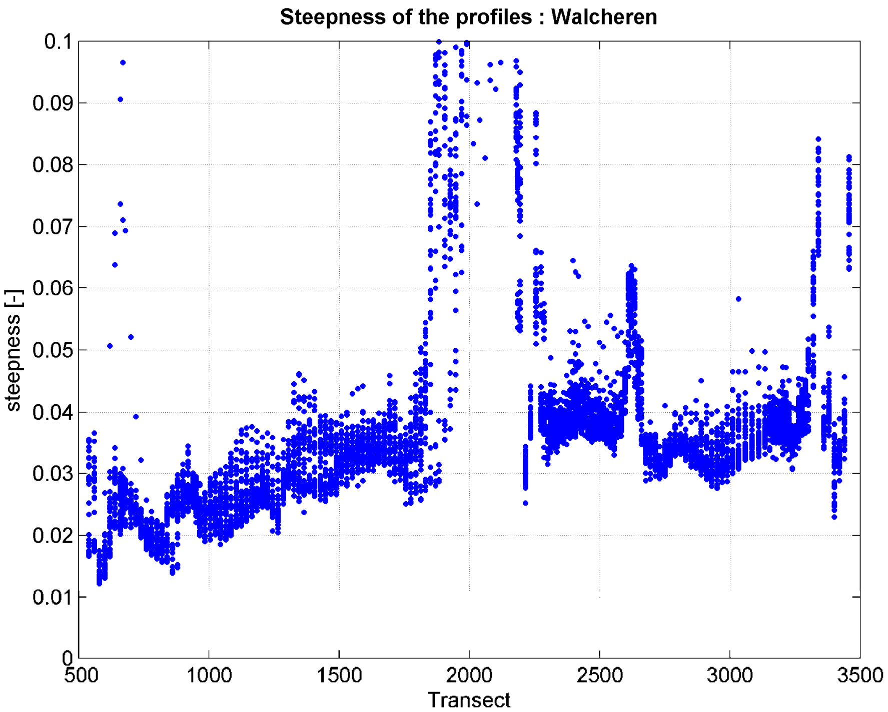
E Steepness of the coastal areas for different regions

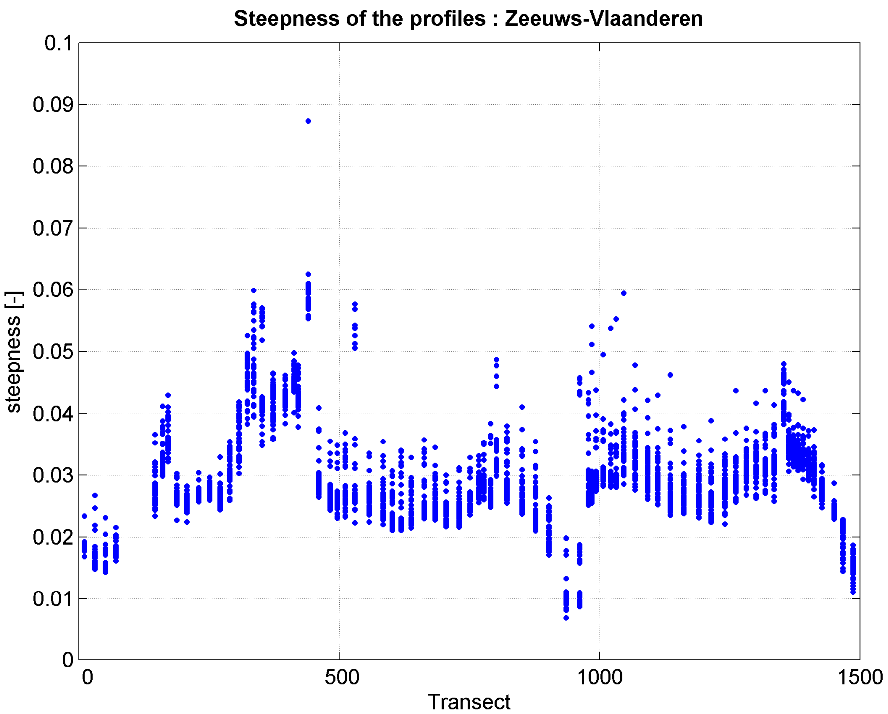





Steepness of the profiles : Schouwen
steepness [-]
Transect
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
200
400
600
800
1000
1200
1400
1600
1800


Steepness of the profiles : Noord-Beveland
steepness [-]
Transect
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
100
200
300
400
500
600


Steepness of the profiles : Walcheren
steepness [-]
Transect
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
500
1000
1500
2000
2500
3000
3500


Steepness of the profiles : Zeeuws-Vlaanderen
steepness [-]
Transect
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0
500
1000
1500

www.deltares.nl

Deltares