Deltares

The state of the coast (Toestand van de kust)

Case study: North Holland

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1206171-003

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Client	Project	Reference	Pages
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Keywords
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Summary
Over more than a thousand years, the Dutch coast has been eroding for large stretches. Coastal retreat puts coastal functions (e.g. safety against flooding) under pressure. Since 1990, the Dutch policy aims at preventing further retreat of the coastline, but in the meantime taking the valuable dynamical behaviour of the coast into account. Therefore, sand nourishments have been preferred over hard structures to counteract the systematic erosion. The Dutch Government is responsible for the planning and realization of the nourishments. Deltares has been commissioned to develop the knowledge needed to carry out an effective nourishment strategy.

Due to its strategic importance, the Dutch coastal area is also one of the most extensive studied areas in the world. However, most of the morphological research so far has focussed into the understanding of just part of the Dutch coastal system (e.g. dune area, foreshore). Hardly any attempt has been made to describe in a quantitative way the complete morphodynamic development of the system from the dunes to deep water and the cumulative effect of the past nourishment strategy at various time- and spatial scales. The aim of this study is the assessment of the functioning of the complete coastal system through a number of indicators describing the morphological system at different time scales. In particular, the relations between anthropogenic intervention (e.g. sediment management over the past 40 years, construction of hard structures), natural yearly variation in storminess and time variation of the indicators are assessed. As a case study, the North Holland coast has been analyzed.

The study shows that the current nourishment strategy has lead to a clear shift in indicators related to safety, nature and recreation towards a "safer" coastline, with larger space suitable for nature and tourism. Hard structures also play a primary role into the morphological development of the coastline. The effect of the yearly variation in storminess appears to be correlated to a number of indicators (e.g. dune foot position). However, nourishments have contributed to damp the effect of these natural forcings. The results of different nourishment strategies applied in different areas have been intercompared with the aim of assessing the most cost-effective management strategy.

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 Gemma Ramaekers (Waterdienst) which have resulted into an improved manuscript. We would also like to thank the photograph Jurriaan Brobbel for the picture on the cover.

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Appendices

1 Introduction

The Netherlands is a low-lying country, where approximately 27 percent of the territory is located below mean sea level and 55 percent is prone to flooding. 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, and new objectives 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 first increased to 6 millions m^3 of sand in 1990 and then to 12 millions m^3 in 2001. Even higher volumes might be necessary in the future to cope with the more severe sea level rise scenarios predicted.
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 Waterdienst to develop the knowledge needed to carry out an effective nourishment strategy (spatially and temporally). Deltares organised this project *Kennis voor Primaire Processen – 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-project of this multi-year program, with the aim of identifying the impact of nourishments for a number of indicators along the Dutch coast. During this first year, the analysis has focused on the North Holland coast. The study will be extended to the entire Dutch coast during the next years.

This report summarizes the main findings from the study. In Chapter 2 the main objectives of the work are described. The assumptions on which this study is based are summarized in Chapter 3. The study area is described in Chapter 4, with focus on the different types of forcings influencing the morphological development of the coast:: anthropogenic (nourishment, dune management and other man-made structures) and natural (storminess during the years, sea level rise and subsidence). In Chapter 5 the morphological development of different stretches of coast is described by means of indicators related to short term safety, medium term safety, long term safety, and nature and recreation. In Chapter 6 a detail discussion on the effects of storms on a number of indicators is given. In Chapter 7, a first attempt of cost-benefit analysis is carried out by comparing the benefits identified by the changes in morphological indicators with the nourishments costs within different areas. Finally, Chapter 8 and 9 summarize the main conclusions from the study and put forward a number of recommendations for further work.

As additional deliverables to this work:

- A complete database has been developed including the evolution of different indicators (in space and time) on a standard NetCDF format, according to the Open Earth philosophy (http://public.deltares.nl/display/OET/OpenEarth) (Appendix B). This database has been used as support tool in different KPP-B&O Kust subprojects (e.g. Beheerregisters).

Moreover partial support has been given to the development of:

- "*The Coastal Viewer*": simple visualization tool with the aim of allowing coastal managers and policy makers for a on-line visualization of the state of the coast, of the past and current morphological trends and management choices (Appendix A).
- Wiki page: "*De Nederlandse Kust in Beeld*" with general explanations concerning the project and a collection of .kml files for on-line visualization (Appendix A).
- *MorphAn* package: a powerful tool which will be used in the near future for for safety assessments as well as visualization tool of morphological trends along the coast (Appendix A).

Three external consultancy companies: *HKV–Lijn in Water, ARCADIS* and *ALTERRA* were also involved in the project with specific tasks described in the next chapters.

2 Objectives

The objective of the present study is twofold:

- *To support the Waterdienst 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 concerns 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, the Waterdienst 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 the Waterdienst on the most efficient nourishment strategy.*
  This is achieved by deriving the effect of the previous nourishment strategy (1990 till present). Learned lessons from the past can be used to improve future nourishment strategies.

In addition, the following hypotheses[1] are validated in this study:

Hypotheses
1) The nourishment strategy of the past years had lead to a positive (seaward) 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 nourishment programmes of the coming years. The focus area of this report is the North Holland coast. During the next year, the same study will be extended to the whole Dutch 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.

Moreover, the main causes inducing the morphological development of the coast (coastal management and storminess) were analyzed, according to the scheme given in Figure 2.1.

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

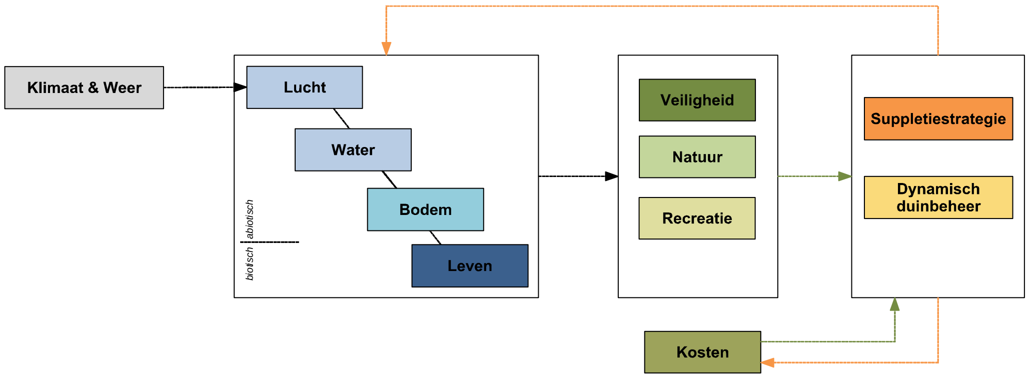

Figure 2.1 Functioning scheme of the coastal system: climate and weather (gray box) and management choices (orange boxes), influence the hydrodynamics and morphological development of the coast (blue boxes). This has an impact on the development of safety, nature and recreation (green boxes).

3 Assumptions

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

Assumption 1
The analysis was subdivided in three periods of time, corresponding to radical changes in the nourishment policy (Paragraph 4.2):

- Period 1965 -1990: characterized by nearly no nourishment along the entire Dutch coast. The main objective of coastal policy was the defence against flooding.
- Period 1991 – 2000: characterized by a nourishment scheme of about 6 millions of m^3 of sand per year along the all Dutch coast. The main objective of the nourishment policy, beside safety, was the preservation of values and functions in the dune area.
- Period 2001 – now: characterized by a nourishment scheme of about 12 millions of m^3 of sand per year along the all Dutch coast. The main objective of the coastal policy was, besides coastline management, the preservation of volumes within the entire coastal foundation in order to keep up with the sea level rise (sustainable management).

The choice of the three time windows is however arbitrary.

Assumption 2
Within these predefined time windows the study tried to identify changes in “linear” trends[2]. The same morphological changes could be possibly described by other fitting functions.

Assumption 3
The analyses was carried out both, at Jarkus transect level and at larger scale (sub-areas). This assumption is related to how these sub-areas are defined. In our case, sub-areas were identified characterized by a homogeneous nourishment policy (e.g. beach nourishments, shoreface nourishments, no nourishment), and a similar autonomous trend (erosive or accretive) (Table 3.1). The autonomous trend was defined by looking at the MKL time variation before 1990. In the same table (last column) the main findings from Wijnberg (2002) on morphological trends for different areas are also given. The location of the different areas is shown in Figure 4.1. The Figures with the nourishment volumes in time for the different sub-areas are shown in Appendix C. In this way, possible hypothesis could be drawn on the relation between different nourishment policies, and the consequent morphological development.

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2. *This assumption is in line with the method (assumption) applied by the Waterdienst to determine the Testing Coastal (BKL Toetsing), as the TKL (Toetsen Kustlijn) is determined based on the linear trend from the Momentary CoastLine (MKL) positions over the last ten years.*

Table 3.1 Division in sub-areas with homogeneous nourishment strategy and autonomous trend.

Area code	Limit sub-region (Jarkus number)	Length (m)	Nourishment strategy / Coastal type	Autonomous trend before 1990	Wijnberg (2002) (km from Den Helder)
1	90 – 588	4 980	Mainly beach nourishment	Eroding	≈ 3 - 8 Eroding, profile steepening
2	608 - 1808	12 000	Mainly shoreface nourishment	Eroding	≈ 8 - 23 Eroding, profile flattening
3	1827 - 2023	1 960	Mainly beach nourishment	Eroding	
4	2041 - 2606	5 650	Hondsbossche Zeewering	-	≈ 23 - 55 Fluctuating
5	2629 - 3200	5 710	Mainly shoreface nourishment	Eroding	
6	3225 - 3925	7 000	Mainly beach nourishmnt	Eroding	
7	3950 - 4975	10 250	Nearly no nourishments	Alternating (erosive-accretive)	
8	5000 - 5500	5 000	Nearly no nourishments – under the effect of Ijmuiden jetties	Accretive	

Assumption 4

Given the fact that the Jarkus transect alongshore resolution was defining the alongshore resolution of the analysis, nothing can be said concerning the morphological developments between two transects.

Assumption 5

The last assumption concerns the choice of the indicators, which best describe the coastal morphological evolution and can be related to policy objectives. These indicators were divided in four different categories according to the time scale at which they are functioning: indicators for short term safety, medium term safety, long term safety and nature and recreation (Table 3.2).

Table 3.2. Indicators chosen for describing the morphological development of the North Holland coast.

System function	Policy objective	Indicator
Short term safety	Maintenance of safety	Erosion length (Par. 5.1.1)
		Probability of breaching (Par. 5.1.1)
Medium term safety	Suistainable maintenance of safety	TKL (Toetsen KustLijn) (Par. 5.2.1)
		MKL (Momentane KustLijn) (Par. 5.2.1)
		BKL (Basis KustLijn) (Par. 5.2.1)
		MDL (Momentane DuneLijn)[3]
Long term safety		Sand volumes at different water depths (Par. 5.3.1)
Nature and recreation	Suistainable maintenance of dunes	Dune foot position (Par. 5.4.1)
		Beach width (Par. 5.4.1)

3. *The values of this indicator were computed and added to the Open Earth database. However, this indicator is not further described in the report.*

4 Study area: morphology, anthropogenic and natural forcing

4.1 Morphological characterization of the study area

The North Holland coast is a sandy, microtidal, wave-dominated coast. This stretch of coast has a length of 55 km, and it is bounded in the North by a tidal inlet (the Marsdiep) and in the South by the 2.5 km long jetties of Ijmuiden. The plan shape of the coast is slightly concave, with some disturbance near the Petten seawall which protrudes into the sea, giving to the shoreline a local convex curvature. The coastline orientation in the North is about 2º with respect to the North, and increases up to 22º at Ijmuiden (Figure 4.1).

Figure 4.1 Plan view of the North Holland coast. The Jarkus number defining the different sub-areas are also indicated (Created with Google Earth mapping TM service).

Tides are semidiurnal with a mean tidal range between 1.4 m in the north and 1.6 m in the south. Waves mainly approach the coast from southwesterly and northnorthwesterly directions. The wave climate is quite homogeneous along the all stretch of coast (Wijnberg, 2002), with a mean annual wave height of about 1.3 m.

A description of the decadal morphological behaviour of the Holland coast is given by Wijnberg (2002). She distinguished different morphological units with similar behaviour (Table 3.1).

1) The coastal behaviour in the northern most stretch of the coast (km 3 - km 8 from Den Helder), is characterised by shoreline retreat, profile steepening, and the presence of a nearshore bar, which was located progressively closer to the shoreline over time. The offshore morphology is mainly determined by a flood-tidal channel of the Marsdiep delta (the Nieuw Schulpen Gat), which is located very close to the shore, i.e. generally less than 1 km from the beach.

2) In the central stretch of the coast (km 8 - km 23 from Den Helder), the shoreline is also retreating but, in contrast to the northern part, the profile has mainly been flattening. In the last few years of observation, however, the tendency of flattening seems to change into profile steepening. One nearshore bar with a stable position is present.

3) More to the south (km 23 – km 55 from Den Helder) the coastline is dominated by slow, temporally and spatially coherent fluctuations in shoreline position and profile shape. The shoreline moves onshore and offshore over a time span of approximately 15 years but the direction of movement varies rhythmically alongshore on about a 2-km scale. This pattern tends to be longshore progressive towards the south. There is also periodic behaviour of the multiple bar system (2 - 3 bars). All bars move offshore (net) with the outer bar decaying offshore and with a new bar being generated near the shoreline; the typical time span of one such cycle is about 15 years. The mean profile steepness exhibits slow fluctuations over similar time spans.

In general terms, Wijnberg (2002) concluded that man-made structures, such as long jetties, appear to have a very large effect on the coastal development on regional scale and in the subdivision between units with a similar morphological behaviour.

The alongshore sediment transport along the Holland coast has been derived by several authors using different models, verified by few field measurements (Kleinhans and Grasmeijer, 2005). A comparison between these results is given by Van Rijn (1995, 1997) (Figure 4.2). Despite the wide spreading between results, the general trend is southward-directed transport between the Ijmuiden jetties and approximately km 30, and northward directed transport for the Northern stretch of coast. The magnitude ranges between -200.000 m^3/m/year in the south up to +500.000 m^3/m/ year in the north. At IJmuiden, the alongshore transport is almost totally blocked by the harbour jetties. Time variation in sediment volumes at different water depths were computed by several authors (e.g. Van Rijn (2010), Vermaas (2010)) based on field measurements (Figure 4.3, Figure 4.4). A general trend from erosive to accretive can be noticed along the all Holland coast, when comparing periods before and after 1990.

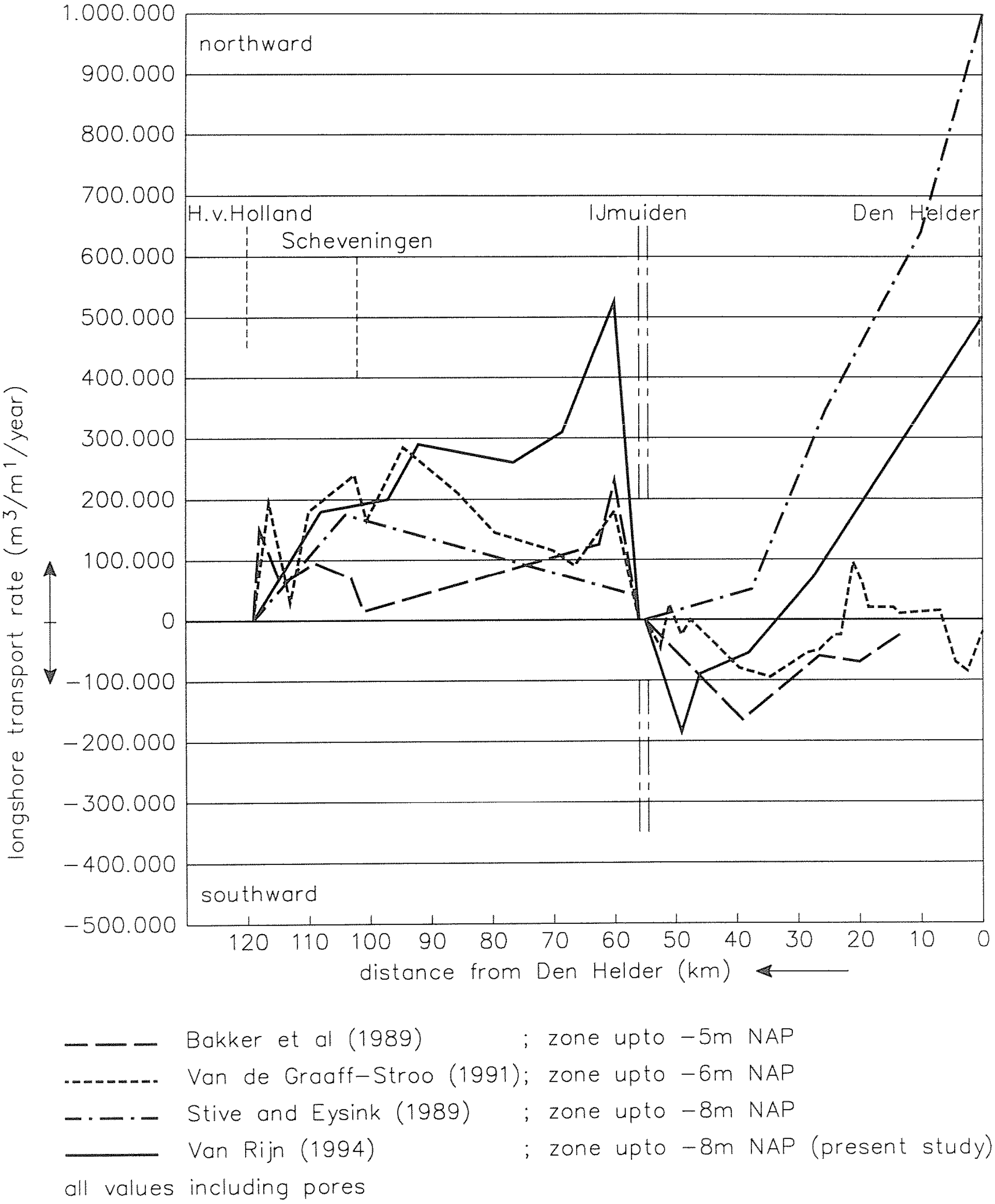

Figure 4.2 Computed alongshore sediment transport rates along the Holland coast according to different authors (Van Rijn, 1995).

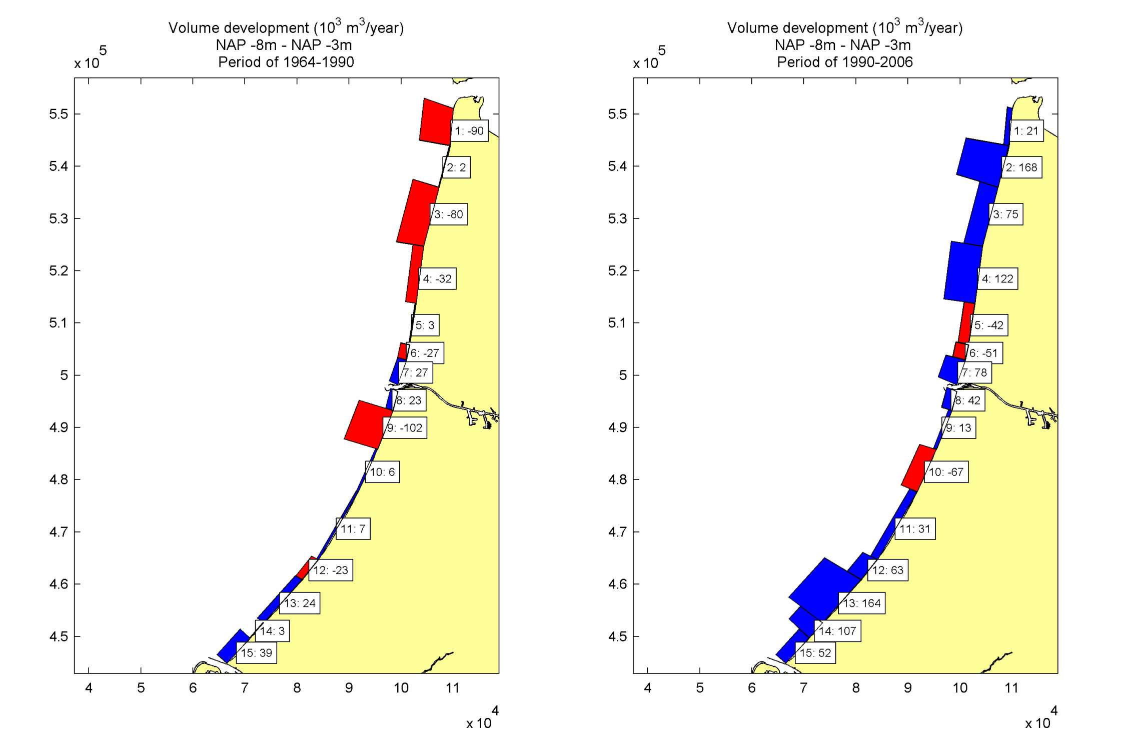

Figure 4.3 Variation in sediment volumes along the Holland coast, between -8 m and -3 m, for the period 1964-1990 (left panel) and 1990-2006 (right panel) (Unit: m^3/year). (Van Rijn, 2010).

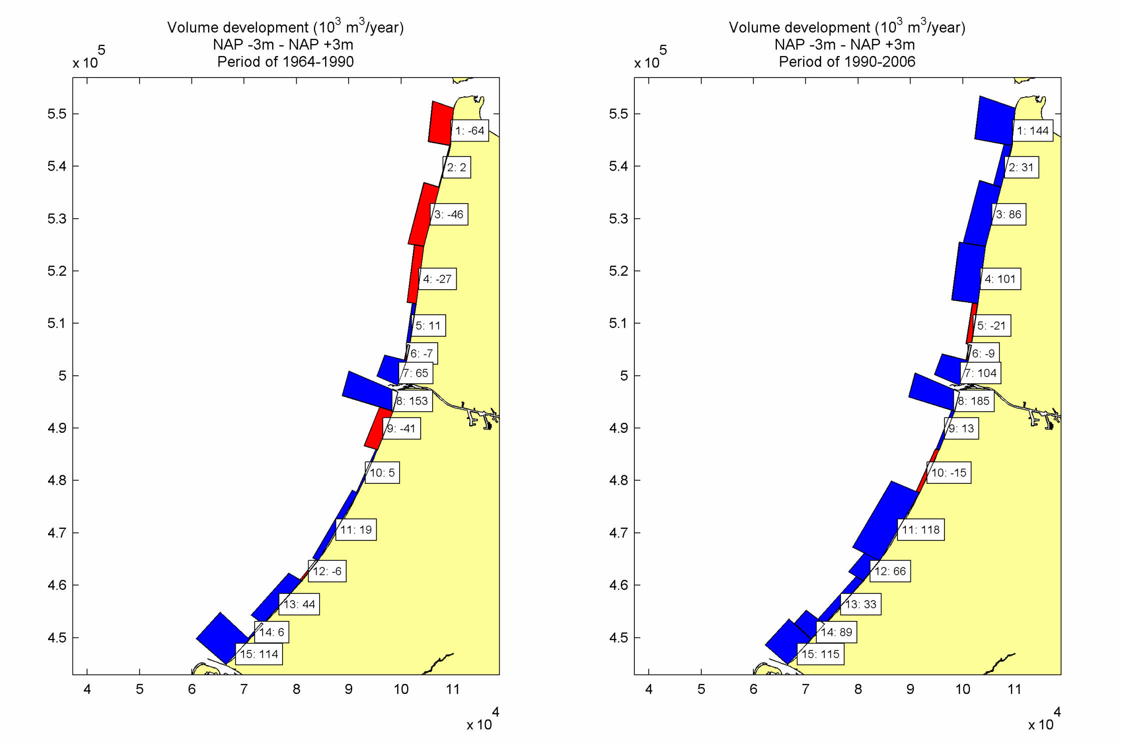

Figure 4.4 Variation in sediment volumes along the Holland coast, between -3 m and +3m, for the period 1964-1990 (left panel) and 1990-2006 (right panel) (Unit: m^3/year). (Van Rijn, 2010).

The sediment is generally fine well sorted sand. The median grain size (D_{50}) on the beach ranges approximately between 200 μm and 350 μm, with a general decrease further offshore. Alonghsore, the finest sediment is found around km 55 (Wijnberg, 2002).

4.2 Anthropogenic forcing

4.2.1 Nourishment policy over the years

The nourishment policy has been undergoing several modifications in the last 20 years. Traditionally, coastal policy in The Netherlands has always put its primary focus on flood protection. Strengthening of the dune was performed in the beginning through local nourishments placed on the dunes and on the beach, eventually combined with hard structures (Giardino et al., 2010a). Once the safety criteria were established in the second half of the 20th century, other criteria and functions, such as ecology, were included in the decision making. This new way of thinking led to the formulation of the policy of 'Dynamic Preservation' in 1990. Besides safety against flooding, it was decided to include the preservation of values and functions in the dune area as policy objective. These principles were implemented through the decision of maintaining the coastline position approximately to that of 1990. The baseline position was defined as Momentary Coastline computed approximately by means of the volumes between the dune foot position and the -5 m line (Figure 4.5). Whenever the coastline would retreat more than this baseline position, sand nourishments were applied (Van Koningsveld and Mulder, 2004, after Rijkswaterstaat 1991). Besides beach nourishments, more economically attractive shoreface nourishments started becoming common practice. The average annual nourished volume between 1990 and 2000 was increased to about $6*10^6$ m^3/year for the all Dutch coast.

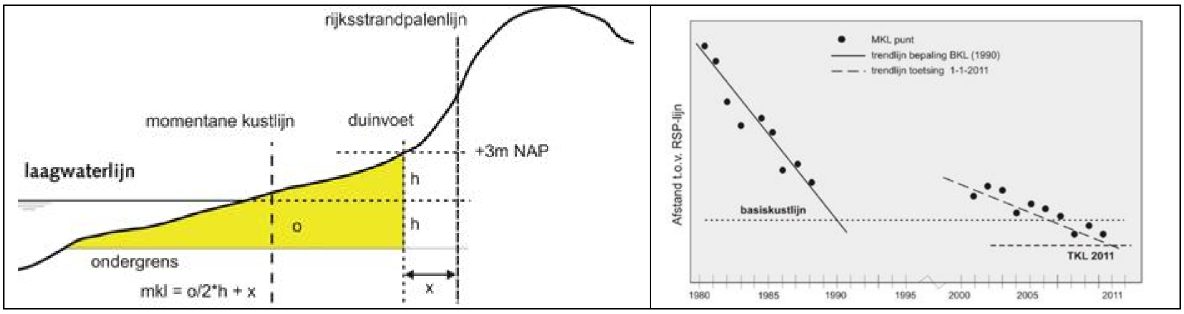

Figure 4.5 Definition of the Momentary Coastline. The yellow area indicates the volume under one Jarkus profile, used to compute the momentary coastline position at one specific year (left panel). In the right panel, the different points refer to different MKL positions at different years, from which a linear trend is derived to predict the position for the next year (TKL).

Evaluation of this policy between 1995 and 2000 pointed out that the maintenance of the coastline was achieved. However, this policy did not consider the morphological development at larger scale, induced for example by sand losses at larger water depth and by sea level rise (Mulder et al., 2011). The hypothesis is that sand losses at deeper water could, in the long term, lead to a loss of sediments also in the upper shoreface. This would result in an extra future afford for maintaining the coastline. Therefore, this policy was considered not to be sustainable at longer time scale. A new concept was developed: the compensation of loss of sediments due to sea level rise including the whole Coastal Foundation. The Coastal Foundation was defined as the area between the dune position and the -20 m depth contour. Nourishment volumes were defined by multiplying the expected sea level rise by the area of the Coastal Foundation. The assumption was that no transport occurs through the -20 m water depth. The sea level rise was estimated in 1.8 mm/year. In view of this new concept,

the nourished volumes for the all Dutch coast were increased from $6*10^6$ m^3/year up to $12*10^6$ m^3/year.
The effect of nourishment volumes on the morphological evolution of the Holland coast were addressed in Santinelli (2010). Natural erosive trends were computed by subtracting the nourishment volumes from the real trend. According to the analysis, natural erosive trends appeared to have increased, since nourishments started being constructed.

The total nourishment volumes applied along the whole North Holland coast for the three different periods are shown in Figure 4.6. Besides the increase in total nourishment volumes, it is clear the tendency towards an increase of shoreface nourishments with respect to beach nourishments. The nourishment volumes applied in the North Holland coast only for the different coastal stretches defined in Chapter 3 and at each Jarkus transect are shown in Appendix C. In particular, nourishment intensity has been very high around the coastal towns of Callantsoog (transect number 1300), Bergen (transect 3100) and Egmond (transect 3800).

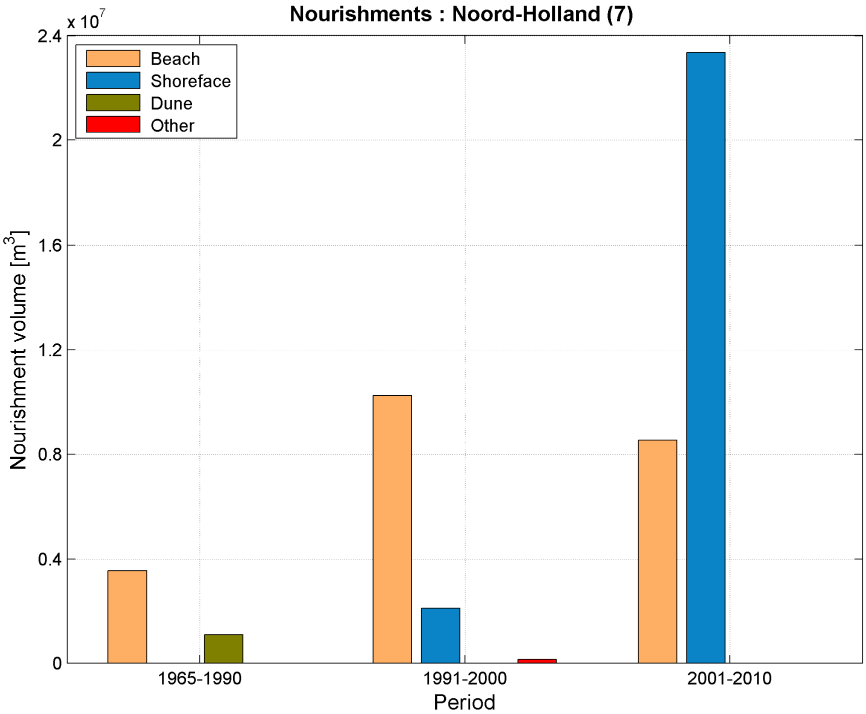

Figure 4.6 Nourishment volumes at North Holland coast for the three different periods: 1965-1990, 1991-2000, and 2001-2010.

4.2.2 Dune management in the years

Human intervention in the foredune area of the central Netherlands' coast date back to the 15th century and intensified from 1850 onwards (Bochev-van der Burgh et al. 2011). Large-scale stabilization of the fore(dune) area was completed in the beginning of the 20th century. Nowadays, only a few kilometres of the foredunes along this part of the coast is considered to be in natural state. Arens and Wiersma (1994) made a classification of the foredunes along the entire Netherlands' coast based on aerial photographs from 1988. The foredunes were classified according to the most prominent type of intervention at that moment. Their classification shows that the foredunes between Den-Helder and IJmuiden have been affected by different management measures, with the type of measures applied changing

over longshore distances of one to a few kilometers. Measures include nourishments, vegetation plantings, sand fence erections and slope adjustments using ground moving equipment. In addition, Arens and Wiersma, (1994) classified some parts of the foredunes in Noord-Holland as being natural, with none or very little management interventions. According to Arens (1994), these natural dunes occur between transects 300–400, 800–1100, 1800–1900 and 5300 to 5500. The foredunes north of the Hondsbossche and Pettemer seawalls are at many locations interrupted by beach entrances. These were constructed to ease access to the groins for maintenance purposes.
Nevertheless, starting from 1990 the dune management has also been undergoing important changes, parallel to the changes in nourishment policy (Paragraph 4.2). Figure 4.7 shows the changes in dune management intensity before and after 1990 along the Holland coast. The dune management intensity in general has decreased, parallel to the increase in nourishment volumes. Bochev-van der Burgh et al. (2011) showed how changes in foredune morphology, are generally related to changes in dunefoot behaviour. Besides variations due to natural changes, large-scale nourishment works have also a clear effect on the foredunes, with an increase in concavity of the dune face as well as an increase in elevation of the dune top. There is however a time delay observed between the onset of the nourishment activity and noticeable change in foredune morphology between 5 and 10 years (Bochev-van der Burgh et al. 2009).

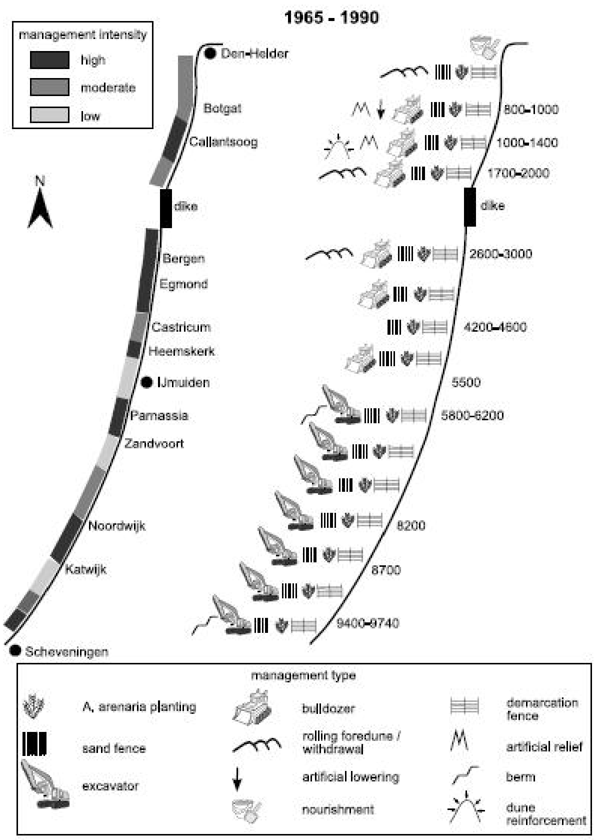

Fig. 4 Management intensity and type before 1990

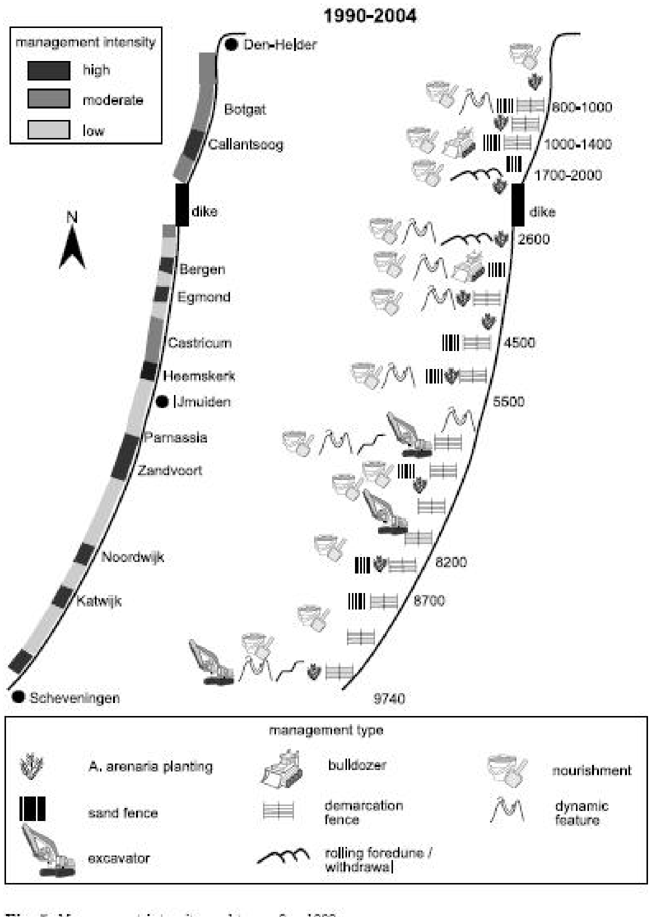

Figure 4.7 Dune management intensity between 1965 and 1990 (upper figure) and between 1990 and 2004 (lower figure)

4.2.3 Other man-made structures

Along the North Holland coast several constructions were made (Table 4.1). The first constructions (the Hondsbossche and Petten seawall) were built as early as the 16th century but had to be relocated several times because of on-going erosion north and south of it (Stolk, 1989). Groins were built in the northern part in the 19th and 20th century. Jetties were constructed at Ijmuiden in the 19th century and extended in the late 60s. The last constructions date back to the 20th century.

Table 4.1. Overview of the man made structures along the North Holland coast (Wijnberg, 2002).

Type of structure and location	Activity	Period	Spatial scale
Seawalls			
Hondsbossche and Petten seawall (km 20 – km 26)	Construction	ca. 1550	?
	Most recent relocation	1823	6 km (alongshore)
Groins			
(km 2 – km 31)	Construction	1838 - 1935	

Harbour jetties			
Ijmuiden (km 55 – km 56)	Construction	1865 - 1879	1.5 km (cross-shore)
	Extension	1962 - 1967	Southern jetty: + 1.5 km Northern jetty: + 1 km
Discharging sluice			
Katwijk (km 86)	Construction	1807	
	Increase discharge	1984	

In Figure 4.8 the different coastal types which can be found along the North Holland coast are shown: broad dunes (brede duinen), narrow dunes (smalle duinen), see dikes (zeedijk), boulevards, harbours and hard structures related to it (buitenhavens, overige dammen).

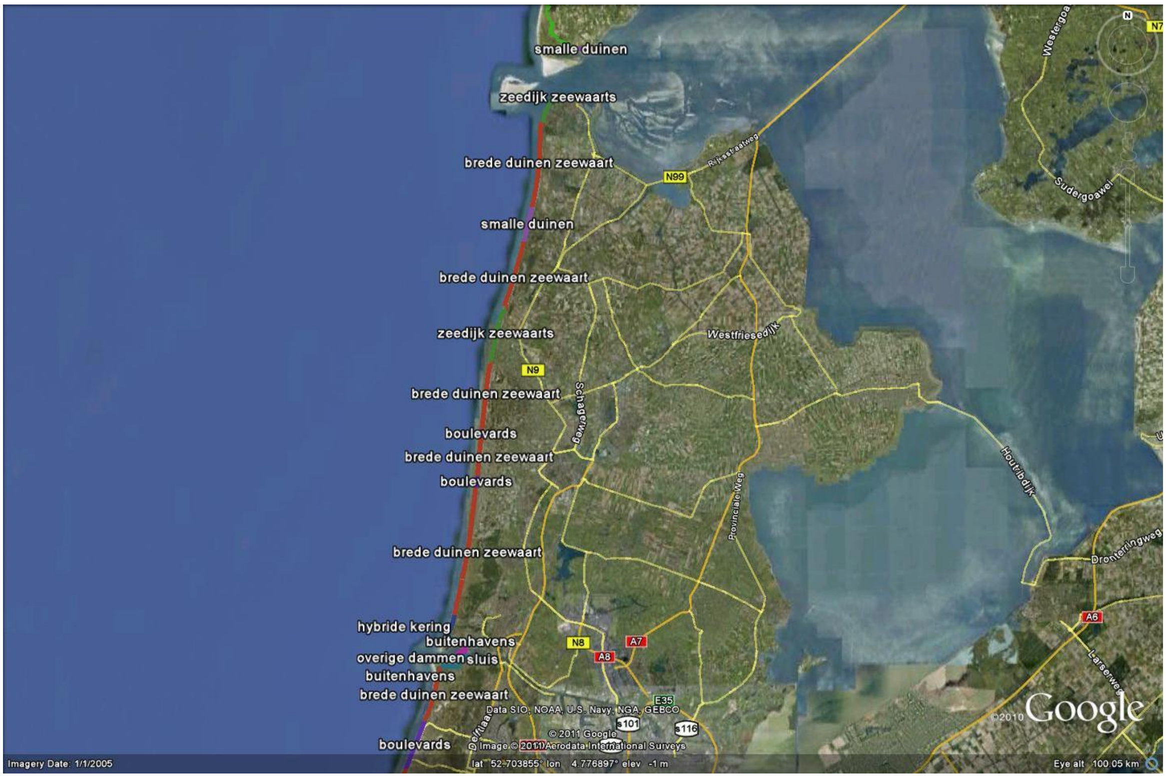

Figure 4.8 Coastal types along the North Holland coast (Created with Google Earth TM mapping Service) (visualization "Coastal Viewer" http://dtvirt13/bwn/optie_compiled/index.html)

Among the different man-made structures, the harbour jetties of IJmuiden protrude the farthest into the sea. According to Van Rijn (1995) the groins block the alongshore transport in the inner surf zone only partially. In the inner surf zone (approximately 200 m seaward) approximately 50 – 70 % of the alongshore transport takes place. The harbour jetties of Hoek van Holland and IJmuiden however, will almost fully block the alongshore transport. The net northward directed tidal flow will go around the jetties, converging south and diverging north of the dams. In the south this will result in an offshore directed current, north of the dams in an onshore directed current. Close to the dams, both north and south, sedimentation will occur in the shallow zone. South and north of the sedimentation areas this will cause erosion.

4.3 Natural forcing

4.3.1 Meteorological forcing

Besides the anthropogenic intervention (nourishments, dune managements, man-made structures), nature plays also a main role into the coastline morphological development. A wide number of researchers have tried to link different meteorological parameters to the coastline morphological development. Ruessink and Jeuken (2002) defined a storminess parameter related to the maximum annual wave height to describe the dune foot dynamics of the Holland coast. Van Puijvelde (2010) linked the foredune development to a storm flood frequency parameter, defined as the number of hours in which the water level was above the mean water level for that period.

In this study, a number of morphological indicators were defined. Given the complexity of the sediment transport processes in the nearshore area, a unique relation between storminess and the different indicators does not exist. In general, extreme high water levels have the potential to erode the lower section of the dune and transport sand downward to the beach and foreshore section of the profile (Arens, 2009). On the other hand, periods with mild wave conditions are characterized by a net shoreward transport. Sand which deposit on the beach, can then be transported by wind action towards the dunes. Wide, low sloping beaches are associated with accreting dunes, because of the higher potential of wind driven sand transport (Damsma, 2009). Narrow, steep beaches, are associated with eroding dunes because wind driven sand transport is reduced.

Moreover, the interference of the anthropogenic action and especially the huge nourishment volumes deposited on the beach, dune and breaker bars in the last years make even more difficult to distinguish between natural and antropogenic processes.

Relationships between storminess and a number of morphological indicators are analyzed in more details in Chapter 6.

4.3.2 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 North Holland 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. In the meanwhile, these scenarios have been accepted as a basis for the government policy. However, the Delta Commission has recently presented new and more drastic figures with sea level rise scenarios (including subsidence) between 0.65 and 1.3 m by 2100 (Deltacommissie, 2008).
A map showing the possible predicted subsidence by year 2050 is shown in Figure 4.9. The map indicates a possible value for subsidence up to 10 cm by year 2050 for the North Holland coast, which is in the same range of the predicted sea level rise. Sea level rise and relative subsidence are nor further analyzed in the report.

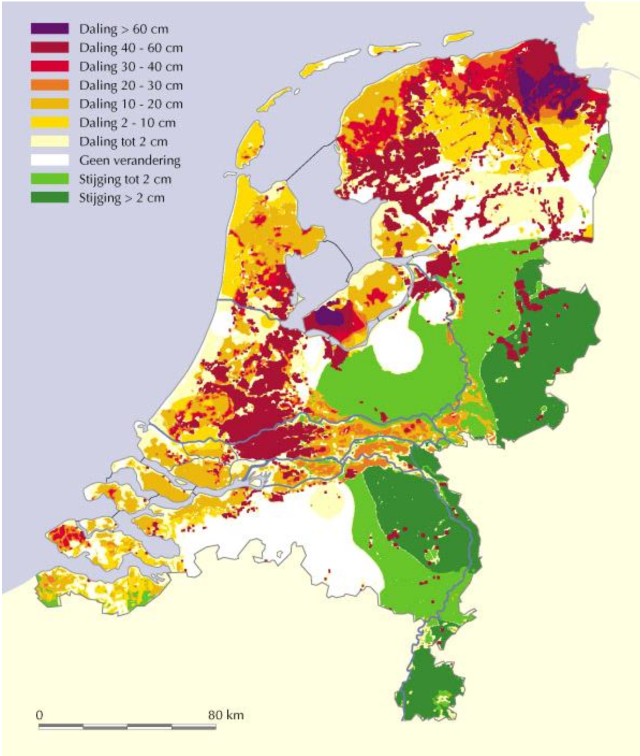

Figure 4.9 Expected subsidence and uplift for the all Netherlands by year 2050 (Rijkswaterstaat, NAM)

5 Morphological development of the North Holland coast

5.1 Short term safety

5.1.1 Probability of breaching and erosion length

As indicators for the short term safety, two indicators have been selected:1) the probability of breaching of the first dune row and 2) the erosion length. The indicators were computed by ARCADIS (Van Santen and Steetzel, 2011) and HKV (Van Balen et al., 2011) for the entire Dutch coast, for the years between 1965 and 2010. Two different modelling approaches have been followed for the computation: the VTV model used by ARCADIS (formal present method for 6 yearly testing procedure) and the PC-Ring model used by HKV (used for the project Veiligheid Nederland in Kaart). Only the probability of breaching has been analyzed within this study, since the two variables are closely interralated[4]. This is the probability that would lead to the failure of the first dune row (X_a landward than X_k in Figure 5.1). More details on the methodology followed for the dune erosion computation can be found in Van Balen et al. (2011).

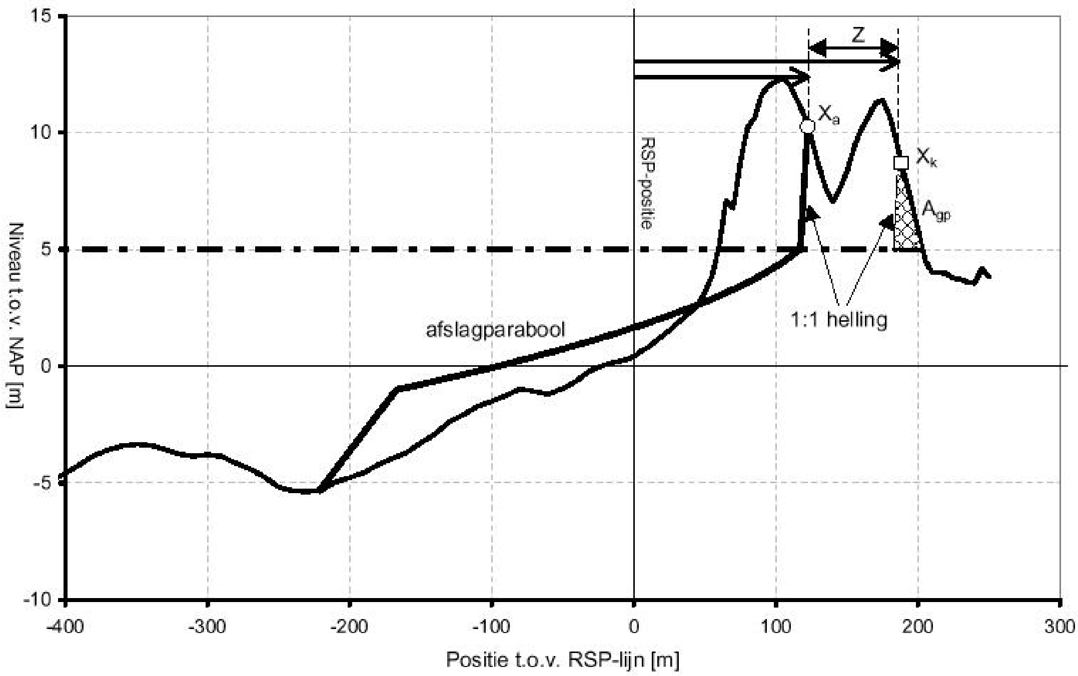

Figure 5.1 Definition of erosion length (X_a) and critical erosion point (X_k) (Van Balen et al., 2011).

Two important assumption related to the modelling approach have to be considered when analysing these data:

- The models only compute the erosion of the first dune row. In case of multiple dune rows, as for example between transects 2606 and 5200 where the dune area has a width of more than 1000 m (Figure 4.8), the computed probability will only refer to this first dune row. The probability of breaching would be much lower when different dune rows are considered.

4. *However, both variables were computed and added to the Open Earth database.*

- The models compute dune erosion and breaching of sand dunes. Therefore, the models are not suitable to compute failure mechanisms of hard structures (e.g. Hondsbossche Zeewering).

5.1.2 Analysis

The time variation of the short term safety was at first analyzed at Jarkus transect level, in relation with the amount of sand nourished. For the transects in area 4, where the coast is defended by hard structure (Hondsbossche Zeewering), the probability of breaching could not be defined. Figure 5.2, Figure 5.3, Figure 5.4 show a number of examples of the analysis carried out for three different transects. In the first figure, the time evolution of the probability of breaching at one transect in area 1 (eroding coast with mainly beach nourishments) is shown. The second transect is part of the stretch of coast number 2 (eroding coast with mainly shoreface nourishments). The last figure refers to area 7 (coastline with no clear autonomous trend and no nourishments). Figure 5.2 and Figure 5.3 clearly show that nourishments led to a 'positive' effect (decrease in probability of breaching) in the stretch of coast where they were applied, confirming our start hypothesis. Safety in general has increased of more than one order of magnitude at the nourished transects since nourishments started being constructed. For clarity, 10^{-5} is the limit admitted by law for wave load during testing of the coastal defences at North Holland. The same clear trend can not be seen for transect 4575, where the probability of breaching seems to oscillate around an average value, most likely due to longshore and cross-shore movement of morphological features (sand waves and breaker bars) (Paragraph 4.1).

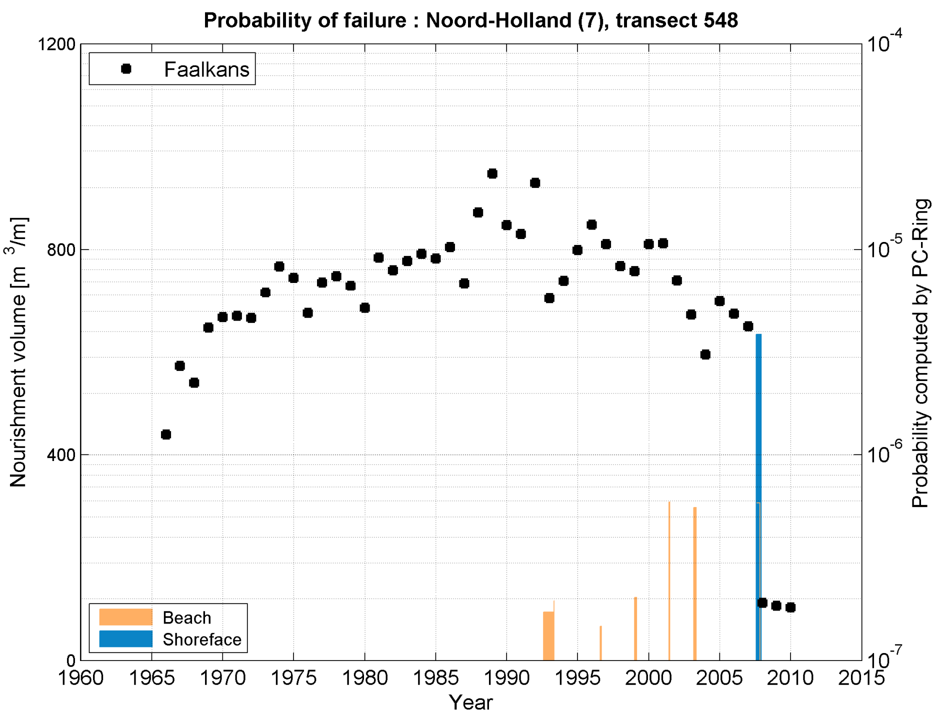

Figure 5.2 Change in probability of breaching (black dots) and nourishment volumes (orange and blue bars) at Jarkus transect 548.

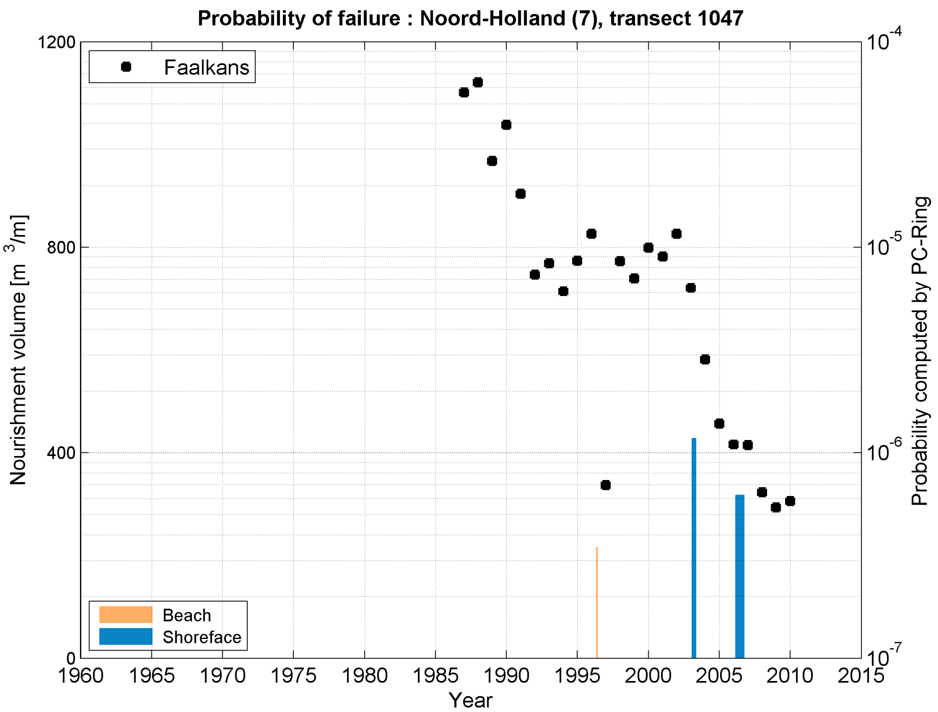

Figure 5.3 Change in probability of breaching (black dots) and nourishment volumes (orange and blue bars) at Jarkus transect 1047.

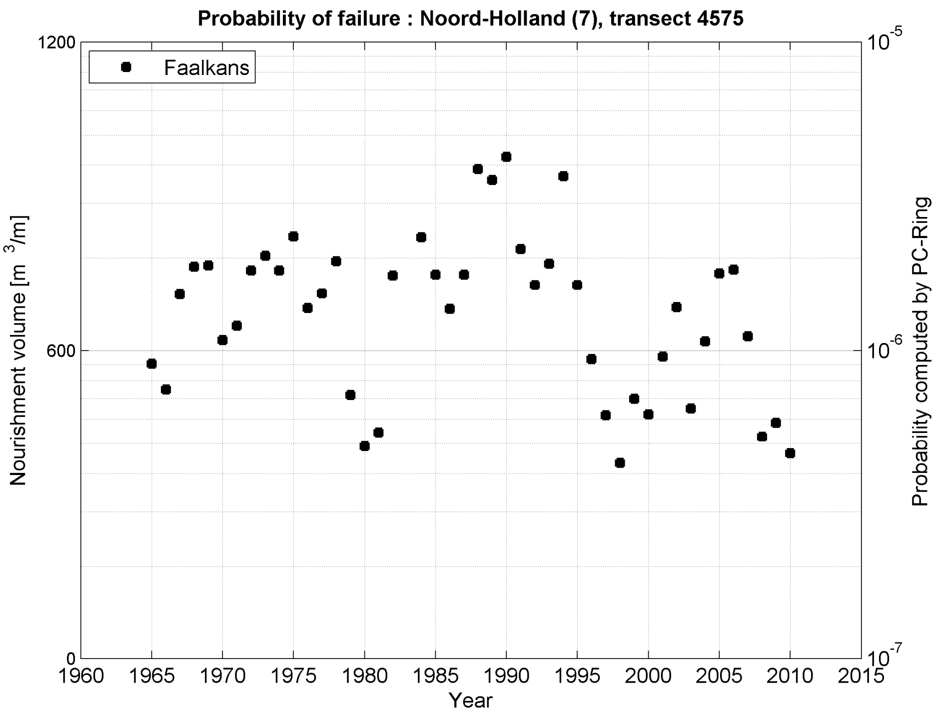

Figure 5.4 Change in probability of breaching (black dots) and nourishment volumes at Jarkus transect 4575.

A trend analysis was carried out using as a basis the three time windows defined in Chapter 3: 1965 – 1990, 1991 – 2000, and 2001 and 2010. Linear trends were computed within each time window for each transect. The trends defined at each transect for the three periods are given in Appendix D, together with the relative confidence interval. Transects which are part of the same area, as defined in Chapter 3, are shown in the same figure. The trend analysis confirms the previous observation that in general nourishments have led to an improvement of safety (change in trend from positive to negative values). A relative change in trend of 0.1 $year^{-1}$ on these plots, correspond to a change of one order of magnitude in safety, for a time window of 10 years.

For an easier and more conclusive comparison between trends from different areas with similar autonomous morphological behaviour and nourishment strategy, the average trend within each region was computed (Figure 5.5). The average trends also show a substantial change towards an average decrease in probability of failure. The change in trend is especially evident for area 1, where mostly beach nourishments were applied. This would suggest that beach nourishments, on this time-scale, have a larger effect than shoreface nourishments towards an increase in safety. This is certainly correct if we look at very short term effects (1 year) of shoreface and beach nourishments, as shown in Figure 5.6. In this Figure, the ratio between the probability of breaching at one year and the year before is shown in function of the nourishment volume at that year. Points in green show the change in probability of breaching at transects where a shoreface nourishment was applied at that year, in red points at which a beach nourishment was applied. Values above 1 indicate a relative increase in probability of breaching, values below one a relative decrease. Trend lines, both for points where beach and shoreface nourishments were applied were derived. The figure shows that bigger nourishment volumes lead to a bigger decrease in probability of breaching after one year. Moreover, the decrease in probability of breaching is stronger after the application of beach nourishments. However, the reader should realize that shoreface nourishments are built considering a long term prospective (5-10 years), rather then short term effects (one year). On the same line are the modelling results presented in Giardino (2010b), which showed that a beach or banquette nourishment of 200 m^3/m would lead to a decrease of 35-47 % in dune erosion for a 10 year return period storm, while a 400 m^3/m shoreface nourishment has the potential of reducing it only of 2-5 %. However, the effect of shoreface nourishments may show up later in time.

Also hard structures such as the Ijmuiden jetties appear to have an effect on increasing safety levels. Area 7 and 8 are characterized by a decrease in the probability of breaching despite no nourishment was applied.
However, it is important to point out that these variations in probability of breaching only refers to the first dune row and, while between transects 2606 and 5200, a multiple dune row system exists. This implies that a decrease in probability of breaching in the more northern transects (i.e. between transects 90 and 2041) has a more significant impact on safety against flooding than in the southern transects (i.e. between transects 2606 and 5200).

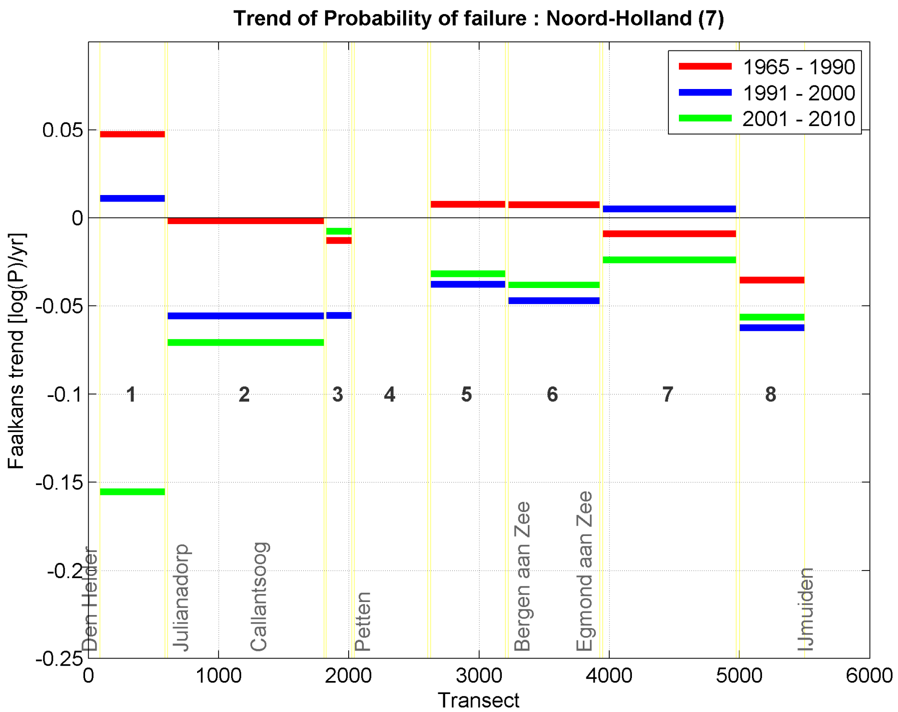

Figure 5.5 Averaged probability of breaching trend within each of the eight areas with homogeneous autonomous trend and nourishment strategy.

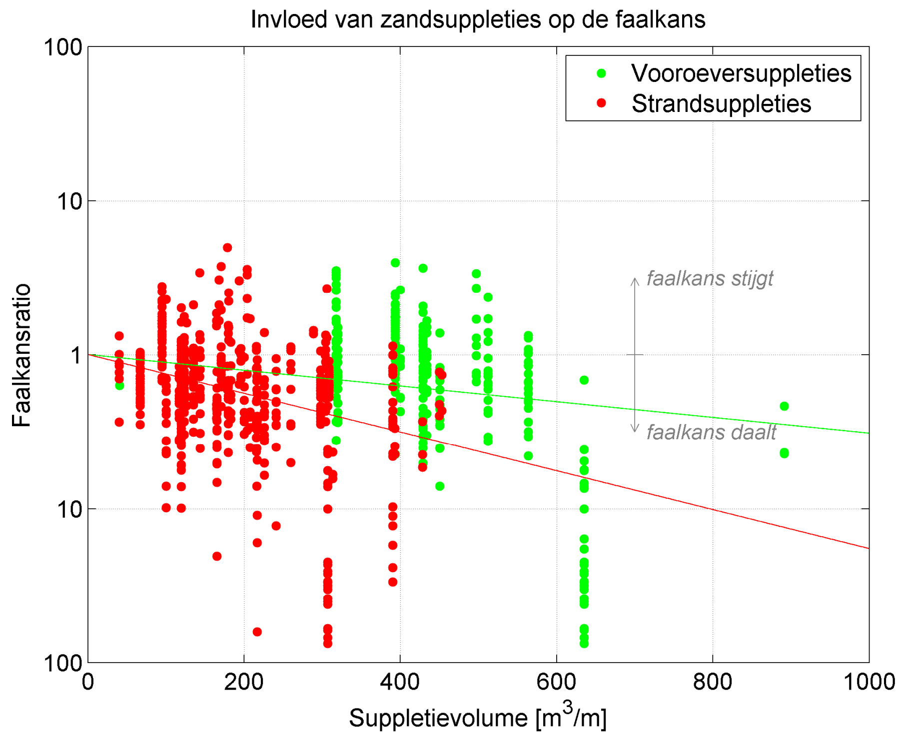

Figure 5.6 Ratio between the probability of breaching for two consequent years, respectively for shoreface nourishments (in green) and beach nourishments (in red) (Van Balen et al., 2011).

5.2 Medium term safety

5.2.1 MKL, TKL and BKL

Variations in medium term safety due to nourishments were evaluated by computing MKL (Momentary Coastline) and TKL (Testing Coastline) trends at each Jarkus transect. These indicators define the coastline position as a function of the volumes of sand in the near shore zone, approximately between the dune foot (+3 m NAP) and -5 m NAP (van Koningsveld and Mulder, 2004). The values were compared to the BKL (Basal Coastline) position, corresponding with the position of the coastline in 1990, and occasionally adapted in later years.

5.2.2 Analysis

As for the short term safety, the time variations in MKL, TKL and BKL positions were computed at each transect and for all the years between 1965 and 2010. For the transects in area 4, where the coast is defended by hard structure (Hondsbossche Zeewering), the MKL values could not be defined. Figure 5.7, Figure 5.8, and Figure 5.9 show three examples of this analysis, respectively for a transect where mainly beach nourishments were applied, a transect mainly characterized by shoreface nourishments, and a transect at which no nourishments have been built. Figure 5.7 clearly shows a change in trend from erosive (before 1990), to accretive (after 1991), with an increase in steepness of the trend line after 2000. These trends clearly support the hypothesis on the 'positive' effects of nourishments volumes on coastline morphology. No clear trend can be identified at transect 4575, where the oscillation are related to natural features (sand waves and bar migration) rather than nourishments. It is also interesting to see how the position of the BKL line has changed in time. These changes are determined by management decisions from DGW (Water Affairs Director General): if the BKL like is shifted seaward, this will imply that Rijkswaterstaat will also have to maintain this new line. At transects 548 and 1047 the BKL line has been changed landward, which will make it relatively easier to protect the coastline since more erosion is allowed.

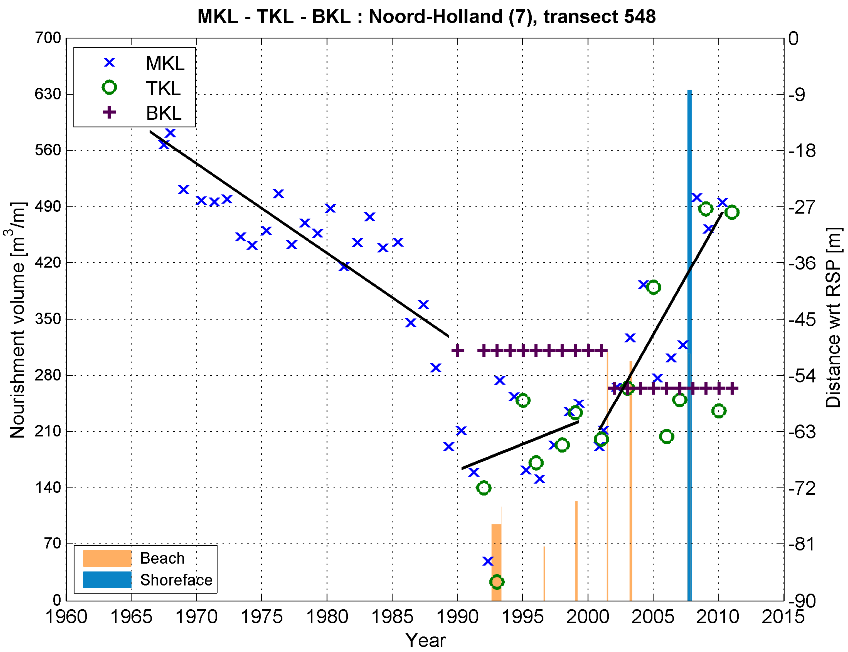

Figure 5.7 Change in MKL, TKL and BKL position at Jarkus transect 548. Orange and blue bars give the nourishment volumes. The black lines represent the linear trends for each time window.

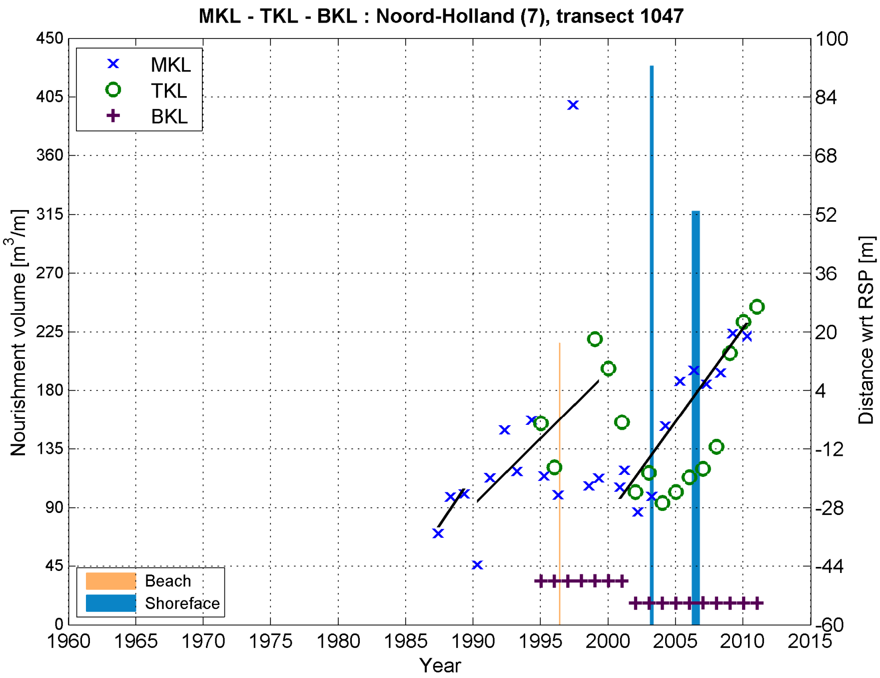

Figure 5.8 Change in MKL, TKL and BKL position at Jarkus transect 1047. Orange and blue bars give the nourishment volumes. The black lines represent the linear trends for each time window.

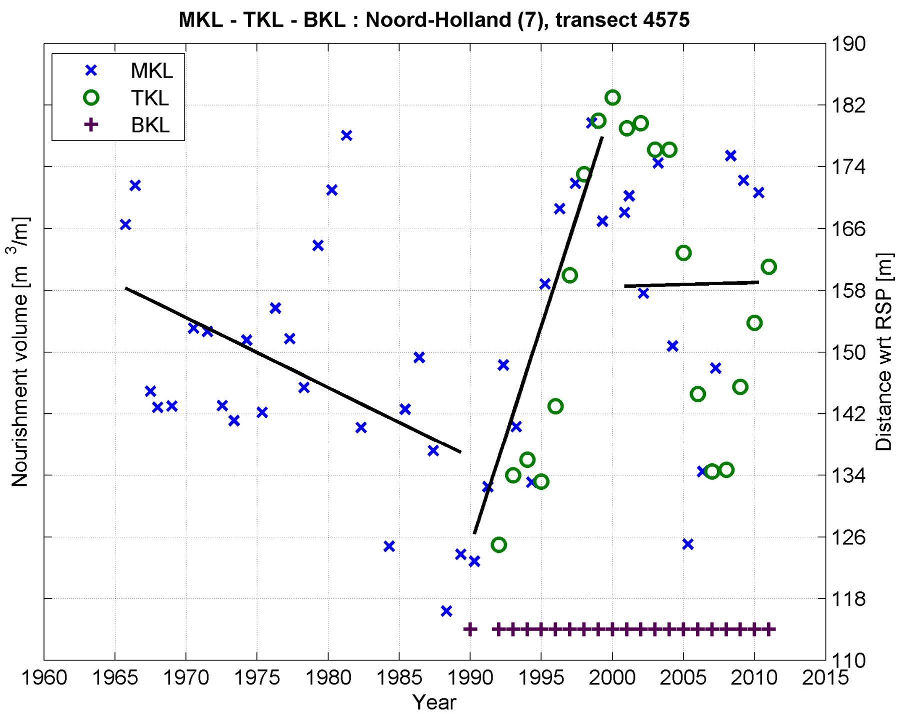

Figure 5.9 Change in MKL, TKL and BKL position at Jarkus transect 4575. The black lines represent the linear trends for each time window.

The difference between the MKL position and the BKL position of year 2011 averaged for each time window is shown transect by transect in Appendix E.1. The figures confirm the previous observation that nourishments have positively affected the morphological state of the North Holland coast. Nearly all transects at which before 1990 the MKL position did not exceed the BKL position, are characterized in the last time windows by a MKL position seaward of the BKL. Few outliers can be highlighted: transects 1647, 4825, 4925 and 4975, where these difference is negative.
This information is summarized in Figure 5.10, where the difference is averaged within each of the time windows and areas defined in Chapter 3. All regions show a seaward averaged coastline development, especially evident for area 1 and 6 where the MKL has shifted seawards about 30 m. Mainly beach nourishments characterized both these regions. The presence of hard structures also seems to play a role for the MKL development of areas 7 and 8.

Linear trends were computed for each time window: 1965 – 1990, 1991 – 2000 and 2001 – 2010 (Appendix D). It is easy to observe that at most transects trends have become more 'positive' (seaward coastline development). This is especially evident for area 1, mainly characterized by beach nourishments, and for transects 900 -1400 approximately, where beach nourishments where combined to a massive use of shoreface nourishments (Appendix E.2). Figure 5.11 shows the average trend for each time window and within each area. In area 1, not only the absolute value of the difference between MKL and BKL is very large but also the steepness of this trend line. On average, the MKL position has shifted from 1990 until 2010 of about 30 m in seaward direction, for the 55 km of the North Holland coast.

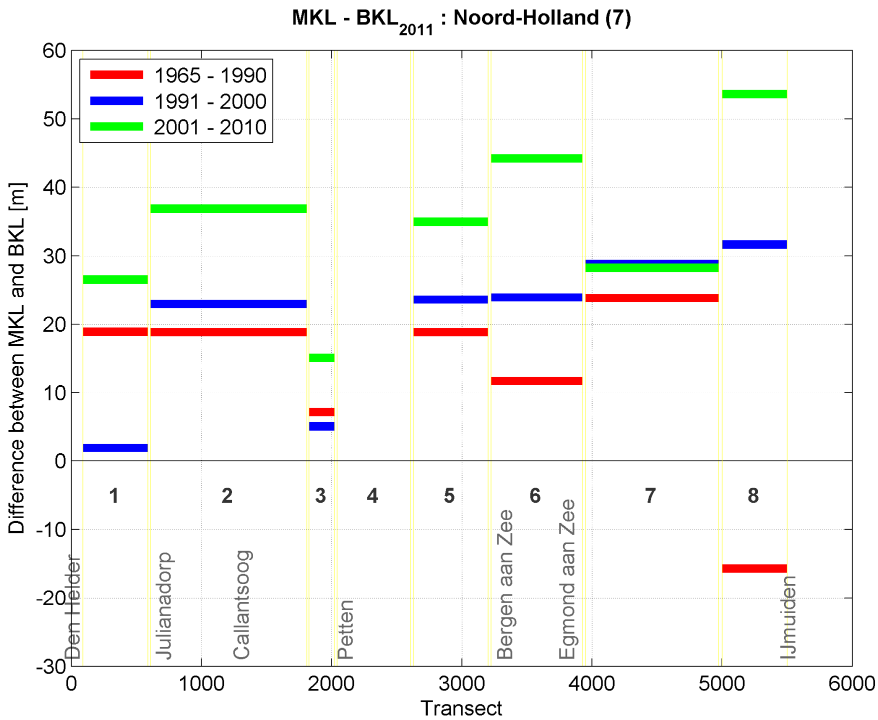

Figure 5.10 Difference between MKL and BKL position of the year 2001 averaged within each of the eight areas, with homogeneous autonomous trend and nourishment strategy.

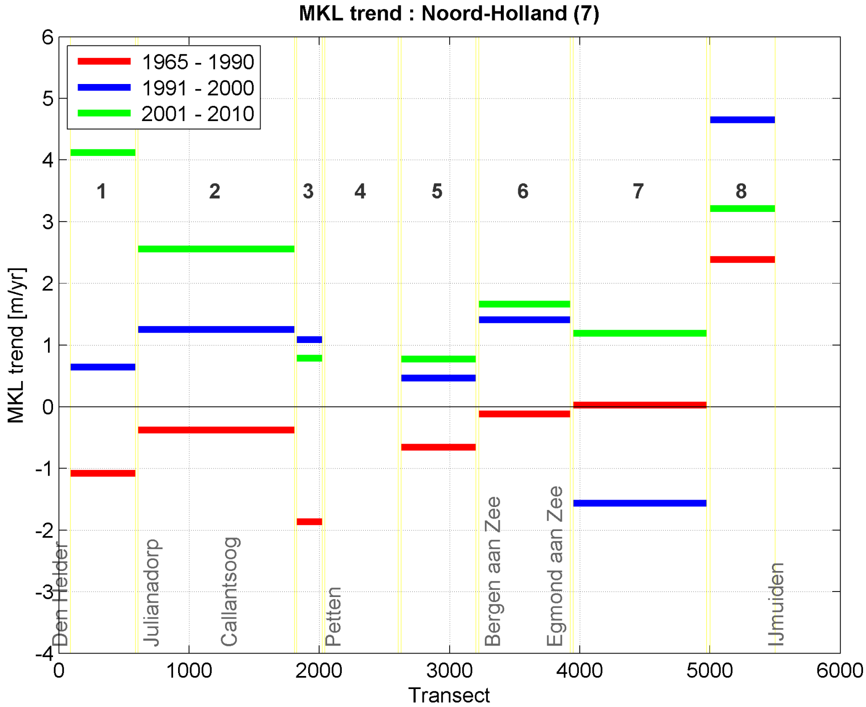

Figure 5.11 Averaged MKL trend within each of the eight areas with homogeneous autonomous trend and nourishment strategy.

5.2.3 Relation between short term and medium term safety indicators

The relation between short term and medium term safety indicators for the all Holland coast was investigated by Van Santen (2011). As an example, Figure 5.12 shows the relation existing between the probability of breaching of the first dune row and the MKL position. A number of specific JARKUS transects are highlighted in the figure: transects 1503, 3300 and 4300 located in North Holland, and transects 6500 and 9000 located in South Holland. It is quite clear that to a seaward MKL movement, will correspond a decrease in the probability of breaching. For each transect, the slope representing the relation between these two variables, can be defined and plotted in function of the Jarkus transect number (Figure 5.13). The figure shows in first place a wide variability in trend coefficients for different Jarkus transects. This is partly related to the steepness of the profile: for a steeper profile, a shift in MKL position will correspond to a bigger change in probability of breaching (or a lower value of the slope coefficient *a*). The horizontal blue line indicates the average slope coefficient from which the following relation between these two indicators can be defined:

$$\Delta(\log_{10}(P)) = -0.0237 * \Delta MKL$$

This means that a seaward shift in MKL position of 42.2 m will lead to a decrease in probability of breaching of one order of magnitude.

The fact that these indicators are, up to a certain extent correlated, also implies that we do not necessary need all of them to describe the morphological development of our coast since they can be derived from each other.

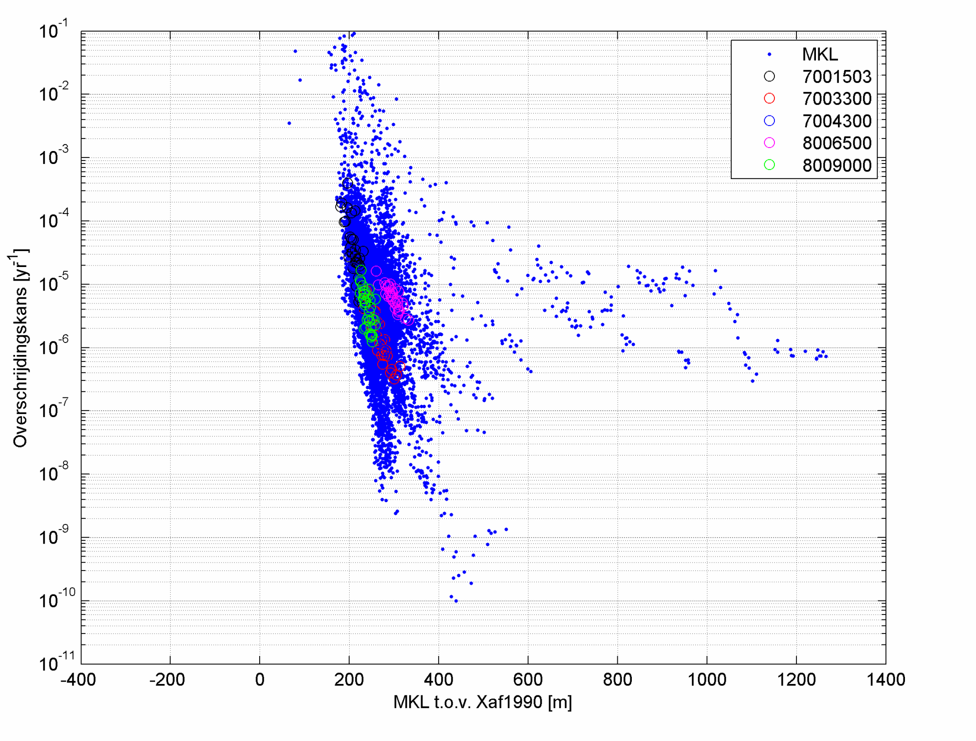

Figure 5.12 Relation between probability of breaching and MKL position for the Holland coast (Van Santen, 2011). A number of Jarkus transects are shown in coloured circles: transects 1503, 3300 and 3300 located in North Holland, and transects 6500 and 9000 located in South Holland.

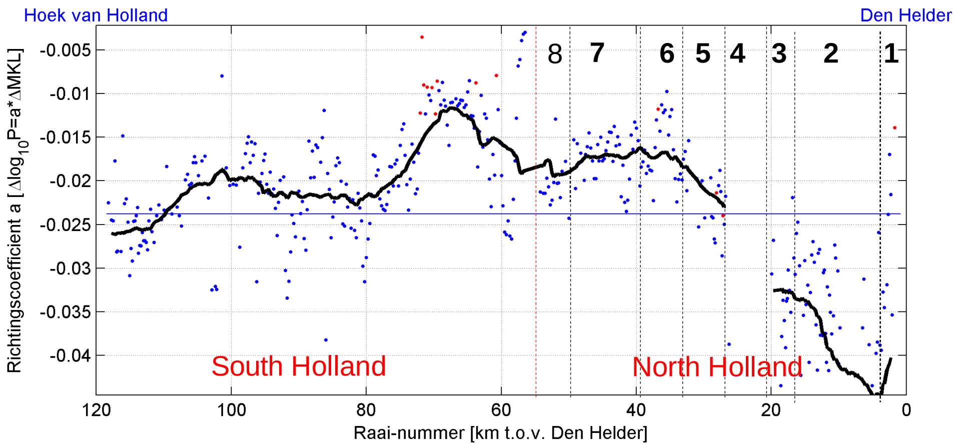

Figure 5.13 Slope coefficient relating changes in probability of breaching and MKL position for each transect of the Holland coast (Van Santen, 2011). The numbers indicate the different sub-areas used to subdivide the North Holland coast.

5.3 Long term safety

5.3.1 Sediment volumes

Several studies have been carried out in the past to determine volume changes at different water depths along the Holland coast. Van Rijn (1997) computed volume changes in different predefined 'boxes' along the coast between -3/-8 m and -8/-12 m water depth. The study was extended to most recent years by Vermaas (2010) and Van Rijn (2010).

In this study, volumes of sand within different intervals were kindly computed and provided by *ALTERRA*. The volumes were computed within the following water depths limits:

- -1 / - 5 m
- -1 / -8 m
- -1 / -12 m
- -5 / -8 m
- -5 / -12 m
- -8 / -12 m

Volumes were computed according to the procedure described in Figure 5.14. All volumes are determined using as a reference the Jarkus transect of the year 1990 (red line). Based on this transect, a landward and a seaward boundary are defined as intersect of the Jarkus profile year 1990 with the given water depths limits, defining the upper and lower boundary (in this case +0 and -2 m). The volume in the reference year corresponds to the red area. Using the same for that specific transect, the volume is computed for each year. When the profile between landward and seaward boundary goes below the lower boundary (i.e. for the profile given in blue), this part of volume is assumed to be negative and subtracted from the overall volume. In the same way, if the profile goes above the upper boundary as in the landward part of the profile, this part of the area is added up to the total volume, defining a new upper boundary.

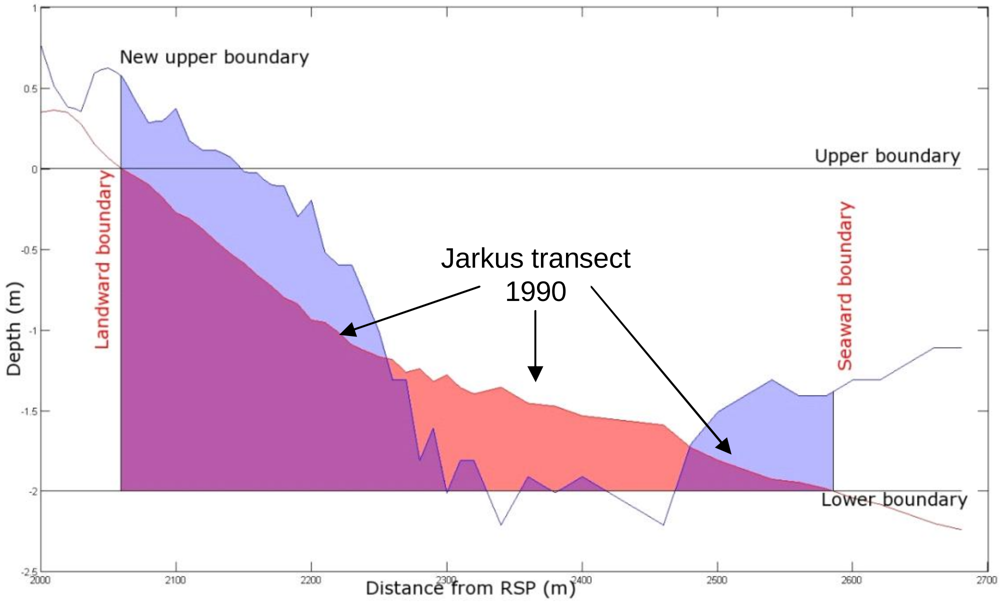

Figure 5.14 Definition of the boundaries for the volume calculation in case of hypothetical depth intervals: 0/ -2 m.

5.3.2 Analysis

As for the other indicators, the time variation in volumes within different depth intervals were computed at each transect and for all the years between 1965 and 2010. As can be expected, volume changes between -1 and -5 m are particular significant when mainly beach nourishments are applied (Figure 5.15). Increase in volumes in deeper water (e.g. between -5 m and -8 m) can be easily recognized when shoreface nourishments are applied (Figure 5.23Figure 5.16).

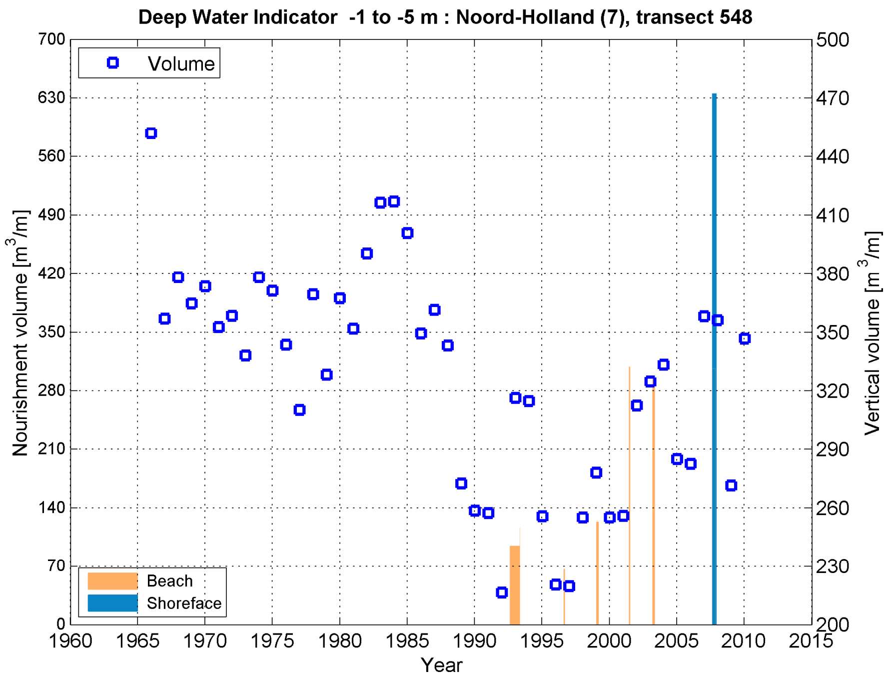

Figure 5.15 Volume variation at Jarkus transect 548 between -1 m and -5 m. Orange and blue bars give the nourishment volumes.

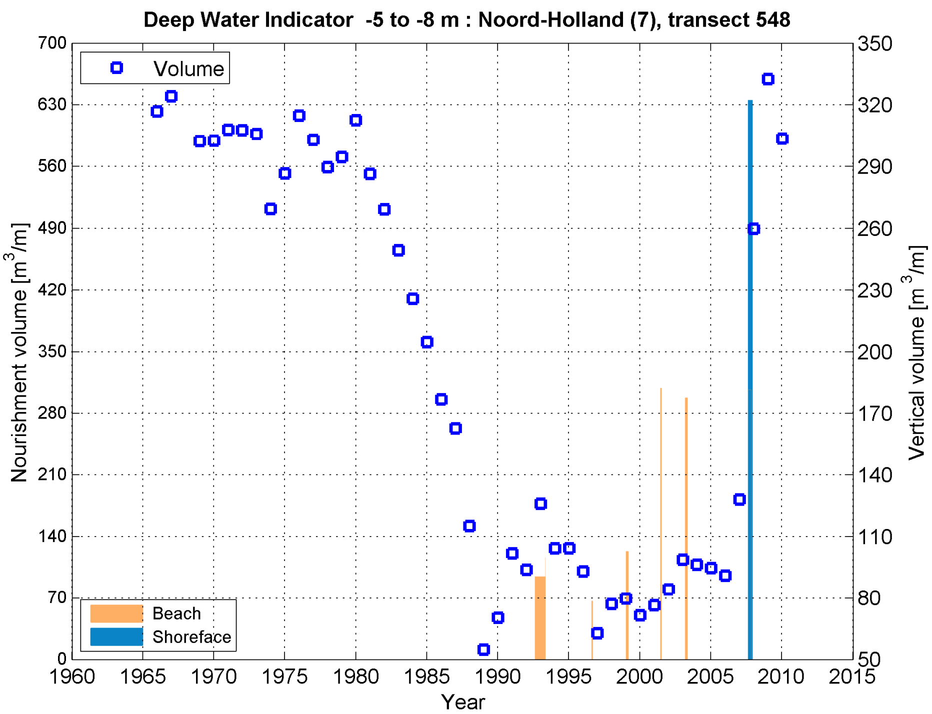

Figure 5.16 Volume variation at Jarkus transect 548 between -5 and -8 m. Orange and blue bars give the nourishment volumes.

The absolute values of sand volumes within water depths -1 m ÷ -5 m, -5 m ÷ -8 m and -8 m ÷ -12 m with respect to the boundaries defined for the year 1990 are given in Appendix F.1. Note that these volumes are averaged within each time window. The linear trends computed

for each time window are given in Appendix F.2. At most transects, volumes appear to have increased, with exception of the region delimited by the Jarkus transects 308 and 588, where a sediment loss was visible especially between -5 m and -8 m, and -8 m and -12 m. This would suggest a steepening of the profile, confirming the observations of Wijnberg (2002) (Paragraph 4.1). Nevertheless, volume trends at these water depths for the last 10 years are positive, indicating that nourishments are effective in re-establishing the sand balance. The relative largest increase is visible between -1 m and -5 m for area 8, where no nourishment was applied. This finding is supported in Paragraph 5.4.2 by a remarkable widening of the beaches in this area. In deeper water (-8 m ÷ - 12 m) values of sand volumes are very scarce, due to the fact that Jarkus measurements often stops around -9 m. The few available measurements which reach -12 m (Jarkus doorlodingen), would suggest some sediment loss also at deeper water, especially in areas 6 and 7.
The average volumes within each time window and area are shown in Figure 5.17 - Figure 5.19. Average values are computed whenever at least 20 % of the measurements are available at that area. For this reason, average values in areas 2, 3 and 8 are missing in Figure 5.19, as Jarkus measurements in deep water are very scarce.
In general, an increase in sand volumes is visible between -1 m ÷ - 5 m, and -5 m ÷ - 8 m. The only exception is area 1, where sand volumes in average have decreased for water depths -5 m ÷ - 8 m and -8 m ÷ - 12 m between the period 1965-1990 and 1991 -2000, and area 7 where a slight decrease is also visible. The areas showing a bigger increase between -1 m ÷ -5 m (Figure 5.17) are the ones mainly characterized by beach nourishments (area 1, 3 and 6).
Absolute volumes in area 8 between -1 m ÷ - 5 m and -5 m ÷ - 8 m are bigger than in other areas, indicating a less steep profile. The fact that more sand volumes are available, also means that a variation of MKL will lead to a smaller variation in erosion length (Figure 5.13).
The average trends per depth interval and for each time window are given in Figure 5.20 - Figure 5.22. Nearly all the trends indicate a tendency towards an increase in volumes for the different water depths.

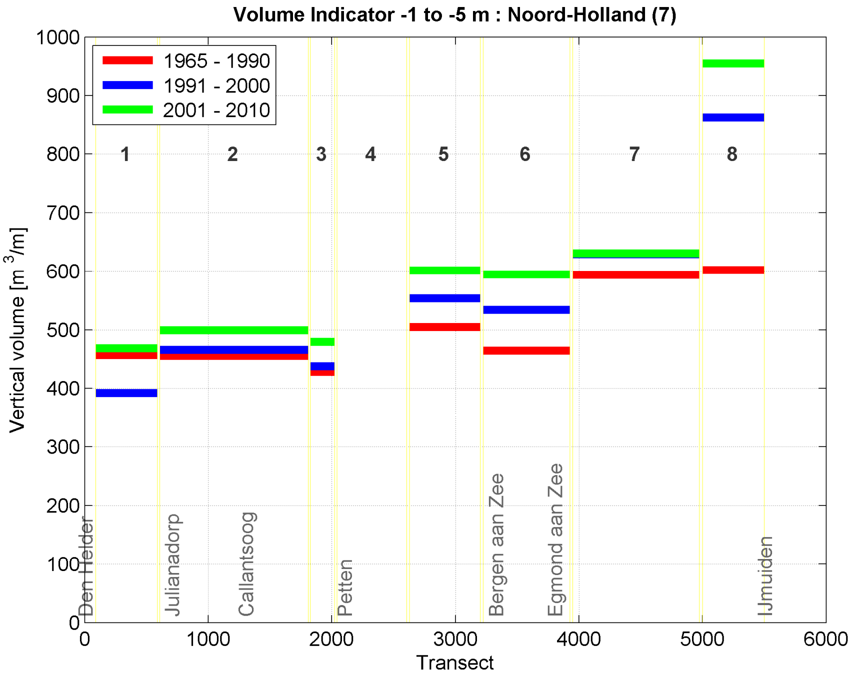

Figure 5.17 Sand volumes between -1 m and -5 m, averaged within each time window, and for each area with homogeneous characteristics.

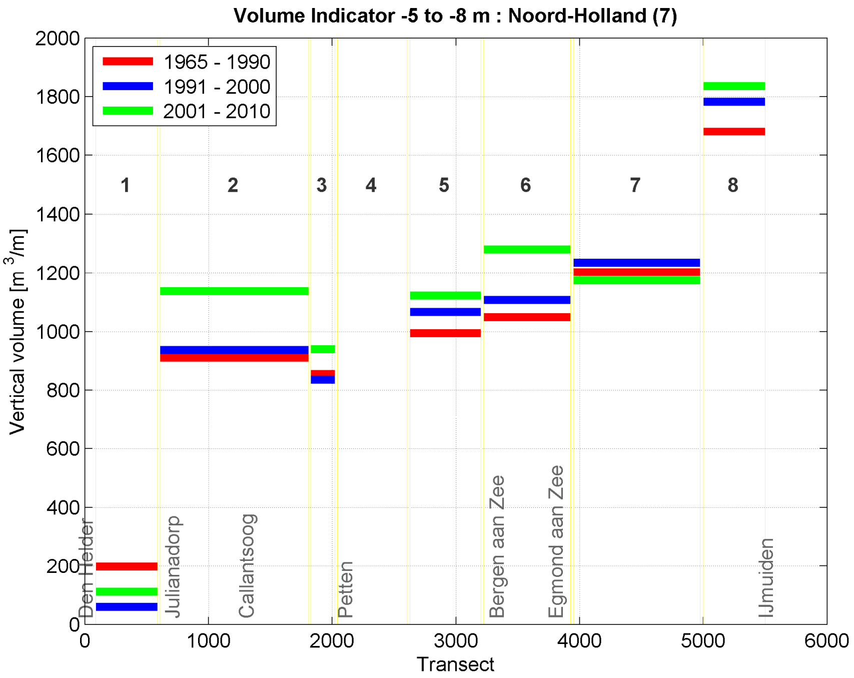

Figure 5.18 Sand volumes between -5 m and -8 m, averaged within each time window, and for each area with homogeneous characteristics.

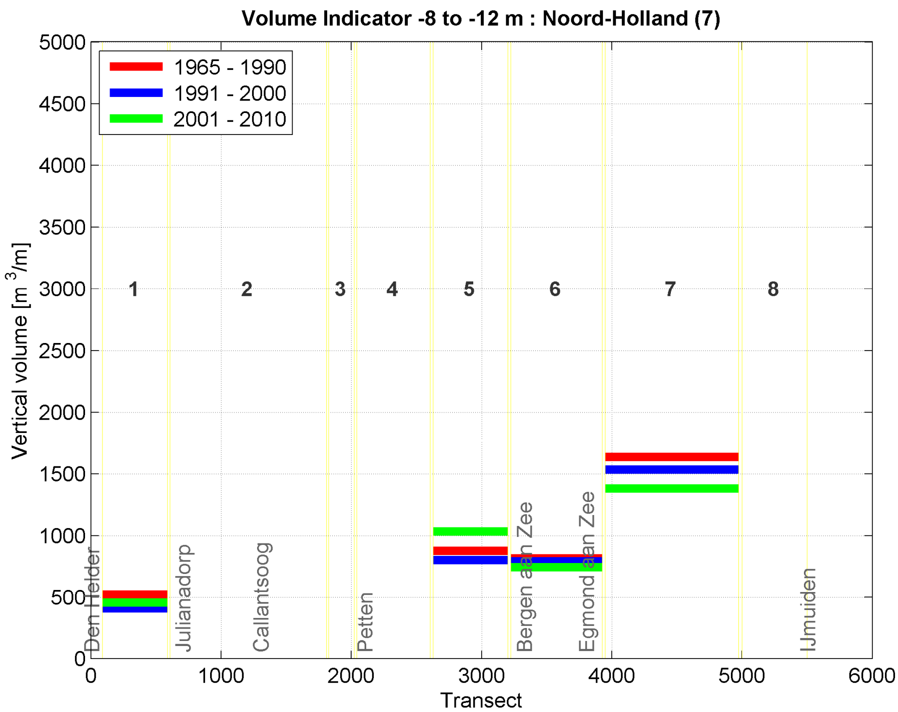

Figure 5.19 Sand volumes between -8 m and -12 m, averaged within each time window, and for each area with homogeneous characteristics. Values computed only for areas where at least 20% of the measurements were available.

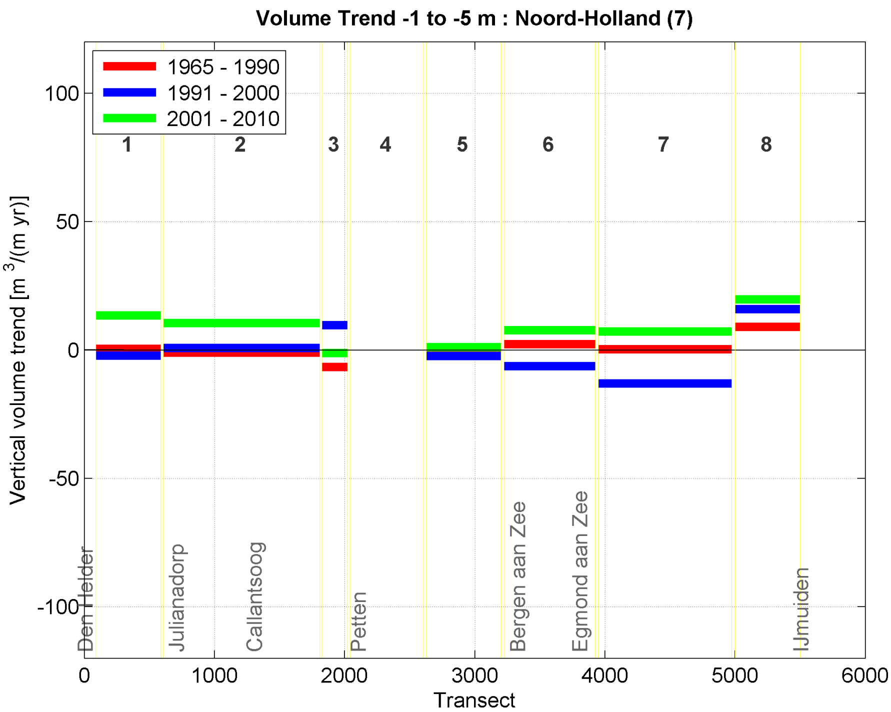

Figure 5.20 Trend of sand volumes between -1 m and -5 m, averaged within each time window, and for each area with homogeneous characteristics.

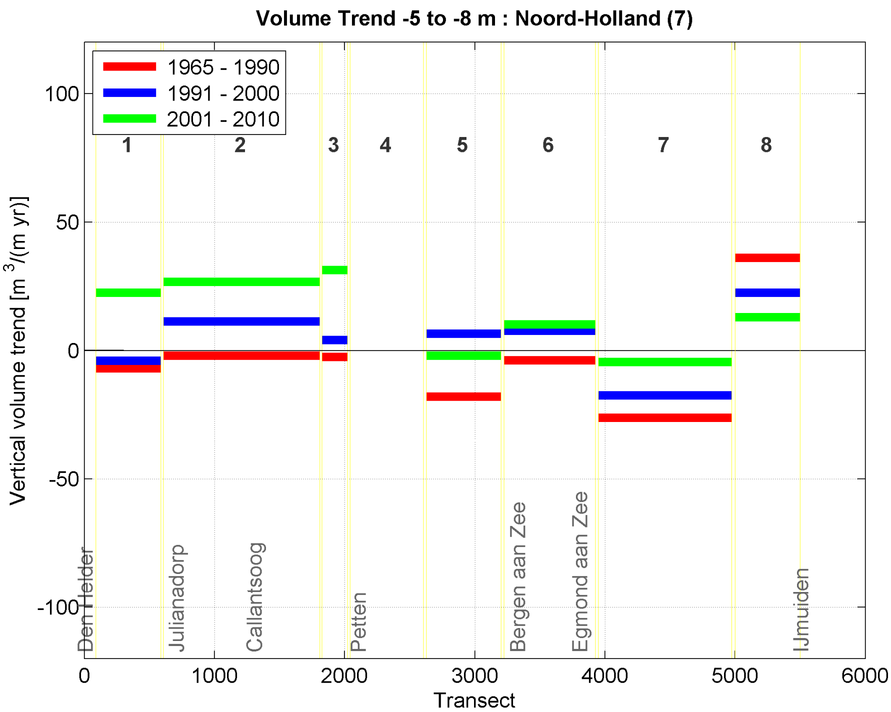

Figure 5.21 Trend of sand volumes between -5 m and -8 m, averaged within each time window, and for each area with homogeneous characteristics.

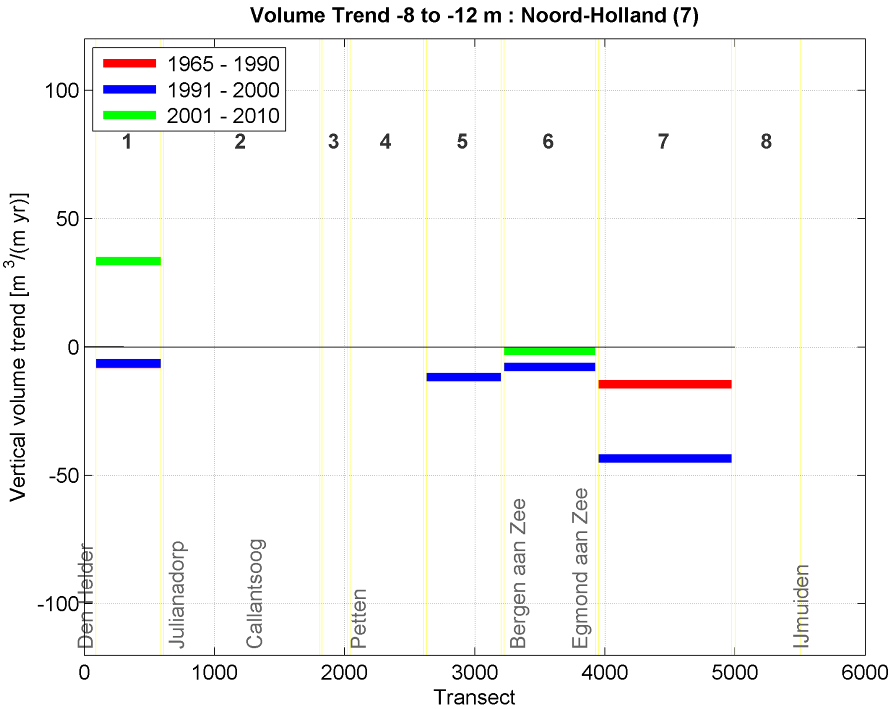

Figure 5.22 Trend of sand volumes between 8 m and -12 m, averaged within each time window, and for each area with homogeneous characteristics.Values computed only for areas where at least 20% of the measurements were available.

5.4 Nature and recreation

5.4.1 Dune foot, dry and wet beach

Several definitions exist in literature to define the position of the dune foot. For this study, we decided to use the standard definition of the dune foot position as the intersection between the dune profile and the +3 m NAP line. The dry beach is defined as the beach area between the dune foot position and the mean high water line, while the wet beach is the part of beach between the mean high water and mean low water line.

Relationships can be found in literature which relate changes in beach width to shift in dune foot position (De Vriend and Roelvink, 1989; Damsma, 2009). In general, a wider beach will lead to a seaward shift of the dune foot position. The migration speed can be determined from Figure 5.23. The adjusting time to equilibrium can be up to 50 years. In this report, we will mainly focus on changes related to the total beach width and of the dune foot position.

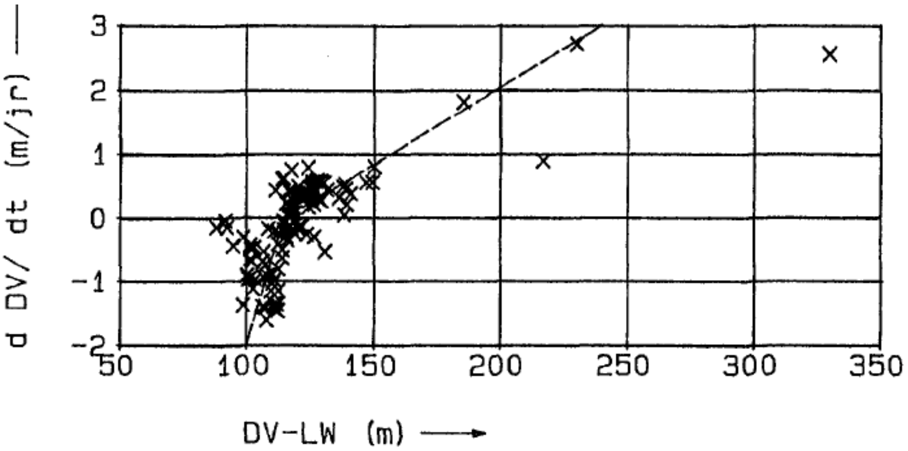

Figure 5.23 Dune foot migration speed in function of beach width (de Viend and Roelvink, 1989).

5.4.2 Analysis of beach width at mean low water (wet + dry beach)

The beach width was computed for all Jarkus transects for the period 1965-2010. The analysis was carried out for wet beach, dry beach and beach width at mean low water (dry + wet beach). Only the analysis related to the beach width at mean low water was described in the report. The changes in absolute values of beach width, averaged within the different time windows and for the different Jarkus transects are shown in Appendix G.1. The trend computed for the different time windows are given in Appendix G.2. At most locations beaches appear to have increased in width of about 20 m, with exception of area 1, where beaches seem to have narrowed in average of more than 10 m, and area 2 where no significant change in beach width can be noticed despite the nourishments. However, trend lines show a potential for beach widening. Very wide beaches are especially visible at area 8, suggesting that the presence of hard structures (i.e. Ijmuiden jetties) has on this indicator an impact stronger than the nourishments.

The information on absolute beach width, averaged for the different time windows and areas is shown in Figure 5.24, while the average trends are given in Figure 5.25. In average, the beach width has increased since 1990 overall of about 8 m for the 55 km length of the North Holland coast, creating additional space for recreation and nature. Attempts to monetizing this additional space can be found in Zijlstra et al. (2007).

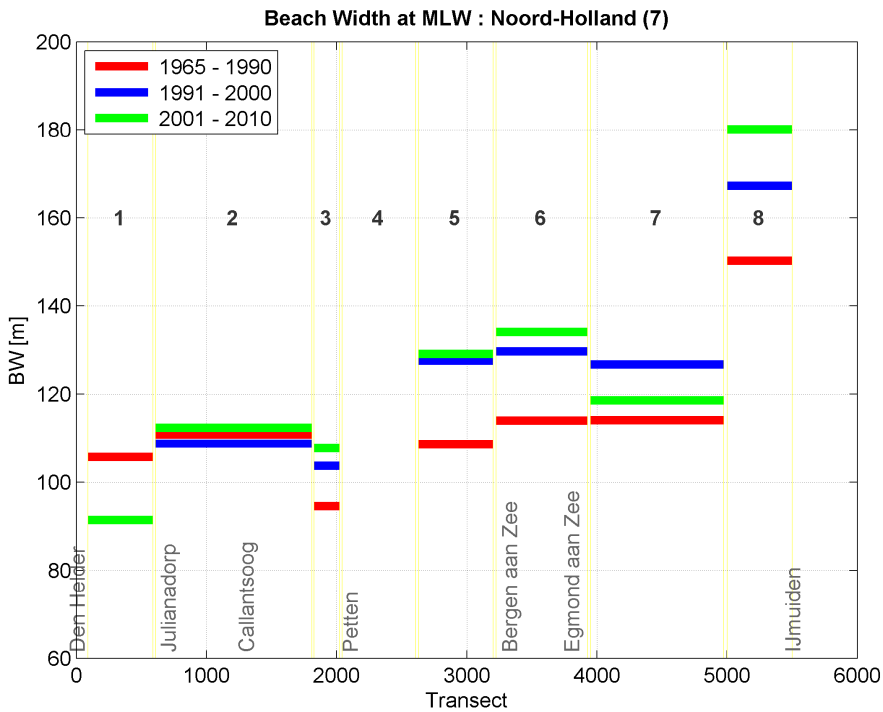

Figure 5.24 Beach width at mean low water (dry + wet beach) averaged within each time window, and for each area with homogeneous characteristics.

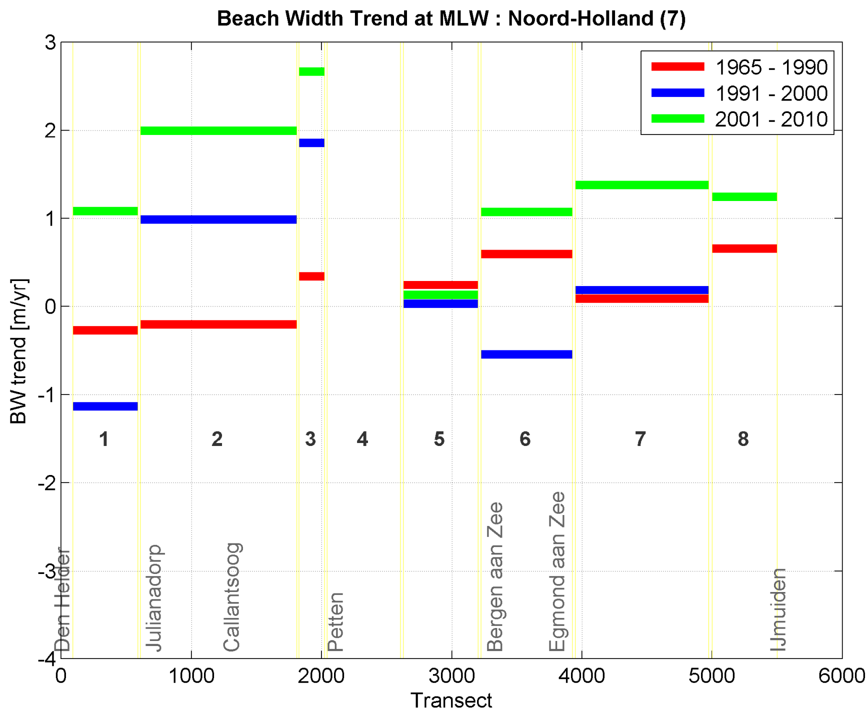

Figure 5.25 Trend in beach width at mean low water (dry + wet beach) averaged within each time window, and for each area with homogeneous characteristics.

5.4.3 Analysis of dune foot

Dune foot migration generally is assumed to be related to changes in beach width and storminess. A wider beach provides boundary conditions for a seaward movement of the dune foot (Paragraph 5.4.2), while a storm leads to a landward retreat (Chapter 6). As an example, a storm such as the one of 2007 might lead to an average dune foot retreat of 5 m (Paragraph 6.2). If we assume a dune foot migration speed as the one given in Figure 5.23, it might take several years to have complete natural recover.

The dune foot time variations between 1965 and now were computed for all transects, together with the position of mean high water and mean low water line. The averaged absolute values within each time window of dune foot position with respect to the 2010 position, are shown in Appendix H.1, while the trends are given in Appendix H.2. At most transects in areas 1, 2 and 8 the dune foot appears to have shifted seaward up to a maximum of 100 m (transect 5500). Remarkable is also the seaward shift up to 40 m in area 1 (transect 308), which is also visible when looking to the shift in MKL position (Appendix E.1). On the other hand beach width at this transect has been undergoing the opposite trend (Appendix G.1). This would suggest the idea of a growing foredune, with steepening of the intertidal area, as described by Wijnberg (2002). The central areas (3, 4, 5, 6, 7) are more subject to natural oscillations related to longshore movements of morphological features such as sand waves.

In Figure 5.26 and Figure 5.27, the same information as in Appendix H is averaged over the different areas. The trends suggest in general a tendency to a growing of the dune area. This tendency however seems to have slow down in the last 10 years, with exception of area 1. From 1990 until 2010 the dune foot has shifted in average over the 55 km of the North Holland coast for about 18 m in seaward direction, leading to the creation of additional space for nature and recreation.

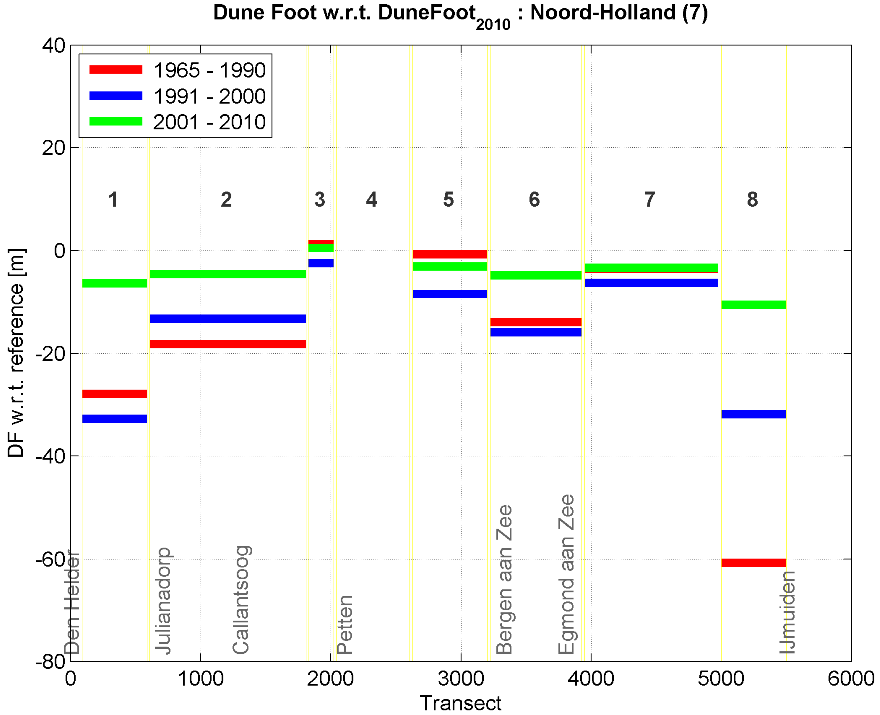

Figure 5.26 Dune foot with respect to the 2010 position averaged within each time window, and for each area with homogeneous characteristics.

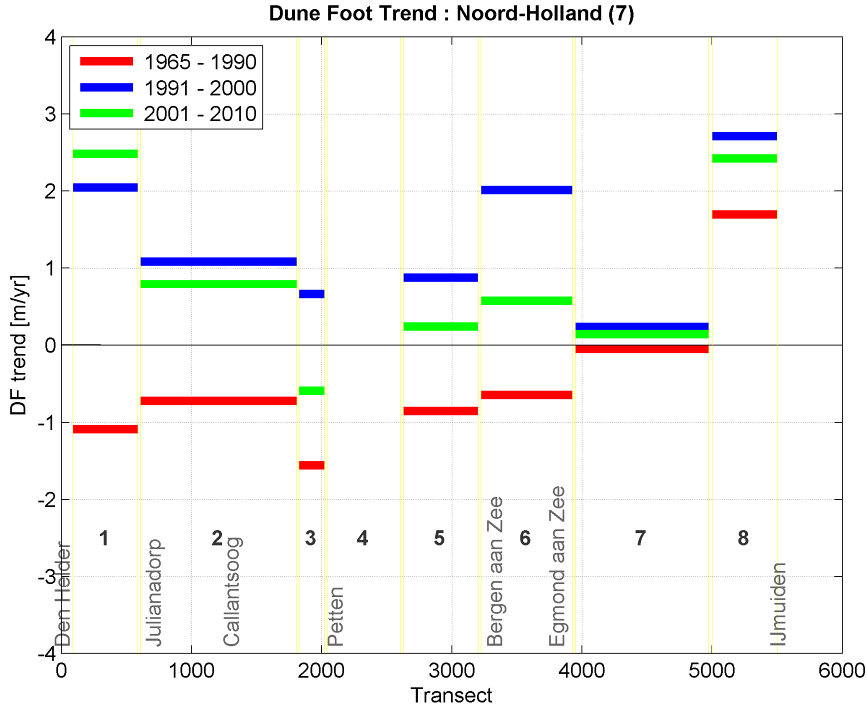

Figure 5.27 Trend in dune foot position averaged within each time window, and for each area with homogeneous characteristics.

6 Effects of storms

6.1 Impact of storms looking at historical data

We decided to asses the morphological evolution for the period 1883-1998 with a methodology analogue to the one implemented by Ruessink et al. (2002) (Paragraph 4.3.1). The trends derived from this analysis are the closest to the natural ones since, before 1990, nourishments were almost absent. For the most recent years, a wider spectrum of relationships between hydrodynamics and morphological parameters could be defined, given the more complete available data (Paragraph 6.2).

For this analysis maximum annual water level data collected at IJmuiden station starting from 1883 were used and considered representative of the all North Holland coast. Data were kindly supplied by Rijkswaterstaat (http://www.helpdeskwater.nl/). The data are shown in Figure 6.1. In particular, the water level relative to the 1953 storm stands out from the time series.

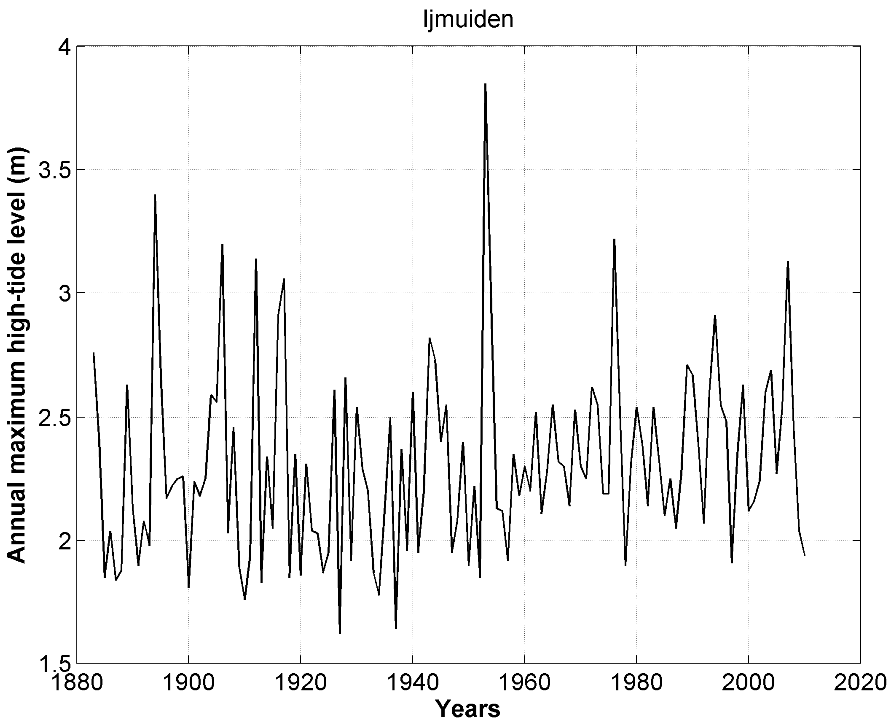

Figure 6.1 Annual maximum water level (m) from 1883 until 2010.

Following the procedure proposed by Ruessink and Jeuken (2002), these data were analyzed together with the annual change in dune foot position. Since, the interest is on the annual variation in dune foot position due to storm events occurred before the dune foot position was measured, two assumptions were made:

- From the maximum yearly storm database, the maximum storm occurred between the 31st of May of the previous year and the 31st of May of the year afterwards was extracted, assuming that dune foot position was usually measured in May-June.
- The dune foot position was de-trended from long-term variations in dune foot position, since these trends are not related to the yearly effect of storms (e.g. long term accretive trends due to the effect of the Ijmuiden jetties).

The yearly variation in dune foot position, averaged over the all North Holland transects ($\Delta_{DF}^{2D} / \Delta t$), was then plotted versus the maximum water level (Figure 6.2). A positive value of $\Delta_{DF}^{2D} / \Delta t$ indicates an average seaward shift in dune foot position. There is a clear correlation between the two variables with correlation coefficient equal to -0.59. According to Figure 6.2, a year with at least one storm event with a maximum storm surge level higher than 1 m with respect to a milder one, leads to an average landwards movement of the dune foot of 5 m. In the Figure, the years after 1990 are shown with red circles. At these years, nourishments started being applied at large scale, leading to shift of the dune foot position in seaward direction despite the presence of storms. This can be clearly seen from the figure where red circles usually appear above the trend line.
The same Figure but for maximum water level and change in beach width (dry beach + wet beach) is shown in Figure 6.3. In this case, there is no clear trend between the two variables. As observed in the previous paragraph, this is due to the fact that during storms the beach is eroded but also receives input of sediments from the dunes. This might lead to a horizontal shift in position (seawards or landwards), but the total width is preserved.

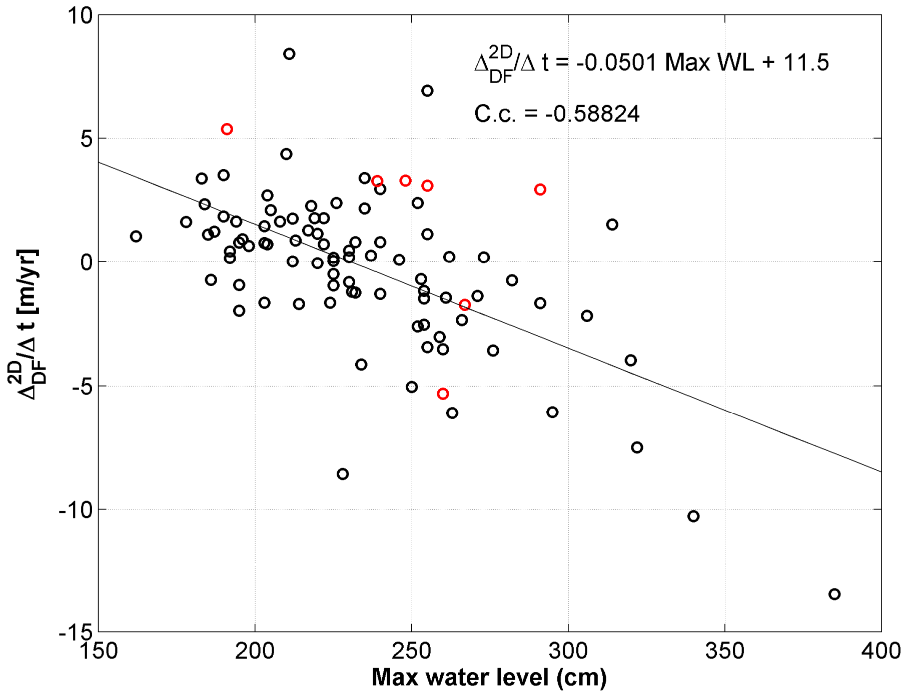

Figure 6.2 Relation between average yearly variation in dune foot position and maximum water level. Red circles represent yearly dune foot variation after 1990.

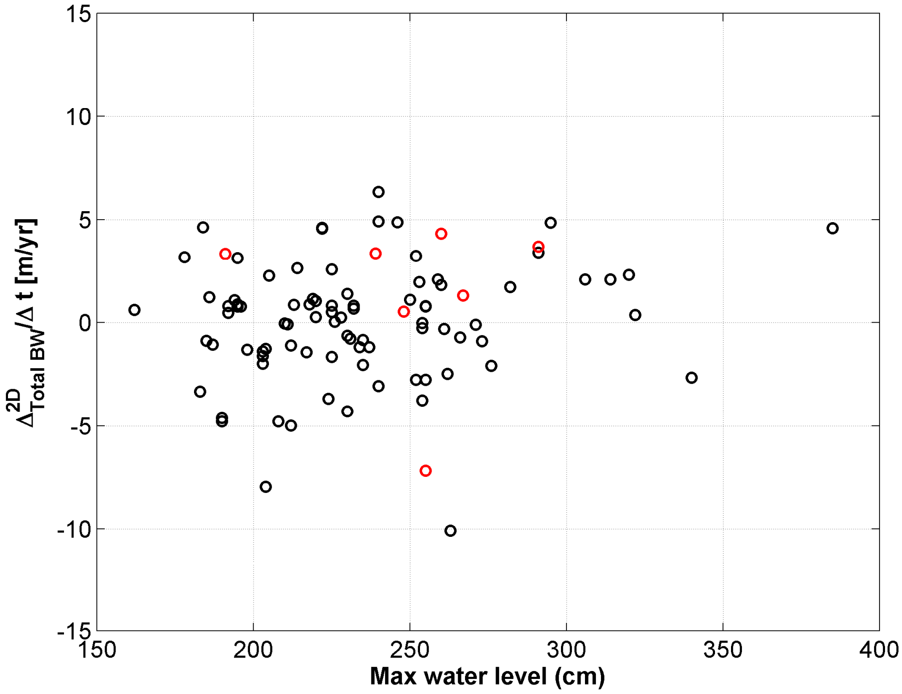

Figure 6.3 Relation between average yearly variation in beach width and maximum water level. Red circles represent yearly dune foot variation after 1990.

6.2 Impact of storms in recent years

A wider range of data has become available in the last years. Water level and wave height time series are now recorded with a time resolution of 10 minutes. Moreover, since 1965 Jarkus data have become available allowing for the computation of a larger number of indicators. The data collected at Ijmuiden station were used for this analysis.

Several storminess parameters were tested, namely wave height, wave energy and number of hours at which water level is above 2 m. To be consistent with the analysis carried out in the previous paragraph, each parameter was computed for a time span corresponding to two Jarkus measurements (e.g. mean wave energy of year 2007 is the mean wave energy between the Jarkus measurement of year 2006 and year 2007). It was found that the yearly mean wave energy parameter (Hs^2) could better describe average yearly changes in dune foot position (Figure 6.4). The Figure clearly shows the influence of years with higher storminess, on dune foot retreat. Years before 1990 are shown in black, years between 1991 and 2000 in red, and between 2001 and 2010 in blue. Most of the values above the trend line relate to years after 1991, when nourishments started taking place, showing that nourishments play an important role in damping the effect of storms. However, years characterized by major storms (e.g. 2007 - Figure 6.5) still have a clear effect onto the morphological development of the coast.

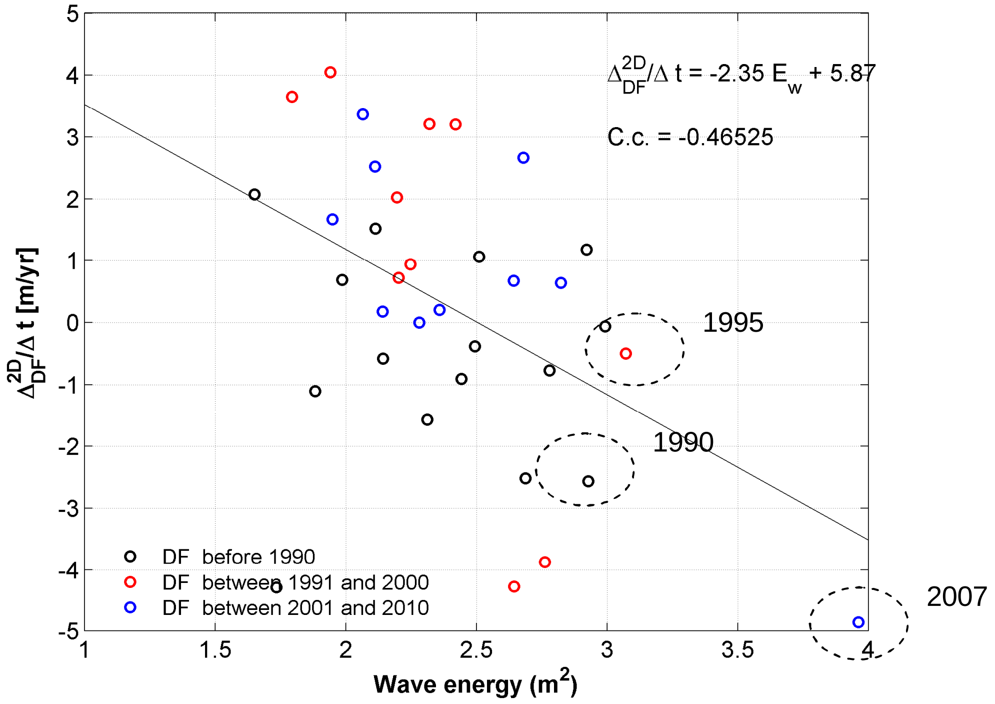

Figure 6.4 Relation between yearly mean wave energy and average changes in dune foot position for the North Holland coast.

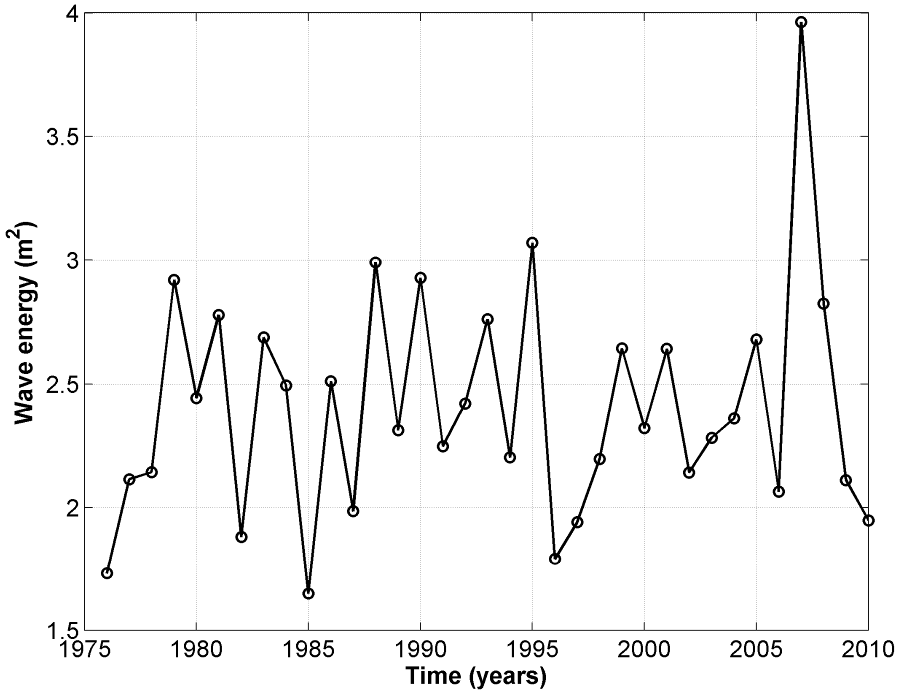

Figure 6.5 Time series of yearly mean wave energy for the period 1976 – 2010.

Besides wave energy, the yearly mean wave direction appears also to play a role. As an example, the wave roses related to years 1995 and 1990, characterized by similar mean wave energy, but different effects in terms of mean dune foot variation are shown (Figure 6.6). It can be expected that years characterized by a larger number of north-westerly storms (Figure 6.6 – left) will increase the south-directed longshore transport, which is then blocked by the Ijmuiden jetties in the south, leading to a relatively smaller average change in dune foot position with respect to years characterized by more dominant westerly or south westerly storms (Figure 6.6 – right). Further investigation is needed to quantify the relative importance of yearly mean wave direction and storminess with respect to the morphological development.

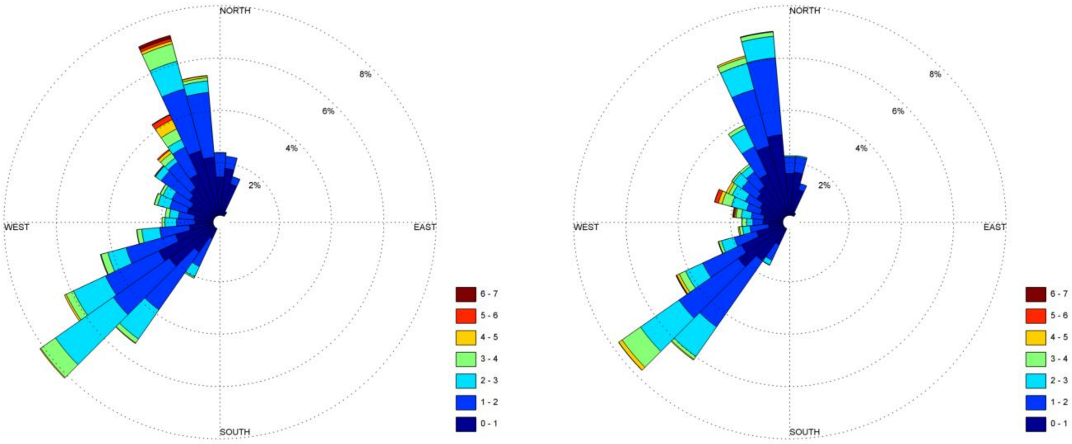

Figure 6.6 Wind roses related to years 1995 (left) and 1990 (right).

The same trend analysis was carried out with respect to changes in MKL position (Figure 6.7). The Figure shows a weaker correlation between changes in MKL position and wave energy. Once again, this is related to the fact that sand lost offshore during storms from the MKL volume, it is partly balanced by the sand transported from the dunes to the MKL volume.

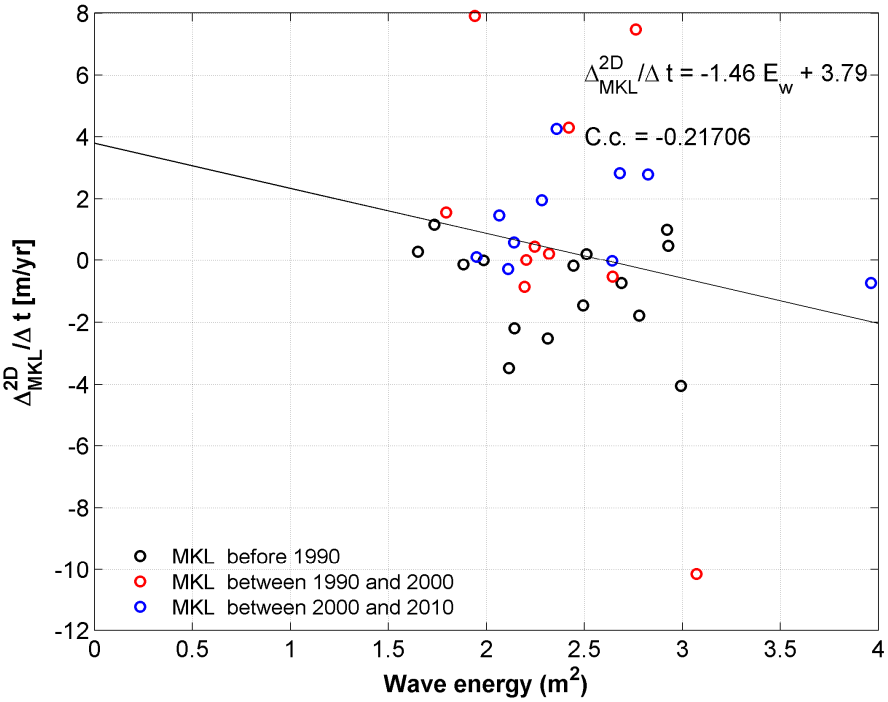

Figure 6.7 Relation between wave energy and average changes in MKL position for the North Holland coast.

7 Costs and benefits of the nourishment strategy

This study has pointed which areas have been more extensively nourished. Moreover, the analysis on a number of morphological indicators has shown what the relative effects are in terms of short, medium and long term safety, resulting from the nourishment strategy in different areas and for different periods.
In this chapter, a number of preliminary conclusions were derived related to the efficiency of the nourishment strategy in different sub-areas. In order to do that, the nourishment costs in Euros/m were derived for the different areas of North Holland, based on 2010 costs (cost for shoreface nourishment = 3.50 €/m; cost for beach nourishment 7.00 €/m). The results of the cost-analysis are summarized in Table 7.1. Area 1 has been characterized by the highest nourishment cost per linear meter of coastline. The costs for nourishing areas 7 and 8 are minor since these stretches of coastline were not subjected to autonomous erosive trend. The same can be said for area 4, which is defended by a sea-wall and nourishments are not strictly necessary[5].
On the other hand, benefits were identified multiplying the average trends for each sub-area by the same number of years and equal to 10. In this way, yearly morphological variations (i.e. due to storms or migrations of longshore features) are filtered out in the analysis. It is important to highlight that this variation is computed from the average trends and might be different by what could be obtained computing the average difference between the last and the first value of the time window. The benefits derived in terms of morphological indicators are shown in Table 7.2, Table 7.3, and Table 7.4 respectively for the time windows 1981-1990, 1991-2000, and 2001-2010. In general, these tables confirm the observation that nourishments have been effective, replacing the erosive trends observable in the first time period with accretive trends. In addition, the probability of breaching has shown a clear decrease especially in the last time window, related to the increase in volume in the dune area. In particular, a value bigger than one in the column related to the relative change in probability of breaching suggests an average increase in probability of breaching (e.g. if the value at the first year is 10^{-5}, after 10 years it will result in a value equal to $1.19 \cdot 10^{-5}$ imaging that the relative variation in the table is *1.19*). On the other hand a value lower than one suggests an average decrease in probability of breaching (e.g. from 10^{-5} to $0.48 \cdot 10^{-5}$ after 10 years, if the coefficient in the table is equal to *0.48*). Multiplying the values in the tables by the length of each sub-area (Table 3.1) is possible to translate these benefits to gains in terms of additional areas (i.e. for nature, recreation…). For example a seaward shift of dune foot equal to 25 m, as shown in area 1 for the period 2001-2010 (Table 7.4), would correspond to an additional space for nature and recreation equal to 25 m $\times$ 4980 m = 0.124 km^2.

The area where the nourishment strategy has been at first glance more cost-effective is area 5, located approximately between Camperduin and Bergen aan Zee (highlighted in green in the tables): the total costs for nourishments are in relative sense smaller than in other areas. However, indicators show a positive response to nourishments, avoiding the excessive changes, which can be seen in other areas. However, more research is needed to draw a complete cost-benefit analysis of the nourishments carried out in the different areas. Moreover, price for nourishments have been undergoing important oscillations over the last years, which should be taken into account in the analysis.

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5. *Nevertheless, nourishments in front of hard structures might help the stability of the structures themselves (ARCADIS, 2011).*

Table 7.1 Costs (€/m) to nourish the different sub-areas of the North Holland coast based on 2010 nourishment price. The nourishment costs are subdivided for nourishment type and time window.

Area code	1965 - 1990		1991 - 2000		2001 – 2010		1965 - 2010
	Beach + dunes	Shoreface	Beach + dunes	Shoreface	Beach + dunes	Shoreface	Total
1	0	0	1885	0	5872	2555	10312
2	2444	0	1150	0	419	2769	6783
3	0	0	3454	0	2940	1580	7974
4	0	0	86	0	655	1483	2224
5	0	0	1923	0	947	2299	5169
6	465	0	3925	1050	926	1426	7791
7	0	0	70	0	415	120	605
8	0	0	628	0	0	0	628

Table 7.2 10-year variation of the different indicators derived from trends: period 1981-1990.

Area code	Δ Prob. Breaching (-)	Δ MKL (m)	Δ Vol -1÷-8m (m^3/m)	Δ Beach width (m): mhw	mlw	Δ Dune foot (m)
1	2.99	-11	-66	5	-3	-11
2	0.96	-4	-35	-3	-2	-7
3	0.74	-19	-92	4	3	-16
4	-	-	-	-	-	-
5	1.19	-7	-135	-2	2	-9
6	1.18	-1	39	-1	6	-6
7	0.81	0	-211	-2	1	-1
8	0.44	24	516	2	7	17

Table 7.3 10-year variation of the different indicators derived from trends: period 1991-2000.

Area code	Δ Prob. Breaching (-)	Δ MKL (m)	Δ Vol -1÷-8m (m^3/m)	Δ Beach width (m): mhw	mlw	Δ Dune foot (m)
1	1.29	6	-62	-11	-11	20
2	0.28	12	120	-2	10	11
3	0.28	11	135	-2	19	7
4	-	-	-	-	-	-
5	0.42	5	41	6	0	9
6	0.34	14	15	7	-5	20
7	1.12	-16	-304	-2	2	2
8	0.24	47	381	23	32	27

Table 7.4 10-year variation of the different indicators derived from trends: period 2001-2010.

Area code	Δ Prob. Breaching (-)	Δ MKL (m)	Δ Vol -1÷-8m (m^3/m)	Δ Beach width (m): mhw	mlw	Δ Dune foot (m)
1	0.03	41	362	-1	11	25
2	0.20	26	372	10	20	8
3	0.84	8	302	-2	27	-6
4	-	-	-	-	-	-
5	0.48	8	-16	1	1	2
6	0.41	17	176	11	11	6
7	0.58	12	23	1	14	1
8	0.27	32	95	7	12	24

8 Conclusions and summary

8.1 Conclusions

The morphological development of the North Holland coast between 1965 and 2010 has been investigated by looking at the development of a number of pre-selected indicators. Four types of indicators were used for the analysis: indicators related to short term safety, medium term safety, long term safety and nature/recreation. The main hyphothesis behind this study was to verify whether the nourishment policy applied since 1990 in The Netherlands had led to a 'positive' (seaward) development of these indicators. As a consequence to this hyphothesis, it was investigated whether nourishments also contributed to an increase in safety levels due to a seaward shift of the erosion point. The analysis was at first carried out for each Jarkus transect looking both at absolute values of the indicators and multi-years trends. In second place, the focus was at sub-regional level by looking at homogeneous areas in terms of autonomous morphological trend and nourishment strategy.
The analysis has shown that the nourishment strategy has in general led to positive effects. Short term safety, described by the probability of breaching of the first dune row, has in general increased overall of more than one order of magnitude. The medium term safety has improved, as shown by an average shift of the MKL indicator of 30 m in seaward direction. Moreover, the erosive trends, which were quite common at most locations before 1990, have been replaced starting from 1990 by accretive trends. Long- term safety also appeared to have increased, due to a general increase of available sand volumes at different water depths, with some exceptions at deeper water, where unfortunately measurements are very scarce.

In addition, the indicators related to nature and recreation confirm the benefits from the nourishment policy. Beaches have been widening and are now in average about 8 m wider than in 1990. Nevertheless, this widening is likely to be temporary since beaches need some time to readjust to the new equilibrium induced by the nourishments, partly redistributing the sand towards the dunes The dune foot has also been migrating seaward in average of about 18 m since 1990.

Besides nourishments, other factors have been identified which played a major role on the coastline development. At first, other man-made structure along the coast (e.g. sea walls and jetties) have an impact, which is not secondary to nourishments. This is supported by the rapid development of the indicators in the southern stretches of the North Holland coast, under the effects of the Ijmuiden jetties, where nearly no nourishments have been applied.

Parallel to the anthropogenic impact on coastline development, the effects of natural forcing has been analysed. Yearly storminess appears to be correlated to dune foot migration. Despite nourishments have reduced the natural oscillations due to yearly storminess, their effect is still remarkable and years characterized by higher storminess (e.g. 2007) can be easily identified by looking at the dune foot position time series. The correlation of storminess with other indicators (e.g. beach width, MKL position) is rather weak given the complex cross-shore sediment exchanges during storms between dunes, beach, MKL volume and the lower shoreface. Besides storminess, other natural phenomena (e.g. sea level rise and subsidence) have en effect especially on the long term safety indicators. However, these effects have not been quantified in this study.

The analysis carried out at aggregated level has pointed out that areas where extensive beach nourishments have been applied (e.g area 1) are also characterized by the biggest changes in the morphological indicators. Moreover, comparing computed nourishment costs with variation of the different morphological indicators, a preliminary cost-benefit analysis has been carried out, highlighting areas where the nourishment strategy has been more efficient.

Possible correlations between indicators were also identified within a parallel research (Van Santen, 2011). In particular, it was shown that short term and medium term safety indicators are in general well correlated and relations can be identified to derive from one type of indicator, different ones.

To conclude, a complete database of indicators has been developed, and is now freely available through the Open Earth system. This database can be used as support tool for several projects dealing with coastline morphology in The Netherlands. The same dataset can now be easily visualized by a number of interfaces which are under development at Deltares (The coastal viewer and Morphan) and be a user friendly support tool for coastal mangers.

8.2 Executive summary

Objectives: Support the Waterdienst on *where* to nourish and on the *most efficient* nourishment strategy.

- A database of indicators has been developed, and which can be used to identify critical spots where nourishments will be needed in the near future. The presence of a sufficient buffer of sand along the coast, which guarantees adequate safety levels, has also been identified and can be used to prioritize areas of interventions, in case of limited financial resources.
- Looking at the nourishment strategy in the past years (volumes and nourishment type) as well as the consequences on the morphological development, conclusions can be drawn on where the nourishment strategy has been more effective. The most cost-effective nourishment strategy appear to be applied in area 5 (approximately between Camperduin and Egmond aan Zee).

Hypothesis 1: *The nourishment strategy of the past years had lead to a positive (seaward) development of a number of "indicators" along the Dutch coast.*

- The effect of nourishments has been analyzed on a number of indicators for the North Holland case study. All the indicators have shown a positive response to the present nourishment strategy. In particular the following changes have been shown:
  - Overall increase of more than one order of magnitude in short-term safety identified by a change in probability of breaching.
  - Average seaward shift of the MKL position of about 30 m.
  - General increase of sediments at least until -8 m. Measurements between -8 m and -12 m are very scarce. However, some sediment loss appears to be visible at deeper water.
  - Increase of recreational space, as a consequence of an average widening of the beaches of about 8 m.
  - Increase in dune area, as a consequence of an average seaward shift in dune foot position of about 18 m.

Hypothesis 2: *Nourishments contribute to an increase of the safety level through a seaward shift of the erosion point.*

- The increase of the safety level due to nourishments has been analyzed by looking at the relative variation in probability of breaching. Besides an overall increase of more than one order of magnitude in short-term safety (hypothesis 1), relationships were identified between nourishment volumes, short term safety and medium term safety indicators. For example, it was shown that an average seaward shift of 42.2 m in MKL position, might lead approximately to a decrease in probability of breaching of one order of magnitude.

What is the effect of storms on the morphological development of the indicators?

- Shift in dune foot position appeared to be well correlated to yearly maximum storm surge levels, and to yearly average wave energy. As an indication, a year with a maximum storm surge level higher than 1 m with respect to a milder one, might lead to an average landward movement of the dune foot of about 5 m.
- Nourishments appeared to have dumped the effects of storms. However, exceptional storms (e.g. storm in 2007) still have a clear effect onto the morphological development of the coast.

9 Recommendations for further work

A number of recommendations have been identified for further research:

- All this research has been based on a number of assumptions. In particular, linear trends have been identified within time windows a priori-defined, and corresponding to changes in the nourishment policy. The same research can be carried out trying to identify trend breaks from the indicators time series, and verify if these are possibly correlated to changes in management policy. Moreover, other functions might be more suitable to describe these trends rather than the linear one.
- The present study has focused only on the North Holland coast. The same type of analysis will be extended to the all Dutch coast, where the relative impact of nourishments and man made structures might be different.
- Within this study, a complete dataset of indicators has been developed, parallel to a detail description of all the nourishment works. This data set could be a useful base for model development and validation. Statistical based models (e.g Brière, 2008 and 2009), physically based models (e.g. Delft3D), and Bayesian models should be ideally able to predict the observed morphological changed described by the indicators.
- A very simple cost-benefit analysis has been carried out to compare nourishment costs with the relative morphological effects. A more detail analysis is suggested, taking into consideration price variations in time of the different types of nourishments. Moreover, a wider spectrum of effects should be taken into consideration, including tourism, potential for economical development, ecology etc.
- Analysis of long term safety was based on JARKUS data and therefore limited to water depths lower than about 10 m. A parallel ongoing study carried out by ALTERRA is looking into the volume development within the entire coastal foundation, by coupling volume change derived from Jarkus data, with volume change from Vakloadingen data and Lidar data of the dune area.

10 References

ARCADIS, 2011. Toekomstbestendigheid verharde zeeweringen. Analyse veiligheidsopgave, veiligheidshorizon en mogelijke maatregelen. Internal report.

Arens, S.M. (1994). Aeolian Processes in the Dutch Foredune. PhD thesis, Laboratory of Physical Geography and Soil Science, University of Amsterdam.

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

Arens, S.M., 2009. Effecten van suppleties op duinontwikkeling, geomorfologie. Rapportage fase 1; Commissioned by Ministerie van LNV and Rijkswaterstaat. Arens Bureau voor Strand- en Duinonderzoek, 68 p.

Bochev-van der Burgh, L.M., Wijnberg, K.M., Hulsher, S.J.M.H., 2009. Dune morphology along a Nourished Coastline. Journal of Coastal Research, Special Issue 56. 292-296 p.

Bochev-van der Burgh, L.M., Wijnberg, K.M., Hulsher, S.J.M.H., 2011. Decadal-scale morphologic variability of managed coastal dunes. Journal of Coastal Engineering 58 , 927-936 p.

Bochev-van der Burgh, L.M., Wijnberg, K.M., Hulsher, S.J.M.H., in press. Foredune management and foredune morphodynamics: A case study of the central Netherlands' coast. Journal of Coastal Conservation manuscript.

Brière, C. and van Den Boogaard, H., 2008. Regression models and uncertainty analysis of coastal state indicators. Proceedings of the Coastal Engineeering Conference ICCE 2008, Hamburg, Germany.

Brière, C. and van Den Boogaard, H., 2009. Statistical modelling of the coastline position along the Holland coast (The Netherlands). Proceedings of the River, Coastal and Estuarine Morphodynamics, Santa Fé, Argentina.

Damsma, T., 2009. Dune growth on natural and nourished beaches: 'A new perspective'. Msc. Thesis, Delft University, 71 p.

De Vriend, H.J. and Roelvink, J.A., 1989. Technisch Rapport 19 (H825); Kustverdediging Na 1990, Ministry of Transport, Public Works and Management.

Deltacommissie, 2008. Samen werken met water: bevindingen van de deltacommissie 2008, Hollandia printing.

Giardino, A., Mulder, J., de Ronde, J., Stronkhorst, J., 2010a. Suistainable development of the Dutch coast: Present and Future. Proceedings of the MCRR3 Conference on Coastal Recreational Resources, Grosseto, Italy.

Giardino, A., 2010b. The impact of sand nourishment design on dune erosion during storm conditions BwN HK3.1c. Design aspects pilot Sand Engine Delfland. Deltares memo. Internal reference 1201770-000-ZKS-0010.

Kleinhans, M.G., and Grasmeijer, B.T., 2005. Alongshore bed load ransport on the shoreface and inner shelf. In L.C. Van Rijn (Editor), EU-Sandpit end-book. Aqua Publications, The Netherlands.

KNMI, 2006. Klimaat in de 21e eeuw: vier scenario's voor Nederland, Drukkerij van de Ridder,Nijkerk, The Netherlands.

Lodder, Q., Van Geer, P., in preparation. MorphAn: a new software tool to assess sandy coasts. NCK days 2012, poster.

Mulder, J.P.M., Hommes, S. and Horstman, E.M., 2011. Implementation of coastal erosion management in The Netherlands. Special issue of the Journal of Ocean & Coastal Management, title: Concepts and Science of Coastal Erosion Management (Conscience), 54, 888 – 897 p.

Rijkswaterstaat, 1991. GWWS-91.006 DE BASISKUSTLIJN een tech-nisch/morfologische uitwerking.

Ruessink, B.G., and Jeuken, C., 2002. Dunefoot dynamics along the Dutch coast. Journal of Earth Surface Processes and Landforms. Vol. 27, Issue 10, 1043 – 1056 p.

Santinelli, G., 2010. Trend analysis of nourishment volumes. Master thesis Università degli Studi di Genova – Deltares, 1-70 p.

Stolk, A., 1989. Zandsysteem kust – Een morfologische karakterisering. Kustverdediging na 1990, Technisch Rapport 1. Rep. GEOPRO 1989-02, Dept. Phys. Geogr., Uthrecht University.

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

Van Koningsveld M. and Mulder JPM, 2004. Sustainable coastal policy developments in The Netherlands. A systematic approach revealed. Journal of Coastal Research. 20 (2): 375-385 p.

Van Puijvelde, 2010. Classification of the Dutch foredunes. Master thesis. University of Utrecht, Faculty of Geosciences.

Van Riijn, L.C., 1995. Sand budget and coastline changes of the central coast of Holland between Den Helder and Hoek van Holland period 1964-2040, Delft Hydraulics, Report H2129.

Van Rijn, L.C.,1997. Sediment transport and budget of the central coastal zone of Holland, Coastal Engineering No., 32, 61-90 p.

Van Rijn, L.C., 2010. Coastal erosion control based on the concept of sediment cells. Conscience project Final Report.

Van Santen, R.B., Steetzel, H.J., 2011 (draft report). Relatie Kustlijnzorg – Kustveiligheid. Project report, ARCADIS Nederland.

Vermaas, T., 2010. Morphological behaviour of the deeper part of the Holland coast. Master thesis. Deltares, The Netherlands.

Wijnberg, K.M., 2002. Environmental controls on decadal morphologic behaviour of the Holland coast. Marine Geology, 189(3-4): 227-247 p.

Zijlstra, R., Smole, A., Evenhuis, E., Gaudeis, J., 2007. Economische Analyse Kustlijnbeleid. Rapport Fase 1: Analyse ex past. Ministerie van verkeer en waterstaat, RIKZ.

A The Coastal viewer, Wiki page and MorphAn

A.1 The Coastal Viewer[6]

The Coastal Viewer is a tool under development in collaboration with the Building with Nature project. The tool is Google Earth based and works at the present state under the Web Browser “Google Chrome”. The aim is to allow coastal managers and policy makers for a on-line visualization of the state of the coast, of the past and current morphological trends and management choices.

To launch the Coastal Viewer:

1) Open the web browser “Google Chrome”. The web browser is freely available on the internet.
2) The coastal viewer can be found at the webpage: (http://dtvirt13/bwn/optie_compiled/index.html).
3) Select the case of interest (in our case :Kustlijnzorg → Rijkswaterstaat → No subcases available).
4) Launch the viewer.
5) Select on the left side of the window the data set to be visualized (
6) Figure A.1). In the Figure for example the nourishment dataset was selected.
7) The dataset will be visualized on the google earth image on the right side of the window.

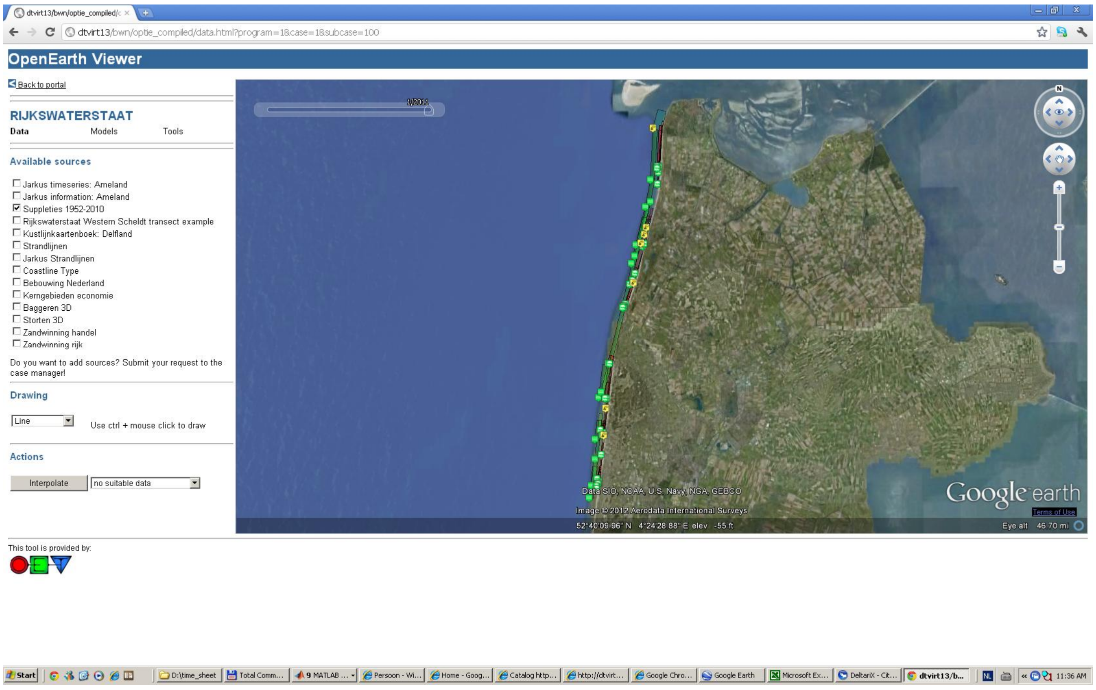


Figure A.1 Screenshot of the Coastal Viewer visualization page.

6. Disclaimer: The tool is under development. The menu might appear different has it shown in the figure. Some of data sets (e.g. Jarkus data) which are rather heavy to be loaded, requires few minutes for being visualized.

A.2 Wiki page: “De Nederlandse Kust in Beeld”[7]

A wiki page containing general explanations about the project and a collection of .kml files for on-line visualization.

Webpage: http://publicwiki.deltares.nl/display/GEC/Home

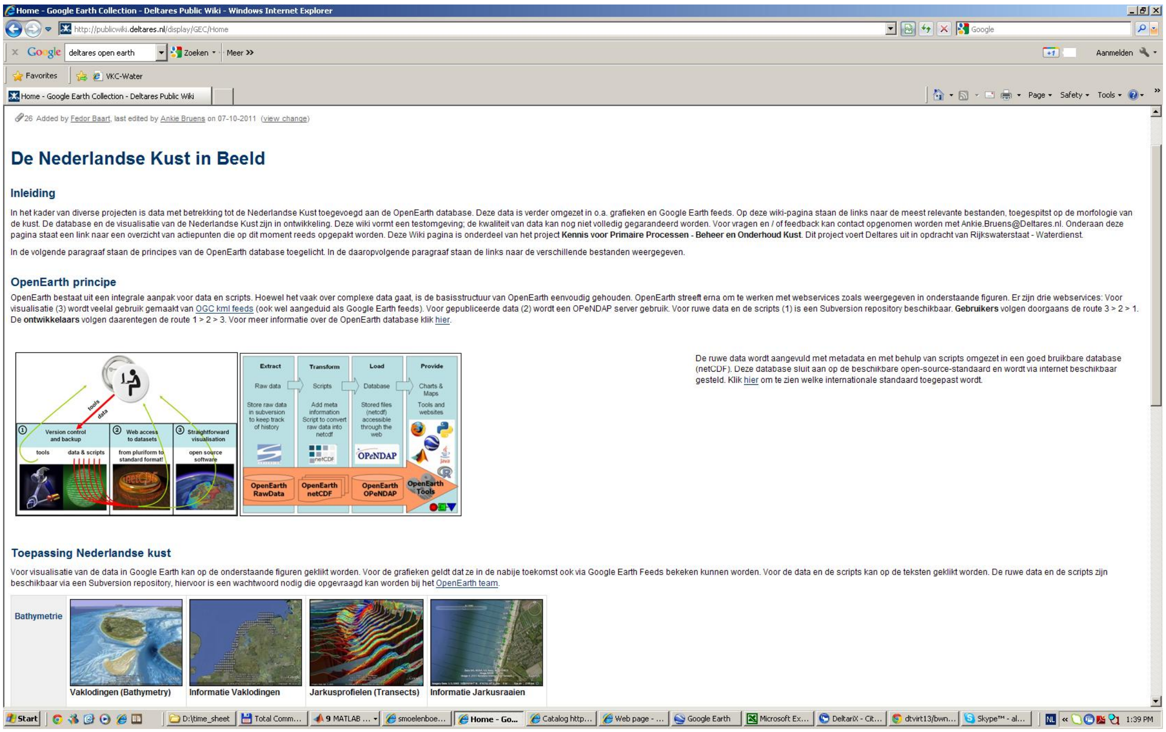


Figure A.2 Screenshot of the Wiki page: “De Nederlandse Kust in Beeld.

7. *Disclaimer: The wiki page is still under development. The page might appear different has it shown in the figure.*

A.3 MorphAn[8]

MorphAn is a new tool that enables easy assessment of sandy coasts (Lodder and Van Geer, in preparation). MorphAn provides the possibility to import data of various formats. Data can be analyzed with a GIS based map view. Furthermore MorphAn includes the possibility to assess coasts for dune safety according the safety assessment rules VTV2006. Calculations of dune erosion according to the Duros+ and D++ model as well as calculation of the normative erosion points are graphically presented within the software program. MorphAn also provides the possibility to calculate the momentary coastline (MKL) and the expected near future coast line position (TKL). In the near future, the software will be freely available.

Contact persons: Pieter van Geer (Deltares), Quirijn Lodder (Waterdienst)

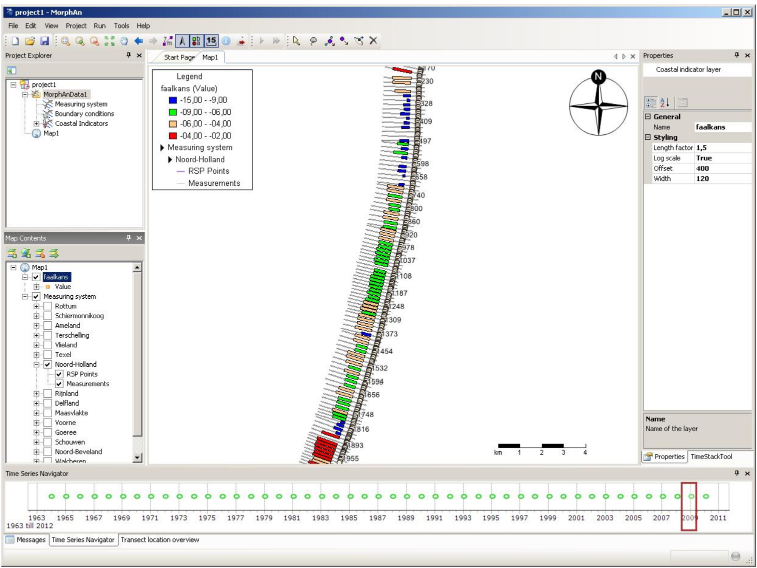


Figure A.3 Screenshot of the Morphan visualization page.

8. *Disclaimer: MorphAn is still under development. The screenshot might appear different than the current version.*

B The indicator database

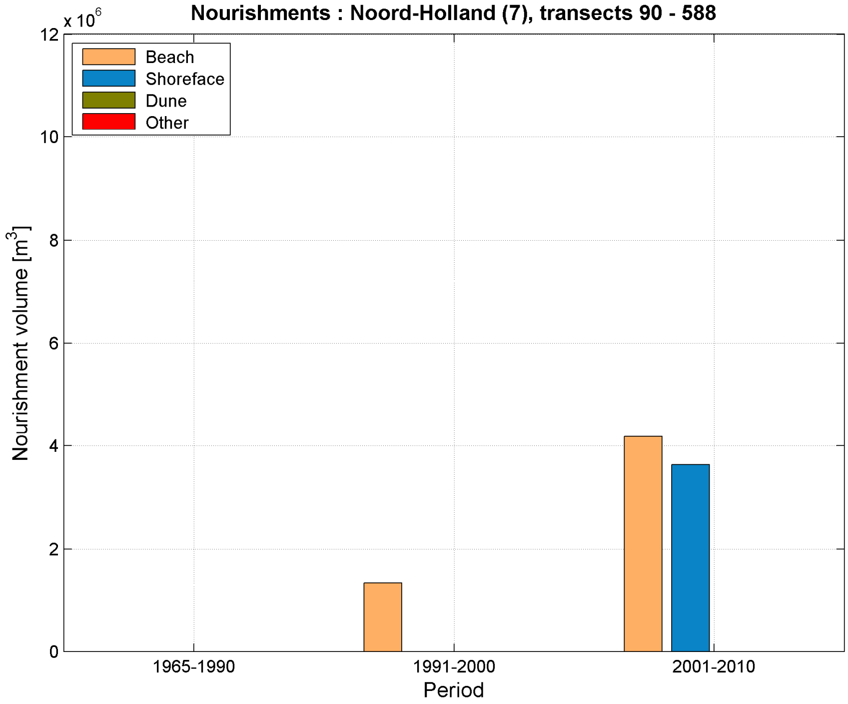
A complete database with the different indicators has been developed within this study. These data are freely available in NetCDF format through the Open Earth system (https://publicwiki.deltares.nl/display/OET/OpenEarth). Table B.1 gives the full list of indicators, accompanied by the URL link from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

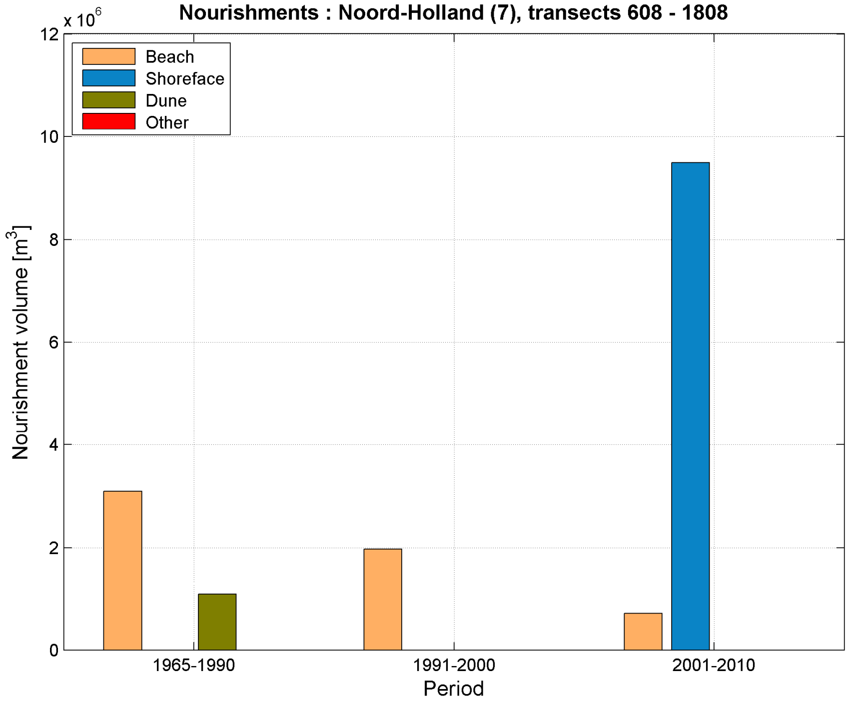
Table B.1 List of indicators with URL from which the dataset can be downloaded

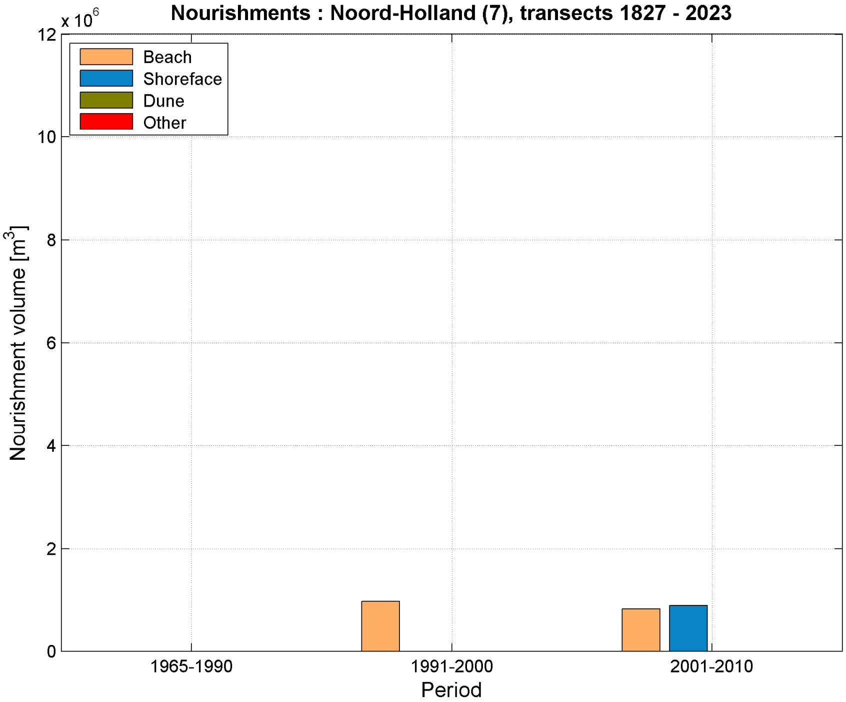
Indicator	URL Link
Nourishments	http://opendap.deltares.nl/thredds/dodsC/opendap/rijkswaterstaat/suppleties/suppleties.nc
Probability of breaching	http://opendap.deltares.nl/thredds/dodsC/opendap/rijkswaterstaat/faalkans_PC-Ring/faalkans.nc
Erosion length, MDL	http://opendap.deltares.nl/thredds/dodsC/opendap/rijkswaterstaat/safetyIndicators_Arcadis/kustlijnindic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

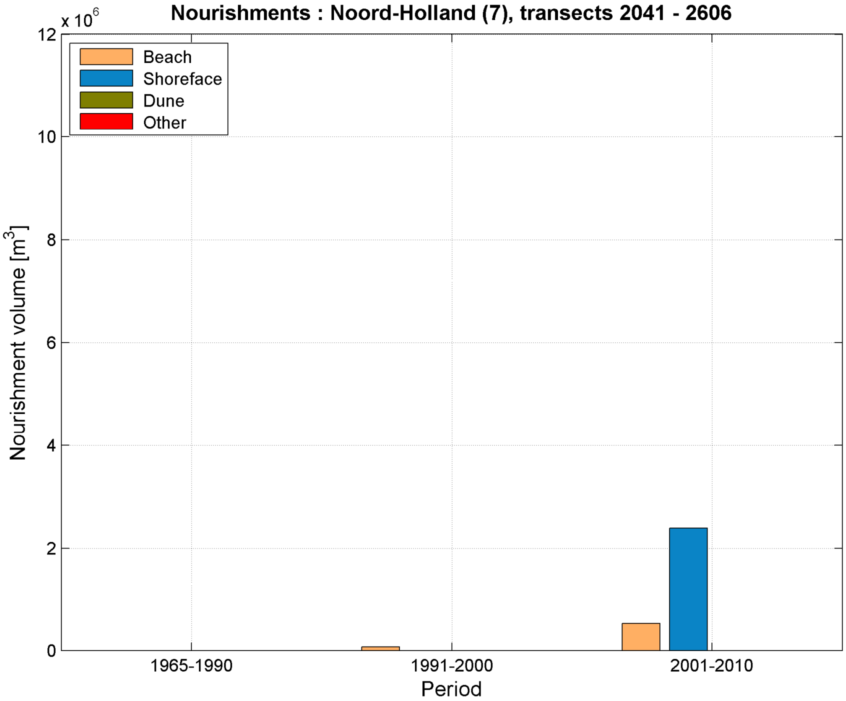
C Nourishment volumes

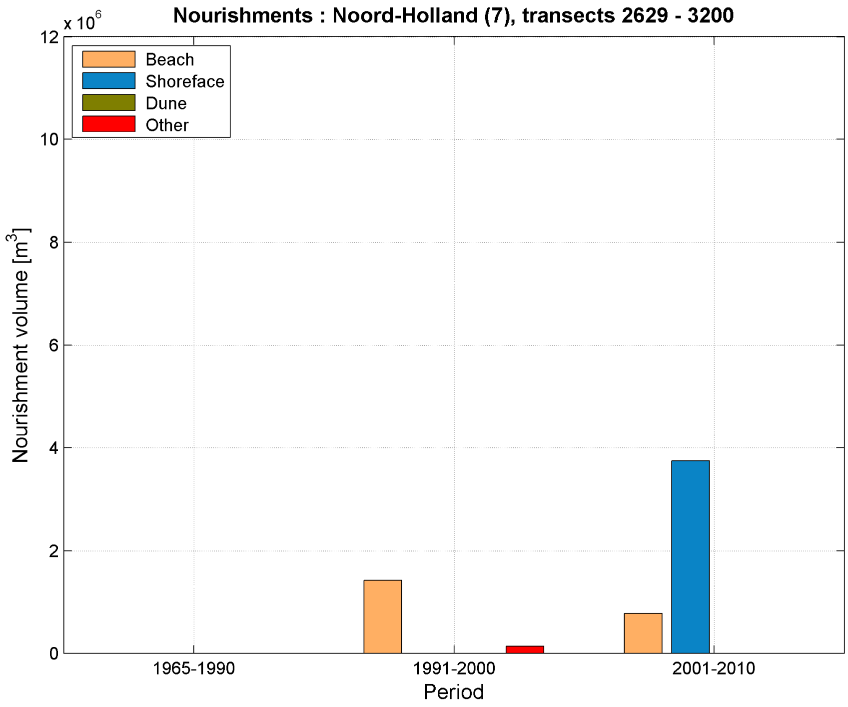
C.1 Nourishment volumes per coastal stretch

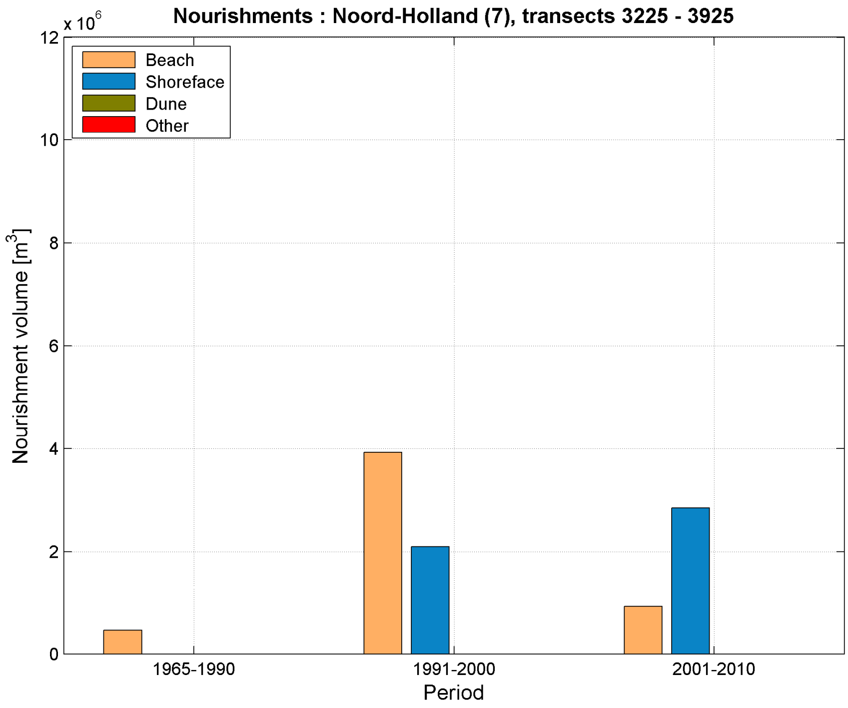


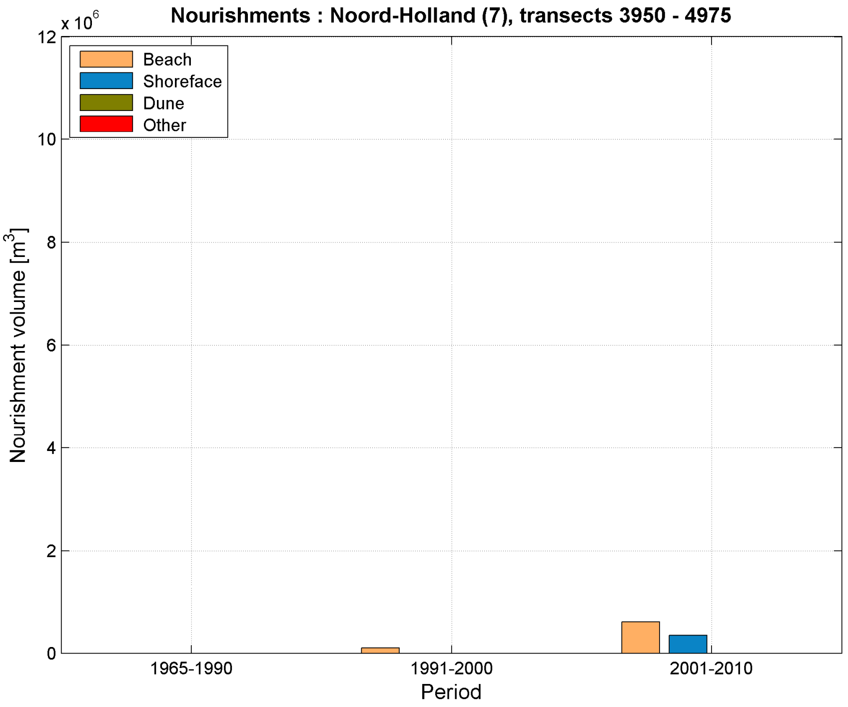


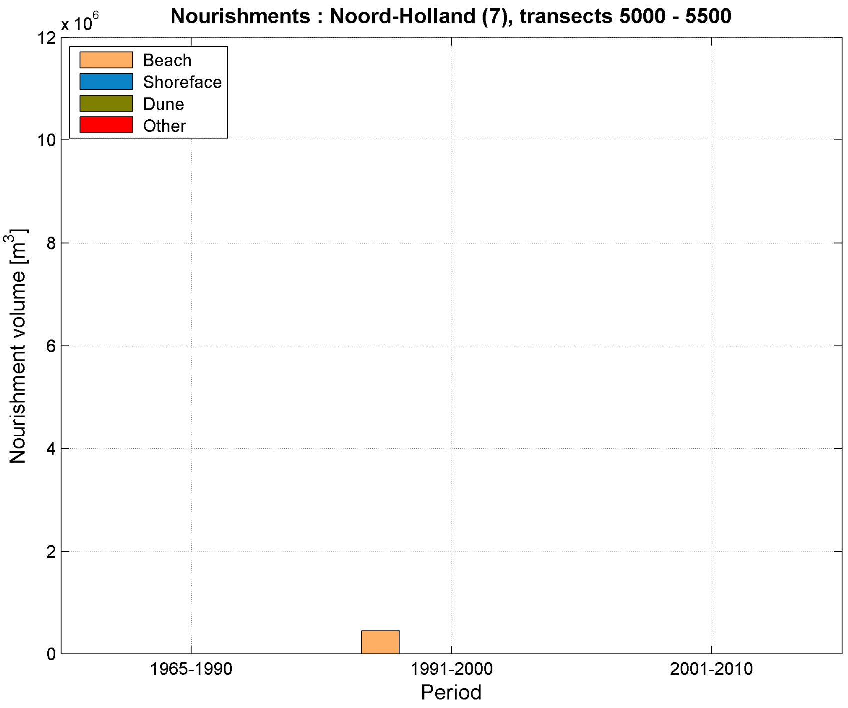

Nourishments : Noord-Holland (7), transects 1827 - 2023
x 10^6
Beach
Shoreface
Dune
Other
Nourishment volume [m³]
1965-1990
1991-2000
2001-2010
Period


Nourishments : Noord-Holland (7), transects 2041 - 2606
x 10^6
Beach
Shoreface
Dune
Other
Nourishment volume [m³]
1965-1990
1991-2000
2001-2010
Period

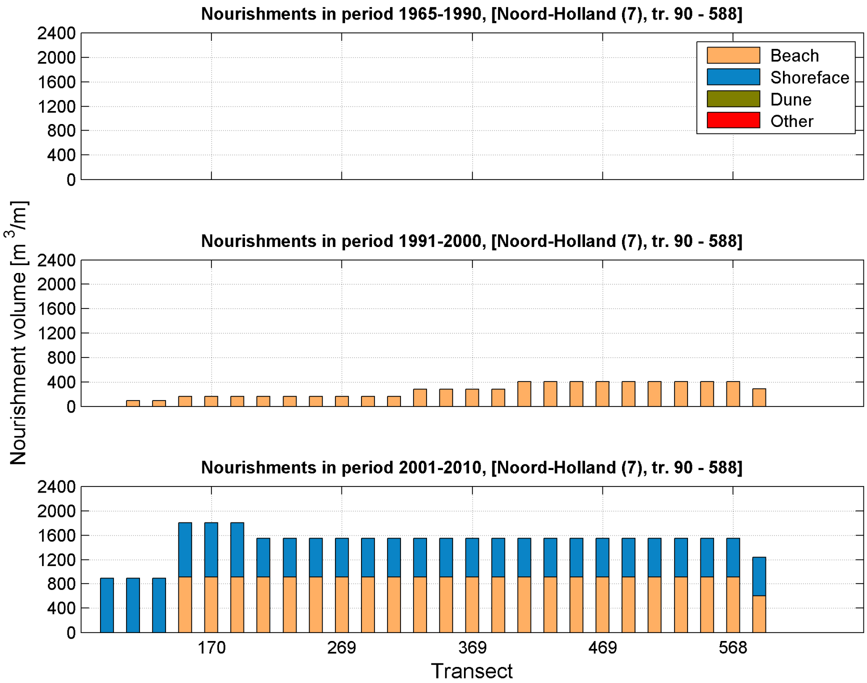

Nourishments : Noord-Holland (7), transects 2629 - 3200
x 10^6
Beach
Shoreface
Dune
Other
Nourishment volume [m^3]
12
10
8
6
4
2
0
1965-1990
1991-2000
2001-2010
Period

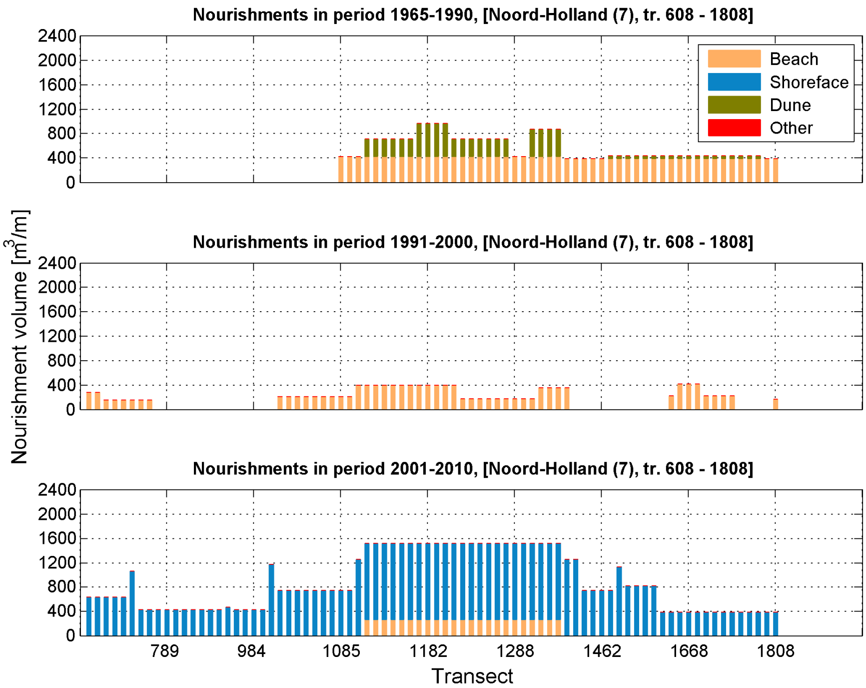

Nourishments : Noord-Holland (7), transects 3225 - 3925
x 10^6
Beach
Shoreface
Dune
Other
Nourishment volume [m^3]
12
10
8
6
4
2
0
1965-1990
1991-2000
2001-2010
Period

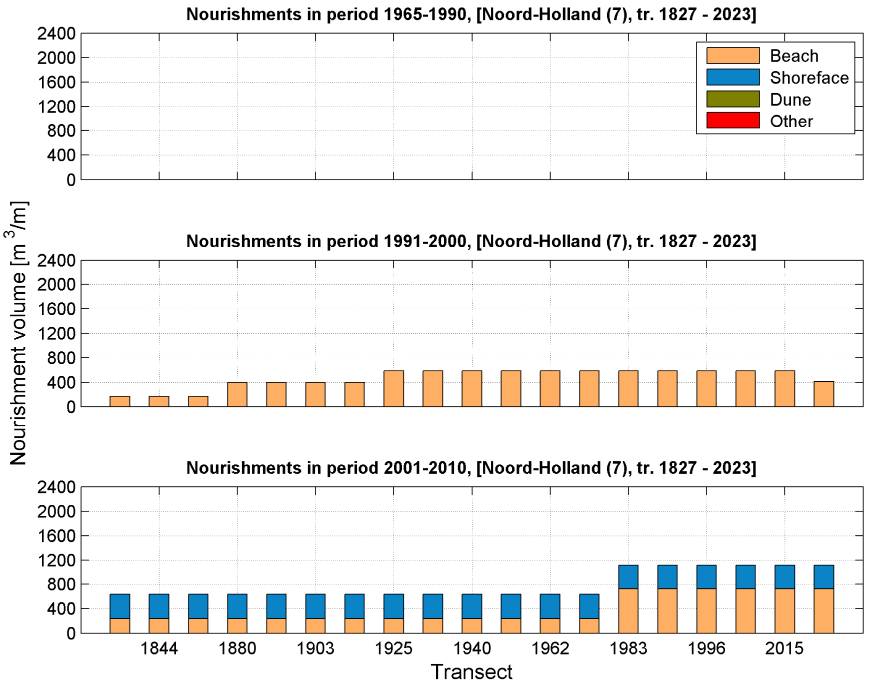

Nourishments : Noord-Holland (7), transects 3950 - 4975
x 10^6
Beach
Shoreface
Dune
Other
Nourishment volume [m^3]
12
10
8
6
4
2
0
1965-1990
1991-2000
2001-2010
Period

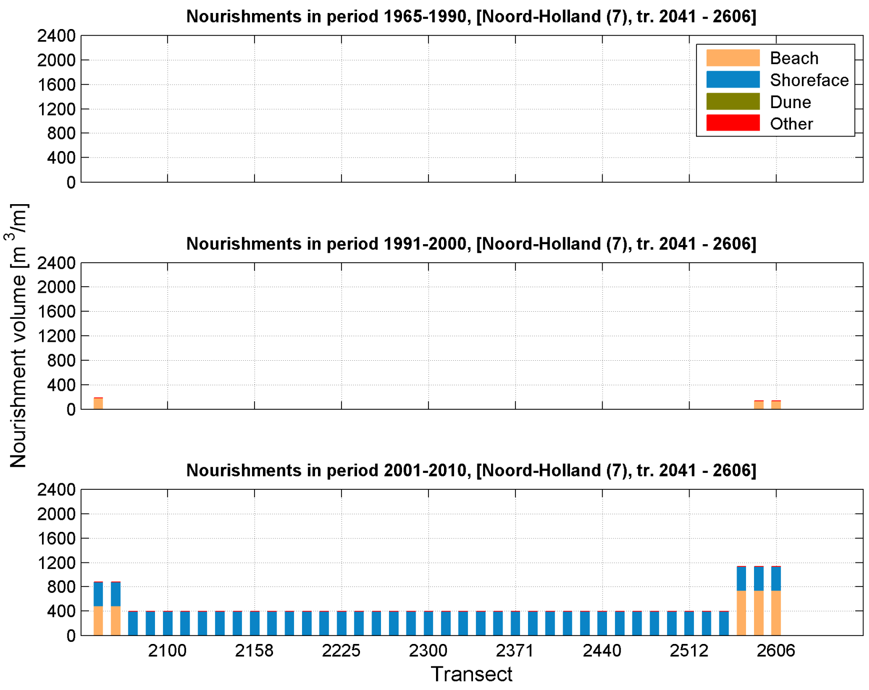

Nourishments : Noord-Holland (7), transects 5000 - 5500
x 10^6
Beach
Shoreface
Dune
Other
Nourishment volume [m^3]
12
10
8
6
4
2
0
1965-1990
1991-2000
2001-2010
Period

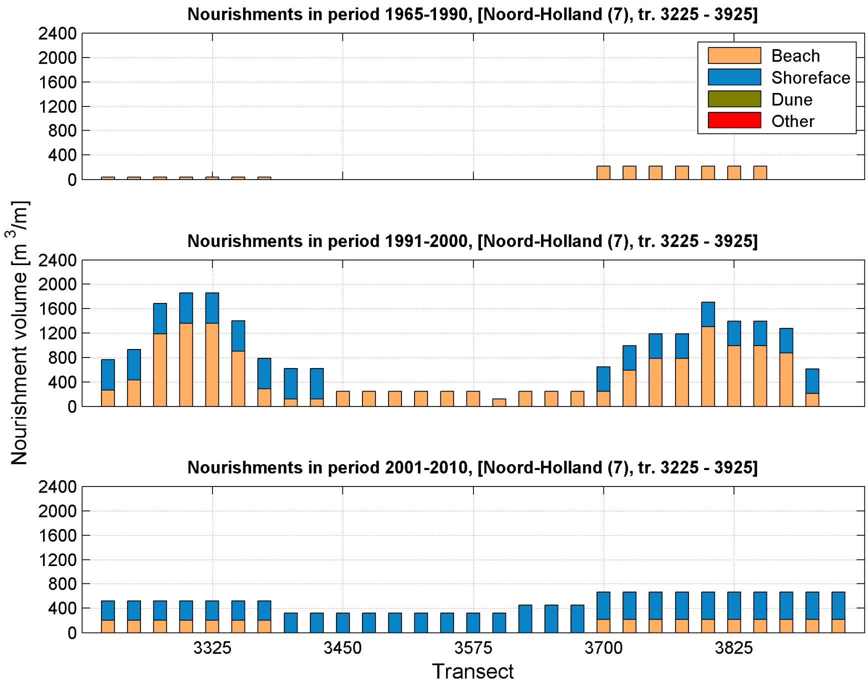
C.2 Nourishment volumes per Jarkus transect



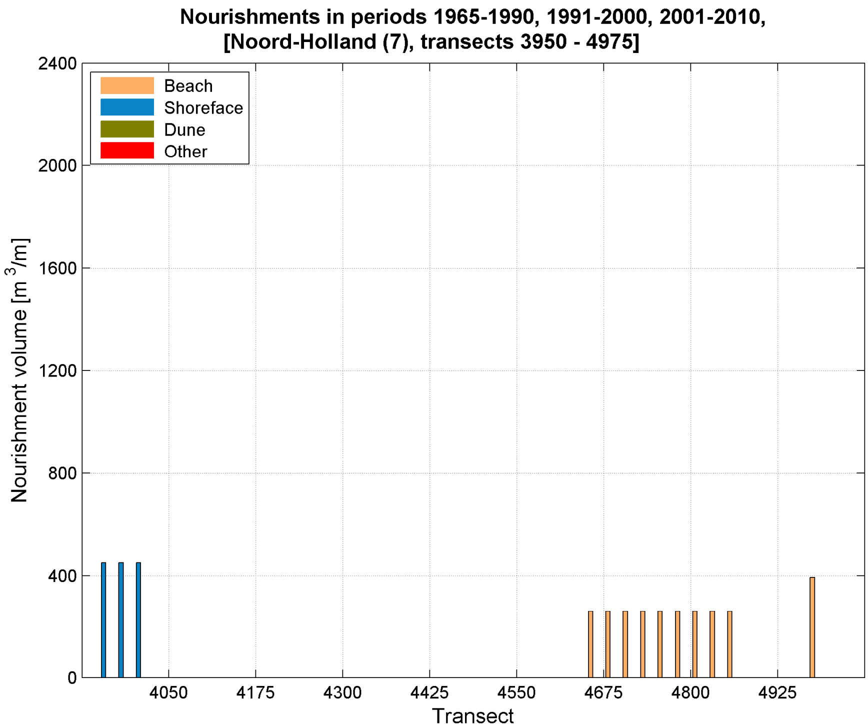



Nourishments in period 1965-1990, [Noord-Holland (7), tr. 1827 - 2023]
Beach
Shoreface
Dune
Other
Nourishments in period 1991-2000, [Noord-Holland (7), tr. 1827 - 2023]
Nourishments in period 2001-2010, [Noord-Holland (7), tr. 1827 - 2023]
Nourishment volume [m 3/m]
2400
2000
1600
1200
800
400
0
1844
1880
1903
1925
1940
1962
1983
1996
2015
Transect

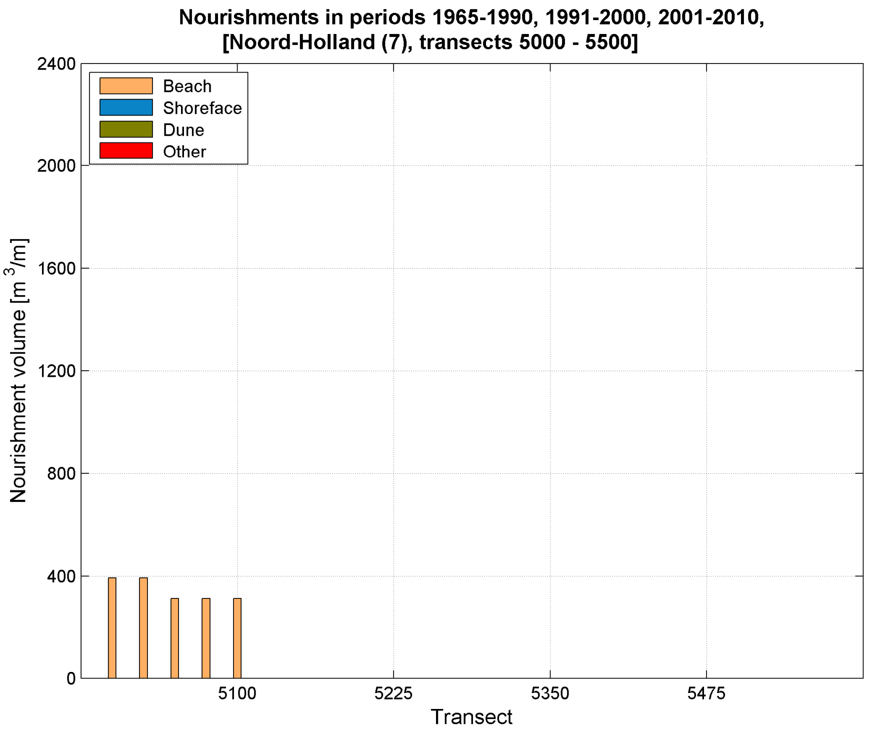

Nourishments in period 1965-1990, [Noord-Holland (7), tr. 2041 - 2606]
Beach
Shoreface
Dune
Other
Nourishments in period 1991-2000, [Noord-Holland (7), tr. 2041 - 2606]
Nourishments in period 2001-2010, [Noord-Holland (7), tr. 2041 - 2606]
Nourishment volume [m 3/m]
2400
2000
1600
1200
800
400
0
2100
2158
2225
2300
2371
2440
2512
2606
Transect



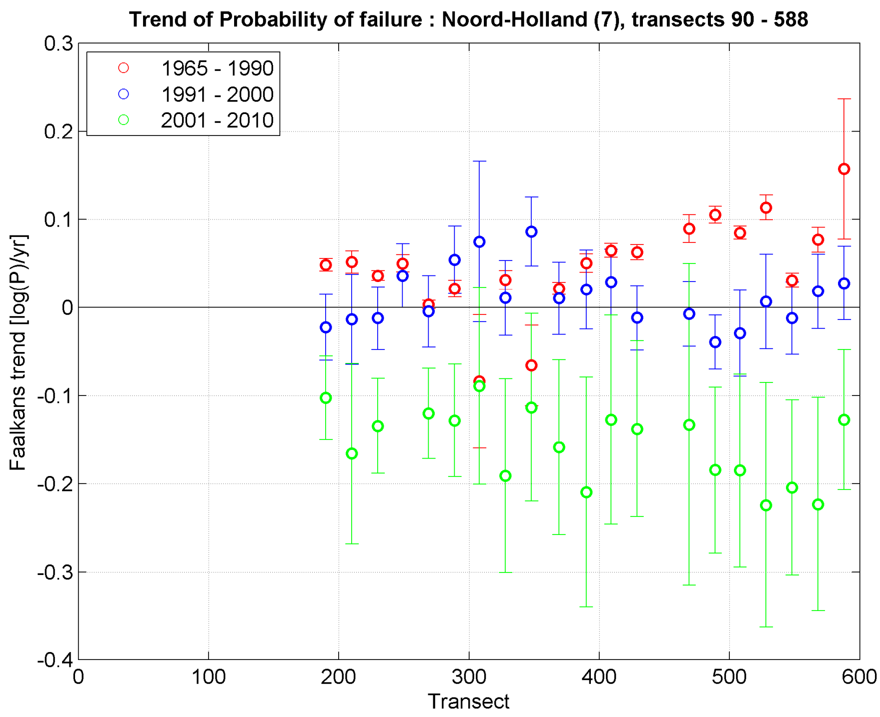
Nourishments in period 1965-1990, [Noord-Holland (7), tr. 3225 - 3925]
Beach
Shoreface
Dune
Other
Nourishments in period 1991-2000, [Noord-Holland (7), tr. 3225 - 3925]
Nourishments in period 2001-2010, [Noord-Holland (7), tr. 3225 - 3925]
Nourishment volume [m 3/m]
2400
2000
1600
1200
800
400
0
3325
3450
3575
3700
3825
Transect

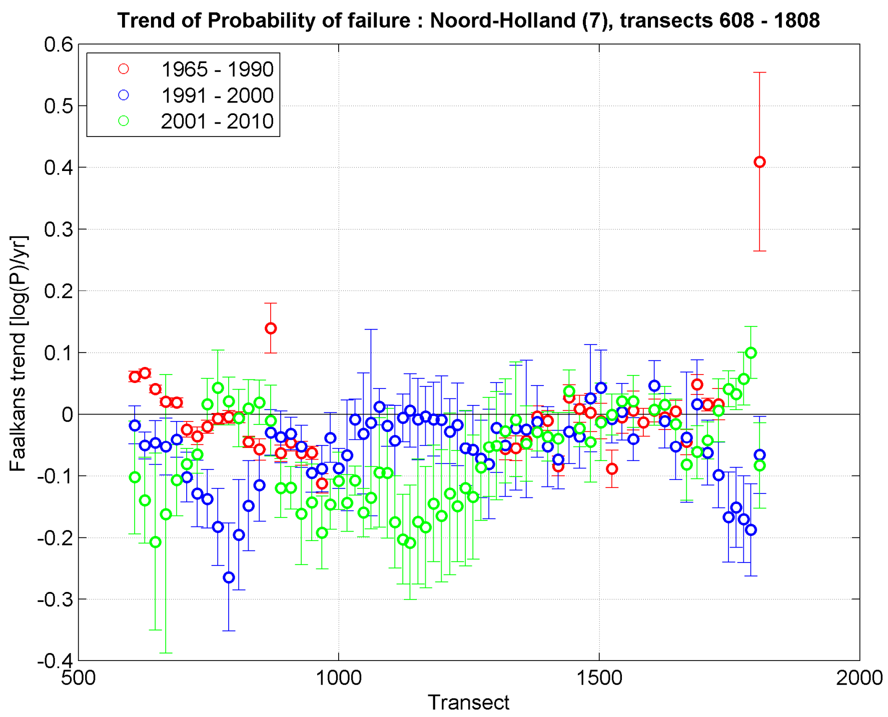


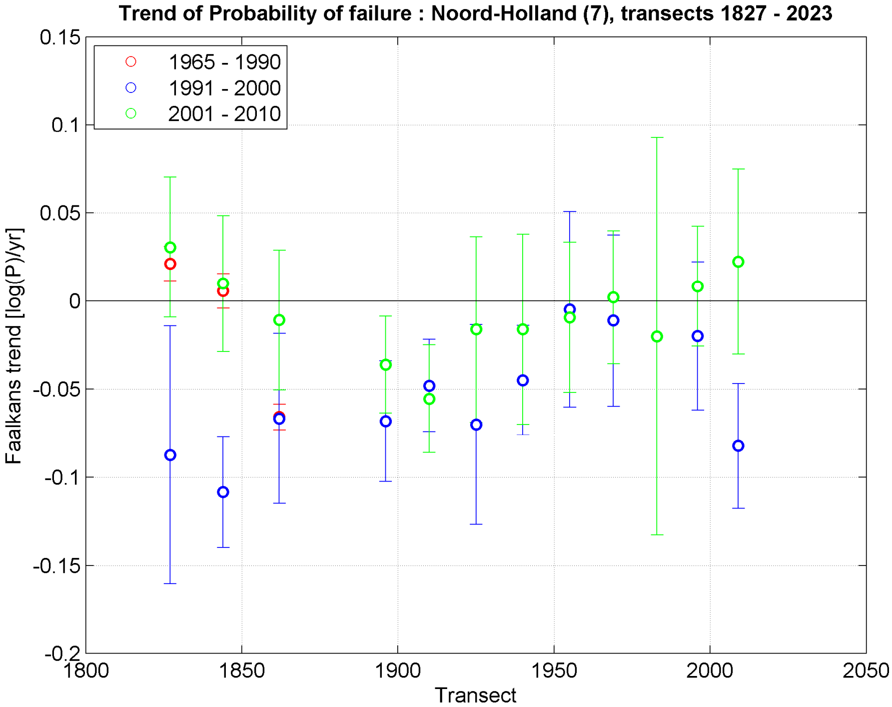
Nourishments in periods 1965-1990, 1991-2000, 2001-2010,
[Noord-Holland (7), transects 3950 - 4975]
Beach
Shoreface
Dune
Other
Nourishment volume [m 3/m]
2400
2000
1600
1200
800
400
0
4050
4175
4300
4425
4550
4675
4800
4925
Transect

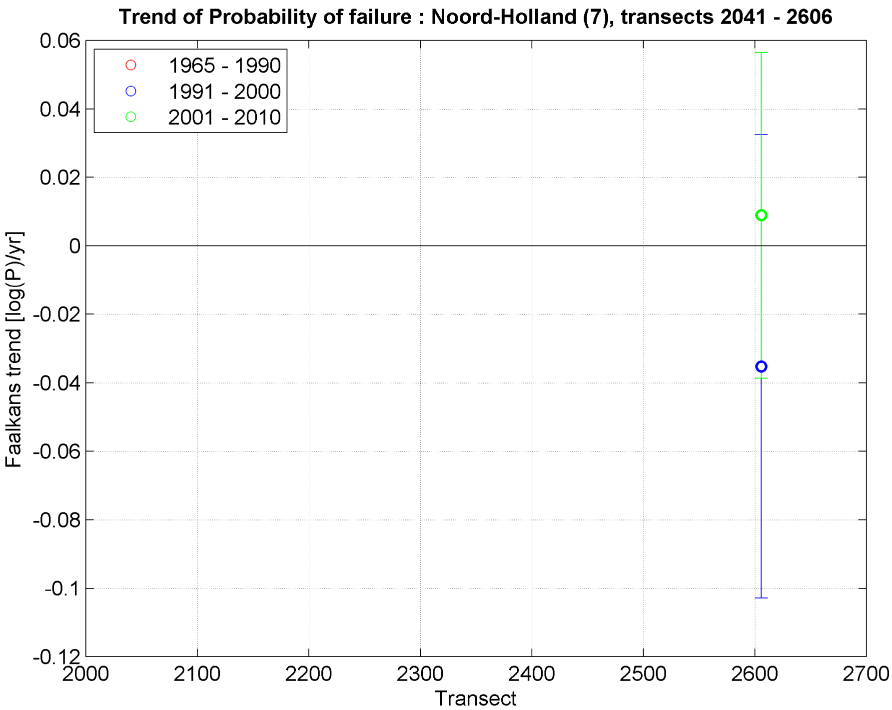

Nourishments in periods 1965-1990, 1991-2000, 2001-2010,
[Noord-Holland (7), transects 5000 - 5500]
Beach
Shoreface
Dune
Other
Nourishment volume [m 3/m]
2400
2000
1600
1200
800
400
0
5100
5225
5350
5475
Transect

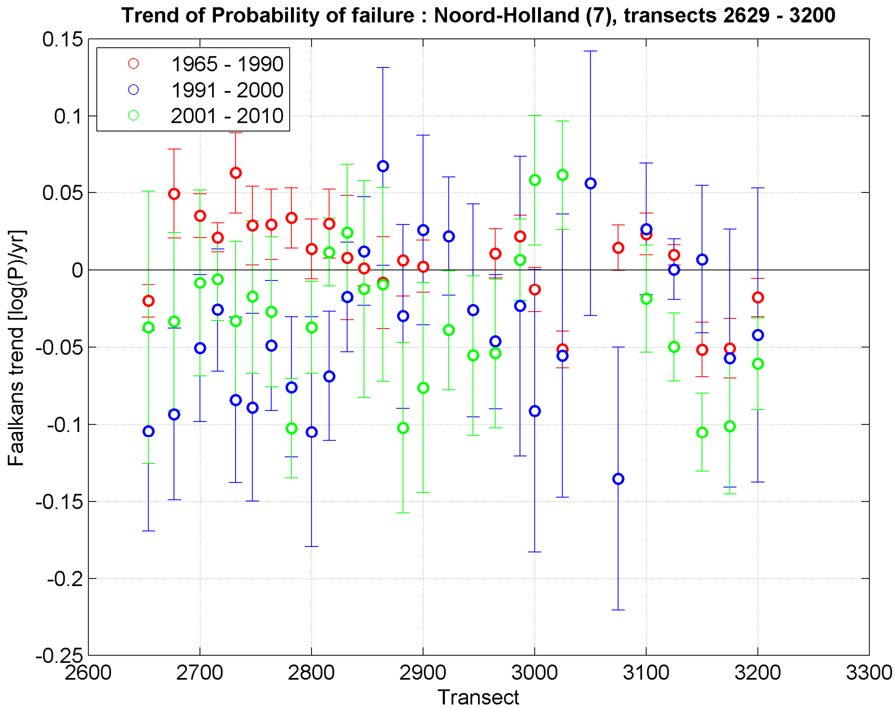
D Probability of breaching

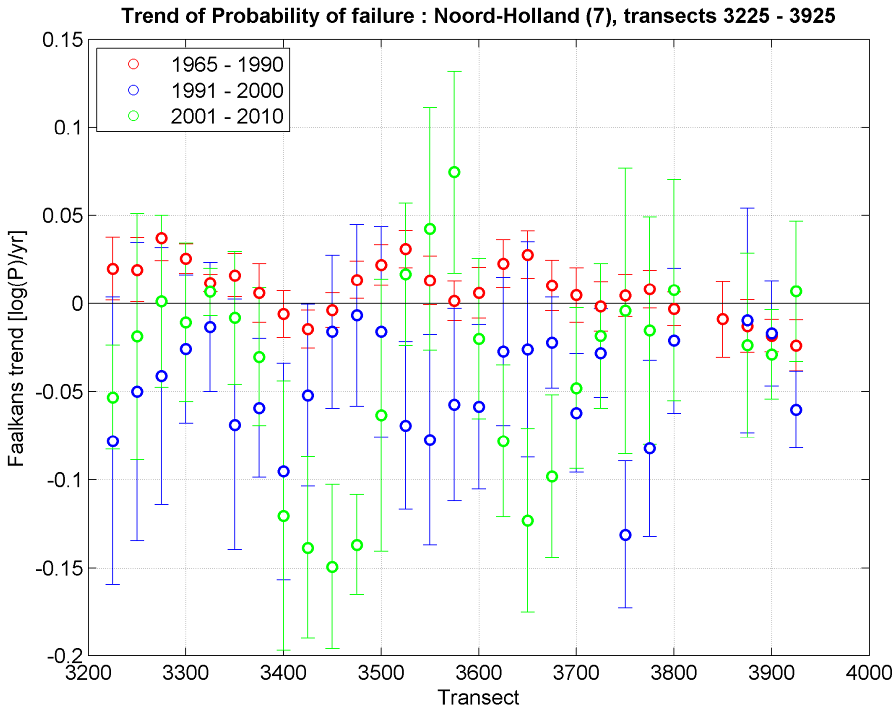


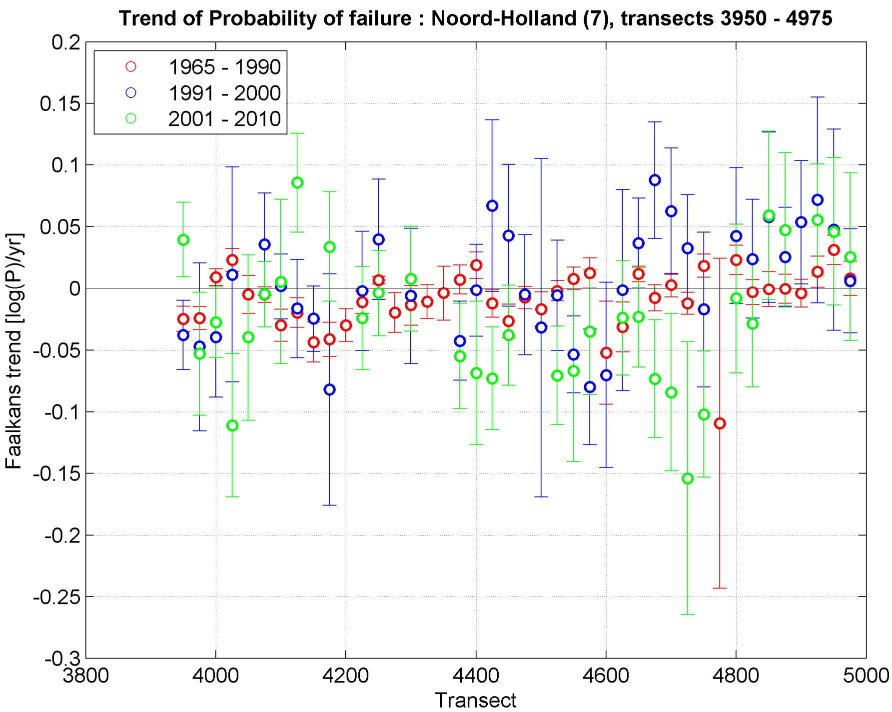


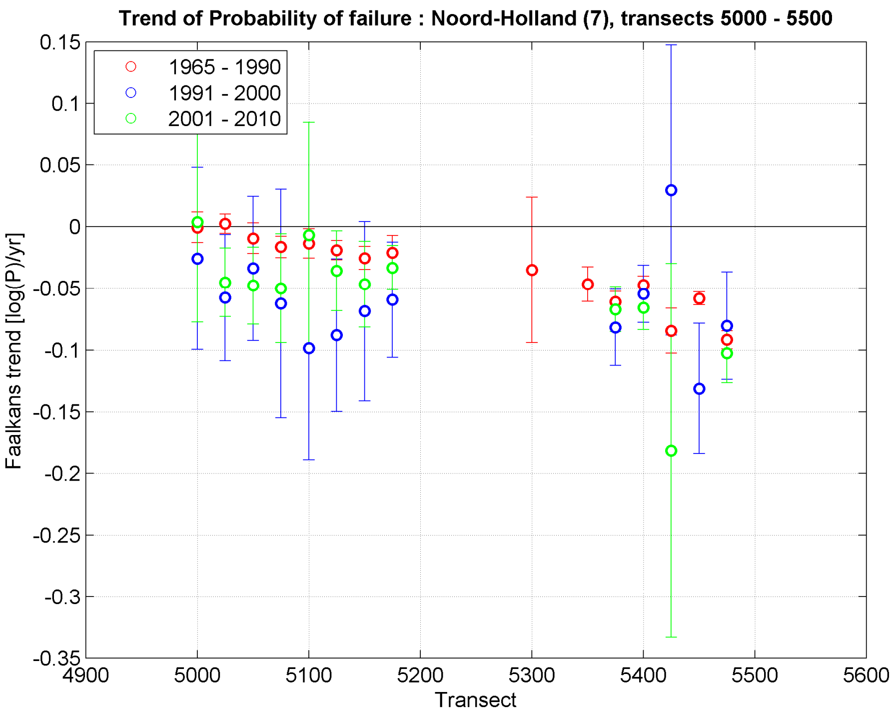

Trend of Probability of failure : Noord-Holland (7), transects 1827 - 2023
1965 - 1990
1991 - 2000
2001 - 2010
Faalkans trend [log(P)/yr]
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
1800
1850
1900
1950
2000
2050
Transect


Trend of Probability of failure : Noord-Holland (7), transects 2041 - 2606
1965 - 1990
1991 - 2000
2001 - 2010
Faalkans trend [log(P)/yr]
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
2000
2100
2200
2300
2400
2500
2600
2700
Transect


Trend of Probability of failure : Noord-Holland (7), transects 2629 - 3200
1965 - 1990
1991 - 2000
2001 - 2010
Faalkans trend [log(P)/yr]
Transect
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
2600
2700
2800
2900
3000
3100
3200
3300

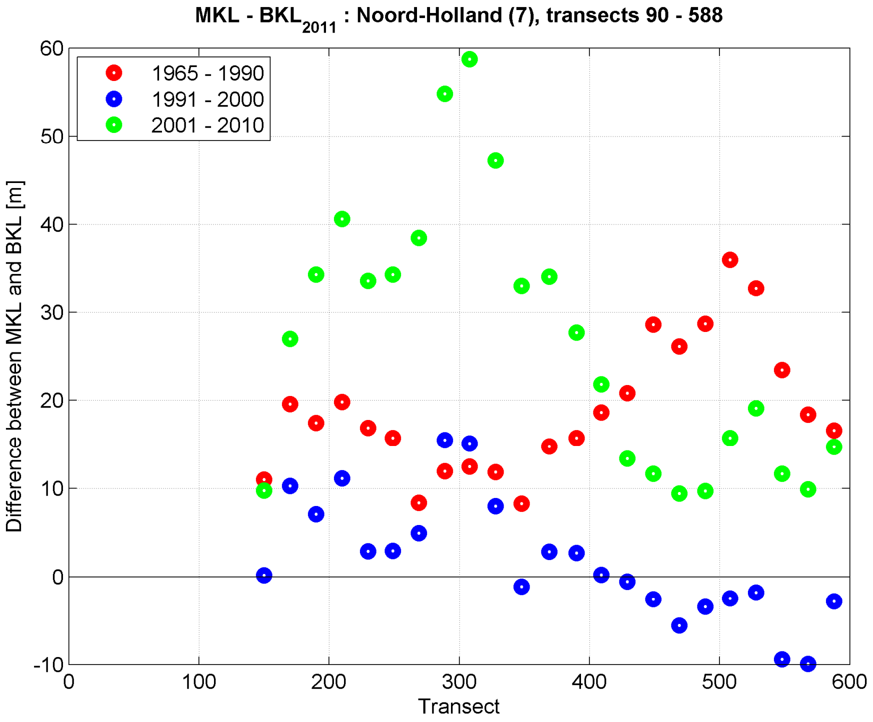

Trend of Probability of failure : Noord-Holland (7), transects 3225 - 3925
1965 - 1990
1991 - 2000
2001 - 2010
Faalkans trend [log(P)/yr]
Transect
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
3200
3300
3400
3500
3600
3700
3800
3900
4000

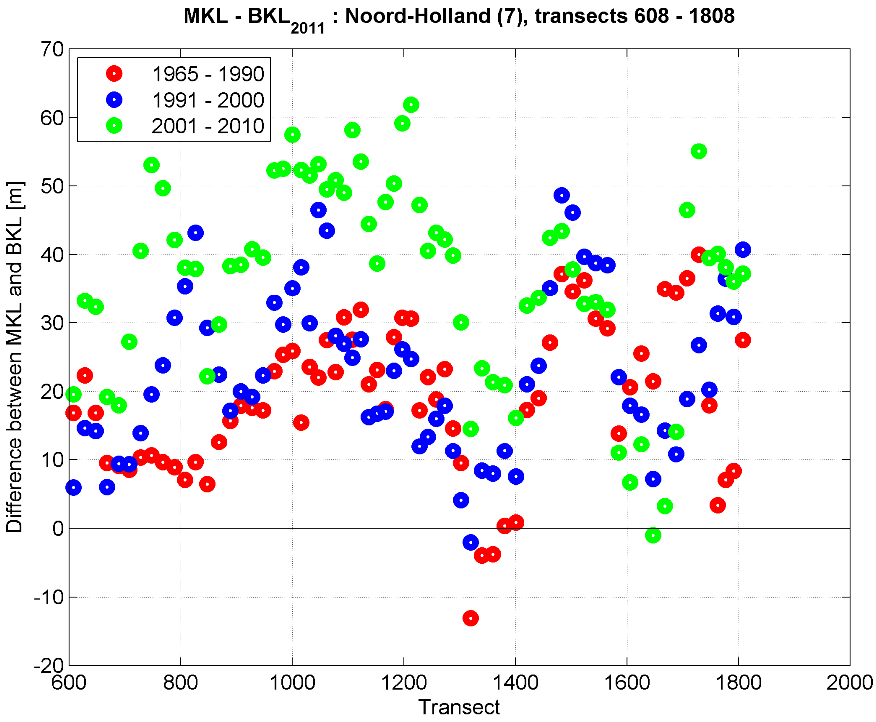

Trend of Probability of failure : Noord-Holland (7), transects 3950 - 4975
1965 - 1990
1991 - 2000
2001 - 2010
Faalkans trend [log(P)/yr]
Transect
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
3800
4000
4200
4400
4600
4800
5000

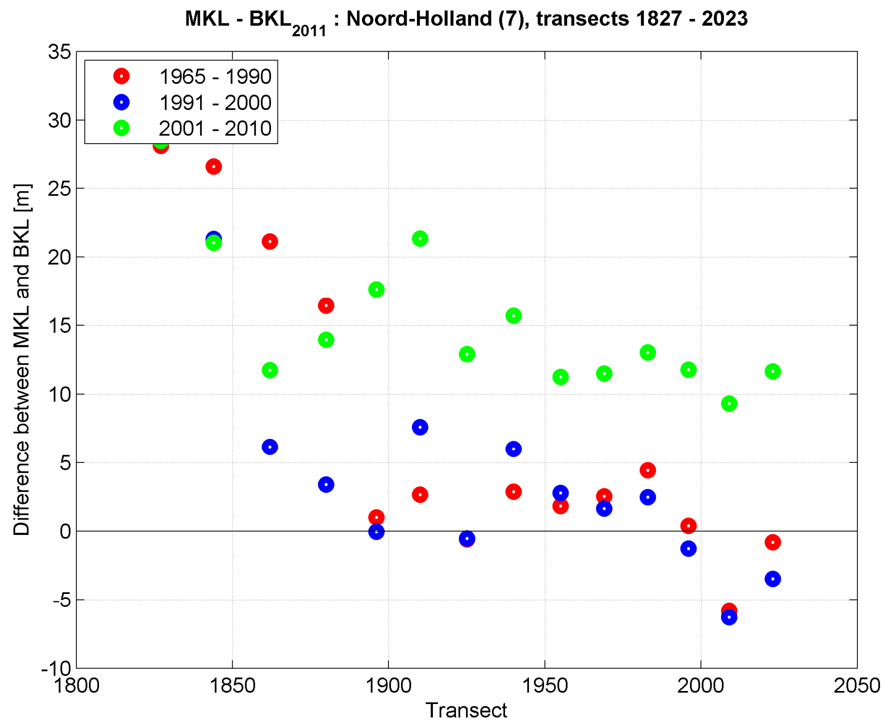

Trend of Probability of failure : Noord-Holland (7), transects 5000 - 5500
1965 - 1990
1991 - 2000
2001 - 2010
Faalkans trend [log(P)/yr]
Transect
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
-0.35
4900
5000
5100
5200
5300
5400
5500
5600

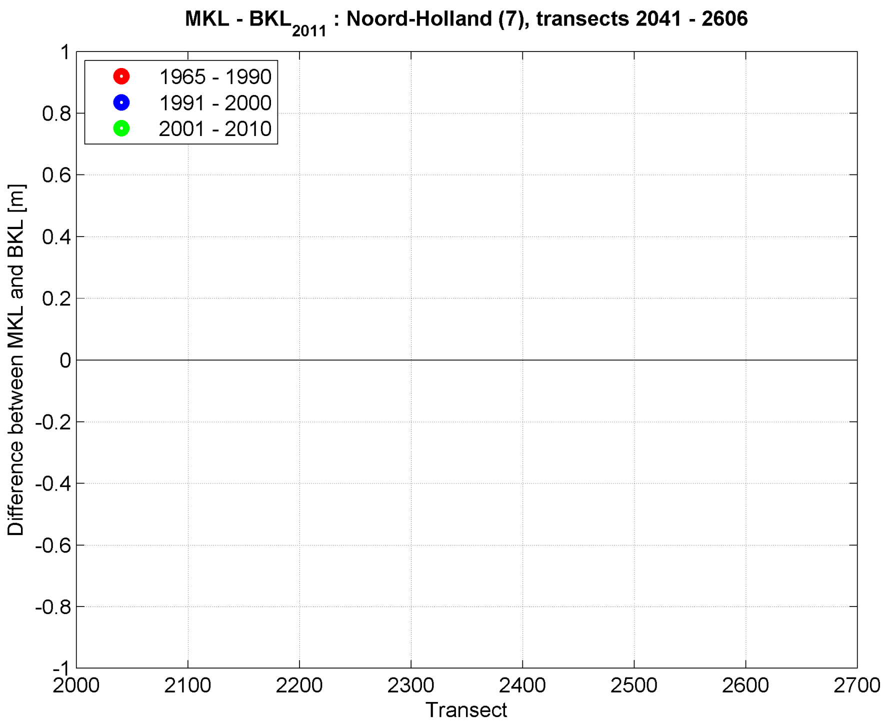
E MKL

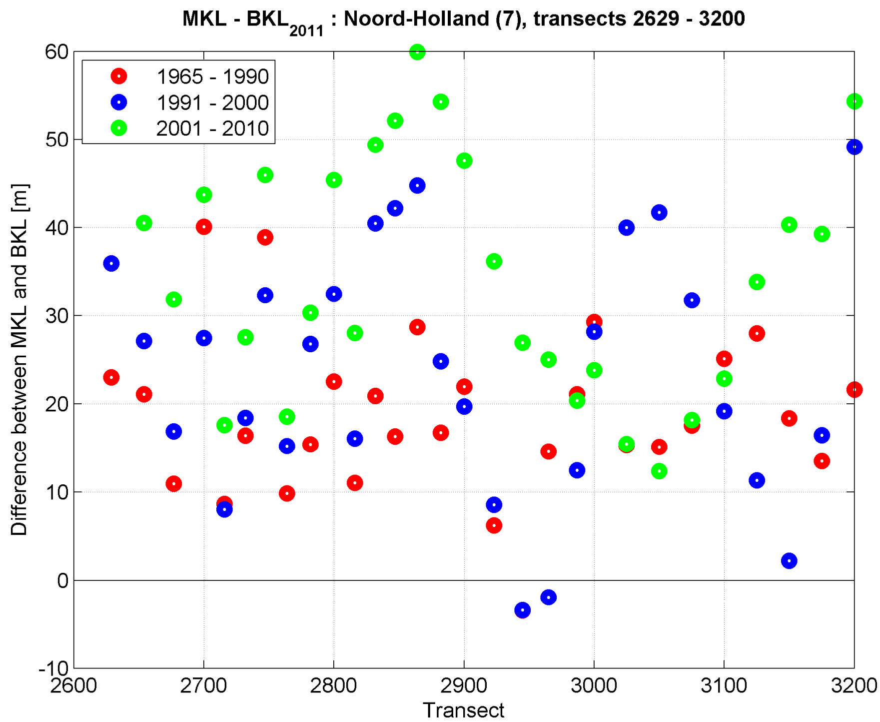
E.1 MKL - BKL 2001

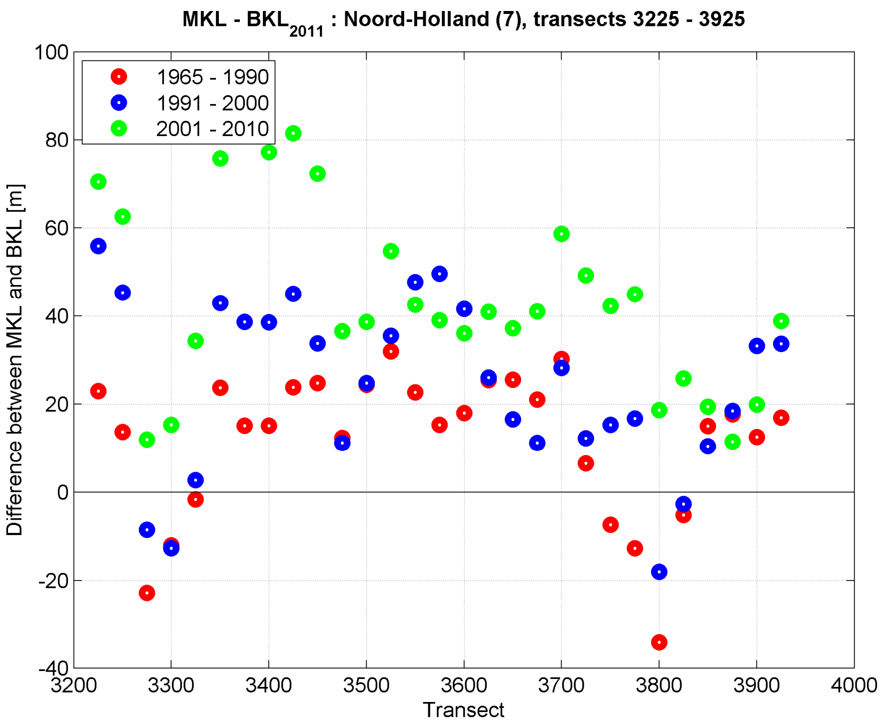


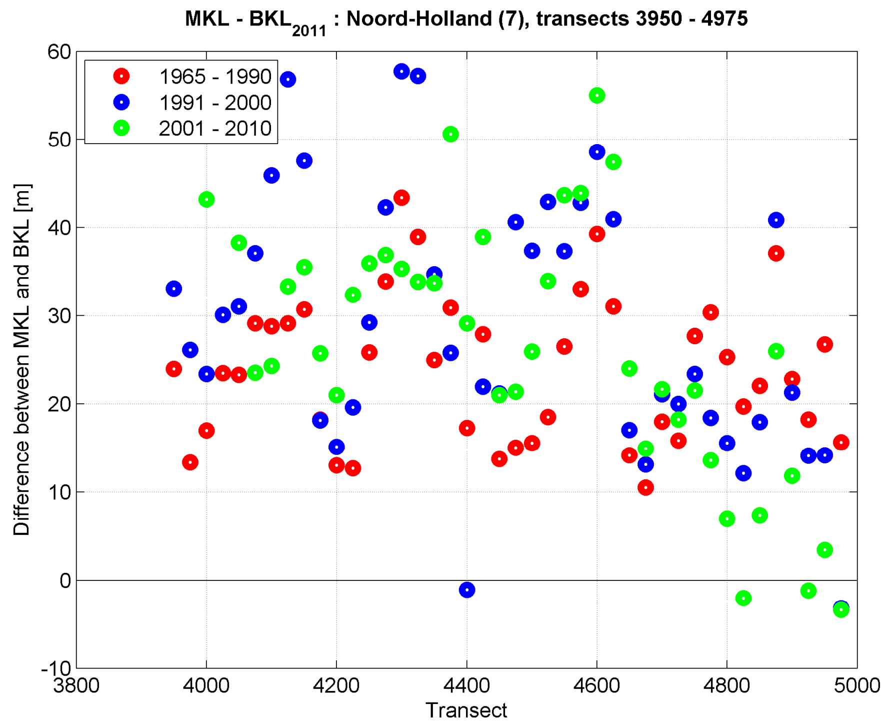


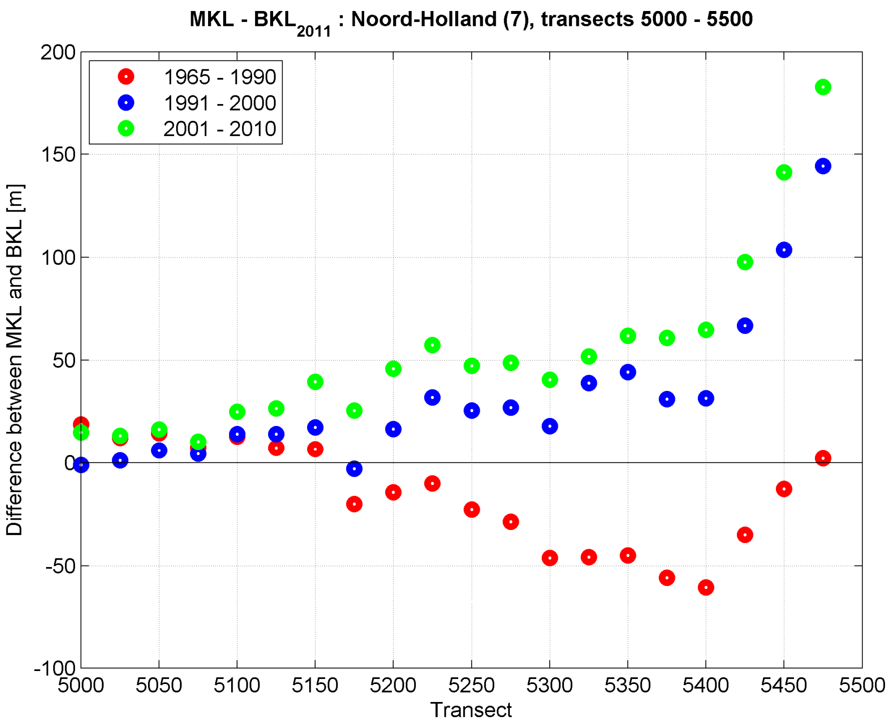

MKL - BKL2011 : Noord-Holland (7), transects 1827 - 2023
1965 - 1990
1991 - 2000
2001 - 2010
Difference between MKL and BKL [m]
Transect
35
30
25
20
15
10
5
0
-5
-10
1800
1850
1900
1950
2000
2050


MKL - BKL2011 : Noord-Holland (7), transects 2041 - 2606
1965 - 1990
1991 - 2000
2001 - 2010
Difference between MKL and BKL [m]
Transect
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
2000
2100
2200
2300
2400
2500
2600
2700

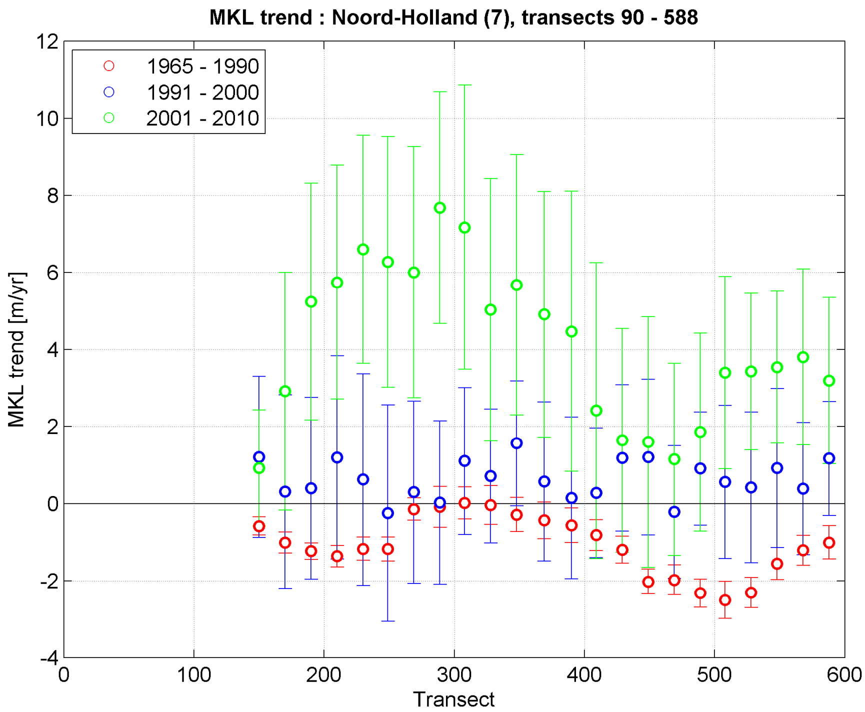

MKL - BKL2011 : Noord-Holland (7), transects 2629 - 3200
1965 - 1990
1991 - 2000
2001 - 2010
Difference between MKL and BKL [m]
Transect
60
50
40
30
20
10
0
-10
2600
2700
2800
2900
3000
3100
3200

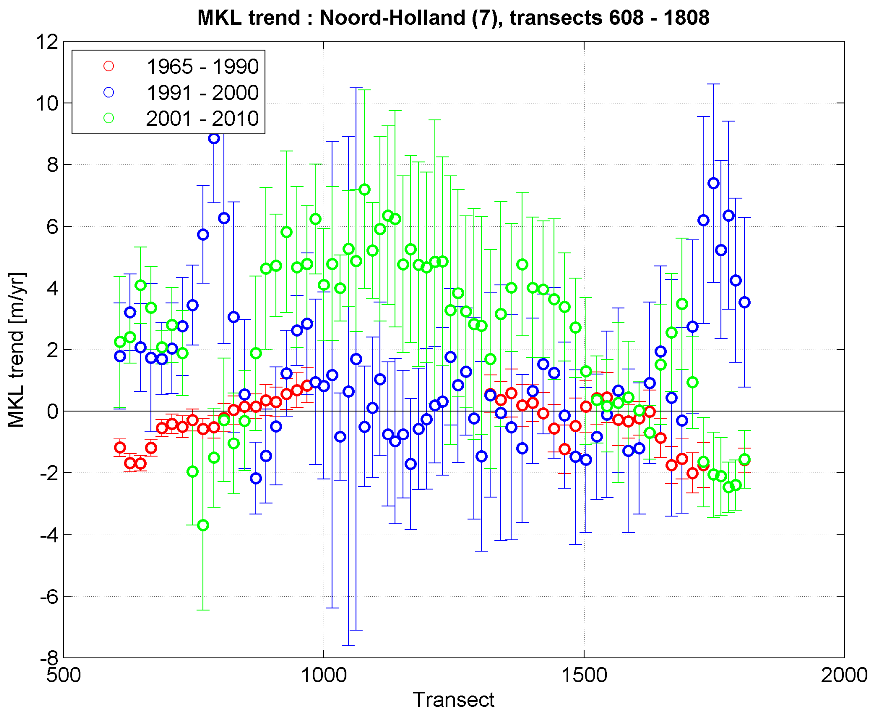

MKL - BKL2011 : Noord-Holland (7), transects 3225 - 3925
1965 - 1990
1991 - 2000
2001 - 2010
Difference between MKL and BKL [m]
Transect
100
80
60
40
20
0
-20
-40
3200
3300
3400
3500
3600
3700
3800
3900
4000

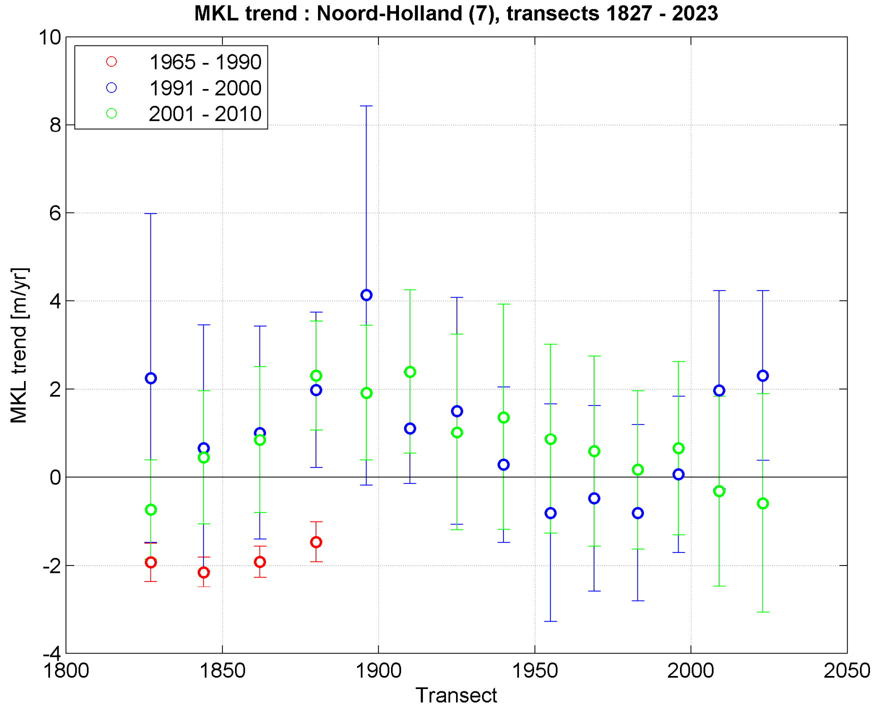

MKL - BKL$_{2011}$: Noord-Holland (7), transects 3950 - 4975
1965 - 1990
1991 - 2000
2001 - 2010
Difference between MKL and BKL [m]
Transect
60
50
40
30
20
10
0
-10
3800
4000
4200
4400
4600
4800
5000

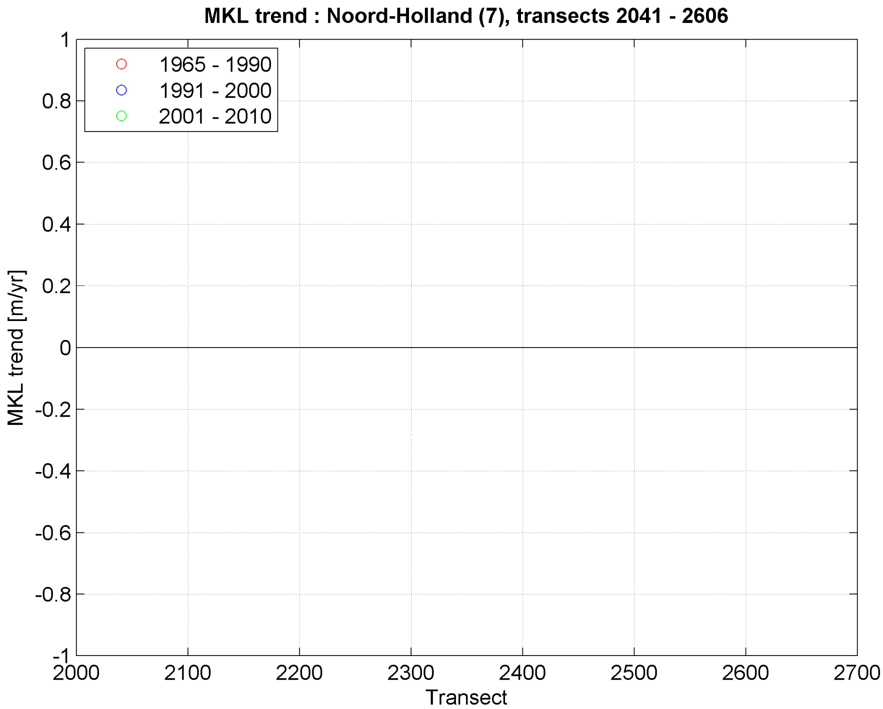

MKL - BKL$_{2011}$: Noord-Holland (7), transects 5000 - 5500
1965 - 1990
1991 - 2000
2001 - 2010
Difference between MKL and BKL [m]
Transect
200
150
100
50
0
-50
-100
5000
5050
5100
5150
5200
5250
5300
5350
5400
5450
5500

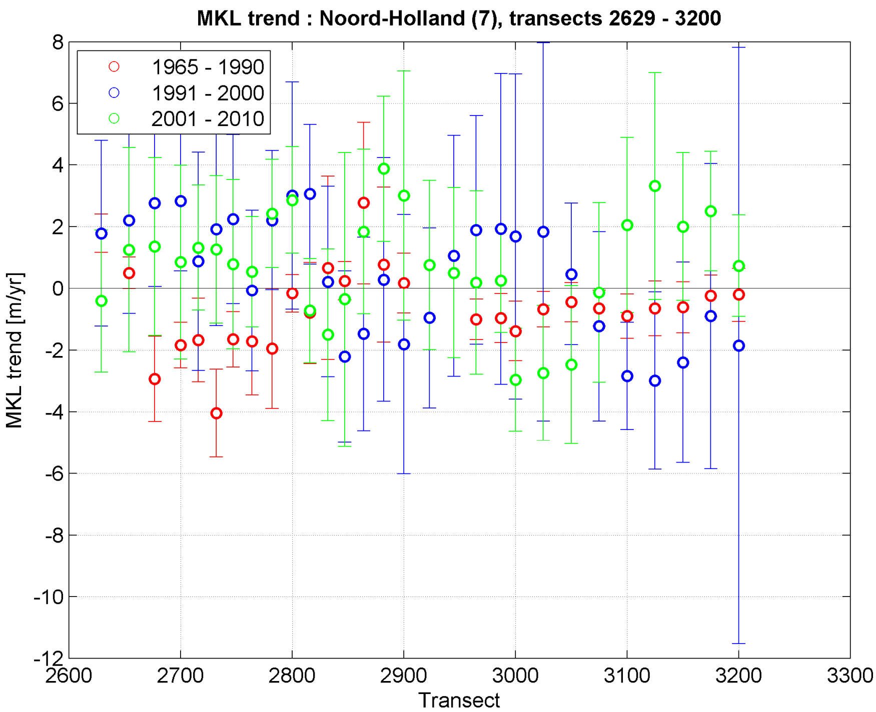
E.2 MKL: trend analysis

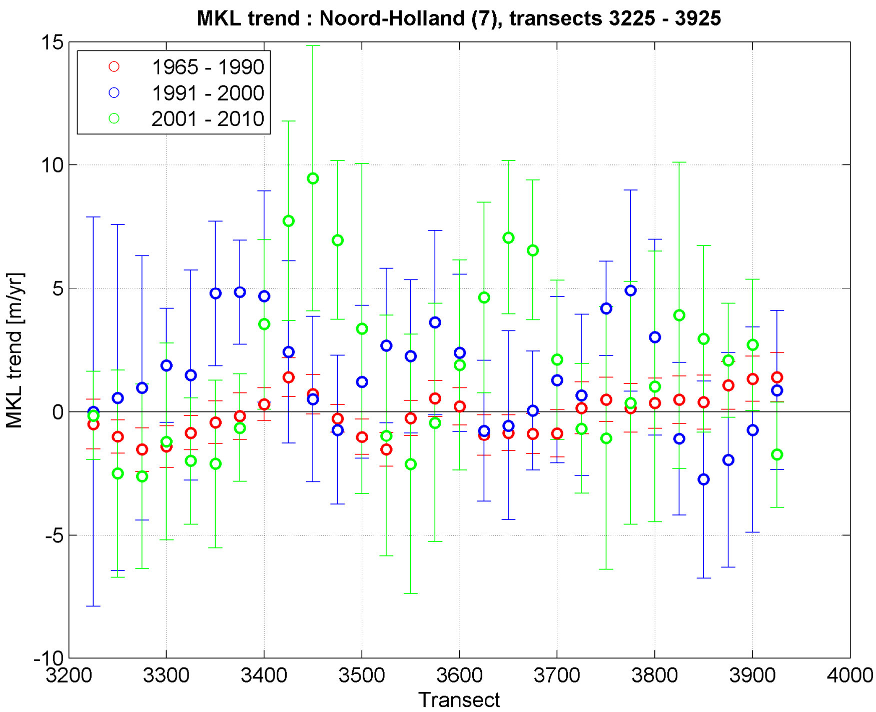


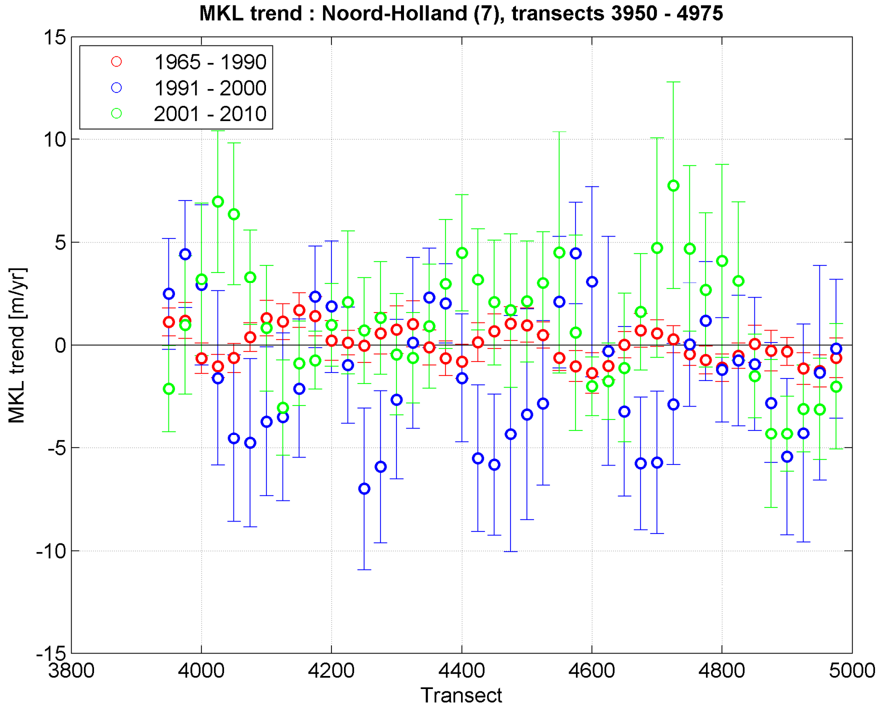


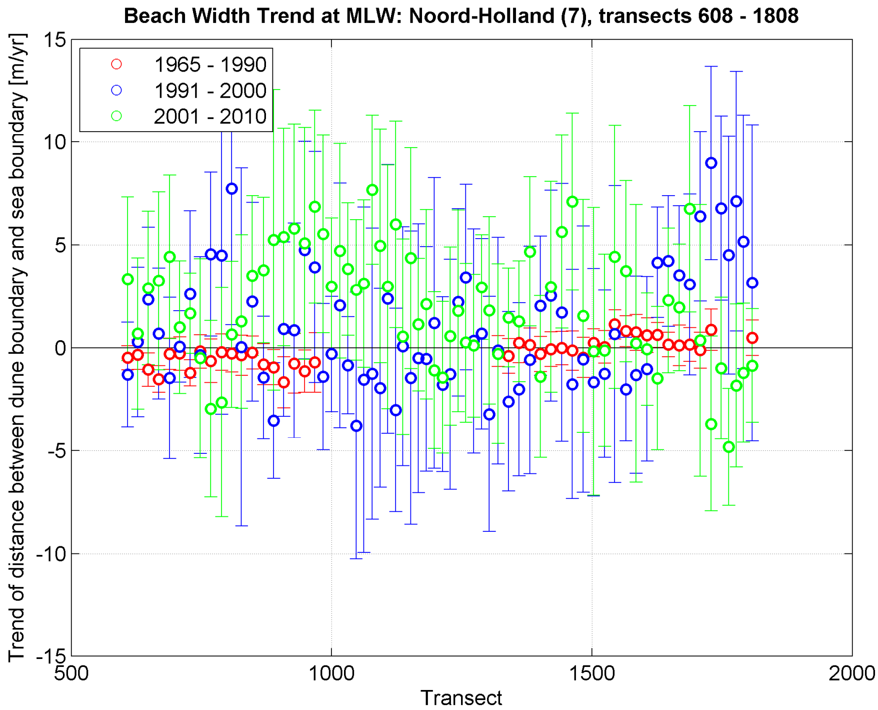

MKL trend : Noord-Holland (7), transects 1827 - 2023
1965 - 1990
1991 - 2000
2001 - 2010
MKL trend [m/yr]
Transect
10
8
6
4
2
0
-2
-4
1800
1850
1900
1950
2000
2050


MKL trend : Noord-Holland (7), transects 2041 - 2606
1965 - 1990
1991 - 2000
2001 - 2010
MKL trend [m/yr]
Transect
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
2000
2100
2200
2300
2400
2500
2600
2700


MKL trend : Noord-Holland (7), transects 2629 - 3200
1965 - 1990
1991 - 2000
2001 - 2010
MKL trend [m/yr]
Transect
8
6
4
2
0
-2
-4
-6
-8
-10
-12
2600
2700
2800
2900
3000
3100
3200
3300


MKL trend : Noord-Holland (7), transects 3225 - 3925
1965 - 1990
1991 - 2000
2001 - 2010
MKL trend [m/yr]
Transect
15
10
5
0
-5
-10
3200
3300
3400
3500
3600
3700
3800
3900
4000

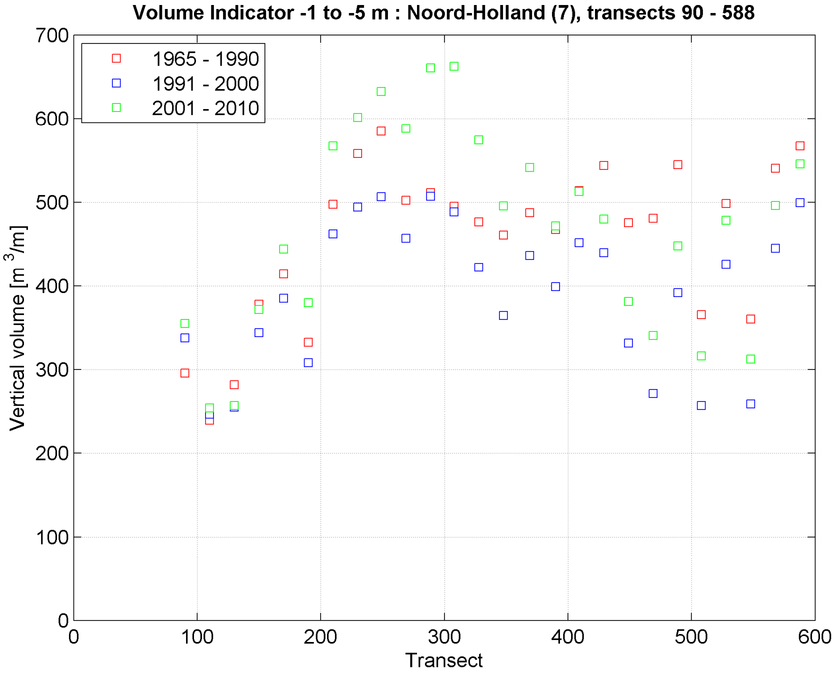

MKL trend : Noord-Holland (7), transects 3950 - 4975
1965 - 1990
1991 - 2000
2001 - 2010
MKL trend [m/yr]
Transect
15
10
5
0
-5
-10
-15
3800
4000
4200
4400
4600
4800
5000

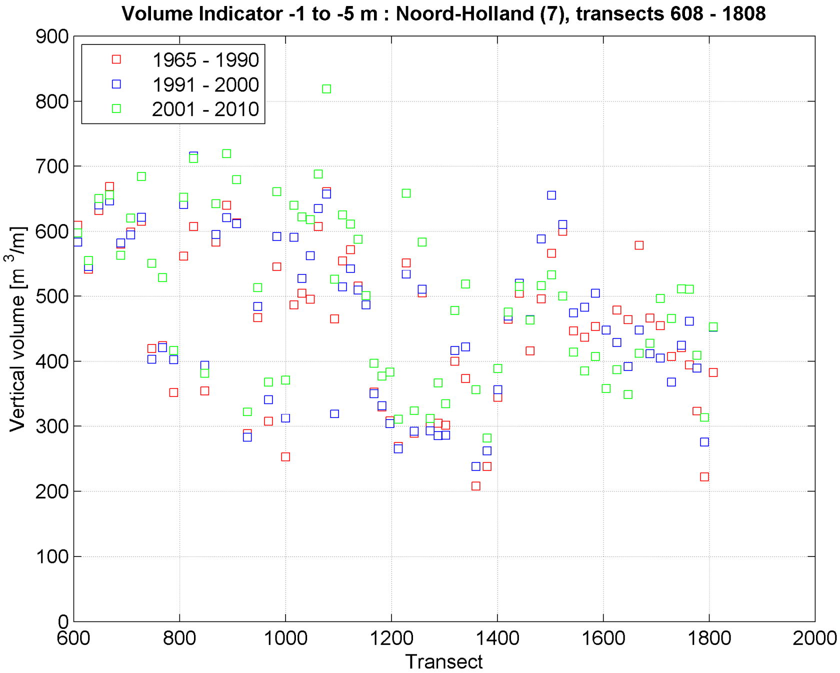

Beach Width Trend at MLW: Noord-Holland (7), transects 608 - 1808
1965 - 1990
1991 - 2000
2001 - 2010
Trend of distance between dune boundary and sea boundary [m/yr]
Transect
15
10
5
0
-5
-10
-15
500
1000
1500
2000

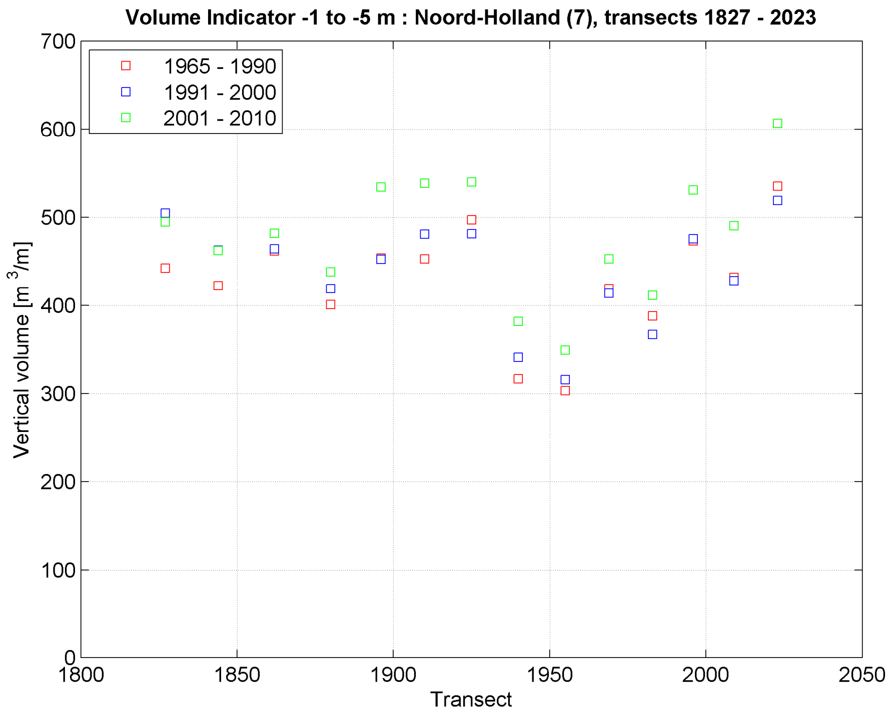
F Sand volumes

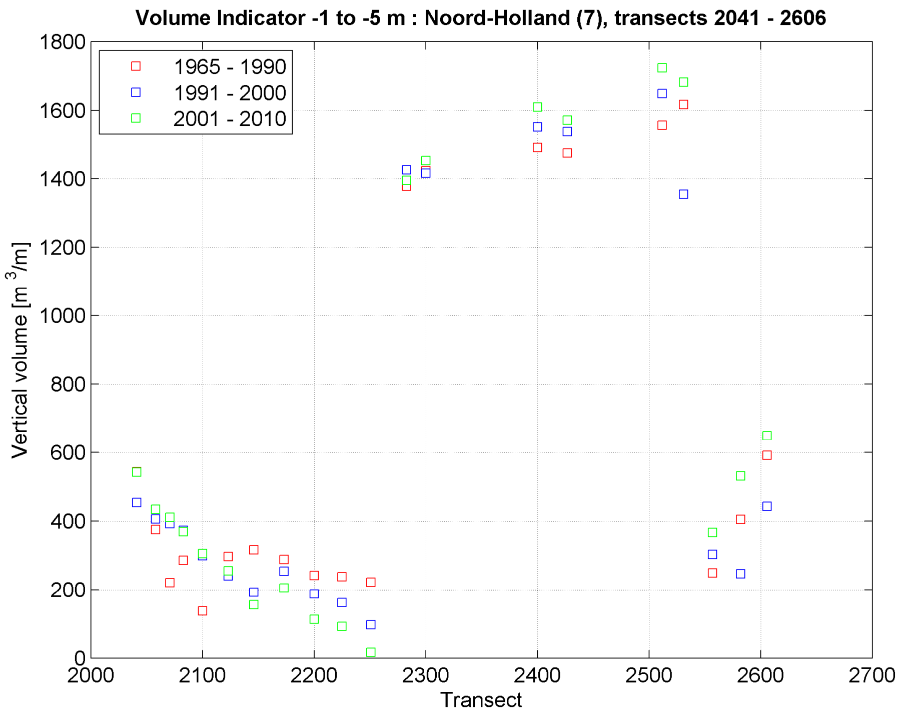
F.1 Sand volumes with respect to boundary year 1990

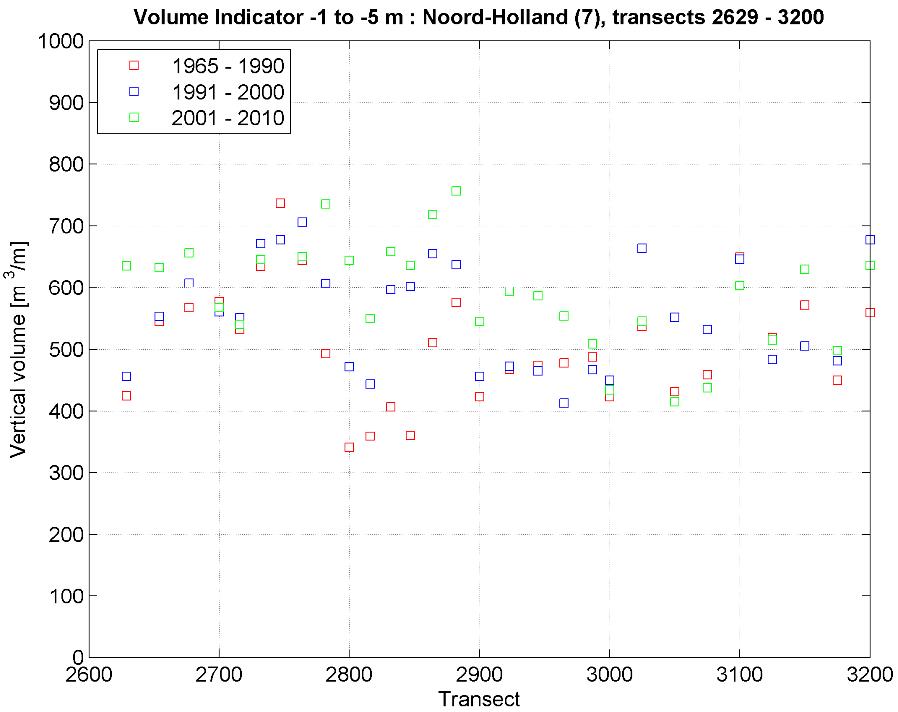
Sand volumes -1 m ÷ -5 m

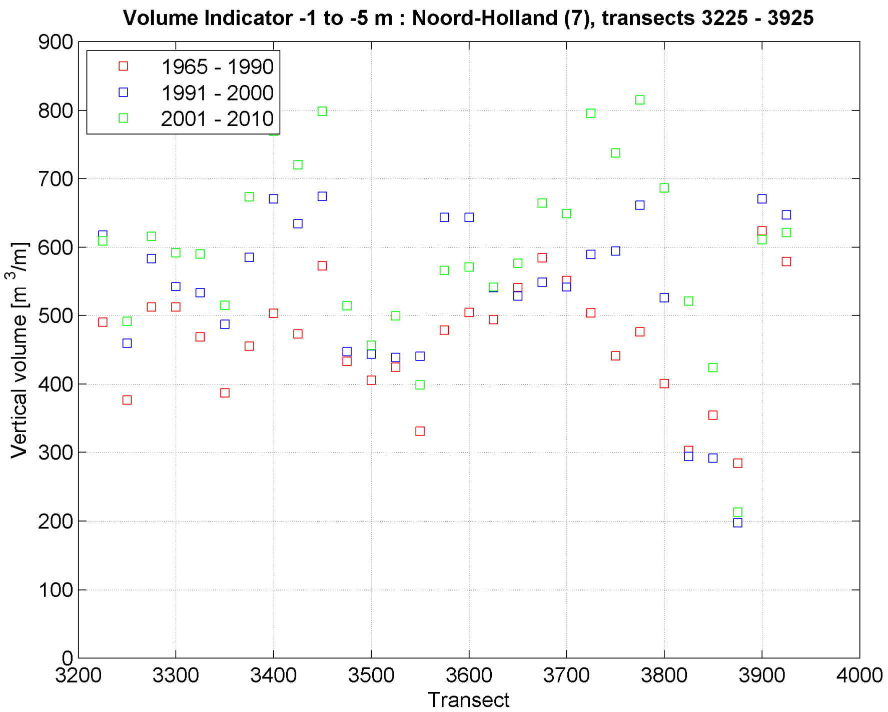


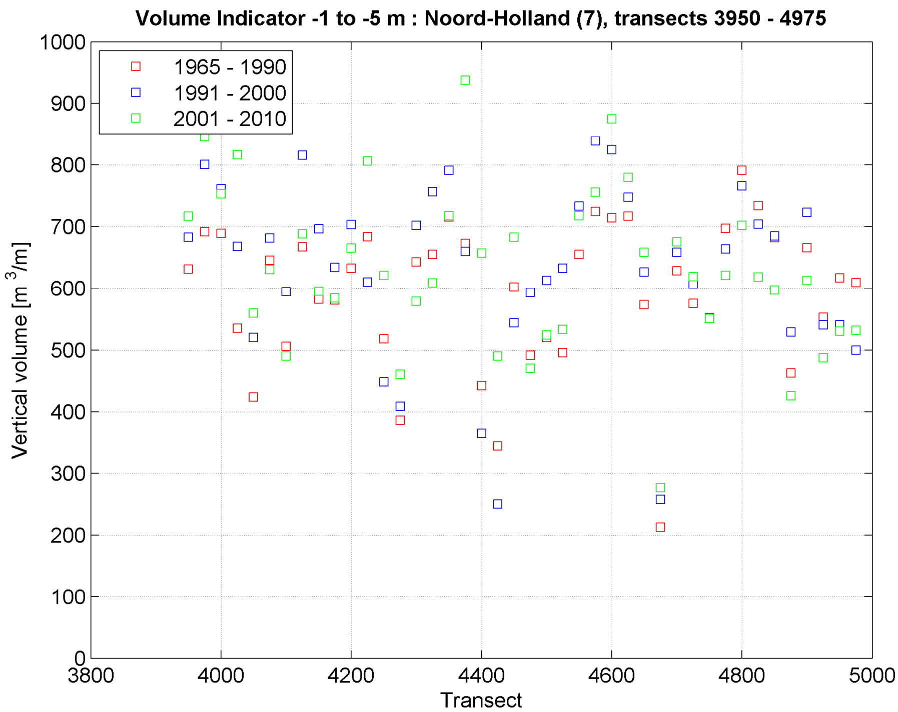


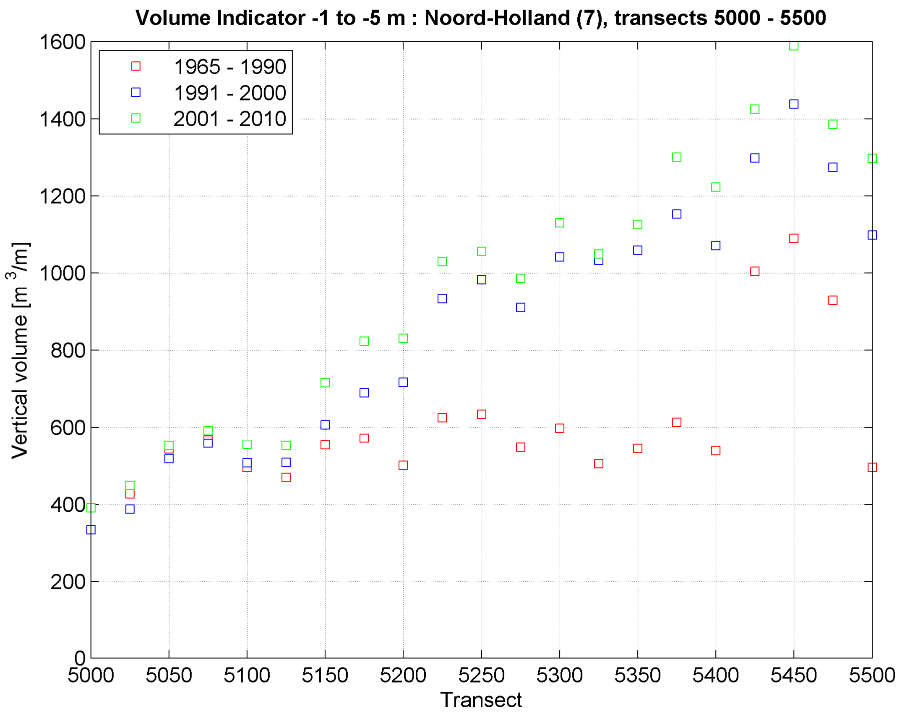

Volume Indicator -1 to -5 m : Noord-Holland (7), transects 1827 - 2023
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume [m ^{3}/m]
Transect
0
100
200
300
400
500
600
700
1800
1850
1900
1950
2000
2050


Volume Indicator -1 to -5 m : Noord-Holland (7), transects 2041 - 2606
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume [m ^{3}/m]
Transect
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2100
2200
2300
2400
2500
2600
2700

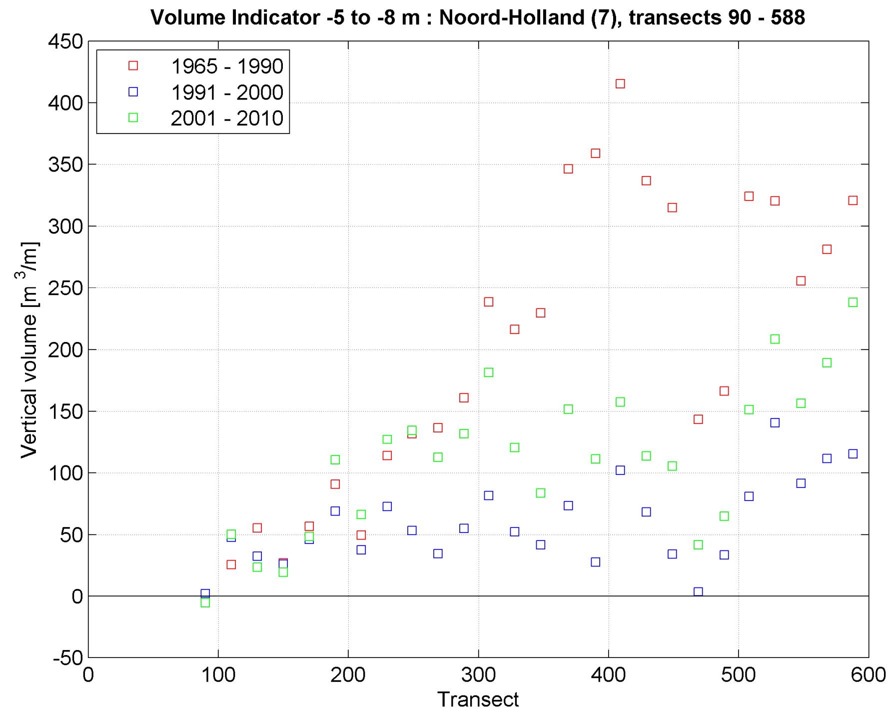

Volume Indicator -1 to -5 m : Noord-Holland (7), transects 2629 - 3200
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume [m 3/m]
Transect
0
100
200
300
400
500
600
700
800
900
1000
2600
2700
2800
2900
3000
3100
3200

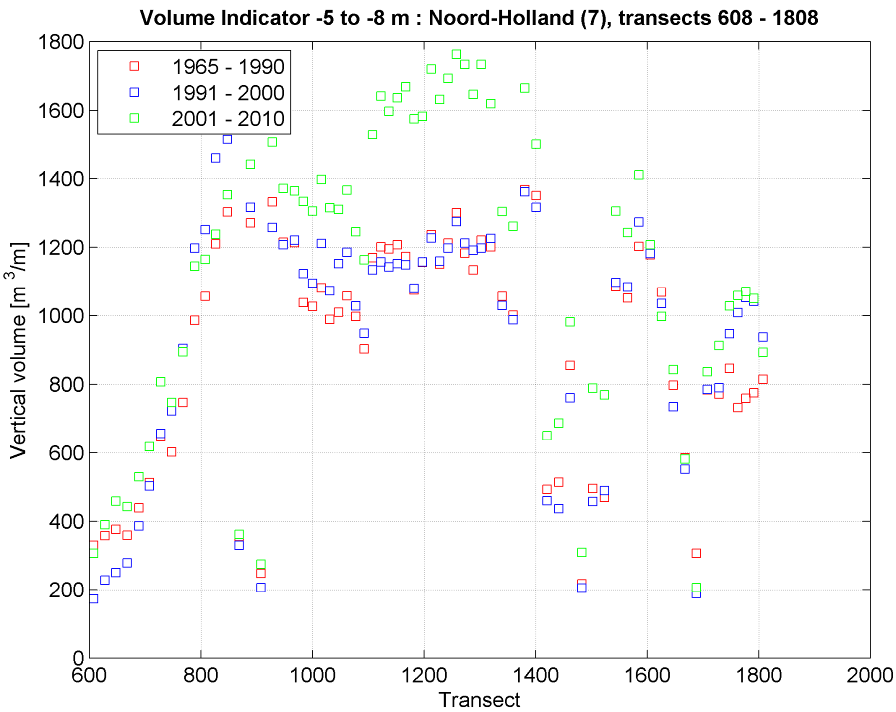

Volume Indicator -1 to -5 m : Noord-Holland (7), transects 3225 - 3925
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume [m 3/m]
Transect
0
100
200
300
400
500
600
700
800
900
3200
3300
3400
3500
3600
3700
3800
3900
4000

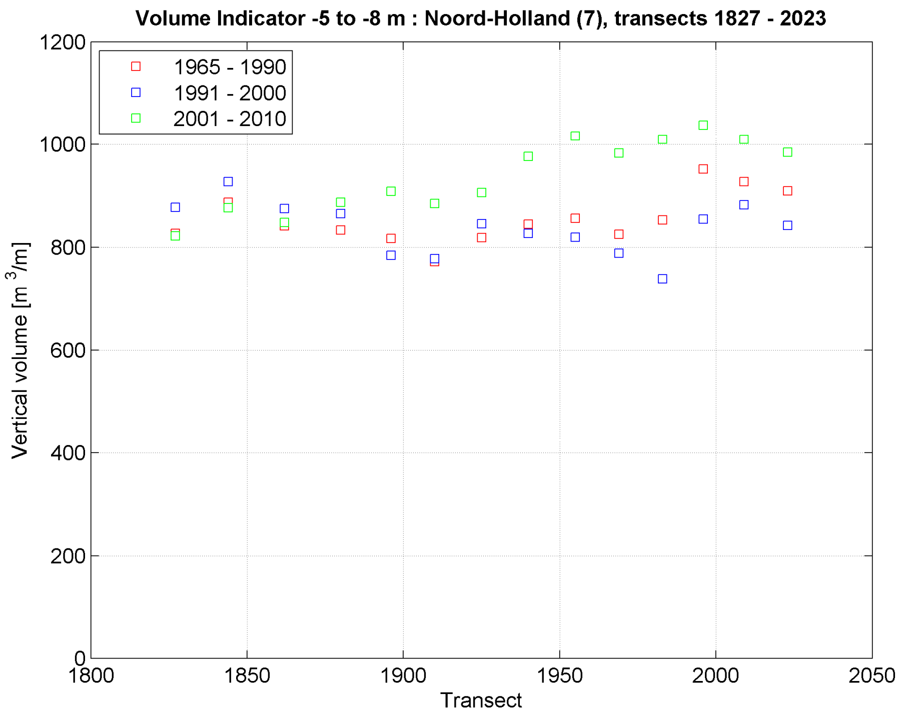

Volume Indicator -1 to -5 m : Noord-Holland (7), transects 3950 - 4975
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume [m 3/m]
Transect
0
100
200
300
400
500
600
700
800
900
1000
3800
4000
4200
4400
4600
4800
5000

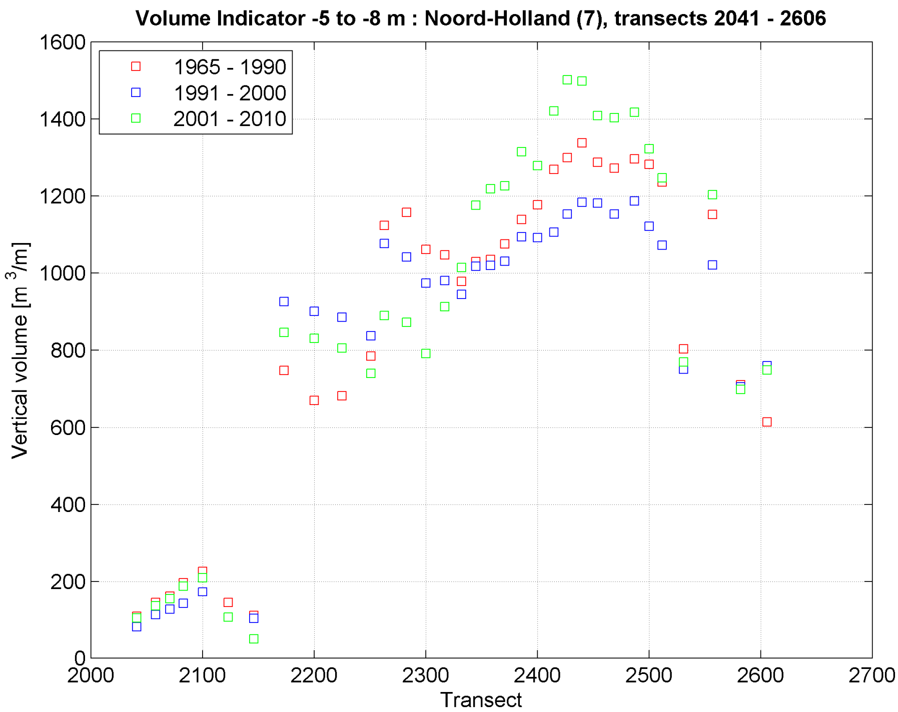

Volume Indicator -1 to -5 m : Noord-Holland (7), transects 5000 - 5500
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume [m 3/m]
Transect
0
200
400
600
800
1000
1200
1400
1600
5000
5050
5100
5150
5200
5250
5300
5350
5400
5450
5500

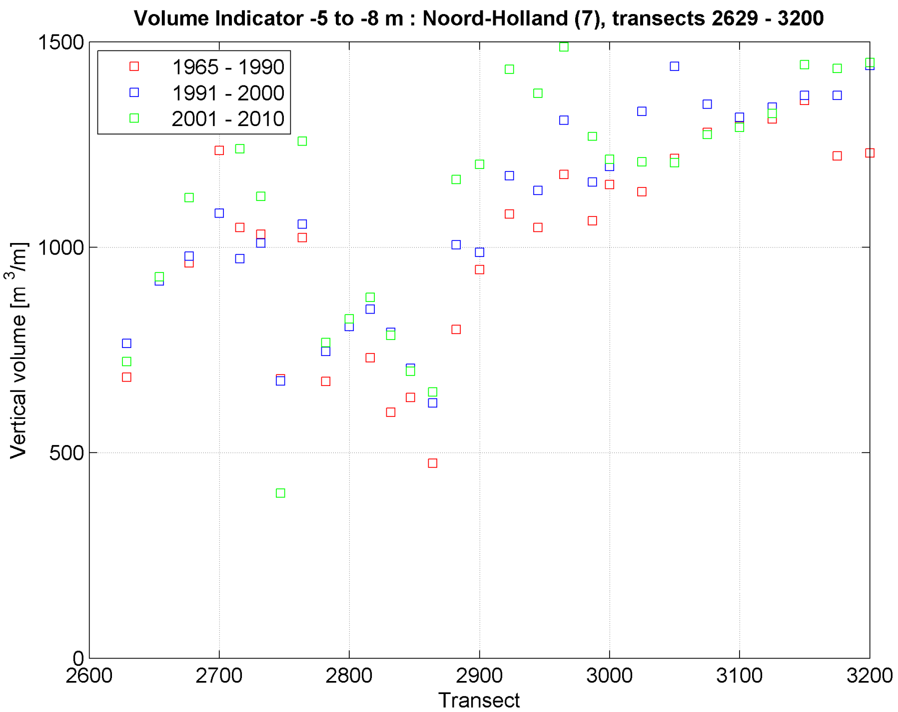
Sand volumes -5 m ÷ -8 m

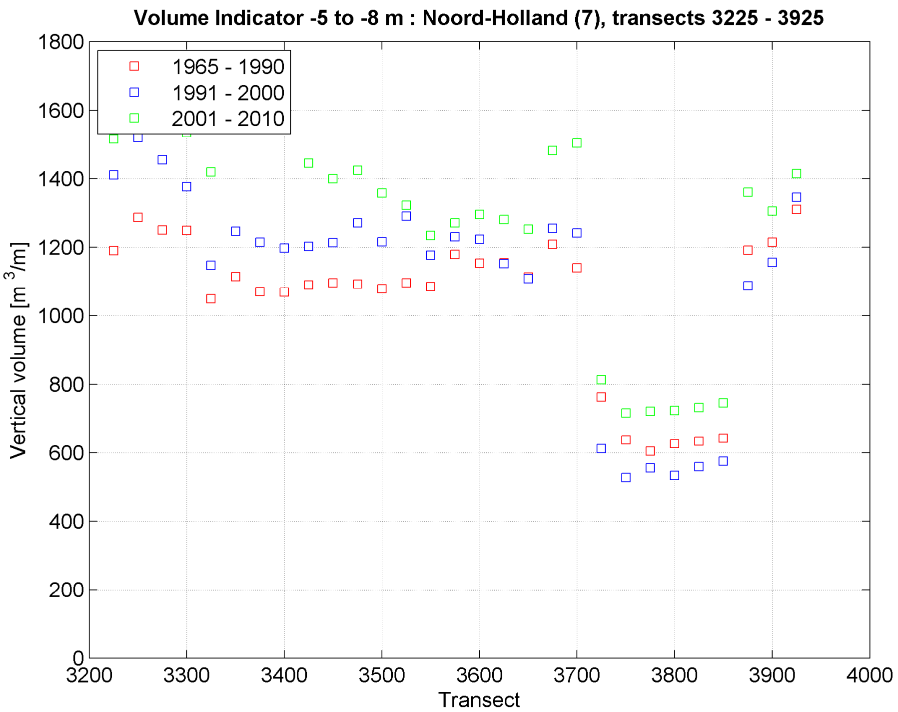


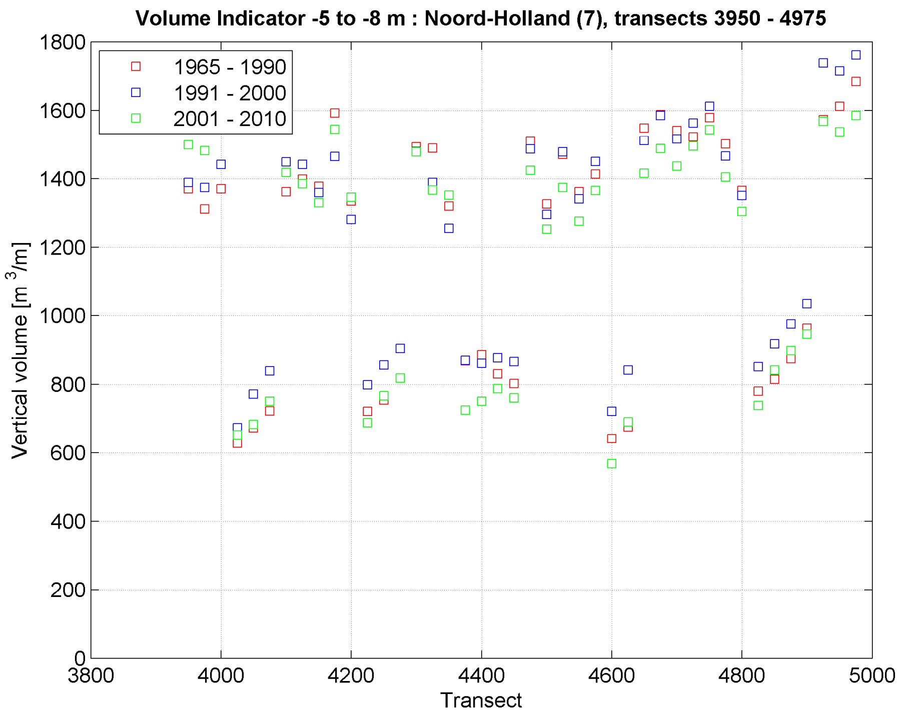


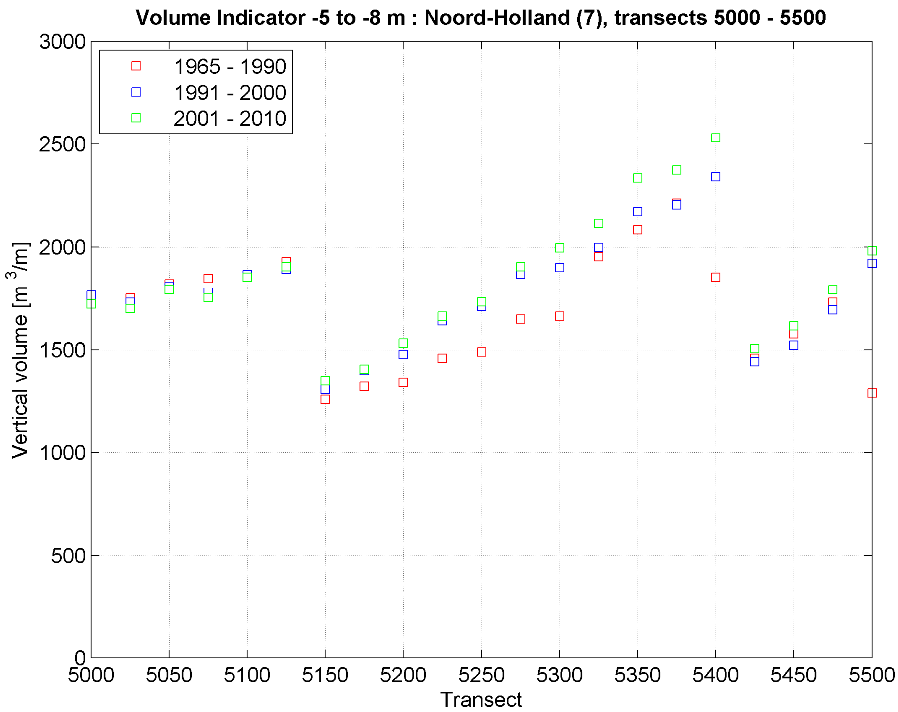

Volume Indicator -5 to -8 m : Noord-Holland (7), transects 1827 - 2023
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume [m 3/m]
Transect
0
200
400
600
800
1000
1200
1800
1850
1900
1950
2000
2050


Volume Indicator -5 to -8 m : Noord-Holland (7), transects 2041 - 2606
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume [m 3/m]
Transect
0
200
400
600
800
1000
1200
1400
1600
2000
2100
2200
2300
2400
2500
2600
2700

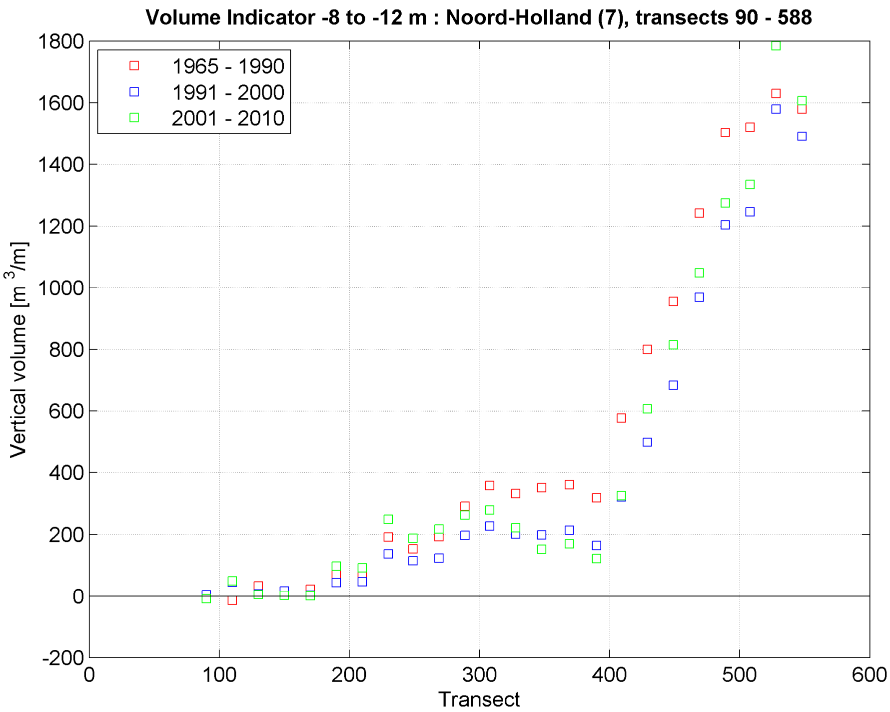

Volume Indicator -5 to -8 m : Noord-Holland (7), transects 2629 - 3200
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume [m 3/m]
Transect
1500
1000
500
0
2600
2700
2800
2900
3000
3100
3200

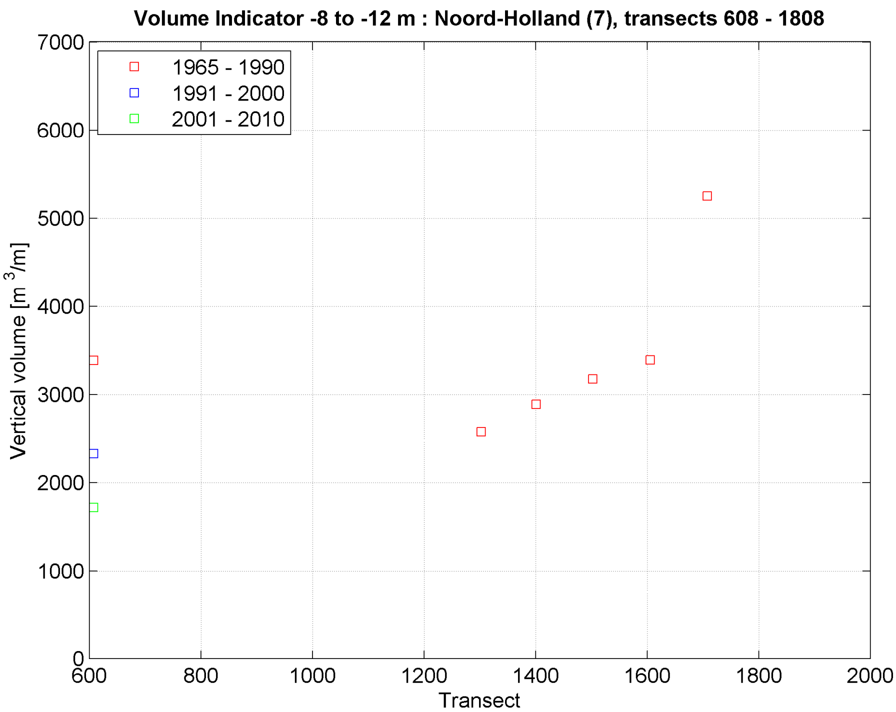

Volume Indicator -5 to -8 m : Noord-Holland (7), transects 3225 - 3925
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume [m 3/m]
Transect
1800
1600
1400
1200
1000
800
600
400
200
0
3200
3300
3400
3500
3600
3700
3800
3900
4000

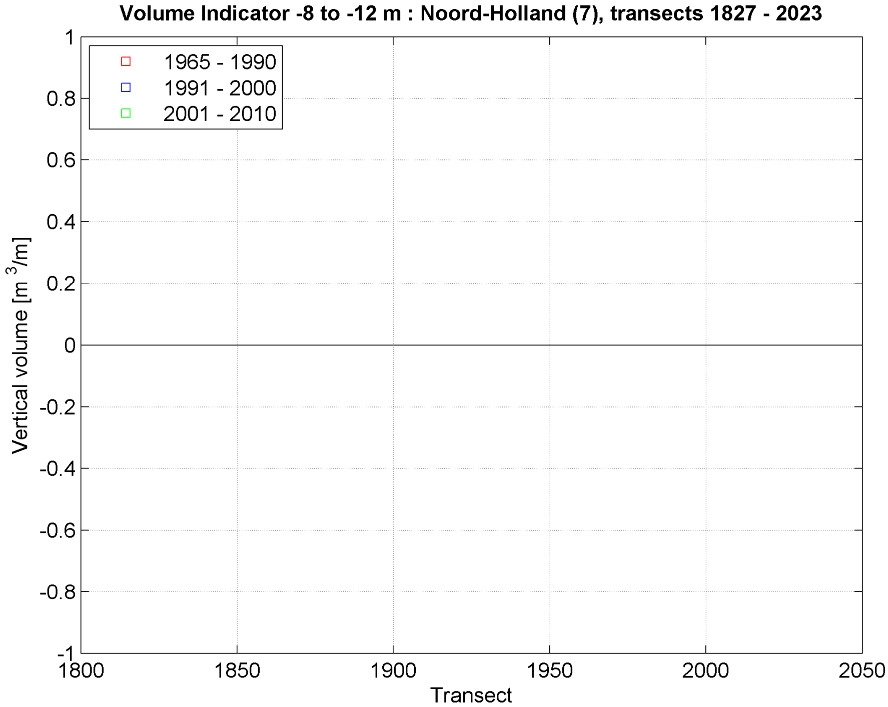

Volume Indicator -5 to -8 m : Noord-Holland (7), transects 3950 - 4975
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume [m 3/m]
Transect
0
200
400
600
800
1000
1200
1400
1600
1800
3800
4000
4200
4400
4600
4800
5000

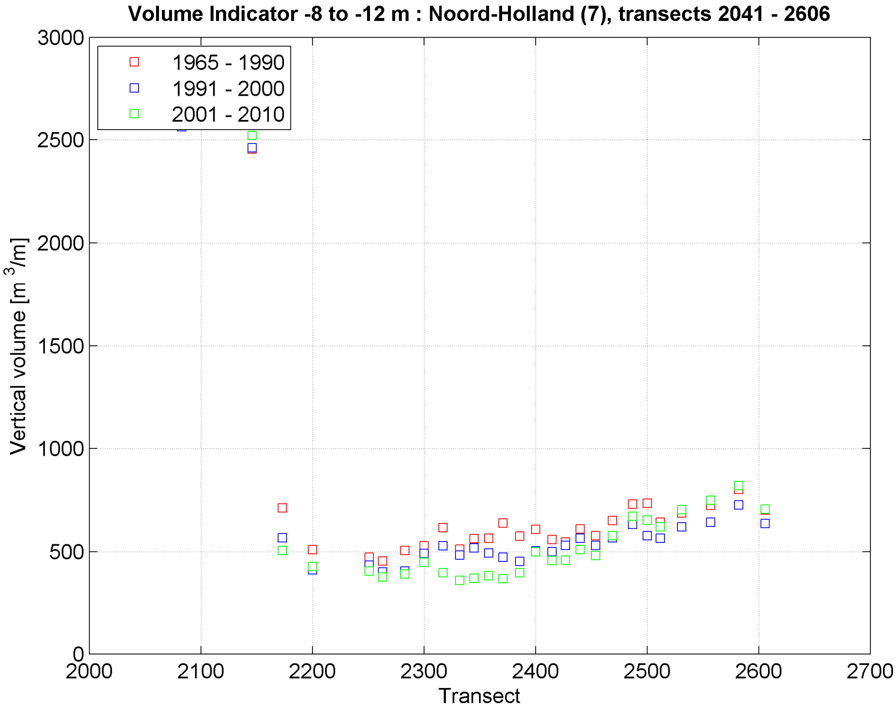

Volume Indicator -5 to -8 m : Noord-Holland (7), transects 5000 - 5500
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume [m 3/m]
Transect
0
500
1000
1500
2000
2500
3000
5000
5050
5100
5150
5200
5250
5300
5350
5400
5450
5500

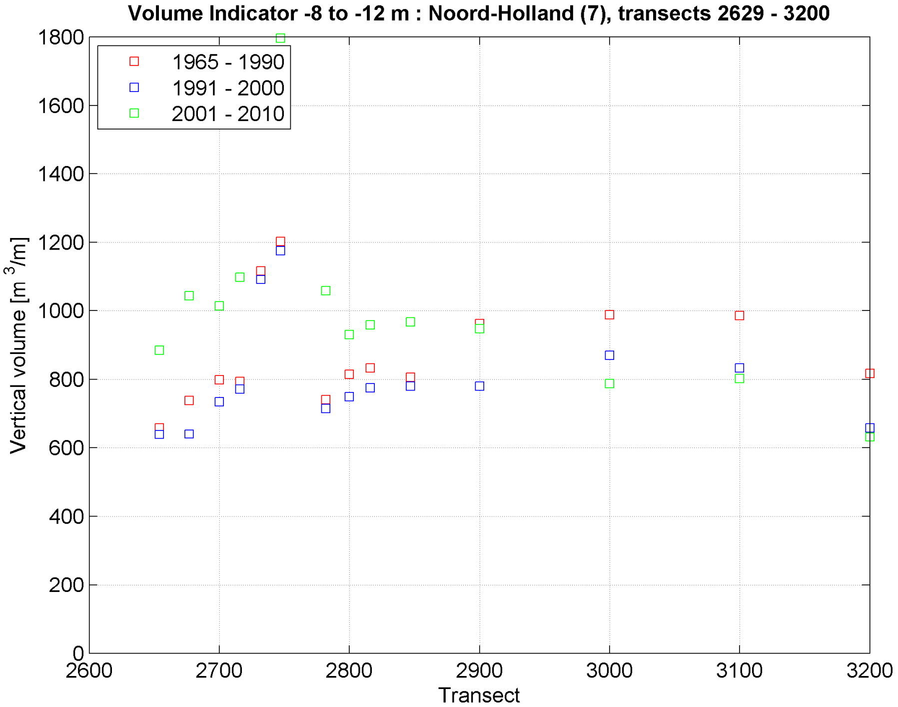
Sand volumes -8 m ÷ -12 m

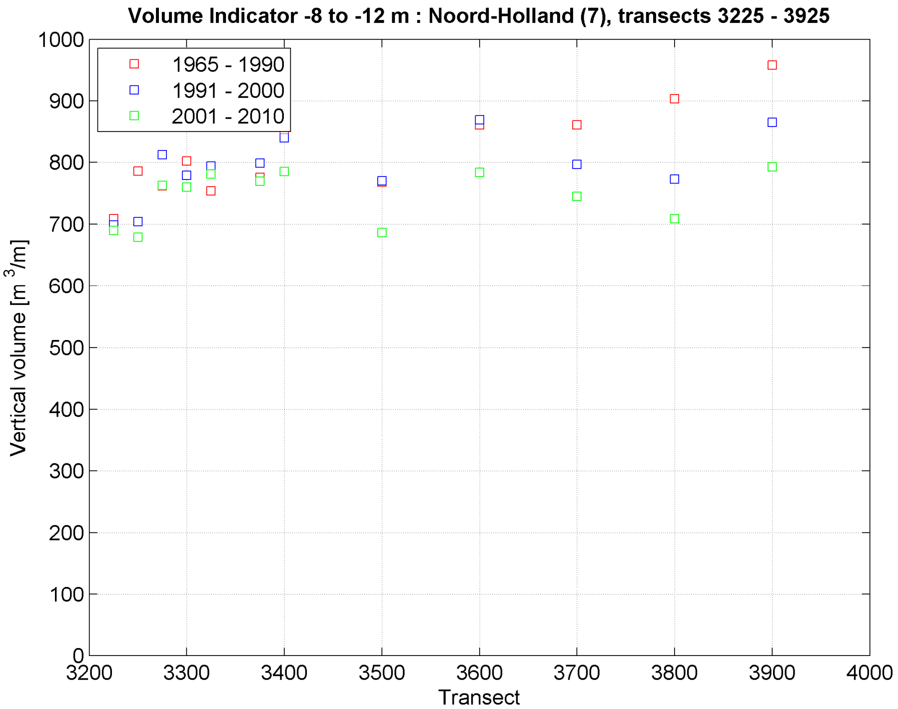


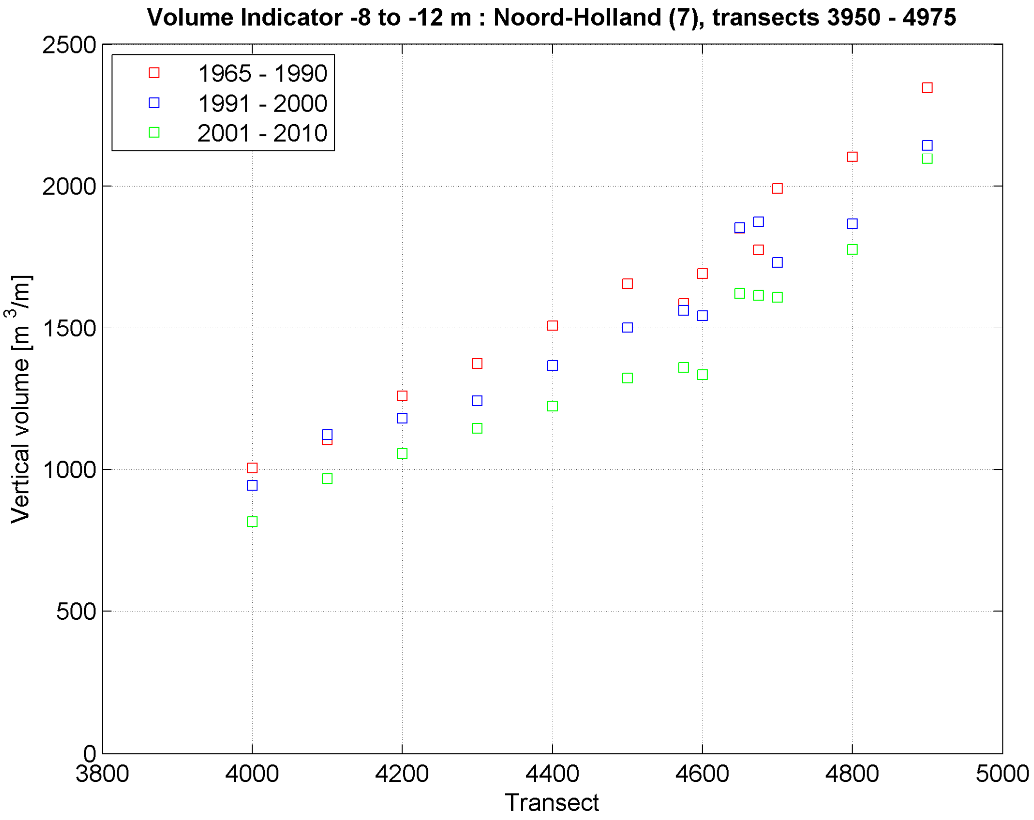


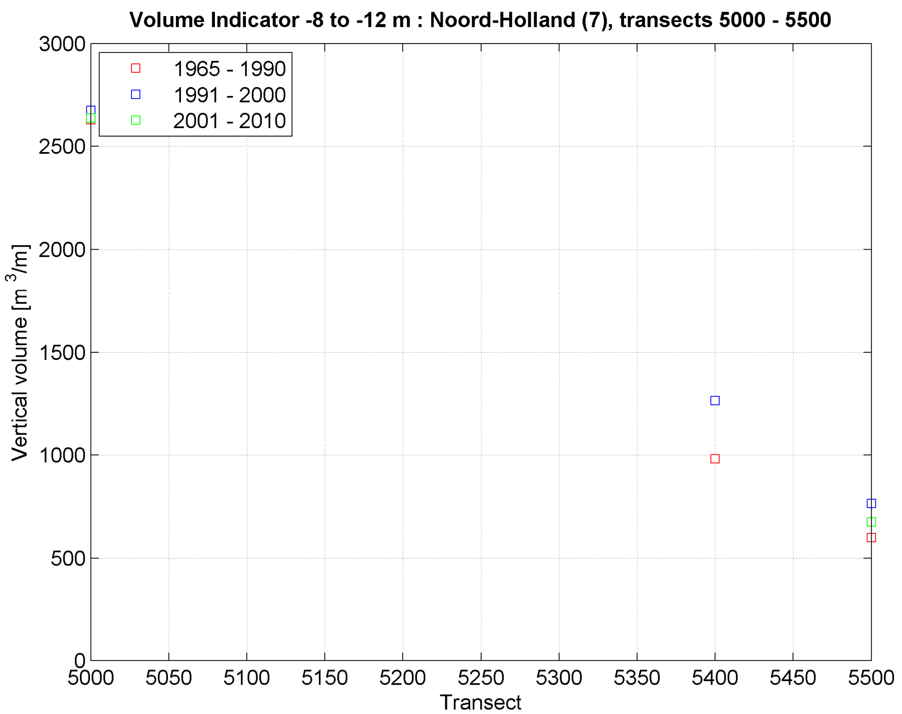

Volume Indicator -8 to -12 m : Noord-Holland (7), transects 1827 - 2023
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume [m 3/m]
Transect


Volume Indicator -8 to -12 m : Noord-Holland (7), transects 2041 - 2606
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume [m 3/m]
Transect


Volume Indicator -8 to -12 m : Noord-Holland (7), transects 2629 - 3200
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume [m 3/m]
Transect
0
200
400
600
800
1000
1200
1400
1600
1800
2600
2700
2800
2900
3000
3100
3200

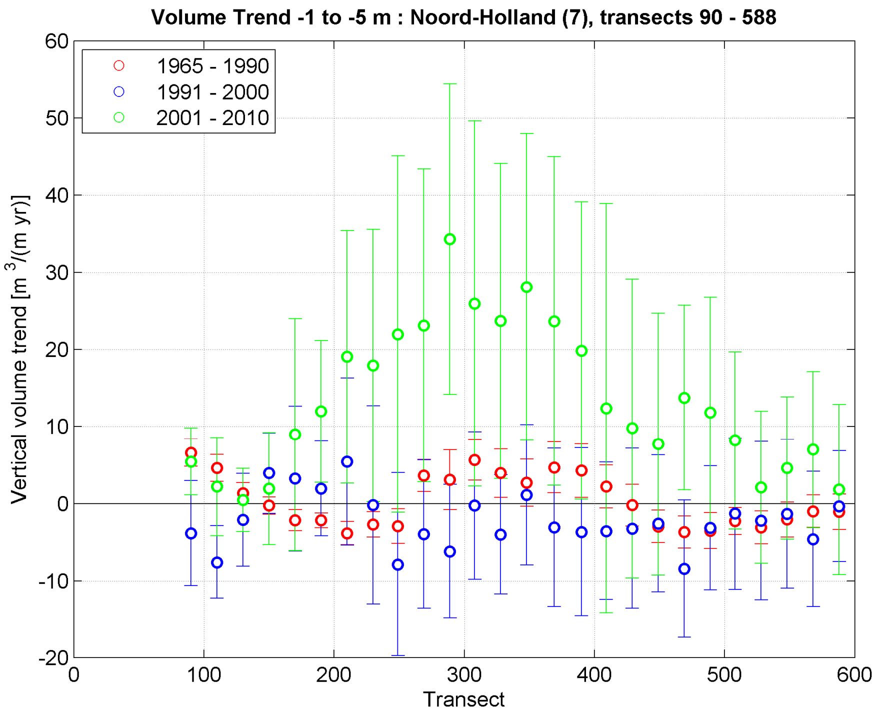

Volume Indicator -8 to -12 m : Noord-Holland (7), transects 3225 - 3925
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume [m 3/m]
Transect
0
100
200
300
400
500
600
700
800
900
1000
3200
3300
3400
3500
3600
3700
3800
3900
4000

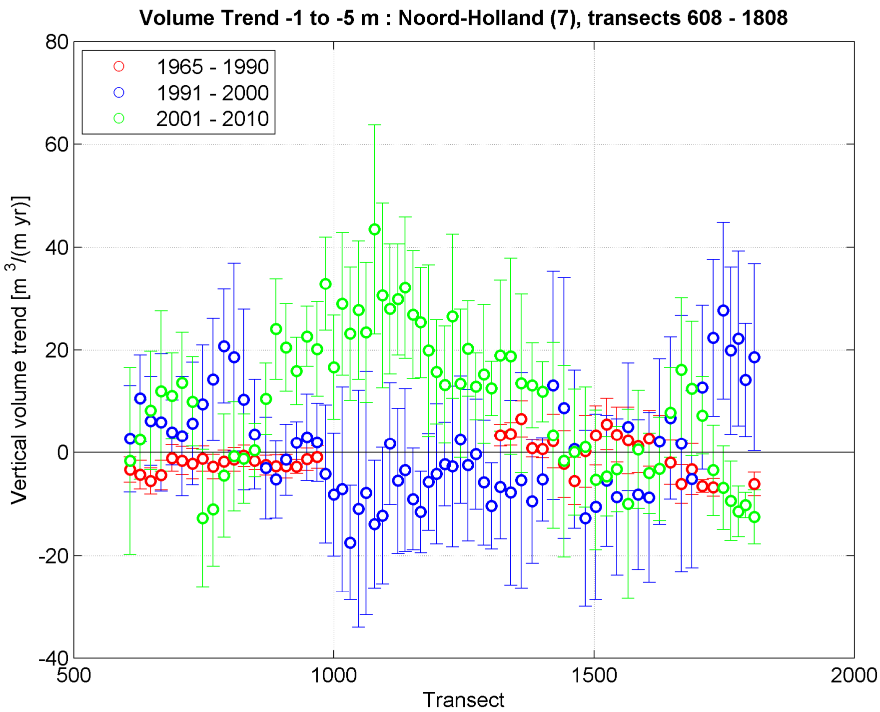

Volume Indicator -8 to -12 m : Noord-Holland (7), transects 3950 - 4975
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume [m 3/m]
0
500
1000
1500
2000
2500
3800
4000
4200
4400
4600
4800
5000
Transect

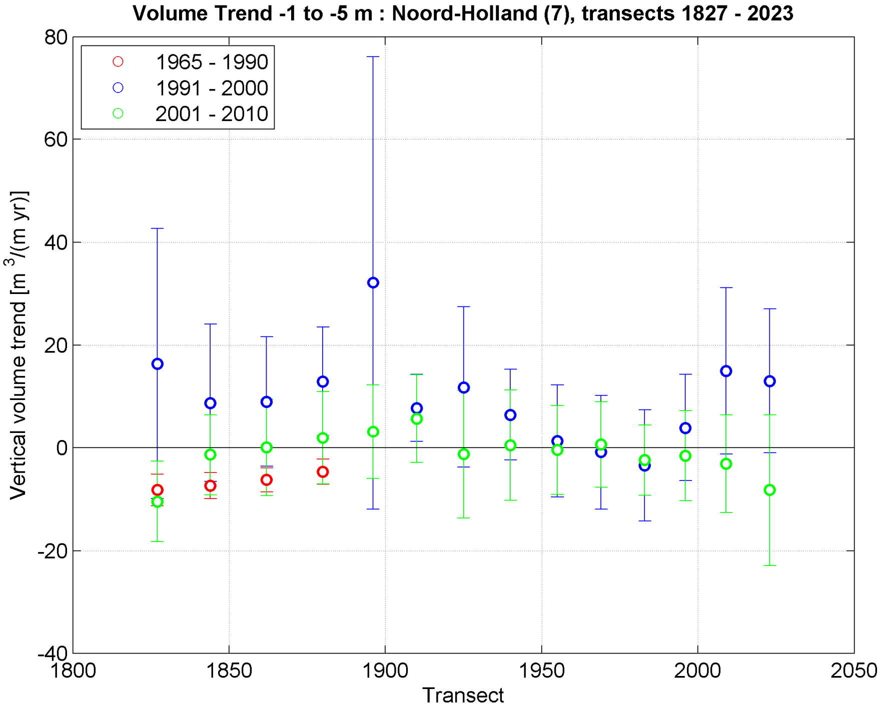

Volume Indicator -8 to -12 m : Noord-Holland (7), transects 5000 - 5500
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume [m 3/m]
0
500
1000
1500
2000
2500
3000
5000
5050
5100
5150
5200
5250
5300
5350
5400
5450
5500
Transect

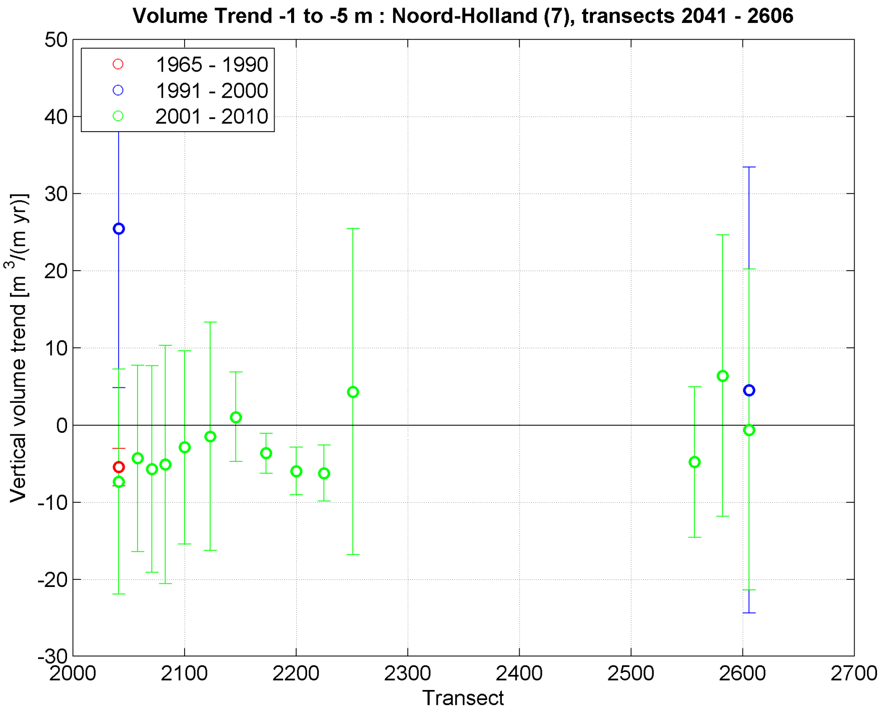
F.2 Nourishment volumes: trend analysis

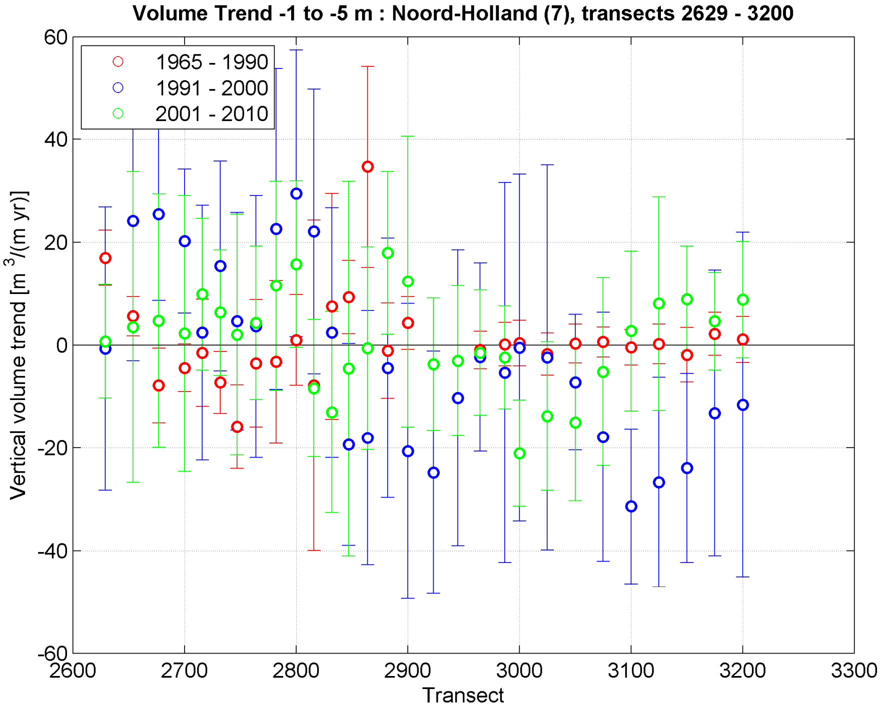
Volume trends -1 m ÷ -5 m

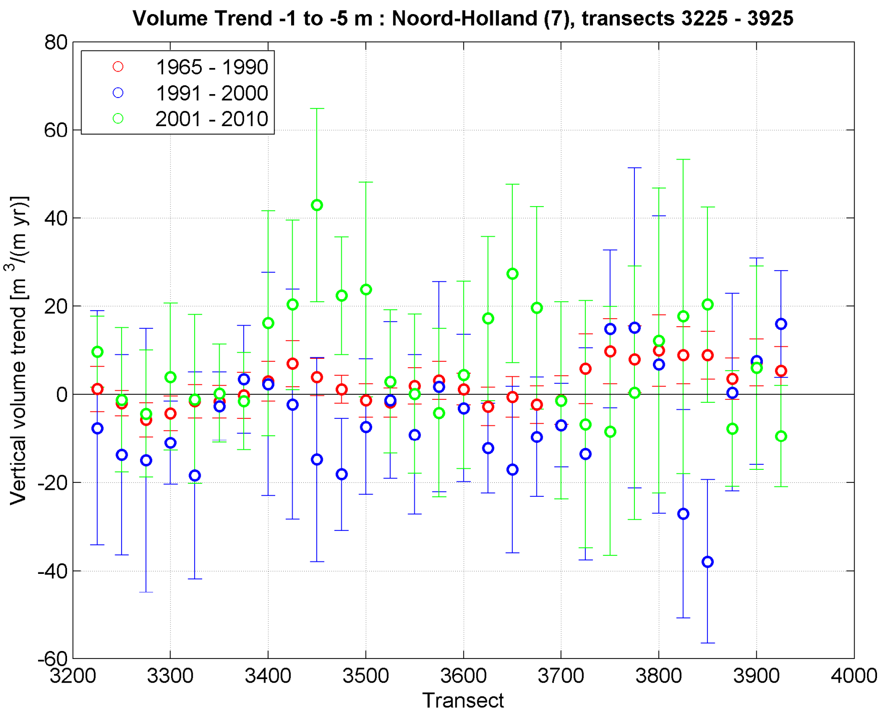


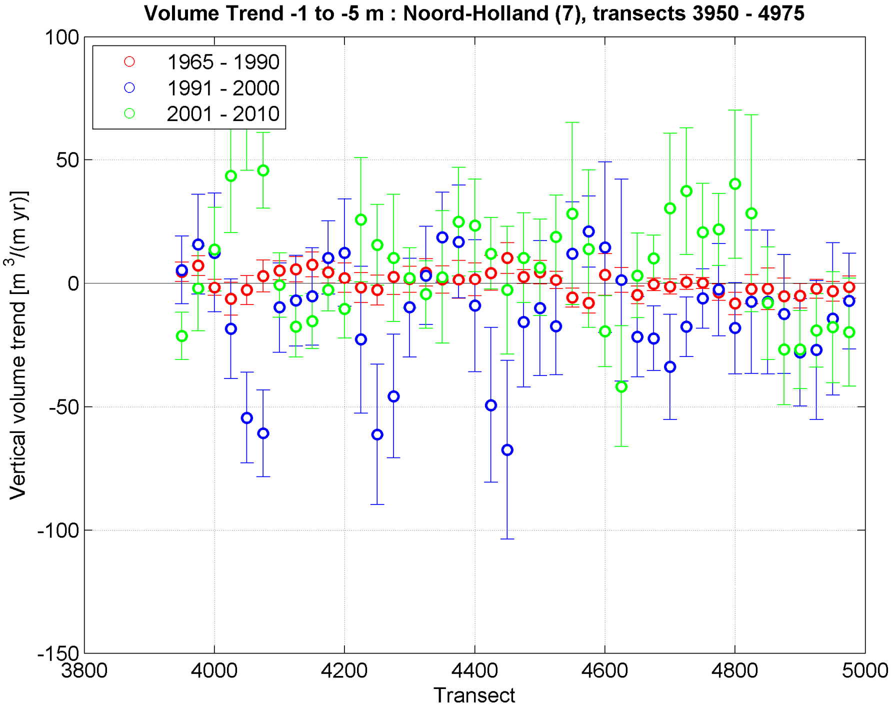


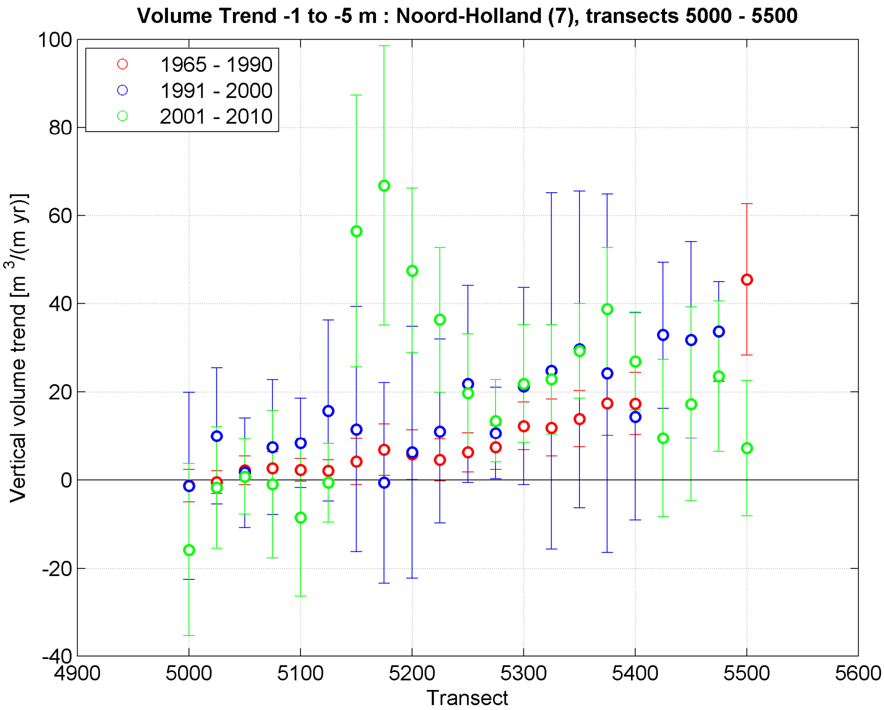

Volume Trend -1 to -5 m : Noord-Holland (7), transects 1827 - 2023
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume trend [m ³/(m yr)]
Transect
80
60
40
20
0
-20
-40
1800
1850
1900
1950
2000
2050


Volume Trend -1 to -5 m : Noord-Holland (7), transects 2041 - 2606
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume trend [m ³/(m yr)]
Transect
50
40
30
20
10
0
-10
-20
-30
2000
2100
2200
2300
2400
2500
2600
2700

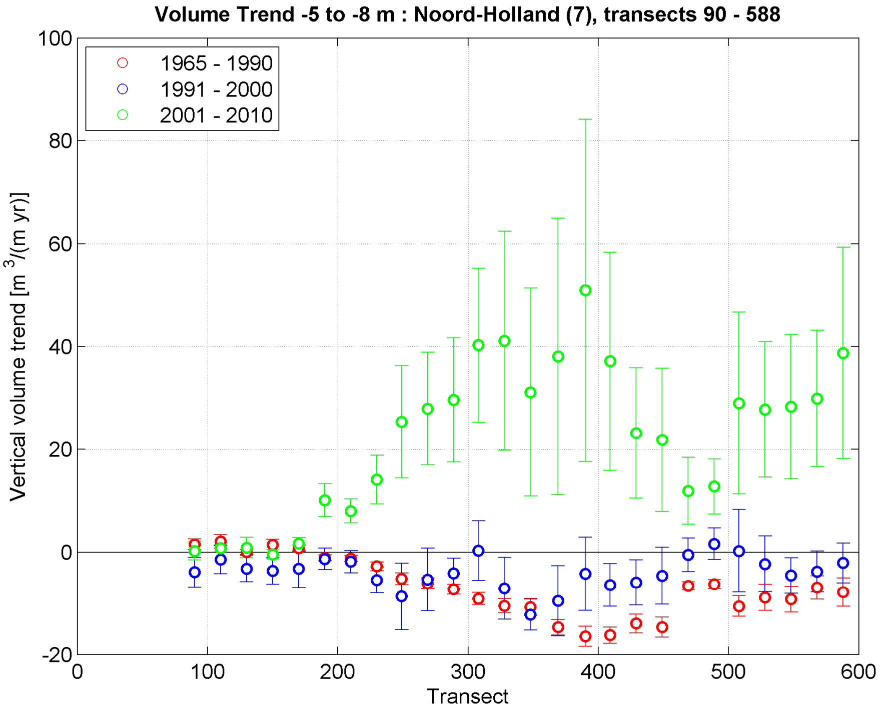

Volume Trend -1 to -5 m : Noord-Holland (7), transects 2629 - 3200
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume trend [m ^{3}/(m yr)]
Transect
60
40
20
0
-20
-40
-60
2600
2700
2800
2900
3000
3100
3200
3300

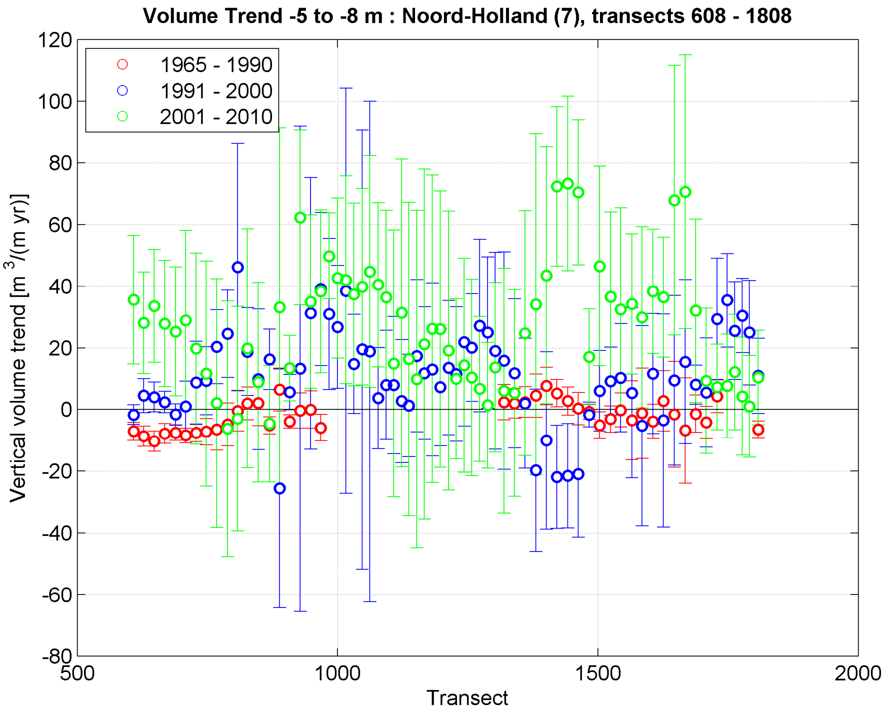

Volume Trend -1 to -5 m : Noord-Holland (7), transects 3225 - 3925
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume trend [m ^{3}/(m yr)]
Transect
80
60
40
20
0
-20
-40
-60
3200
3300
3400
3500
3600
3700
3800
3900
4000

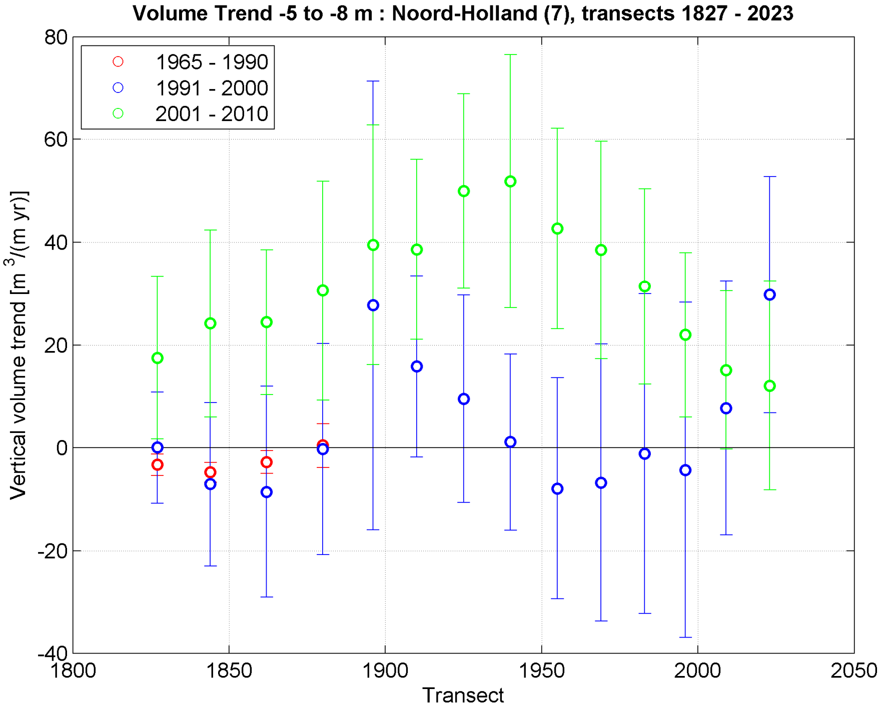

Volume Trend -1 to -5 m : Noord-Holland (7), transects 3950 - 4975
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume trend [m 3/(m yr)]
100
50
0
-50
-100
-150
3800
4000
4200
4400
4600
4800
5000
Transect

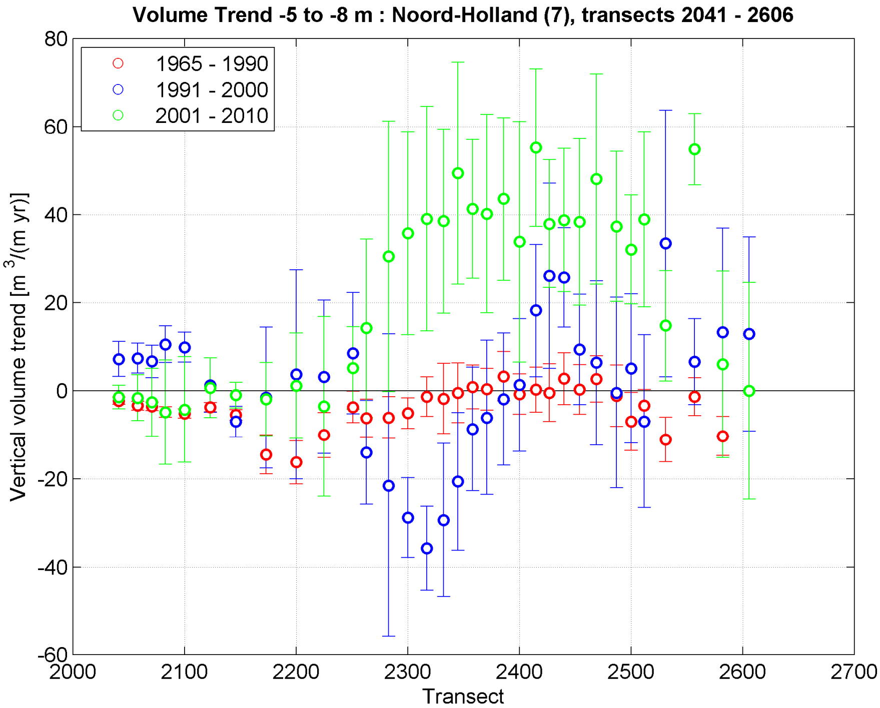

Volume Trend -1 to -5 m : Noord-Holland (7), transects 5000 - 5500
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume trend [m 3/(m yr)]
100
80
60
40
20
0
-20
-40
4900
5000
5100
5200
5300
5400
5500
5600
Transect

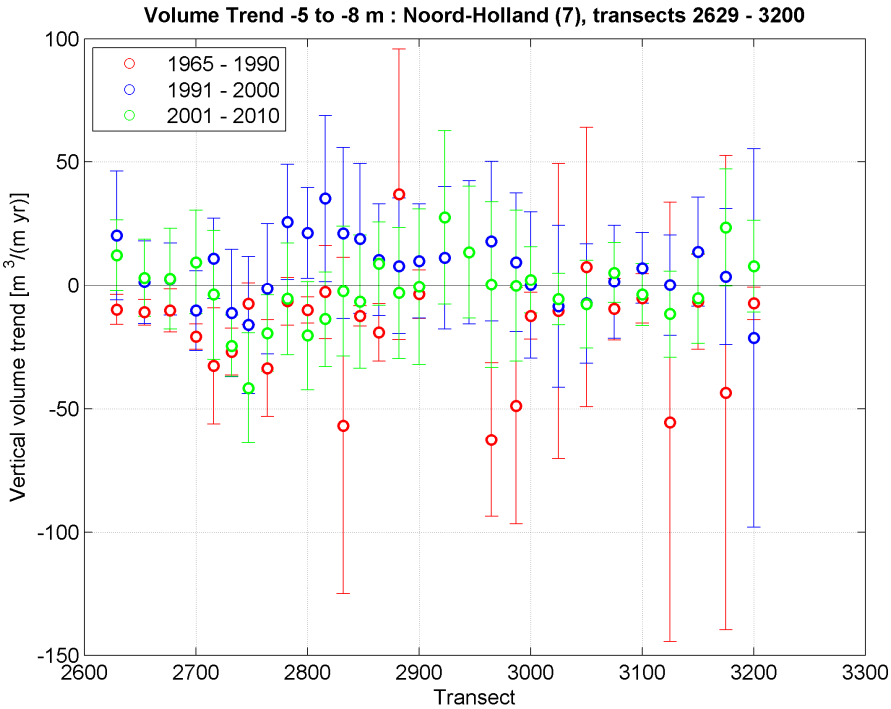
Volume trends -5 m ÷ -8 m

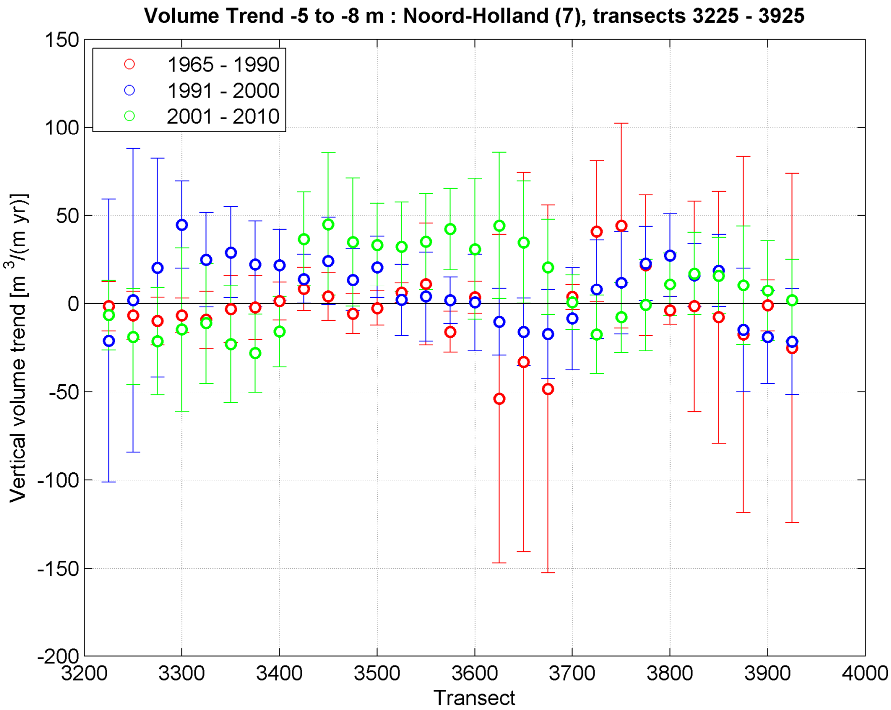


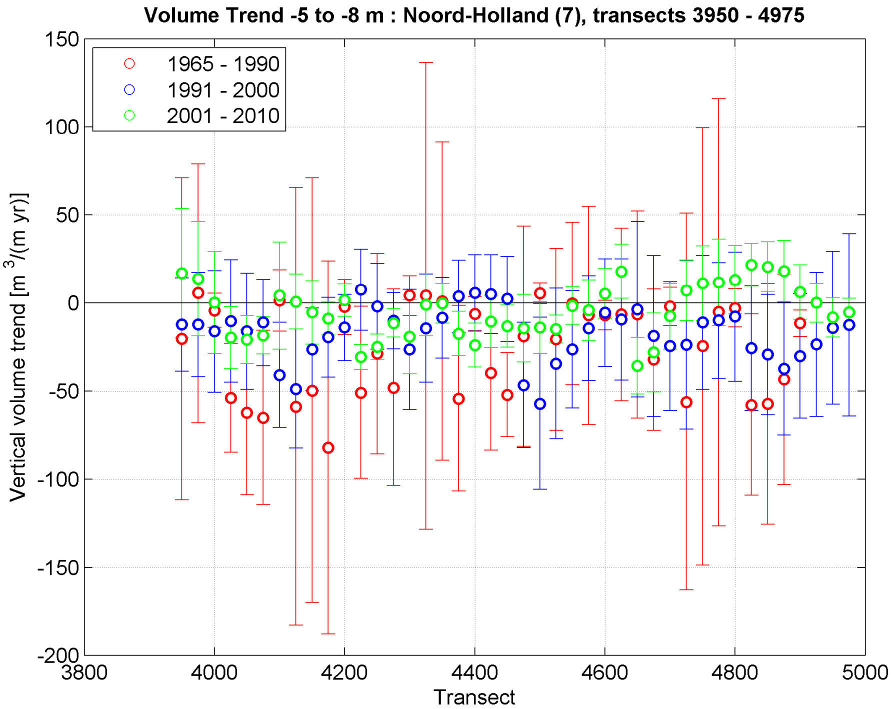


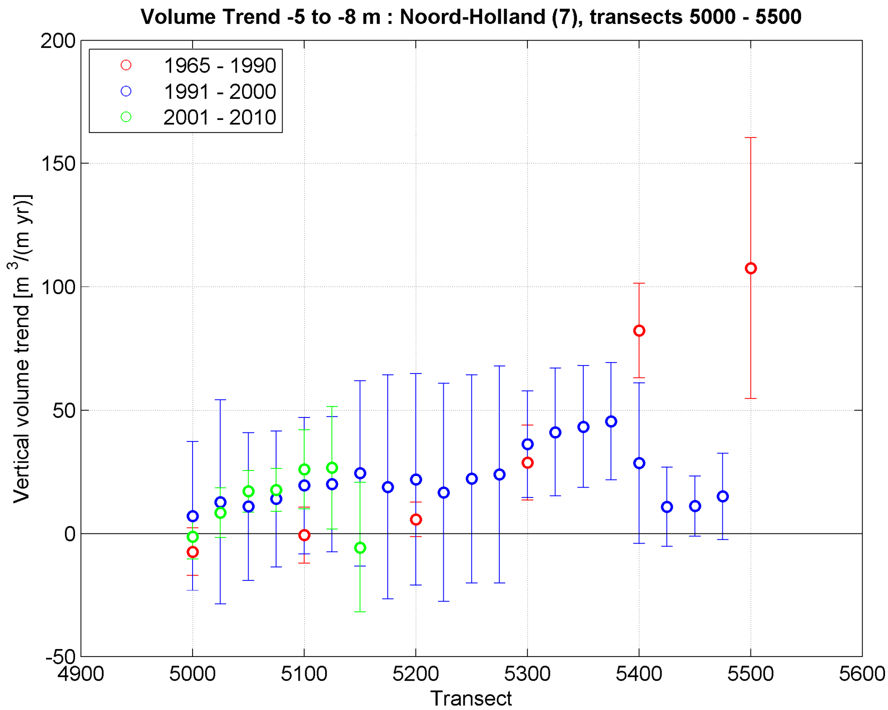

Volume Trend -5 to -8 m : Noord-Holland (7), transects 1827 - 2023
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume trend [m 3/(m yr)]
Transect
80
60
40
20
0
-20
-40
1800
1850
1900
1950
2000
2050


Volume Trend -5 to -8 m : Noord-Holland (7), transects 2041 - 2606
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume trend [m 3/(m yr)]
Transect
80
60
40
20
0
-20
-40
-60
2000
2100
2200
2300
2400
2500
2600
2700

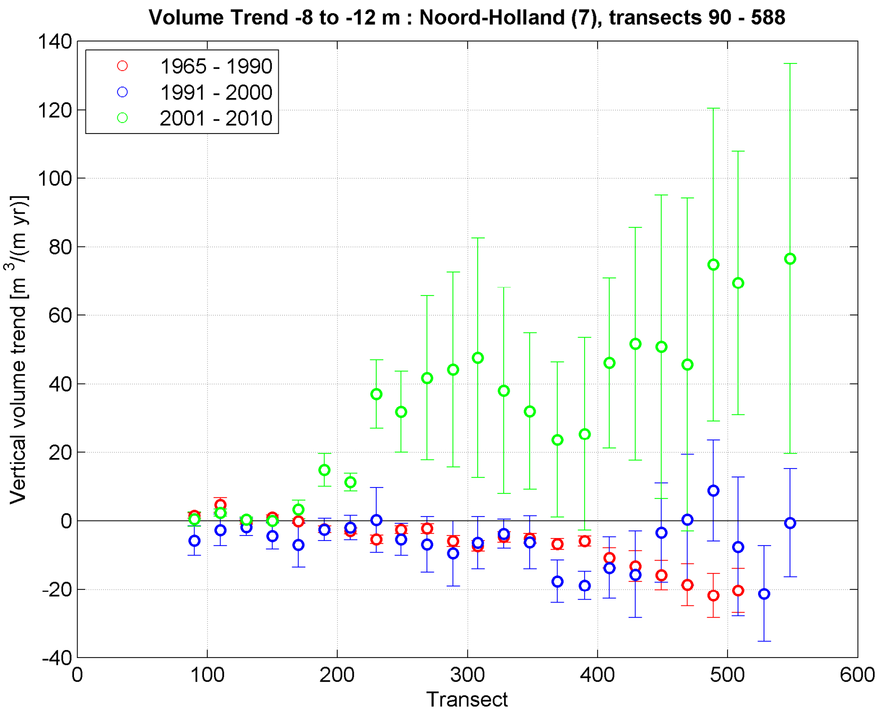

Volume Trend -5 to -8 m : Noord-Holland (7), transects 2629 - 3200
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume trend [m 3/(m yr)]
Transect
100
50
0
-50
-100
-150
2600
2700
2800
2900
3000
3100
3200
3300

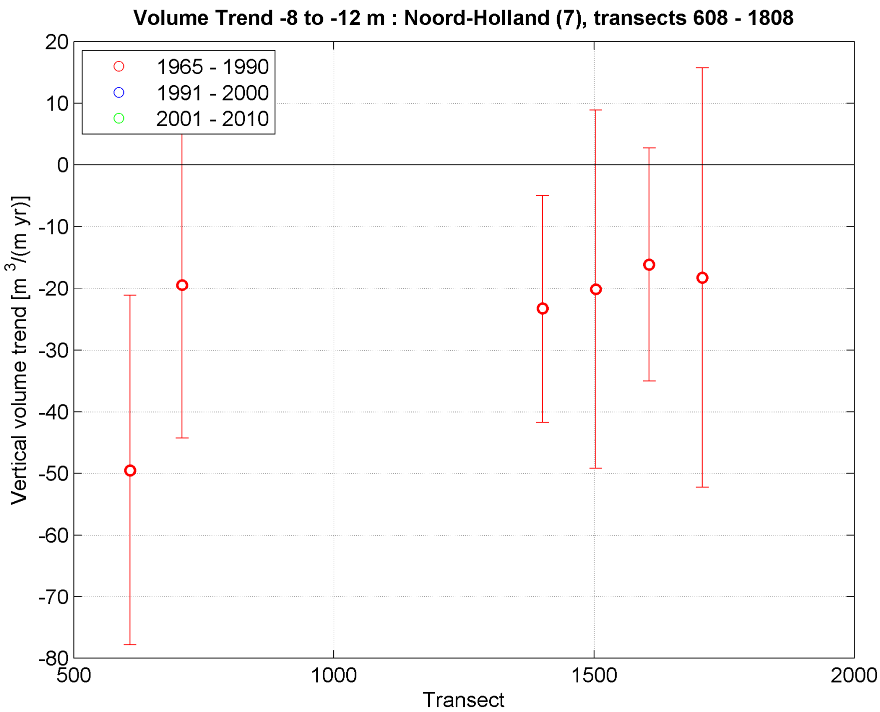

Volume Trend -5 to -8 m : Noord-Holland (7), transects 3225 - 3925
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume trend [m 3/(m yr)]
Transect
150
100
50
0
-50
-100
-150
-200
3200
3300
3400
3500
3600
3700
3800
3900
4000

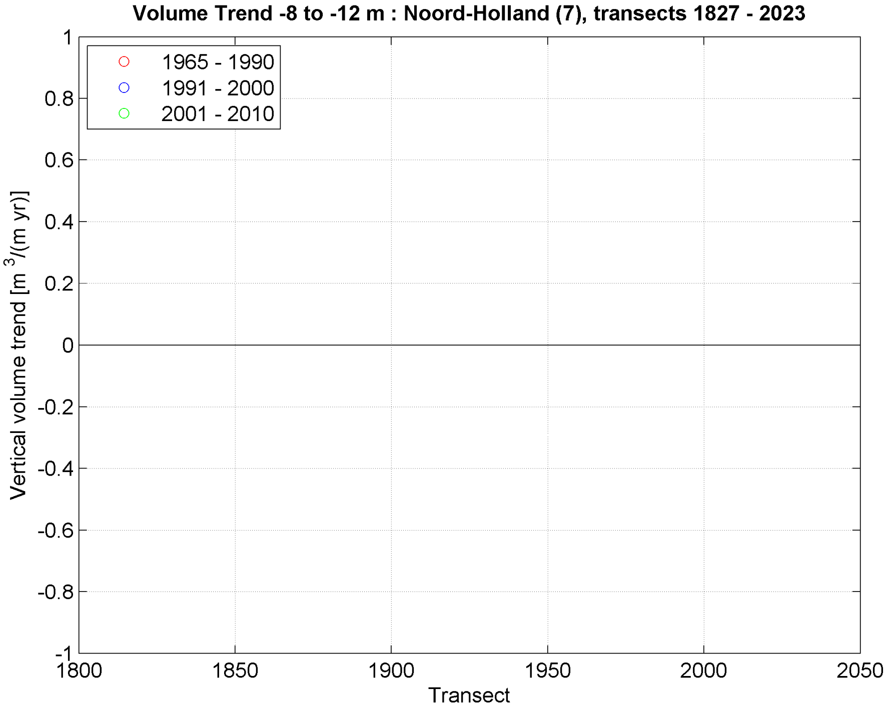

Volume Trend -5 to -8 m : Noord-Holland (7), transects 3950 - 4975
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume trend [m 3/(m yr)]
Transect
150
100
50
0
-50
-100
-150
-200
3800
4000
4200
4400
4600
4800
5000

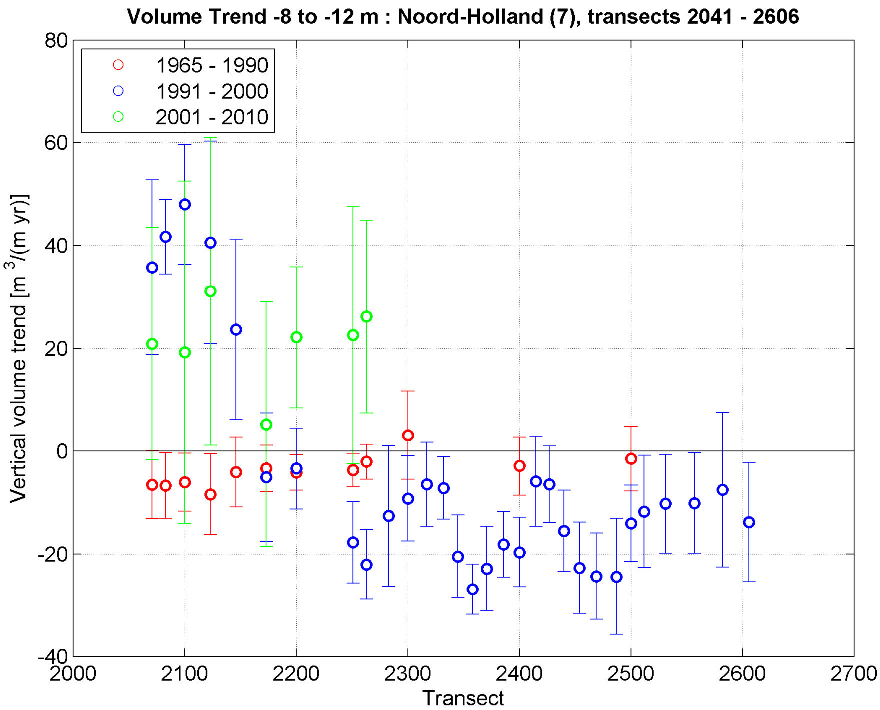

Volume Trend -5 to -8 m : Noord-Holland (7), transects 5000 - 5500
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume trend [m 3/(m yr)]
Transect
200
150
100
50
0
-50
4900
5000
5100
5200
5300
5400
5500
5600

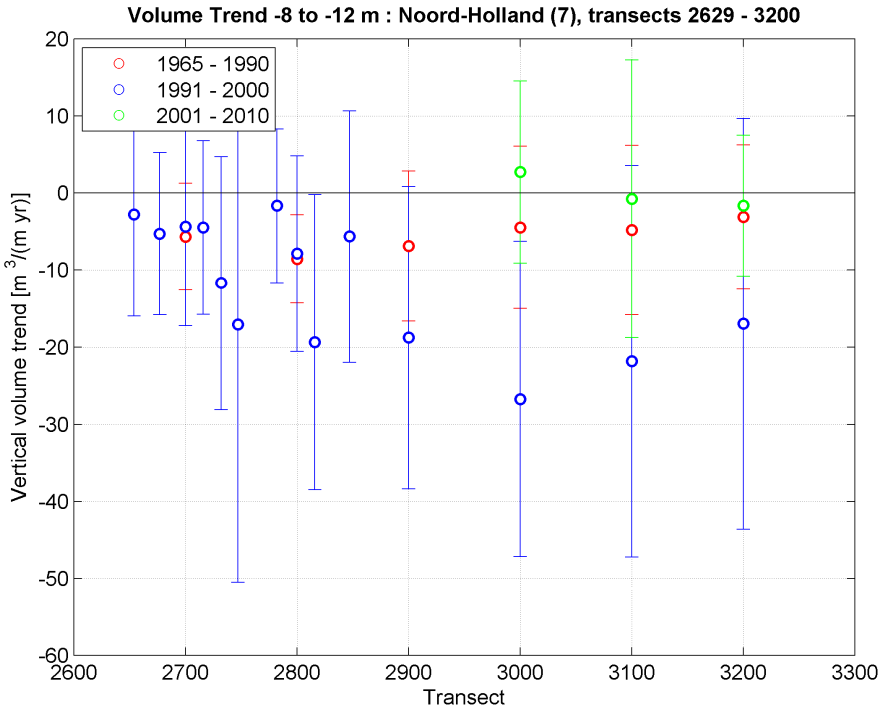
Volume trends -8 m ÷ -12 m

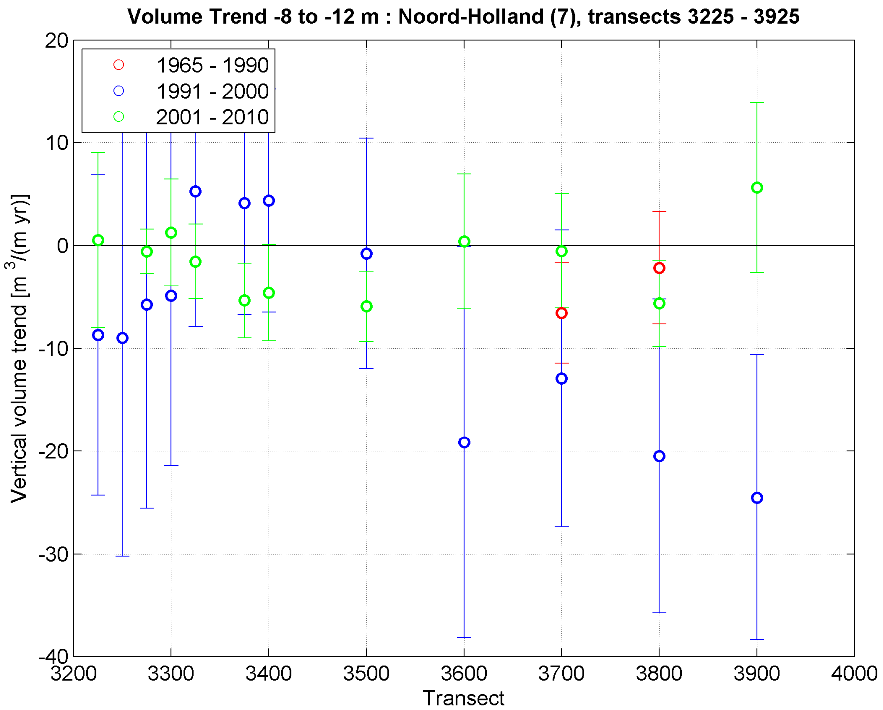


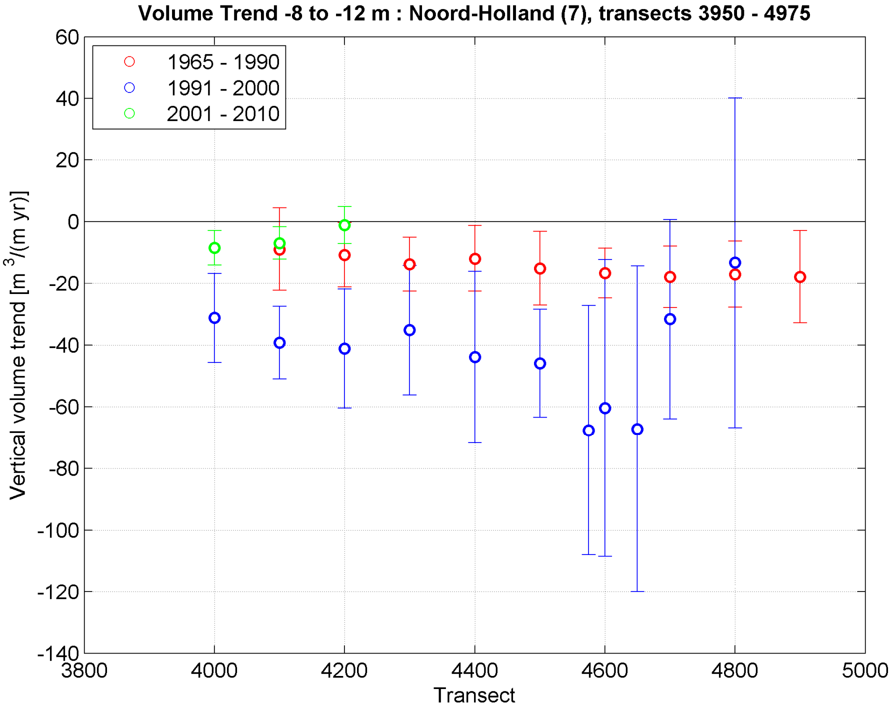


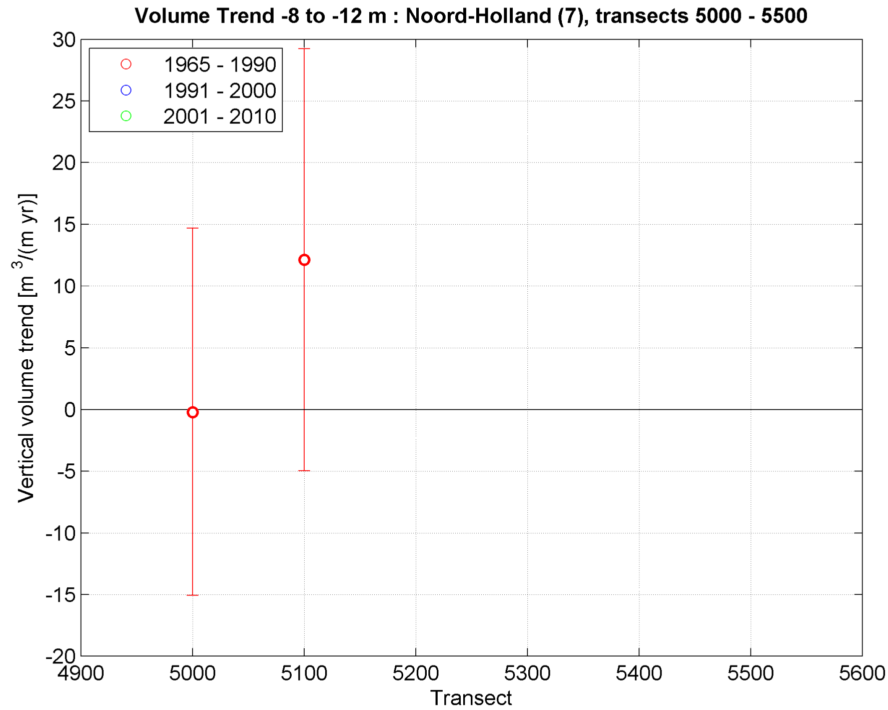

Volume Trend -8 to -12 m : Noord-Holland (7), transects 1827 - 2023
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume trend [m 3/(m yr)]
Transect
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
1800
1850
1900
1950
2000
2050


Volume Trend -8 to -12 m : Noord-Holland (7), transects 2041 - 2606
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume trend [m 3/(m yr)]
Transect
80
60
40
20
0
-20
-40
2000
2100
2200
2300
2400
2500
2600
2700


Volume Trend -8 to -12 m : Noord-Holland (7), transects 2629 - 3200
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume trend [m 3/(m yr)]
Transect
20
10
0
-10
-20
-30
-40
-50
-60
2600
2700
2800
2900
3000
3100
3200
3300

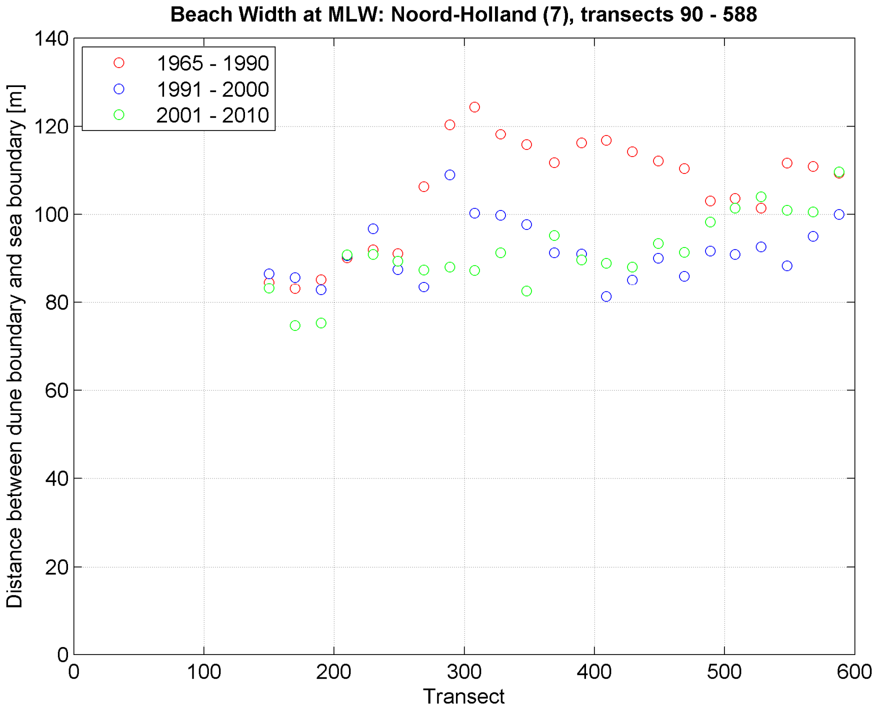

Volume Trend -8 to -12 m : Noord-Holland (7), transects 3225 - 3925
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume trend [m 3/(m yr)]
Transect
20
10
0
-10
-20
-30
-40
3200
3300
3400
3500
3600
3700
3800
3900
4000

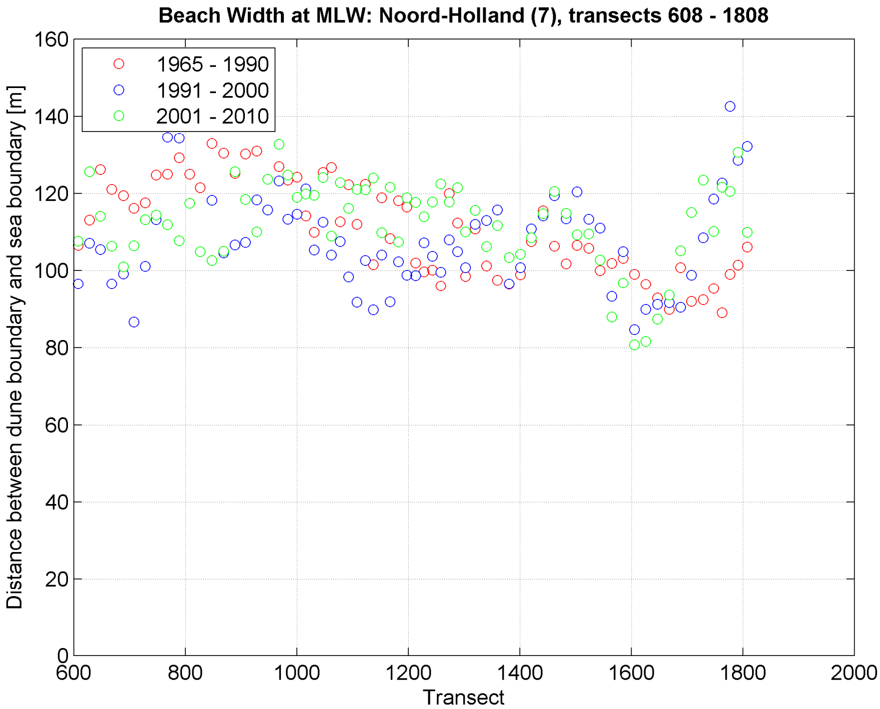

Volume Trend -8 to -12 m : Noord-Holland (7), transects 3950 - 4975
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume trend [m 3/(m yr)]
Transect
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
3800
4000
4200
4400
4600
4800
5000

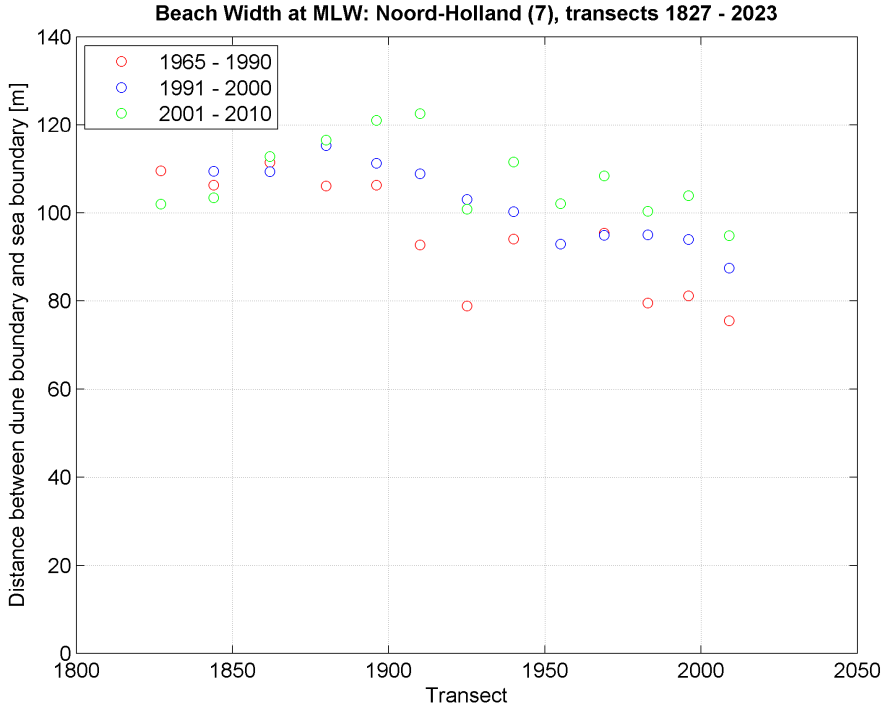

Volume Trend -8 to -12 m : Noord-Holland (7), transects 5000 - 5500
1965 - 1990
1991 - 2000
2001 - 2010
Vertical volume trend [m 3/(m yr)]
Transect
30
25
20
15
10
5
0
-5
-10
-15
-20
4900
5000
5100
5200
5300
5400
5500
5600

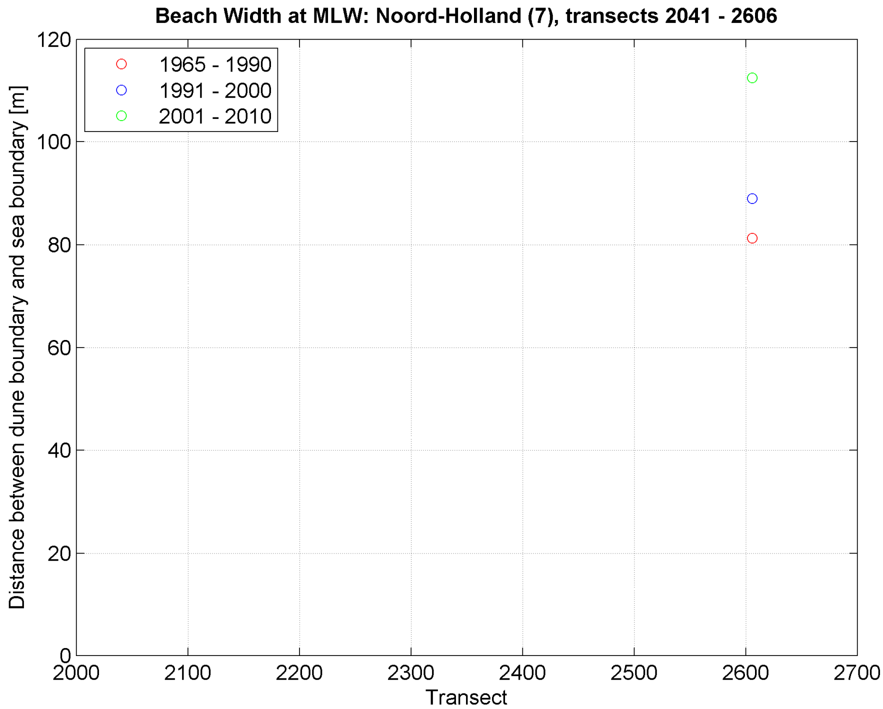
G Beach width

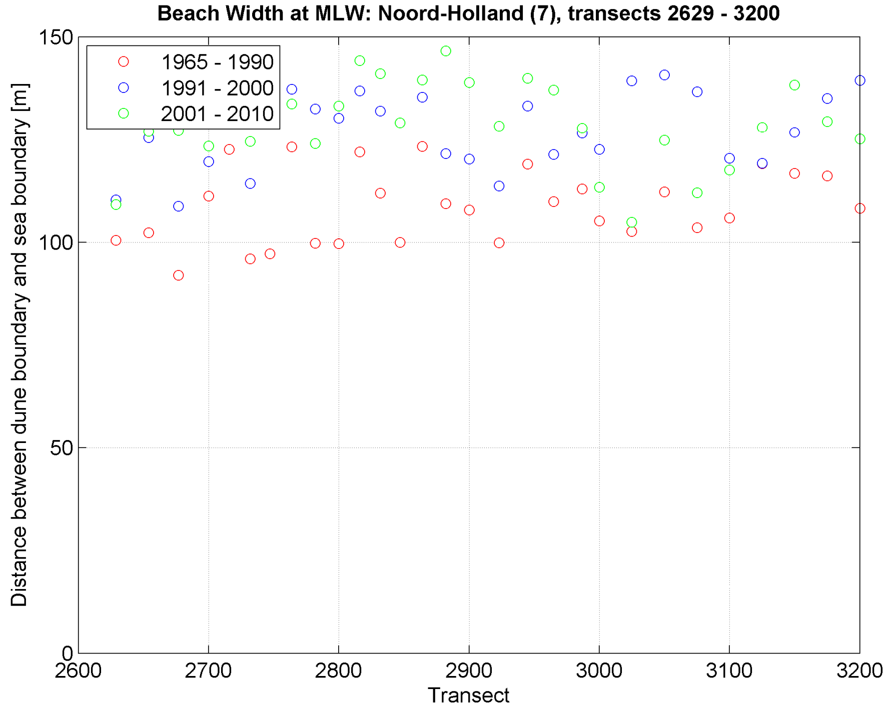
G.1 Beach width at MLW: absolute values

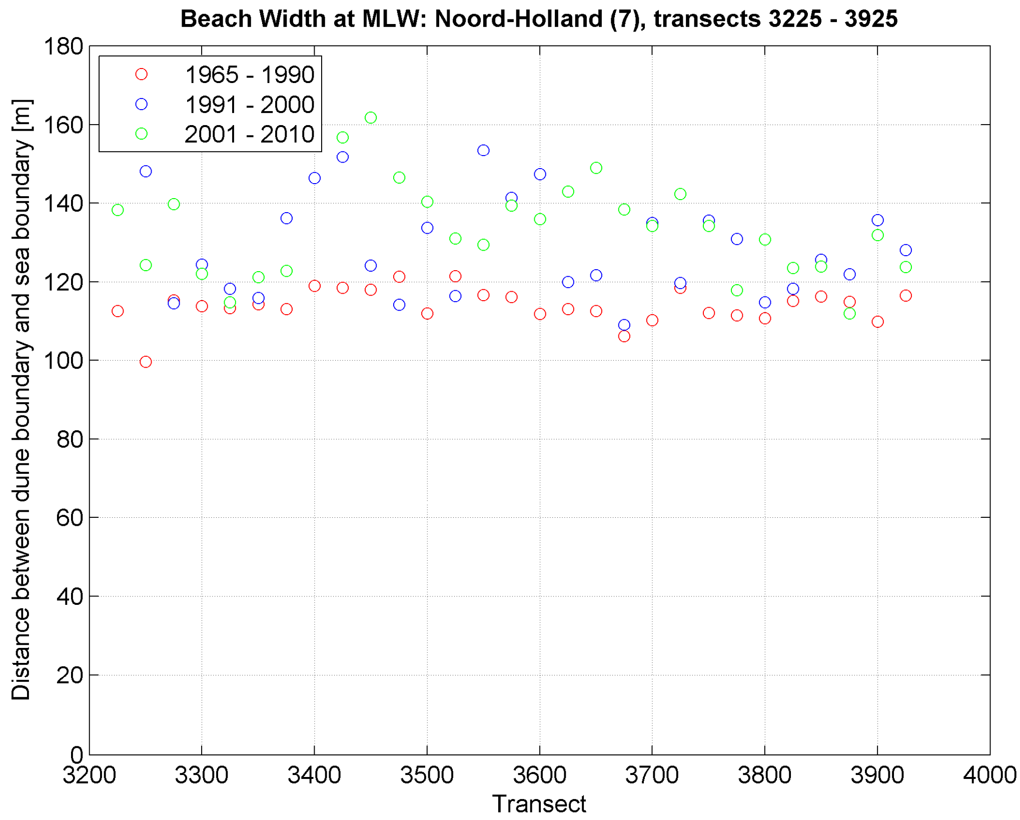


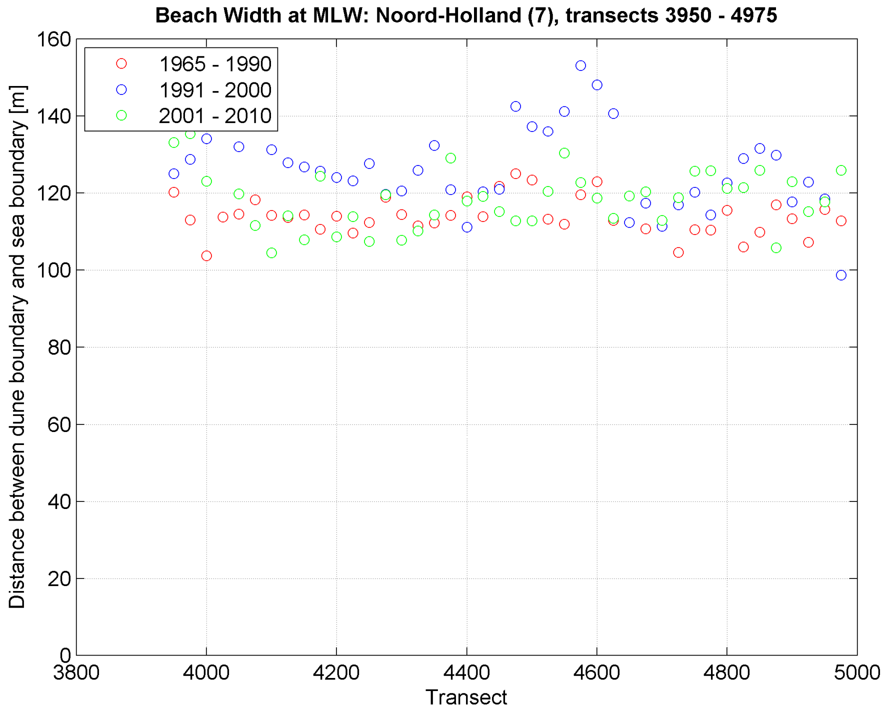


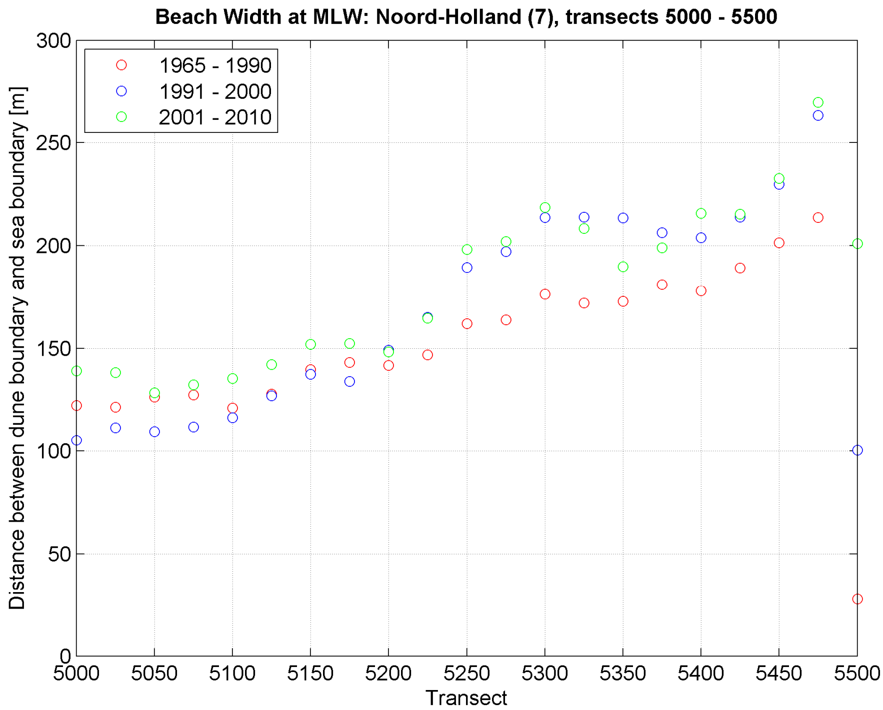

Beach Width at MLW: Noord-Holland (7), transects 1827 - 2023
1965 - 1990
1991 - 2000
2001 - 2010
Distance between dune boundary and sea boundary [m]
Transect
0
20
40
60
80
100
120
140
1800
1850
1900
1950
2000
2050


Beach Width at MLW: Noord-Holland (7), transects 2041 - 2606
1965 - 1990
1991 - 2000
2001 - 2010
Distance between dune boundary and sea boundary [m]
Transect
0
20
40
60
80
100
120
2000
2100
2200
2300
2400
2500
2600
2700

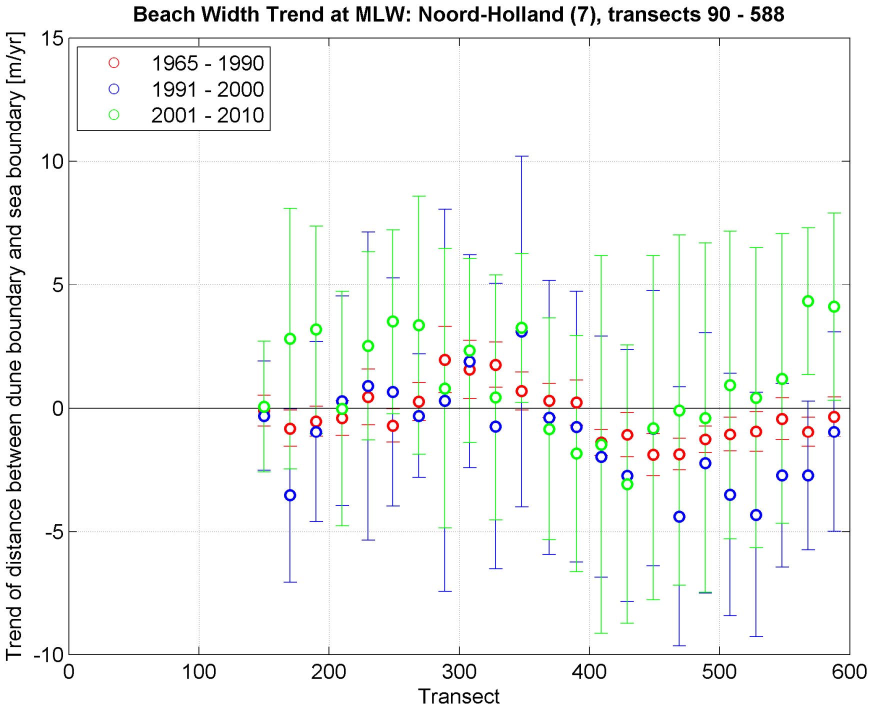

Beach Width at MLW: Noord-Holland (7), transects 2629 - 3200
1965 - 1990
1991 - 2000
2001 - 2010
Distance between dune boundary and sea boundary [m]
Transect

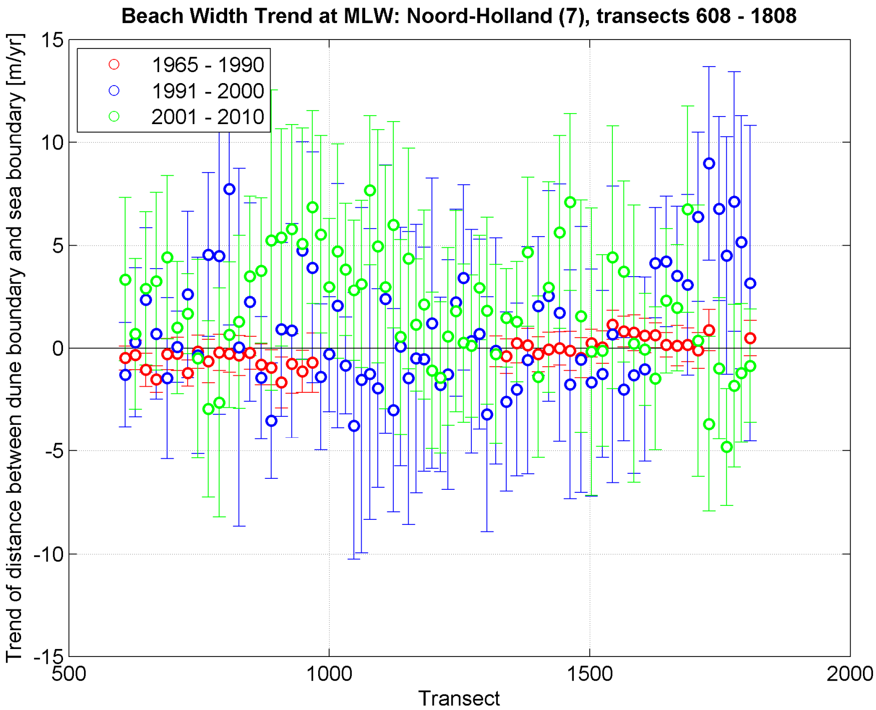

Beach Width at MLW: Noord-Holland (7), transects 3225 - 3925
1965 - 1990
1991 - 2000
2001 - 2010
Distance between dune boundary and sea boundary [m]
Transect

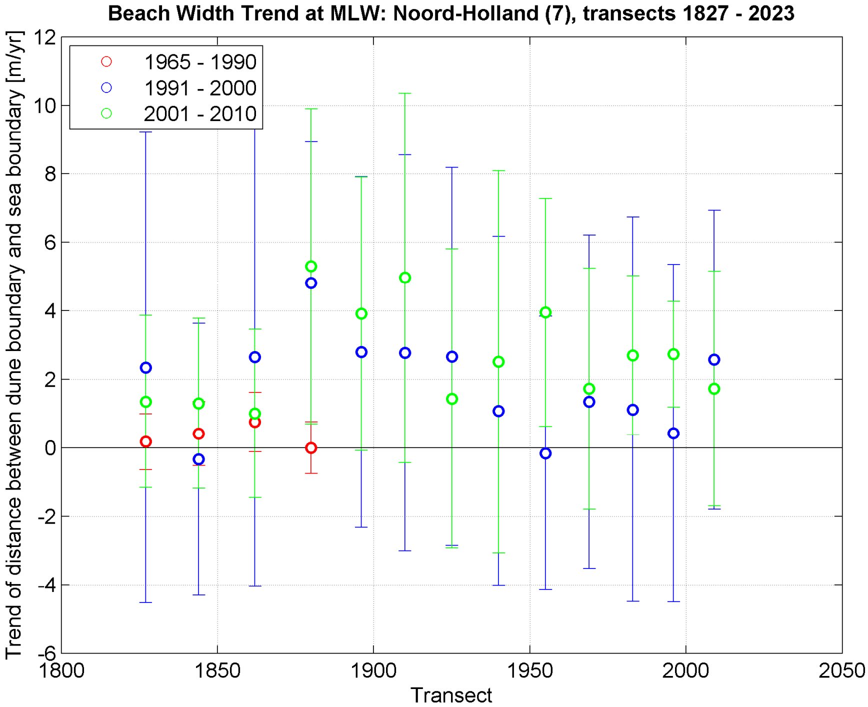

Beach Width at MLW: Noord-Holland (7), transects 3950 - 4975
1965 - 1990
1991 - 2000
2001 - 2010
Distance between dune boundary and sea boundary [m]
Transect

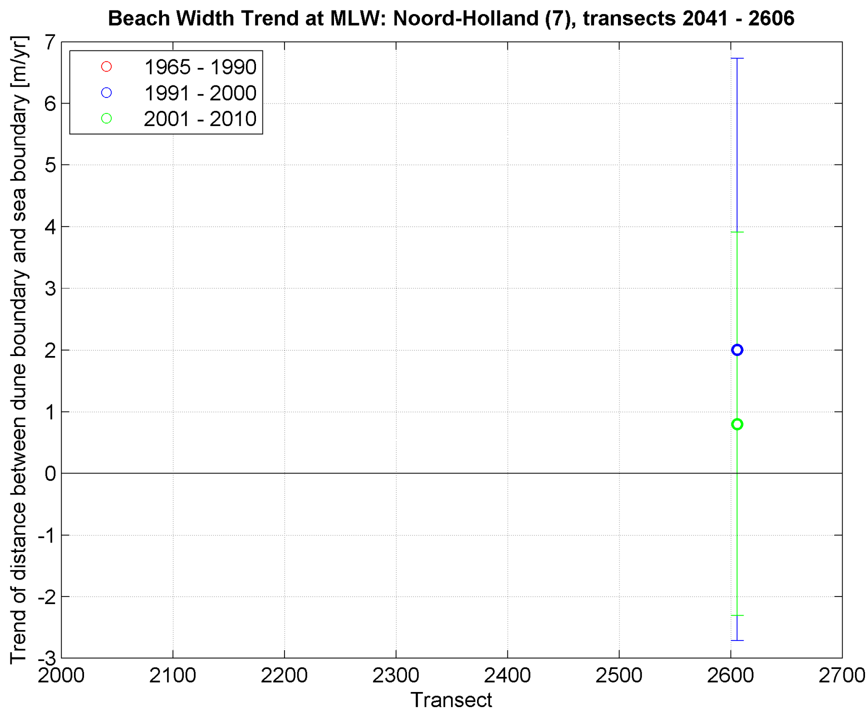

Beach Width at MLW: Noord-Holland (7), transects 5000 - 5500
1965 - 1990
1991 - 2000
2001 - 2010
Distance between dune boundary and sea boundary [m]
Transect

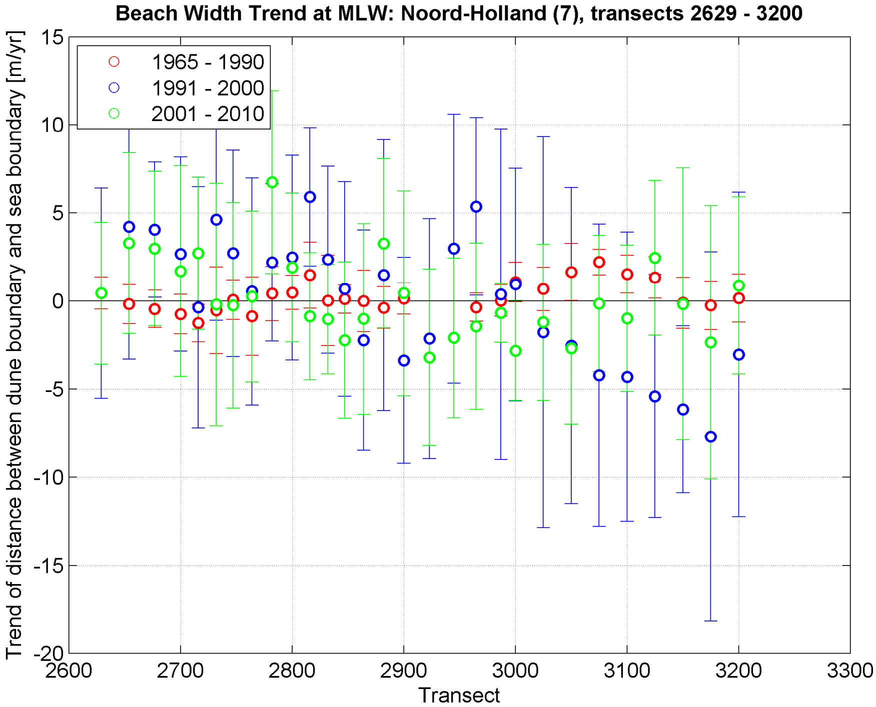
G.2 Beach width: trend analysis

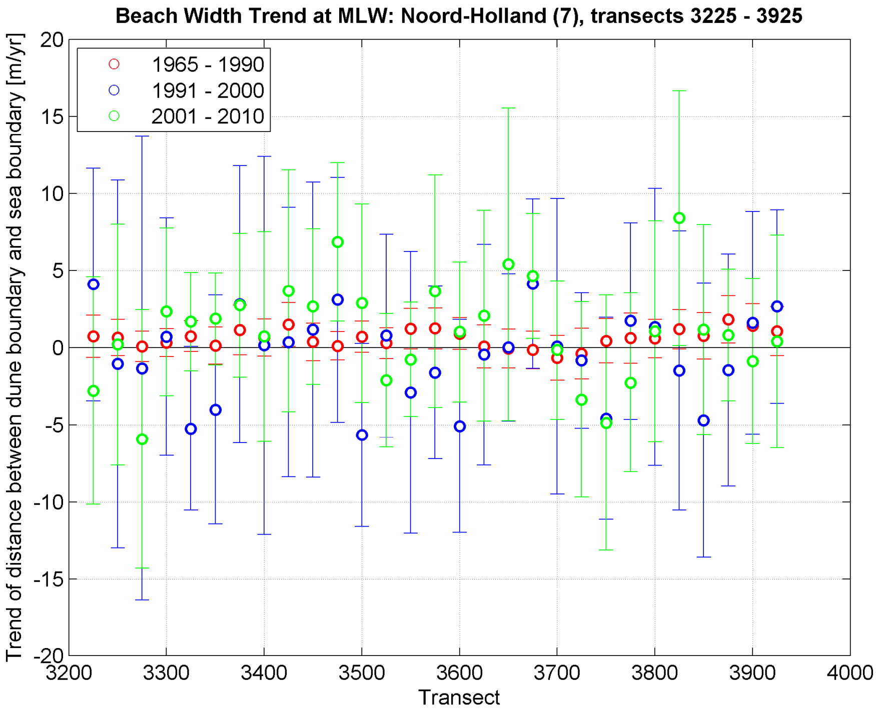


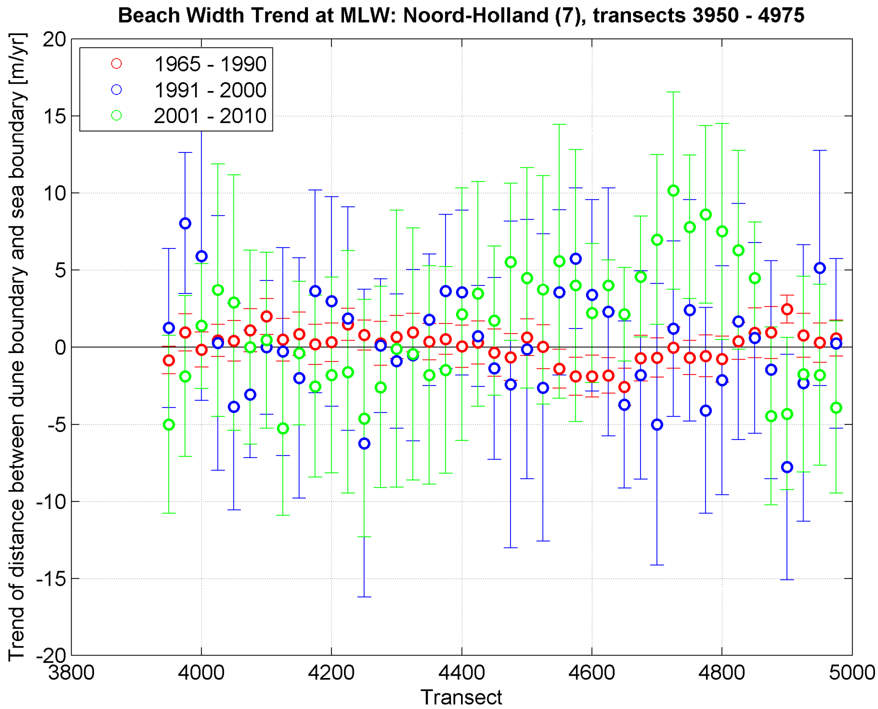


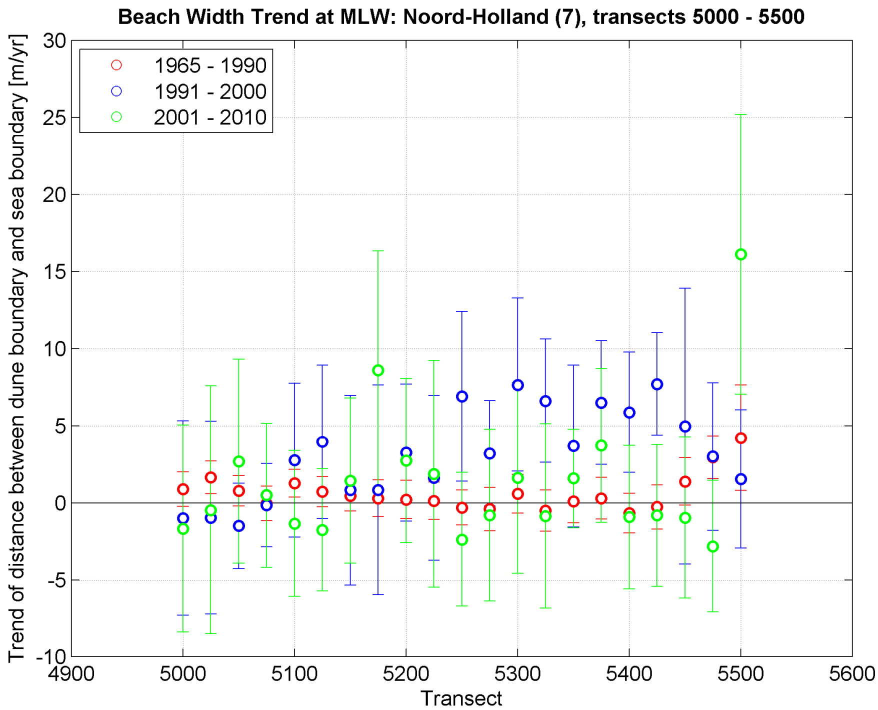

Beach Width Trend at MLW: Noord-Holland (7), transects 1827 - 2023
Trend of distance between dune boundary and sea boundary [m/yr]
Transect
1965 - 1990
1991 - 2000
2001 - 2010
12
10
8
6
4
2
0
-2
-4
-6
1800
1850
1900
1950
2000
2050


Beach Width Trend at MLW: Noord-Holland (7), transects 2041 - 2606
Trend of distance between dune boundary and sea boundary [m/yr]
Transect
1965 - 1990
1991 - 2000
2001 - 2010
7
6
5
4
3
2
1
0
-1
-2
-3
2000
2100
2200
2300
2400
2500
2600
2700


Beach Width Trend at MLW: Noord-Holland (7), transects 2629 - 3200
1965 - 1990
1991 - 2000
2001 - 2010
Trend of distance between dune boundary and sea boundary [m/yr]
15
10
5
0
-5
-10
-15
-20
2600
2700
2800
2900
3000
3100
3200
3300
Transect

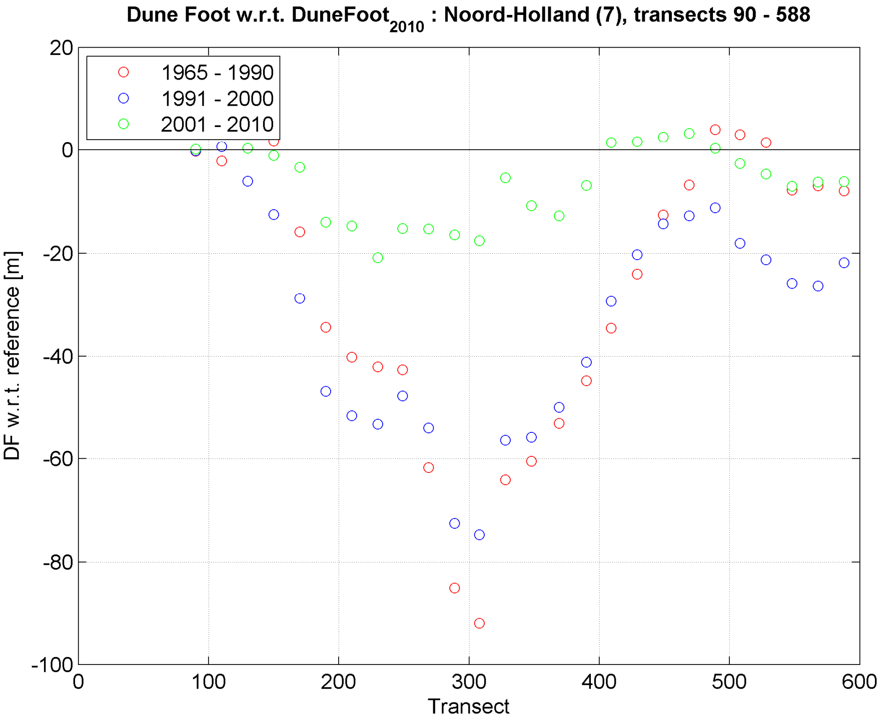

Beach Width Trend at MLW: Noord-Holland (7), transects 3225 - 3925
1965 - 1990
1991 - 2000
2001 - 2010
Trend of distance between dune boundary and sea boundary [m/yr]
20
15
10
5
0
-5
-10
-15
-20
3200
3300
3400
3500
3600
3700
3800
3900
4000
Transect

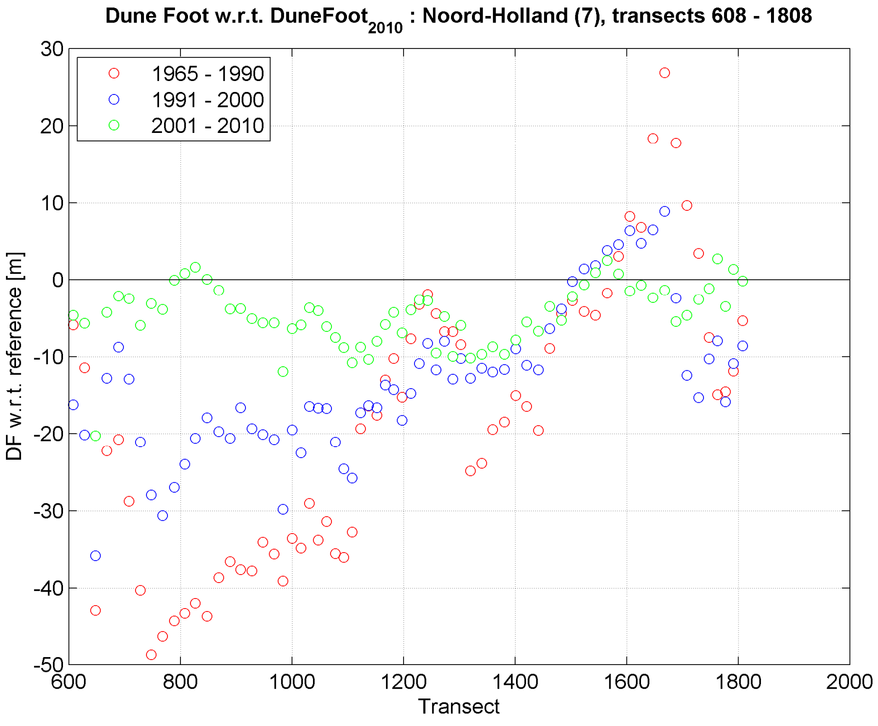

Beach Width Trend at MLW: Noord-Holland (7), transects 3950 - 4975
1965 - 1990
1991 - 2000
2001 - 2010
Trend of distance between dune boundary and sea boundary [m/yr]
20
15
10
5
0
-5
-10
-15
-20
3800
4000
4200
4400
4600
4800
5000
Transect

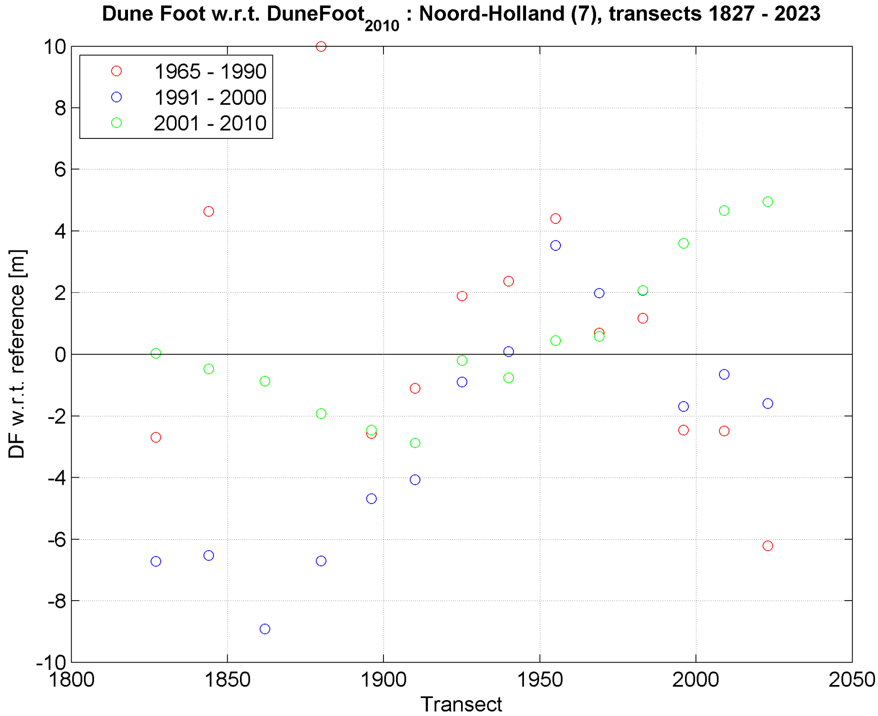

Beach Width Trend at MLW: Noord-Holland (7), transects 5000 - 5500
1965 - 1990
1991 - 2000
2001 - 2010
Trend of distance between dune boundary and sea boundary [m/yr]
30
25
20
15
10
5
0
-5
-10
4900
5000
5100
5200
5300
5400
5500
5600
Transect

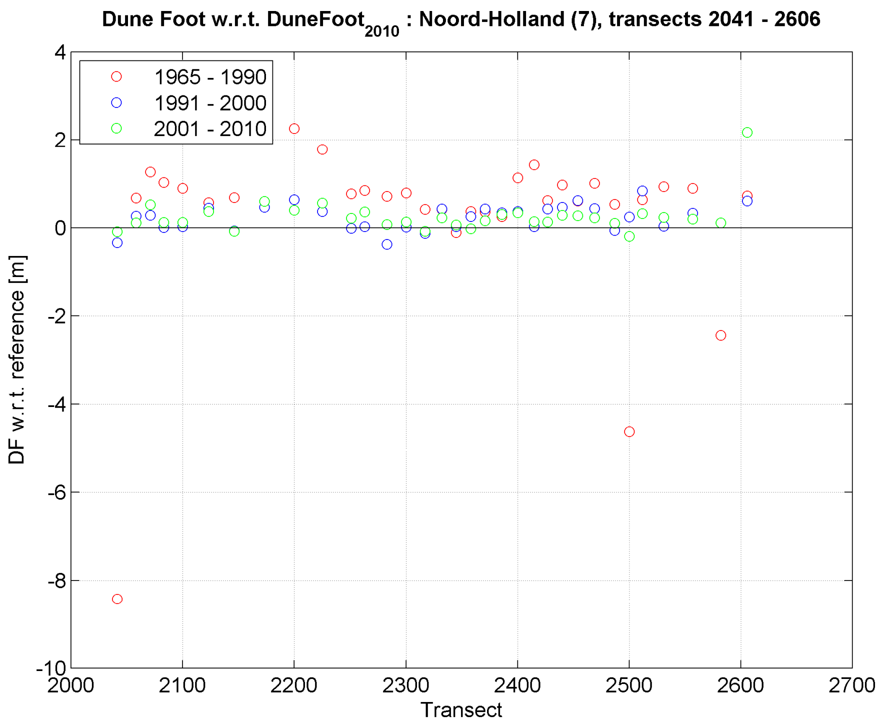
H Dune foot

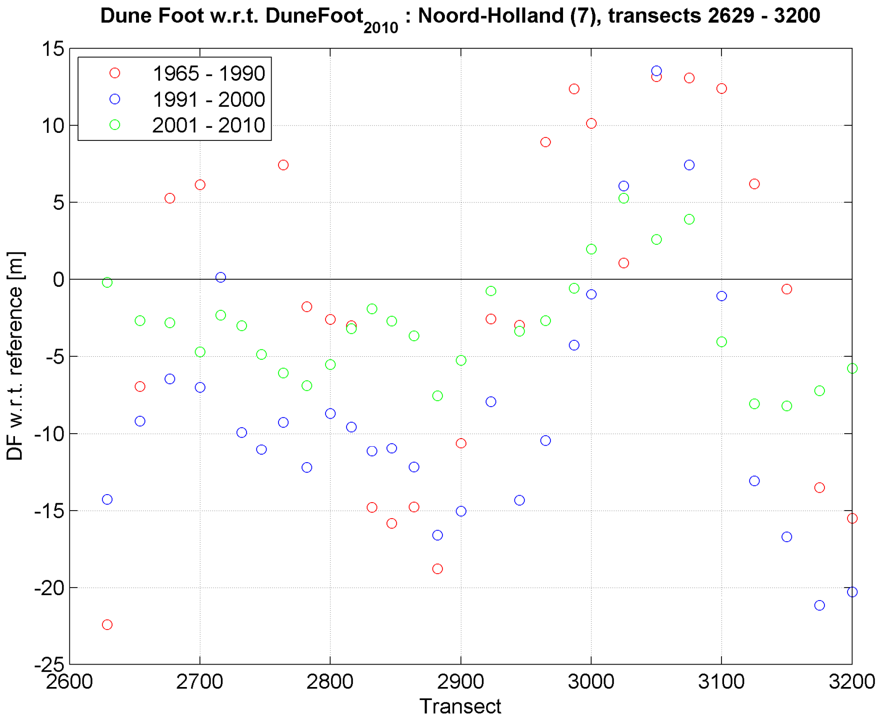
H.1 Dune foot with respect to the 2010 position: absolute values

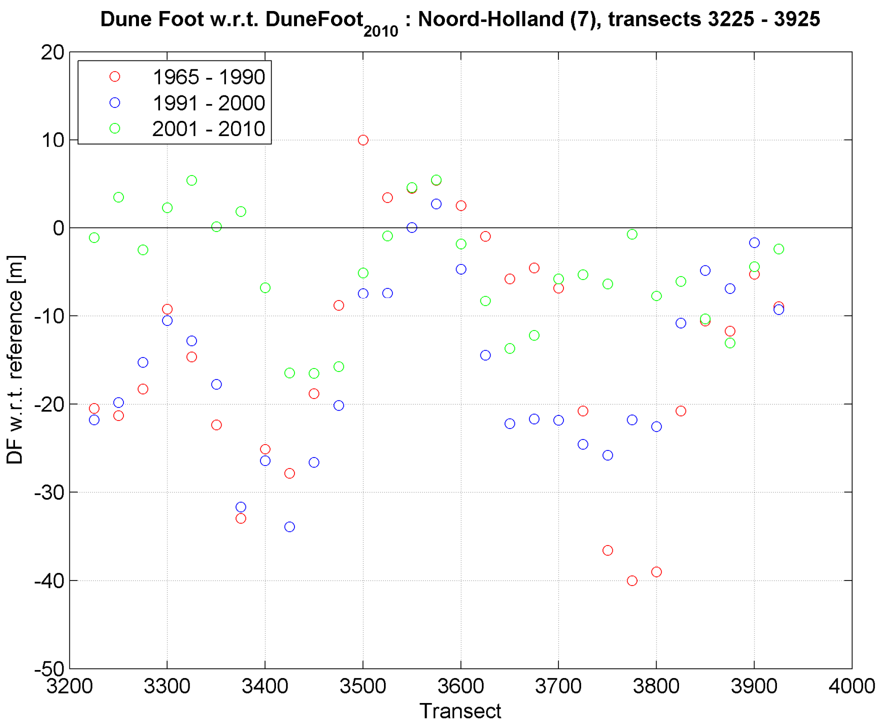


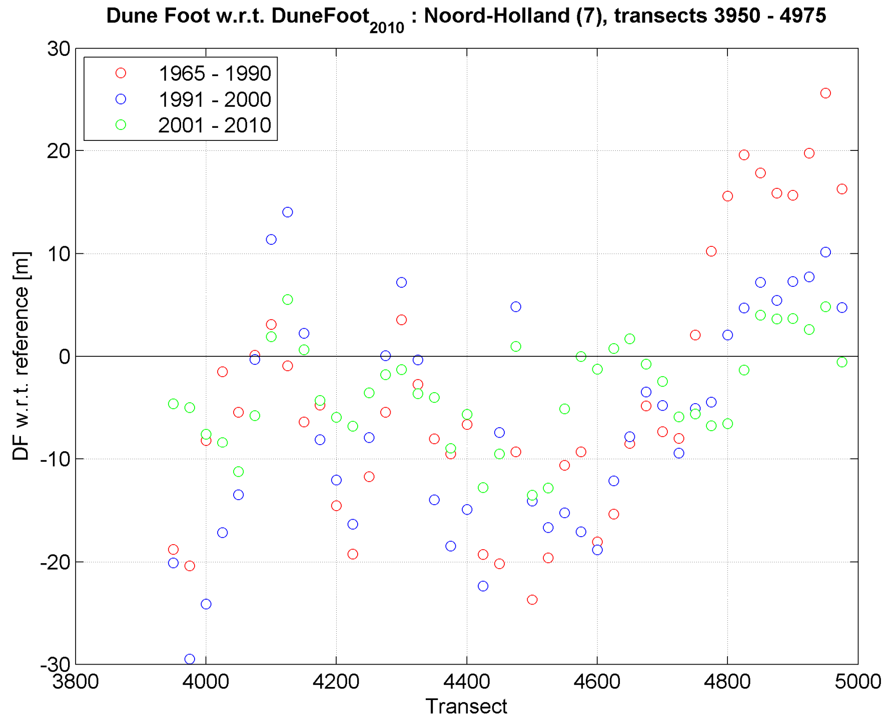


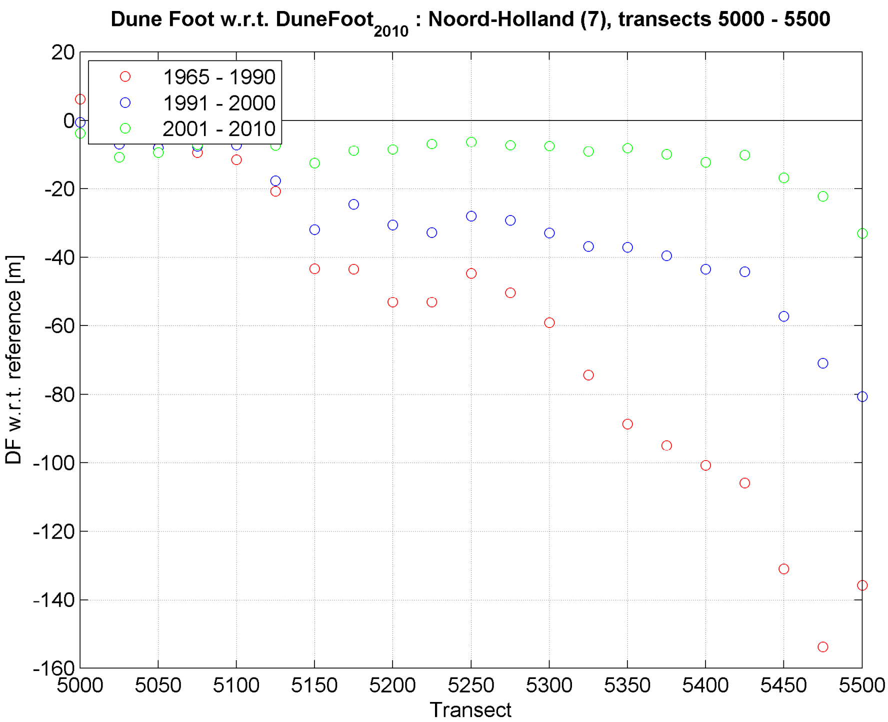

Dune Foot w.r.t. DuneFoot2010 : Noord-Holland (7), transects 1827 - 2023
1965 - 1990
1991 - 2000
2001 - 2010
DF w.r.t. reference [m]
Transect
10
8
6
4
2
0
-2
-4
-6
-8
-10
1800
1850
1900
1950
2000
2050


Dune Foot w.r.t. DuneFoot2010 : Noord-Holland (7), transects 2041 - 2606
1965 - 1990
1991 - 2000
2001 - 2010
DF w.r.t. reference [m]
Transect
4
2
0
-2
-4
-6
-8
-10
2000
2100
2200
2300
2400
2500
2600
2700

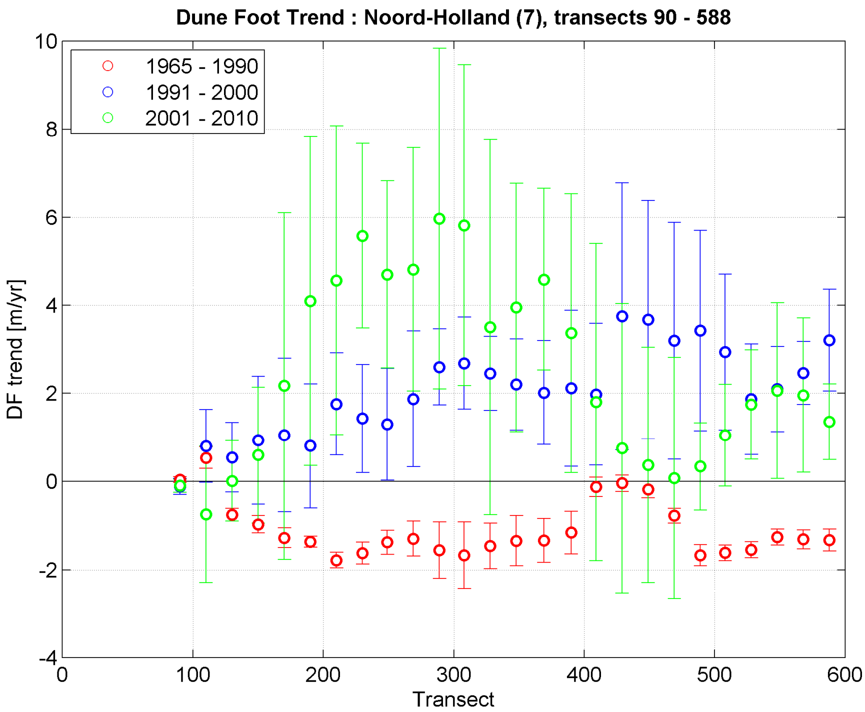

Dune Foot w.r.t. DuneFoot2010 : Noord-Holland (7), transects 2629 - 3200
1965 - 1990
1991 - 2000
2001 - 2010
DF w.r.t. reference [m]
Transect
15
10
5
0
-5
-10
-15
-20
-25
2600
2700
2800
2900
3000
3100
3200

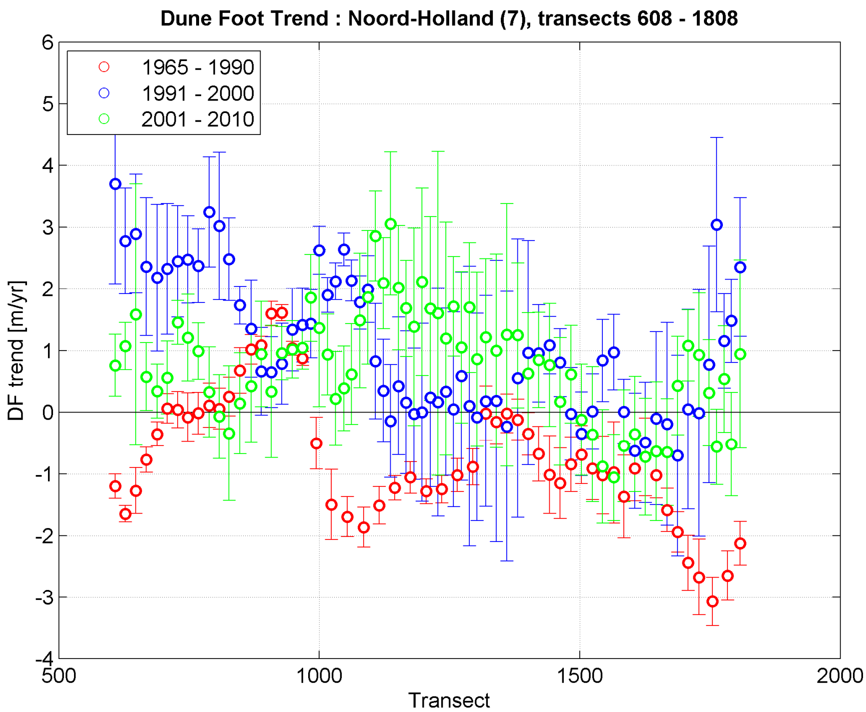

Dune Foot w.r.t. DuneFoot2010 : Noord-Holland (7), transects 3225 - 3925
1965 - 1990
1991 - 2000
2001 - 2010
DF w.r.t. reference [m]
Transect
20
10
0
-10
-20
-30
-40
-50
3200
3300
3400
3500
3600
3700
3800
3900
4000

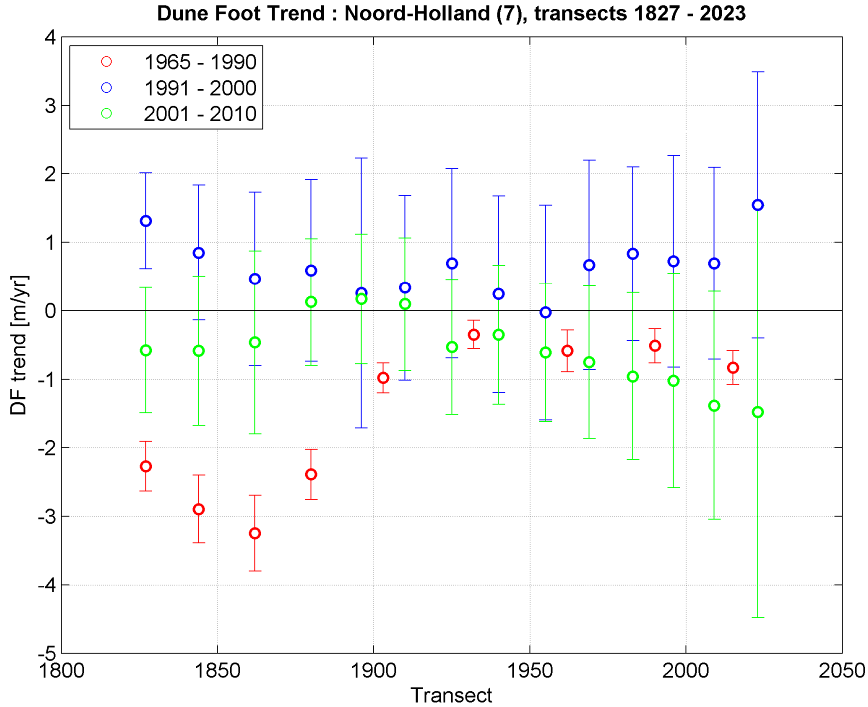

Dune Foot w.r.t. DuneFoot2010 : Noord-Holland (7), transects 3950 - 4975
1965 - 1990
1991 - 2000
2001 - 2010
DF w.r.t. reference [m]
30
20
10
0
-10
-20
-30
3800
4000
4200
4400
4600
4800
5000
Transect

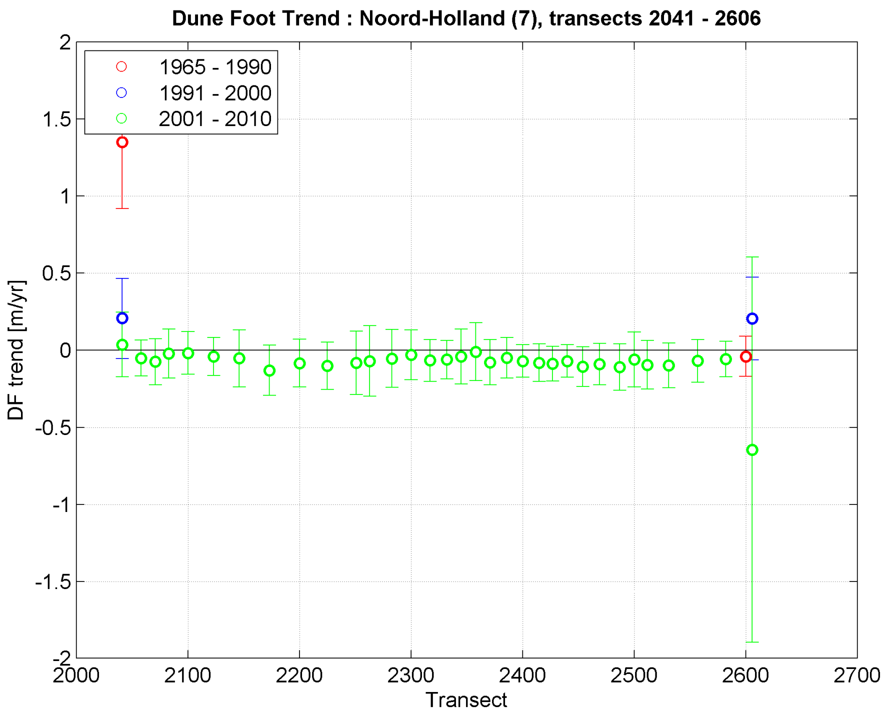

Dune Foot w.r.t. DuneFoot2010 : Noord-Holland (7), transects 5000 - 5500
1965 - 1990
1991 - 2000
2001 - 2010
DF w.r.t. reference [m]
20
0
-20
-40
-60
-80
-100
-120
-140
-160
5000
5050
5100
5150
5200
5250
5300
5350
5400
5450
5500
Transect

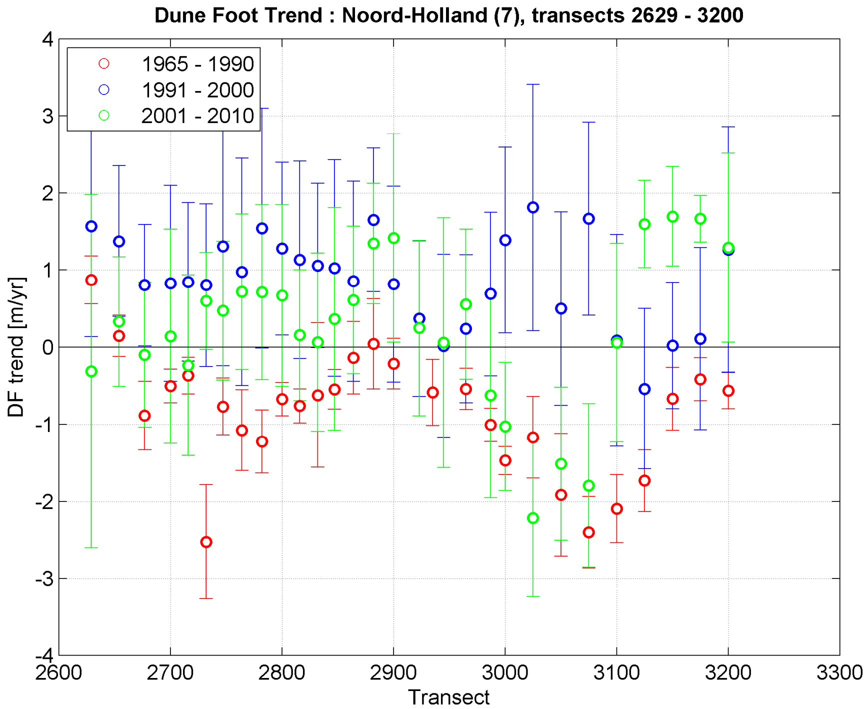
H.2 Dune foot : trend analysis

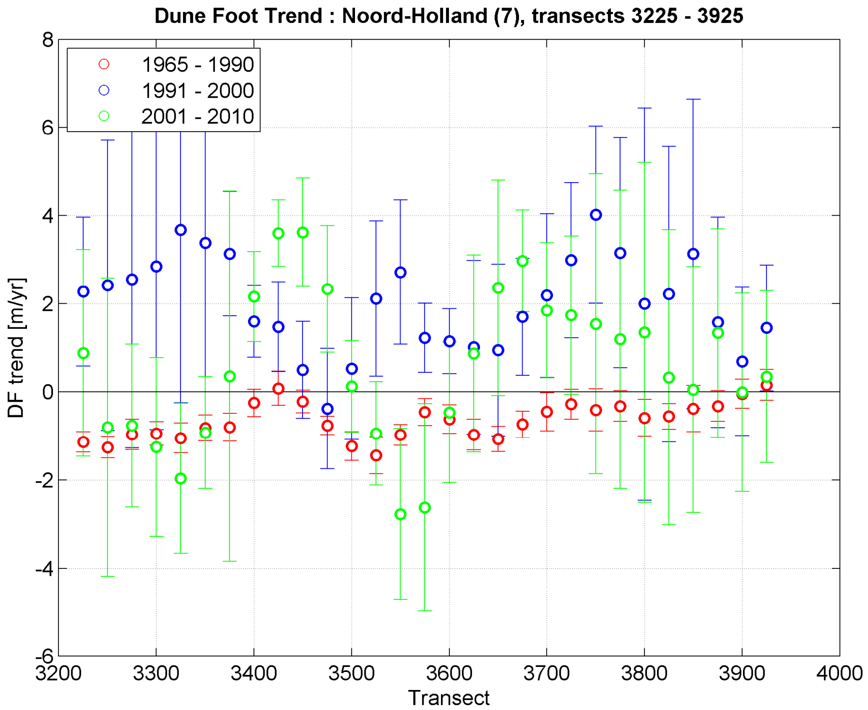


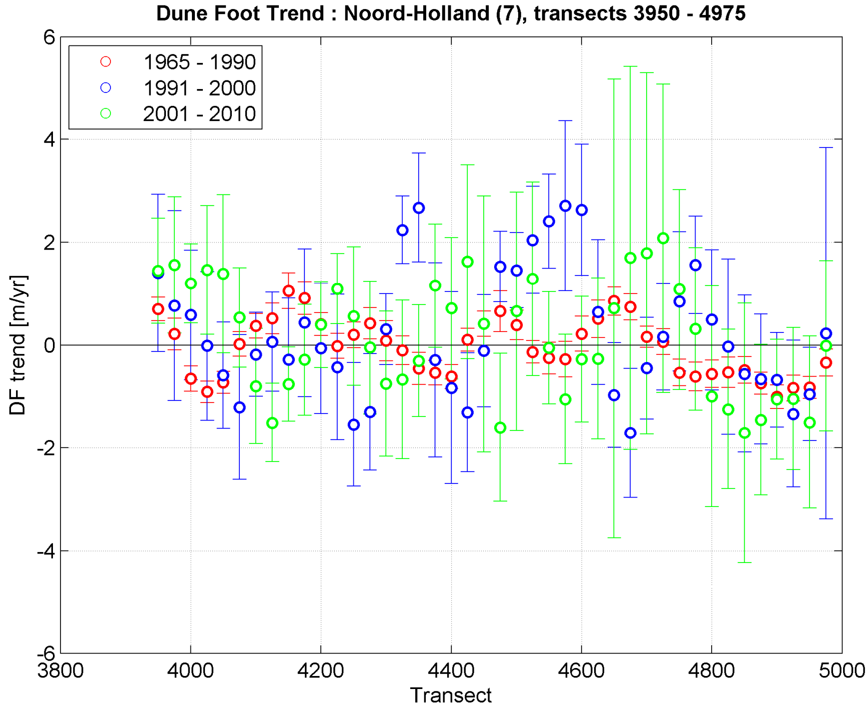


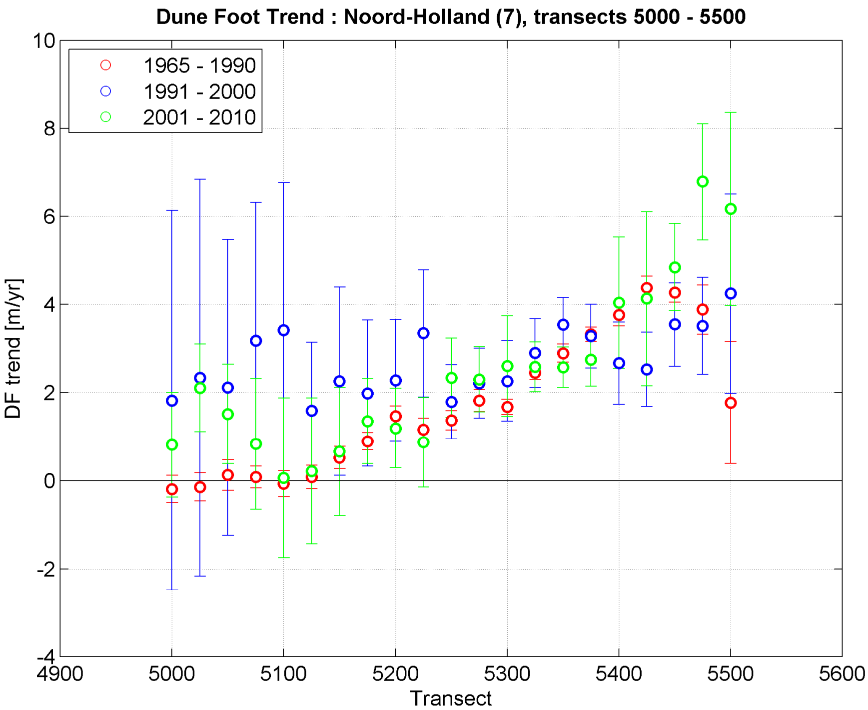

Dune Foot Trend : Noord-Holland (7), transects 1827 - 2023
1965 - 1990
1991 - 2000
2001 - 2010
DF trend [m/yr]
Transect


Dune Foot Trend : Noord-Holland (7), transects 2041 - 2606
1965 - 1990
1991 - 2000
2001 - 2010
DF trend [m/yr]
Transect


Dune Foot Trend : Noord-Holland (7), transects 2629 - 3200
1965 - 1990
1991 - 2000
2001 - 2010
DF trend [m/yr]
Transect
4
3
2
1
0
-1
-2
-3
-4
2600
2700
2800
2900
3000
3100
3200
3300


Dune Foot Trend : Noord-Holland (7), transects 3225 - 3925
1965 - 1990
1991 - 2000
2001 - 2010
DF trend [m/yr]
Transect
8
6
4
2
0
-2
-4
-6
3200
3300
3400
3500
3600
3700
3800
3900
4000


Dune Foot Trend : Noord-Holland (7), transects 3950 - 4975
1965 - 1990
1991 - 2000
2001 - 2010
DF trend [m/yr]
Transect


Dune Foot Trend : Noord-Holland (7), transects 5000 - 5500
1965 - 1990
1991 - 2000
2001 - 2010
DF trend [m/yr]
Transect