Nearshore dynamics of a nourished coast with respect to a neighbouring natural coast

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Abstract

The Dutch coast belongs to one the most heavily engineered coasts around the world. In order to protect the coast from structural erosion, the Dutch government decided to dynamically maintain the coastline of 1990, by making use of nourishments. This thesis focuses on the impact of these nourishments on nearshore dynamics, in terms of bar behaviour and volume trends. However, a problem with nourishments is that a proper comparison to 'natural behaviour' is always hampered by either time or location. This thesis tackles this problem by comparing a nourished coast to a directly adjacent unnourished site. To do so, 2250 transects from the JARKUS data set, measured perpendicular to the coast of Egmond aan Zee (The Netherlands), were studied. These transects consisted of 45 locations, with a longshore spacing of 250 m and a total length of 11 km, and contained a nourished part and an unnourished part of 5 km and 6 km respectively.

The study of exact bar behaviour, in terms of cross-shore location and volume, required a method which could isolate bar positions from these profiles. This method was based on techniques used earlier by Ribas et al. (2010) and Radermacher et al. (2018). It appeared that the intersections of the first derivative with the mean slope is the best approximation of the bar edge. By making use of this strategy, all bars present near Egmond in the period 1964 to 2013 could be found and studied, based on their cross-shore location and volume.

This led to the following conclusions: First of all, corroborating other studies on nourishing, erosion trends of the dunes and nearshore area turned into accretion trends. Secondly, implementation of the shoreface nourishments near Egmond locked the bar system landward of the nourishment and 'froze' the bar positions for periods up to five years. Next, in the unnourished section (south of the nourished section), Net Offshore Migration (NOM) continued, causing large longshore jumps in cross-shore bar positions, which ultimately resulted in a complete bar switch episode in 2001. Then, after depletion of the outer bar in the unnourished section, the oblique orientation of the whole bar section turned around and 3D structures such as crescent bar shapes and sand waves started to migrate in the opposite direction. Finally, although volume trends in the nearshore area became positive, bar volume did not change, which suggests that sandbars play a minor role in the spreading of sand throughout the surf zone.

Contents

1. Introduction

The Dutch coast belongs to the most heavily engineered coasts around the world. This is the result of centuries of ongoing subsidence and erosion. Nowadays nearly 30% of the country's land area resides below mean sea level (Hoeksema, 2007). Moreover, according to the Dutch Environmental Assessment Agency, nearly 55% is susceptible to flooding by either sea or rivers (Planbureau voor de Leefomgeving, 2010). Since the economical, demographical and political centres of the Netherlands are all located in these vulnerable areas, measures are needed to ensure societal and economical safety. Despite the fact that the Dutch coast is heavily engineered, only 15% of its total stretch of 350 km is protected by dikes. The vast majority (75%), including the central Holland coast, is protected by dunes (Mulder & Tonnon, 2010).

Change in policy

That the sea is a serious threat to the country became clear after the storm surge disaster of 1953: During a western storm, dikes in the southern part of the Netherlands collapsed at various locations, leading to the flooding of 135,000 ha of land and killing 1835 people (d'Angremond, 2003). In the slipstream of this large flooding, coastal policy became a national priority and in order to prevent disasters on such scale, coastal safety became implemented into law. At first, series of hard structures, such as dams and dikes were constructed, closing off most of the tidal inlets. These structures were intended to drastically reduce the total length of the coastline. However, over the decades following 1953, the coastal safety strategy shifted from defensive towards sustainable. Over the years, economical, ecological and recreational aspects were also taken into account. The Eastern Scheldt storm surge barrier, completed in 1986, allowed the exchange of salt water during calm weather conditions. Therefore, this barrier may be seen as a first example of this gradual paradigm shift (Van Koningsveld & Mulder, 2004).

Dynamic Preservation

After 1986, more focus came on sand nourishments, which became policy in 1990 with the implementation of 'dynamic preservation'. Core of the policy was to maintain the coastline of 1990, referred to as the Basal Coastline ('Basiskustlijn' or 'BKL' in Dutch), against all cost. However, due to ongoing erosion of the lower shoreface an enhanced effort was needed to ensure future coastal stability (e.g. Van der Spek & Lodder, 2015). Since then, a yearly amount of 7 Mm3 has been applied to the beaches and shoreface to stop structural erosion of the Dutch coast (e.g. Taal et al., 2006; Hillen & Roelse, 1995). In 2000, the nourishment program was intensified and the annual sand load was increased towards 12 Mm3/yr, taking into account the following principles (Taal et al., 2006):

1. Maintenance of the sediment budget in the Coastal Foundation, enabling free sediment to spread through natural dynamics.
2. Application of beach nourishments where necessary.
3. Building of hard constructions where no other options are available.

Altogether over 250 Mm^3 of sand has been supplied on the Dutch coast since 1990 (Kustlijnkaarten 2007; Kustlijnkaarten 2017)[1].

Two scales

The impact of these nourishments has been analysed on either local kilometer scale (e.g. Ojeda et al., 2008; Ruessink et al., 2012; Grunnet & Ruessink, 2005; Kroon et al., 1995; Van der Grinten & Ruessink,

[1] Based on summation ofnumbers in figure 3.1 and 4.1 of *Kustlijnkaarten 2007 and Kustlijnkaarten 2017, respectively*

2012; Van Rijn & Walstra, 2004), or on macro scales with a scale of tens of kilometers (Pot, 2011; Wijnberg, 2002; Van der Spek & Elias, 2013; Lodder & Sørensen, 2015; Bruins, 2016; Hamm et al., 2002; De Sonneville & Van der Spek, 2012; Roelse, 1996; Spanhoff et al., 2005; Van der Spek & Lodder, 2015).

On small scales, the emphasis of (older) research is on the description of morphological behaviour of a coast as a result of single nourishments (Grunnet & Ruessink., 2005; Kroon et al., 1995; Ojeda et al., 2008). Other studies give an attempt to model the behaviour of nourishments (Van Rijn & Walstra, 2004; Van Duin et al., 2004). The results from these papers contain a wide range of different behaviour of nourishments in terms of duration, migration rates and 3D-features. Ojeda et al. (2008) suggested three possible causes for these differences:

i. The location of the nourishment in the cross shore profile
ii. Grain size of the nourished material
iii. Relative amount of nourished sand, compared to the size of sandbars

(Ojeda et al., 2008)

After the study of Ojeda et al. (2008) near Noordwijk, Van der Grinten and Ruessink(2012) and Ruessink et al.(2012) analysed the effect of two consecutive nourishments at the same location in 1998 and 2006. Their common conclusion was that nourishments reduce the natural dynamics and stop the autonomous net offshore bar migration. However, none of these studies included exact bar volumes after implementation of the nourishment.

Research on a larger scale was performed by De Sonneville & Van der Spek (2012), Lodder & Sørensen (2015), Bruins (2016), Spanhoff et al. (2004), Spanhoff et al. (2005) and Van der Spek & Elias (2013). These are based on inter-site comparison of nourishments. When assessing nourishments on a larger scale, this is often done in terms of sand budget and volume trends (Roelse et al., 1996; Pot,2011; Van der Spek & Lodder, 2015, Van der Spek et al., 2013). These can be seen as a follow-up of the studies performed by Wijnberg (2002), Wijnberg & Terwindt (1995) and Van Rijn (1995).

In this thesis attempts to create an intermediate scale between the two described above. This allows the study of exact bar behaviour in an area, in terms of volume, but still taking into account the morphological development of the surrounding areas. To do so, 50 years of bathymetrical data was analysed near the coastal town of Egmond aan Zee, the Netherlands. Here, two adjacent sites are maintained in opposite ways since 1990: near the town of Egmond aan Zee, multiple nourishments took place, including beach and shoreface nourishments, while south of Egmond no nourishments took place at all. This allows for a fair comparison: how does the same part of the coast react when treated differently? The study site near Egmond is not only suitable due to its large contrast in maintenance: near Egmond also two ARGUS video monitoring systems were situated, enabling daily study of bar patterns from 1999 to 2015. In this thesis it was not possible to use these data, but it still provides interesting opportunities for future research.

The aim of this thesis is to define bar positions and volumes and to compare them to overall erosion/accretion trends in both areas near Egmond. This allows to study the role of bars in sediment distribution in nourished and unnourished situations.

1.1 Reader's Guide

In order to enhance the readability of this thesis, the number of chapters are extended from the conventional layout. However, the scientific structure remains the same: in Chapter 2 and Chapter 3, literature is discussed on natural bar dynamics and nourishments, respectively. After the literature review, the research questions are listed in Chapter 4. The core of this thesis is the development of a bar detection method. To that end, the methods are divided into three chapters. First, conform conventional geomorphological practise, a field site description is provided in Chapter 5. In Chapter 6, the data set is presented, complete transects are created and cross-shore volumes are determined. Since the steps performed in this section are regularly applied when working with JARKUS data, these are separated from the next chapter. In Chapter 7, the actual method, unique to this thesis, is presented. In the second part of the thesis, conventional scientific layout is applied again: In Chapter 8, Chapter 9 and Chapter 10 the results, discussion and conclusion are presented.

2. Natural bar dynamics

In this chapter, the behaviour of bars under natural conditions is discussed. This comprises a literature review of current knowledge about natural bar dynamics under various of conditions. For the sake of this thesis, emphasis is laid on Egmond.

2.1 Cross-shore sandbar behaviour

Along almost the whole Dutch coast sandbars are present. These are shallow submerged ridges parallel to the shoreline and can be found along wave-dominated beaches throughout the world (e.g. Rutten et al., 2018; Price et al., 2014). Bars are formed by the interaction between waves and sediment and belong to the most dynamic part of the coastal profile. The lifecycle of a sandbar has been described by numerous authors (e.g. Ruessink & Kroon, 1994; Shand et al., 1999; Grunnet & Ruessink, 2005; Pape et al., 2010; De Sonneville & Van der Spek, 2012; Walstra et al., 2012; Cohn et al., 2014; Aleman et al., 2017) and consists of 3 distinct phases:

I. Nearshore generation of the bar
II. Net offshore migration of the bar throughout the surf zone. During this process the bar growths in width and height.
III. Flattening and finally disintegration/depletion of the bar in the outer nearshore. This happens generally at a depth of 5-10 m.

The disintegration of a bar triggers the generation of a new bar, leading to a repetition of the processes described above. Ruessink & Kroon (1994) were the first to describe the offshore migration cycle of bars along the Dutch coast. They found a cycle of 12-15 years near the Wadden-Island of Terschelling. However, these numbers appeared to change along the Dutch coast: Wijnberg & Terwindt (1995) identified 5 different regions along the Holland coast with various bar cycle intervals. These vary from no net offshore migration to 15 years near Egmond. The Dutch system is relatively slow compared to other locations worldwide: Observations from Japan and Australia show much faster bar life cycles of 1 and 2,5 years respectively (Pape et al., 2010). This is in agreement with observations of Shand et al. (1999), who related Net Offshore Migration (NOM) to hydrodynamic and morphological conditions. According to Shand et al. (1999), NOM is influenced by wave-energy and a low cross-shore slope: under high energetic conditions, combined with a flat profile, bars tend to have a larger volume. Since larger volumes simply require more time to migrate offshore, this may lead to longer bar cycles.

In 1985, Wright et al. presented a 'beach-state' model, including an empirical parameter, Ω, describing the different types of coastal behaviour. According to Wright et al. (1985), a coastal morphology is a combination of topography and fluid dynamics and therefore specific wave-conditions will lead to a specific type of coastal behaviour, summarized in this formula:

$$\Omega = \frac{H_b}{w_s * T}$$

In this formula, Ω is a dimensionless expression representing the beach state, H_b wave height (m), w_s the sediment fall velocity (m/s) and T the wave period (s). Based on observations along the Australian coast beaches are reflective, dissipative or intermediate, see Table 1 Summary of morphological character different beach states as defined by Wright et al. (1985) for characteristics.

Table 1 Summary of morphological character different beach states as defined by Wright et al. (1985)

Type of behaviour		Ω	Characteristics
Dissipative	D	6	• Spilling breakers • Fine sands • Flat, wide, multi-barred beaches • Shoreward growth of flows due to infragravity oscillations • No rips
Longshore Bar and Trough	LBT	5 - 5.5	• Steeper profile than D • Higher bars • Wave dissipation ceases after trough • Weak rips • Sea waves dominate sediment transport
Rhythmic Bar and Beach	RBB	4 - 4.5	• As RBB • Rhythmic longshore undulations • Stronger rips
Transverse Bar and Rip	TBR	3 - 3.5	• Strongest rip circulation • Result of crescentic bars welding to the coast (mega-cusps)
Longshore Tide Terrace / Ridge Runnel	LTT/ RR	2 - 2.5	• Small/weak rips • Flat terrace/bar near low tide level • Steep beach face at high tide
Reflective	R	1-1.5	• Collapsing breakers • Steep beach • Coarse Material • Beach cusps • Sea wave dominated

Short (1992) applied the model to the Holland coast and concluded that all locations experience intermediate conditions. However, throughout the surf zone, a trend is present from dissipative towards reflective: On the outer third bar (if present) Longshore Bar Trough (LBT) conditions are present whilst the middle bar TBR is the prevailing condition. Near the shore, the inner bar is mostly in the Ridge and Runnel-state (RR). All these bar-states are so-called modal-states. However, beaches and bars in the intermediate state can display a wide range of states. Bar 2 (middle or outer bar) belongs to the most dynamic part of the system (Short, 1992).

During the last decades bar behaviour has been studied and monitored along various sites in the world. In the following sections, observations and results from these studies are discussed. It is important to consider timescale when studying bar migration. One of the most important and easy determinable scales is Net Offshore Migration on a multi-annual timescale, as mentioned above. These migration rates are in the order of 0.04 to 0.55 m/day, depending on the location (Van Enckevort & Ruessink,2003). More specific are the smaller timescales: Van Enckevort & Ruessink (2003a) studied uniform bar migration near Noordwijk and found that migration rates become larger and even may be onshore directed on smaller timescales. In Table 2 Cross-shore bar migration rates near Noordwijk (retrieved from Van Enckevort & Ruessink et al., 2003a) an overview is given of the results obtained by Van Enckevort & Ruessink (2003a). Note that the offshore migration exceeds onshore migration on all timescales (Table 2 Cross-shore bar migration rates near Noordwijk (retrieved from Van Enckevort & Ruessink et al., 2003a)). On an inter-annual timescale, onshore migration does not even exist. Further note that the outer bar tends to be more dynamic than the inner bar. Both the mean and maximum migration rate of the outer bar are higher, except for onshore migration on a weekly scale.

Table 2 Cross-shore bar migration rates near Noordwijk (retrieved from Van Enckevort & Ruessink et al., 2003a)

Statistics of cross-shore bar migration rates

	Offshore migration (m/day)			Onshore migration (m/day)		
	Weekly	Seasonal	Inter-annual	Weekly	Seasonal	Inter-annual
Outer bar						
Mean	1.57	0.16	0.07	1.21	0.11	0.00
St. dev.	1.80	0.09	0.05	1.27	0.07	0.00
Max.	10.12	0.53	0.15	6.73	0.53	0.00
Inner bar						
Mean	1.17	0.09	0.04	1.04	0.05	0.00
St. dev.	1.34	0.07	0.02	1.13	0.04	0.00
Max.	9.98	0.39	0.08	7.48	0.29	0.01

2.2 Drivers of cross-shore sandbar migration

In the last section, part of the theory regarding bar behaviour has been explained. The papers discussed in this part are all strongly coupled to observations, but provide limited insight into the factors controlling bar behaviour. This part focuses on the mechanisms explaining behaviour of bars, in terms of migration. Two papers that explain large parts of the migration behaviour of bars will be examined here.

Walstra et al. (2012) discussed the controlling factors of bar growth and migration. With the Unibest-TC model, bar behaviour was hindcast, based on field measurements and wave-data. Their first remarkable conclusion is that NOM, as discussed above, is not the most common behaviour displayed by sandbars. Most of the time (61% - 71%) bars migrate towards the shore and decrease in size instead of growing. Therefore, it is important to understand which parameters determine this behaviour.

One of the most important factors controlling bar migration and growth is the longshore current. This current is generally stronger than the cross-shore dynamics and therefore determines the amount of sediment stirring near bars. The longshore current in turn is determined by both the wave-height (available energy) and the angle of wave incidence (θ_{xb}). When waves are shore-normal-directed, the longshore current decreases significantly, leading to less stirring in the bar trough, and consequently, bar decay under all conditions. Whether this decay is onshore or offshore is determined by cross-shore conditions (Figure 2.1: Bar behaviour as a result of changing angle of wave incidence (θxb) and water depth above the bar crest (hxb). Panel a: change in bar amplitude; panel b: migration rate. Used wave conditions: Hrms=1,7 m, Tp=8 s and η=0 m. SD= Seaward Decay; SG = Seaward Growth; LG = Landward Growth; LD= Landward Decay. Retrieved from Walstra et al., 2012.). However, when the angle of wave-incidence increases, the longshore current also increases, with long-shore velocities considerably larger than cross-shore velocities. The offshore transport peak therefore moves towards the landward trough, leading to seaward bar growth in most cases (SG in Figure 2.1: Bar behaviour as a result of changing angle of wave incidence (θxb) and water depth above the bar crest (hxb). Panel a: change in bar amplitude; panel b: migration rate. Used wave conditions: Hrms=1,7 m, Tp=8 s and η=0 m. SD= Seaward Decay; SG = Seaward Growth; LG = Landward Growth; LD= Landward Decay. Retrieved from Walstra et al., 2012.). In the combination of landward transport at the seaward slope of the bar a bar may grow in the landward direction (LG in Figure 2.1: Bar behaviour as a result of changing angle of wave incidence (θxb) and water depth above the bar crest (hxb). Panel a: change in bar amplitude; panel b: migration rate. Used wave conditions: Hrms=1,7 m, Tp=8 s and η=0 m. SD= Seaward Decay; SG = Seaward Growth; LG = Landward Growth; LD= Landward Decay. Retrieved from Walstra et al., 2012.).

The second bar-controlling parameter found by Walstra et al. (2012) is the water-depth above the bar crest (h_{xb}). Increasing depth decreases the influence of waves and currents on a bar, leading to smaller perturbations. Below a water depth of 5 m, bars even cease to migrate, irrespective of angle of wave incidence (see blue area in Figure 2.1**)**. Water depth can be used as an indicator of location of a bar in the cross-shore profile. This may shed light on the depletion of bars at the seaward end of the surf zone.

As stated above, the bars migrate most of the time in landward direction and are depleting. That NOM nevertheless takes place is caused by the fact that seaward migration and growth occur with relatively fast rates compared to bar decay and landward migration (almost zero in Figure 2.1: Bar behaviour as a result of changing angle of wave incidence (θxb) and water depth above the bar crest (hxb). Panel a: change in bar amplitude; panel b: migration rate. Used wave conditions: Hrms=1,7 m, Tp=8 s and η=0 m. SD= Seaward Decay; SG = Seaward Growth; LG = Landward Growth; LD= Landward Decay. Retrieved from Walstra et al., 2012.). Seaward migration therefore dominates the inter-annual migration.

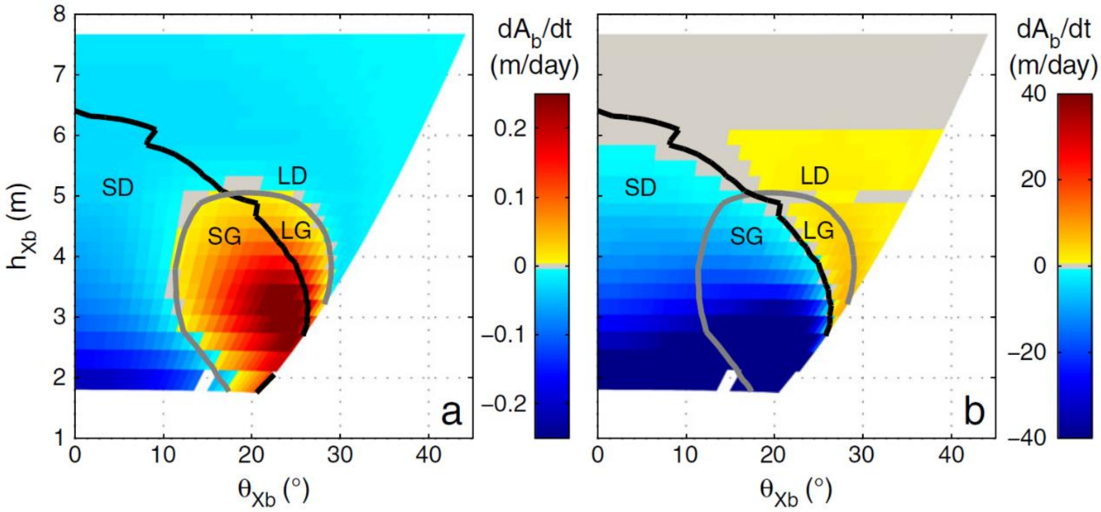


Figure 2.1: Bar behaviour as a result of changing angle of wave incidence (θ_{xb}) and water depth above the bar crest (h_{xb}). Panel a: change in bar amplitude; panel b: migration rate. Used wave conditions: H_{rms}=1,7 m, T_p=8 s and η=0 m. SD= Seaward Decay; SG = Seaward Growth; LG = Landward Growth; LD= Landward Decay. Retrieved from Walstra et al., 2012.

Another possibility of assessing bar migration is to study a zone as a system that tends to reach its equilibrium. Pape et al. (2010) did this for three different locations and determined an equilibrium location and accompanying response time of a bar, based on wave-data.

The first of these concepts is the equilibrium position of a bar, which is the location in the cross-shore system where a bar ideally would reside under a certain set of conditions. The location of this position differs from site to site and depends on the wave-conditions. During high wave events the equilibrium location shifts offshore. The parameters determining the direction of bar migration is the response time. Positive response times during periods of pronounced breaking cause migration towards the sandbar equilibrium locations. Negative response times occur during periods of no or little breaking and cause migration away from the equilibrium location. However, whether this causes on or offshore migration depends on which side of the equilibrium location a sandbar resides.

Pape et al. (2010) studied the equilibrium locations of bars at several locations around the world, including Egmond. Near Egmond aan Zee, and the Dutch coast in general, bar migration is slower than at other locations. Equilibrium locations appeared to reside relatively far offshore, even beyond the zone where sandbars can naturally exist. Moreover, bars near Egmond are relatively large compared to other locations, making them relatively inert. Altogether, this explains the bar behaviour near Egmond from a fundamental perspective: moving away from its seaward equilibrium position during calm conditions (negative response time) and offshore migration during periods of wave breaking. Ultimately, offshore migration leads to decay when wave influence becomes limited.

2.3 Alongshore-variable sandbar behaviour

Near Egmond, bars display a strong crescent pattern. Crescent shapes are found around the world on low sloping sandy beaches and may be shore-attached, also referred to as mega-cusps or shoreline sand waves (e.g. Van Enckevort et al., 2004). They have longshore lengths of 380 m to 3000 m (Van Enckevort & Ruessink, 2003b).

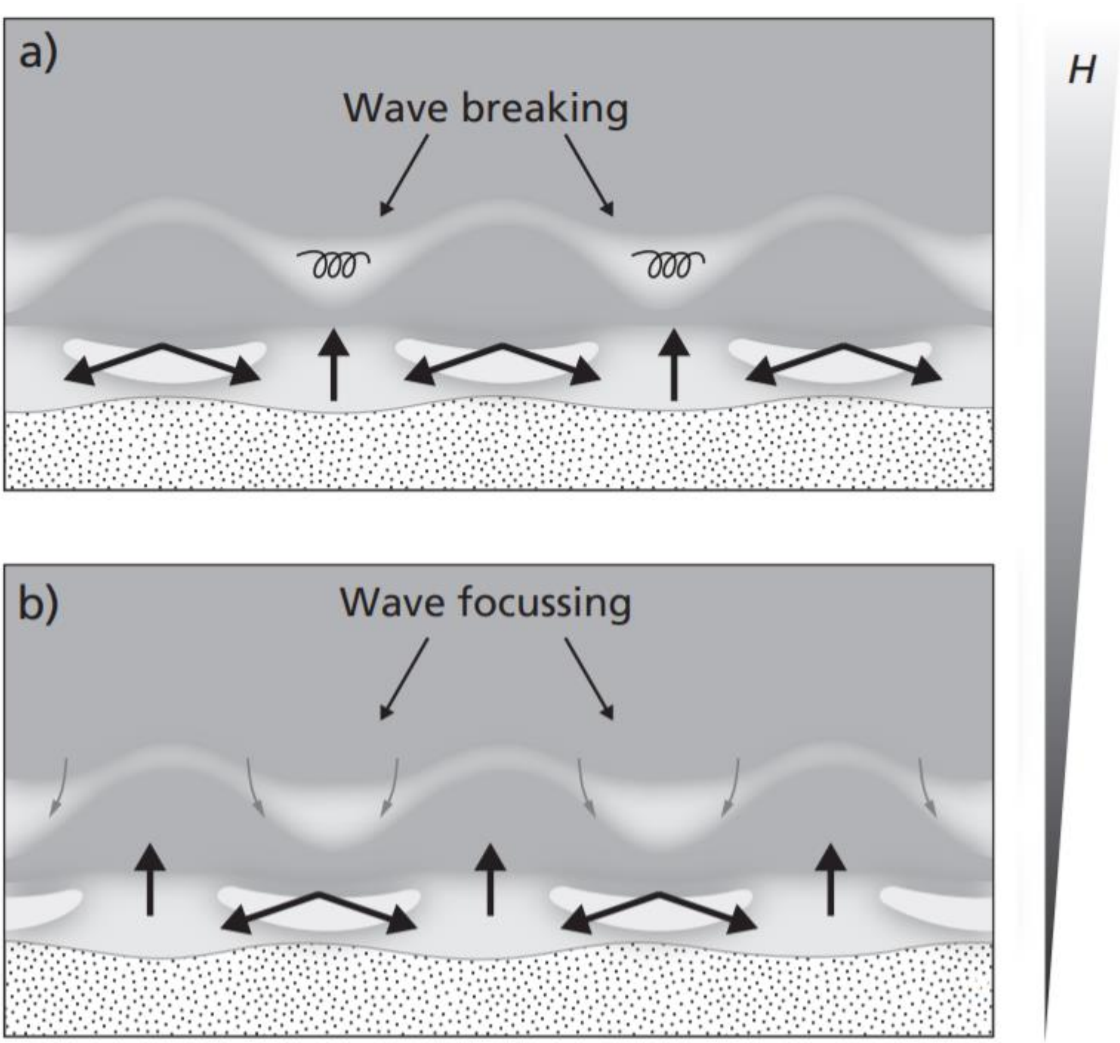


Figure 2.2 Conceptual diagram of coupled bar behaviour by Castelle et al., 2010. (Retrieved from: Price et al., 2014)

The lifetime of crescent forms is in the range of a few days (e.g. Van Enckevort et al., 2004) to 37 months (Van Enckevort & Ruessink, 2003b). They mainly form under calm conditions in the absence of infragravity waves and display a straightening trend under storm conditions, influenced by these same infragravity waves. However, in areas with larger bar systems this explanation does not completely cover all processes, since in Noordwijk crescent patterns were able to resist the heaviest storm in a decade (Van Enckevort et al., 2004). Although waves play a significant role in the persistence of crescentic shapes, they do not completely control the state of crescentic forms. There is also no field evidence of cross-shore migration of crescent forms influenced by waves, but in the longshore direction they migrate in the direction of wave advance, reaching maxima of 150 m/day near Egmond (Van Enckevort & Ruessink, 2003b; Ruessink et al., 2000; Van Enckevort et al., 2004).

The topic of research is whether there is a sort of template providing an organized pre-position of bars shapes. According to Enckevort et al. (2004), there is indeed some self-regulation by the bars itself, since an irregularly shaped crescent bar tends to form into a regular shaped bar: often the largest crescent breaks, thereby creating smaller crescents and smaller crescent merge towards a larger one.

When multiple bars are present, these bars can also display coupled behaviour**.** Price et al. (2011), Ruessink et al. (2007), Price et al. (2014) and Castelle et al. (2010) studied this type of behaviour. Important for this type is wave height and wave direction. When waves are shore-normal, coupling can occur as a result of wave breaking at the outer bar. Since the outer bar longshore varies in depth, longshore gradients in wave height gradients occur, causing an out-of-phase coupling between the inner and outer bar. When wave breaking is smaller, waves refract influenced by the bar depth, thereby creating an in-phase coupling between the inner and outer bars (Figure 2.2)

3. Nourishments

In this chapter a broad introduction is given into nourishments. Since this thesis focuses on nourishments on the Dutch coast and the Netherlands, which has the longest and most intense nourishment record of the world, this chapter is focused on the Dutch coast.

3.1 Background and design

This section proves insight into the processes which ultimately led to the application of shoreface nourishments, nowadays a common measure. The second part introduces the various scales of nourishing and in the last part attention is being paid to the design and intended functioning.

3.1.1 Historic perspective

The Dutch coast has been subject to erosion for centuries. As a result, the core of the challenges facing the Dutch coast is counteracting this erosion. Rates of erosion have been determined by Stolk (1989), Van Rijn (1995) and De Ruig & Louisse (1991). Van Rijn (1995) summarised the results of literature published on erosion. Since 1600, especially in the Northern part of the Netherlands, erosion took place with rates up to 5-7 m/year). The coastal town of Egmond even partially disappeared due to coastal erosion during this period (De Ruig, 1998).

Table 3 Coastal retreat in meters over the period 1600-1990 (Data: After Van Rijn (1995), table 1.3.2 and 1.3.1)

km	Location	Coastal retreat (m)				
		1600-1700	1700-1800	1800-1990	1900-1990	Total (m)
0	Huisduinen	450	300	150	100	1000
13	Callantsoog	250	150	80	100	550
23	Seawall Petten	400	300	100	70	900
38	Egmond	150	100	30	100	280
100	Scheveningen	100	80	40	30	250
110	Terheide	500	300	100	50	950
115	Terheide	700	400	100	-50*	1050

* effect of the harbour dam near Hoek van Holland (entrance to Rotterdam Harbour).

As can be seen in Table 3, erosion is predominant in the northern (0-55 km) and southern (97-118 km) part of the Holland coast. The middle part, not presented in Table 3 Coastal retreat in meters over the period 1600-1990 (Data: After Van Rijn (1995), table 1.3.2 and 1.3.1)between 55 km and 97 km, is accreting. De Ruig & Louisse (1991) studied sedimentation along the Dutch Holland coast. They found that there is more or less a balance between erosion over the entire coastal section: The Northern and Southern tip erode with rates of 0.20 Mm^3/yr and 0.25 Mm^3/yr respectively, while accretion of 0.45 Mm^3 is present on the central Holland coast. Relative erosion and accretion rates are 23 m^3/m/yr and 49 m^3/m/yr respectively. However, there are also cross-shore differences: the beach and dune system along the coast largely experience accretion, while the breaker zone and lower shoreface suffer erosion almost everywhere, except for IJmuiden. The latter is caused by the 2 km long harbour jetties, disturbing the longshore drift, leading to local sedimentation (Wijnberg (2002)).

3.1.2 Scales of nourishing

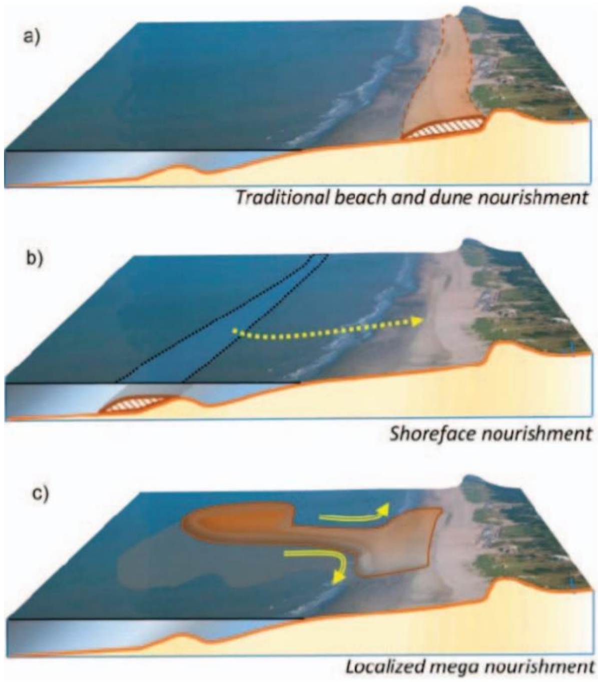


Figure 3.1 Concept of the three different scales types nourishments. (Retrieved from: Stive et al., 2013)

When considering nourishing, there are three different scales of nourishments, which are explained in Mulder & Tonnon (2010). The traditional way of nourishing is focused on strengthening the weak spots in the dunes and has one primary function: flood protection. This is done by dune nourishments and is regularly performed since 1952. These dune nourishments appeared to be successful and led to the introduction of the dynamic preservation policy in 1990 (e.g. Hamm et al., 2002; van Duin et al., 2004; Stive et al., 2013; Van der Spek & Elias, 2013), already discussed in the introduction. This policy consisted of the maintenance of the basal coastline of 1990 and required a new scale of nourishing: beach nourishments. With beach nourishments it is possible to apply larger amounts of sand on the coast, thereby widening the beach (creating more possibilities for recreation) and protect both dunes and beach from erosion on a scale up to several kilometers. Since 1990, numerous beach nourishments were implemented along the Dutch coast, with a general size of 100,000-500,000 m3 (Rijkswaterstaat). Dune and beach nourishments appeared to be a successful measure against erosion, but they have disadvantages as well. Important disadvantages are the high costs, relatively short lifetime of the nourishments and the frequent disturbing of the beach (de Sonneville & Van der Spek, 2012). In an attempt to tackle these drawbacks, the shoreface nourishment was invented: implementation of sand at the end of the surf zone creates the boundary conditions which ensure both beach growth and dune growth on a longer timescale. Since the sand is applied underwater, larger amounts can be applied, which protects larger parts of the coast, up to several kilometers, for a longer period (Mulder & Tonnon, 2010). A typical shoreface nourishment is in the size of 1-2 Mm^3 (Rijkswaterstaat) and has a general lifetime of about five years (Van der Spek et al., 2014). After a successful experiment in 1993 with a shoreface nourishment near the Island of Terschelling (Kroon et al., 1995; Grunnet & Ruessink, 2005), they became core of the Dutch nourishment strategy and are widely applied since then. The intention of the switch in policy was to sustainably preserve the coast in terms of decades and on a longshore scale of 10-100 km. To reach this, the amount of nourished sand increased from 7 Mm^3/yr to 12 Mm^3/yr (Mulder & Tonnon, 2010).

Despite this effort, the main objective remained unachieved: maintenance of the active sand volume in the Coastal Foundation. The Coastal Foundation is the area between the -20 m depth contour and the dune foot, located at +3 m NAP. The theory is that maintaining the active sand volume in this area provides background conditions for long term coastal safety (Stive et al., 2013). However, especially on the lower shoreface, continuous erosion takes places. In order to compensate for this loss, the annual nourishment volume should be raised towards 20 Mm^3/m (Van der Spek & Lodder, 2015). When taking future sea level rise into account, future amounts may rise towards 85 Mm^3/year (Mulder & Tonnon, 2010). A recent attempt to provide these amounts is the introduction of mega-nourishments. Near the coastal town of Monster, located at 105 km south of Den Helder, a mega nourishment was placed in 2011, with a volume of 21 Mm^3. This nourishment is supposed to spread out over the entire coastal section (Stive et al., 2013).

3.1.3 Implementation and intended functioning

The protecting function of a shoreface nourishment is supposed to be twofold: in Van Duin et al. (2004) these are explained. First of all, a shoreface nourishment causes more offshore wave breaking, which results in a calm wave climate landward of the nourishment. This effect is referred to as the lee-effect (e.g. Ojeda et al., 2008). Less energetic waves reduce the longshore current, which has three effects (Figure 3.2):

1. A decrease of the longshore transport
2. Updrift sedimentation
3. Downdrift erosion

   (Citation from: Van Duin et al., 2004)

Also, another direct effect of the nourishment arises: due to the breaking of the larger waves on the nourishment, the smaller waves remain. These waves induce onshore transport via shoaling. In the same time the smaller waves cause a smaller wave-induced return flow which lead to the following two effects, as noted by Van Duin et al. (2004) (Figure 3.2 Imposed effect of a shoreface nourishment, with the two functions a nourishment can have in the left and right panel. a) A nourishment as a stable reef, creating the conditions in which sedimentation can occur. b) Direct sedimentation from the nourishment on the shore, referred to as feeder berm. Retrieved from: Van Duin et al., 2004):

1. An increase of the onshore sediment transport
2. A reduction of the offshore sediment transport (Citation from: Van Duin et al., 2004)

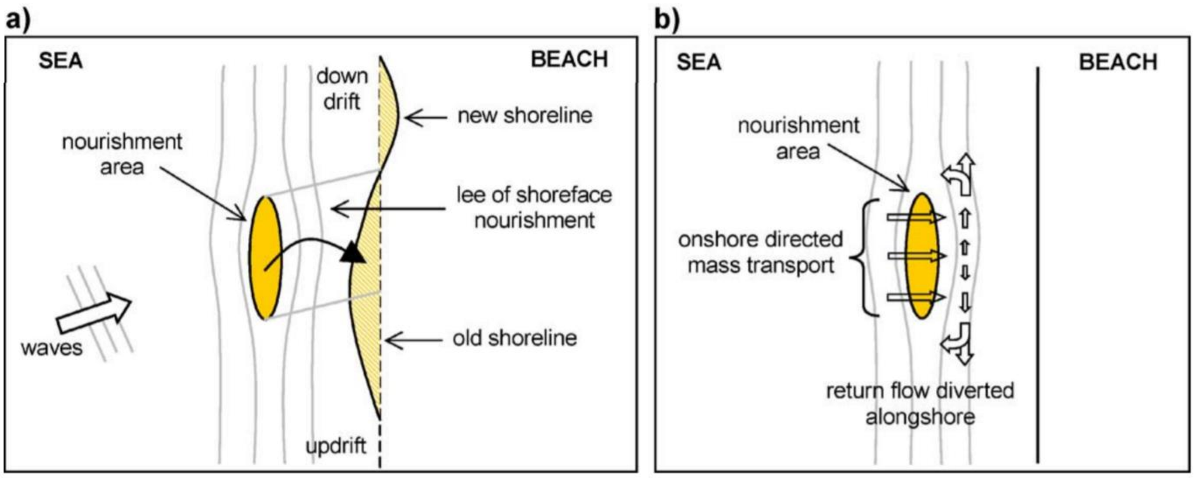


Figure 3.2 Imposed effect of a shoreface nourishment, with the two functions a nourishment can have in the left and right panel. a) A nourishment as a stable reef, creating the conditions in which sedimentation can occur. b) Direct sedimentation from the nourishment on the shore, referred to as feeder berm. Retrieved from: Van Duin et al., 2004

Rijkswaterstaat, the institute responsible for coastal protection in the Netherlands, provides guidelines for implementation of nourishments, published in their Richtlijnen Onderwatersuppleties (2007). In this report, a framework is provided for nourishing activities, both on the beach and on the foreshore. The region around a depth of 5 meter is chosen as the most suitable location for a nourishment, since the profile adapts quickly (generally after less than one winter) after implementation. In an attempt to stimulate the behaviour of the placed sand as a natural bar, the amount of nourished sand should more or less equal the volume of a regular outer bar. In Schipper et al. (2016) a volume range of 400 to 600 m^3/m is given as the most common size. Side effects may be present up to 2 km from both flanks.

Shoreface nourishments are either placed on the flank of the outer bar or on the offshore position where bars generally decay. The first option is intended to push the outer bar back towards the shore, thereby raising the sand volume in the nearshore zone. With the second option, bar migration is halted and the system becomes 'frozen' and sand is kept nearshore.

3.2 Observations

Since 1990, multiple articles have been published about nourishing. Among them, there are three types of articles:

1. Observations of single or multiple nourishments, sometimes with an attempt to model bar behaviour after implementation
2. Comparisons between different nourished sites.
3. A large scale analyses of system changes after implementation.

In this section, these different approaches are discussed, according with a literature overview of nourishments in the Netherlands. Focus will be on the application of shoreface nourishments, as they interfere most with sandbars.

3.2.1 Terschelling

The first experiment in the Netherlands with a shoreface nourishment took place at the Wadden island of Terschelling in 1993. Terschelling has similar wave conditions as the rest of the Netherlands, but differs because of its WSW-ENE orientation, causing sandbars to displace longshore with rates of 800 m/yr to 1200 m/yr in eastern direction (Ruessink & Kroon, 1994). The placement of the nourishment was intended to compensate for a 2.9 m/yr shoreline retreat for a period of 8 years over a distance of 4.6 km. This would require a minimum nourishment of 1.8 Mm^3 (Hamm et al., 2002). The nourishment here was part of the NOURTEC scientific programme and was intended as a testcase for largescale use of shoreface nourishments. The nourishment was, in contrast to later shoreface nourishments, placed between the inner and outer bar, thereby filling up the trough (Figure 3.3). The total volume placed volume was 2.0 Mm^3 which equals 454 m^3/m (Rijkswaterstaat).

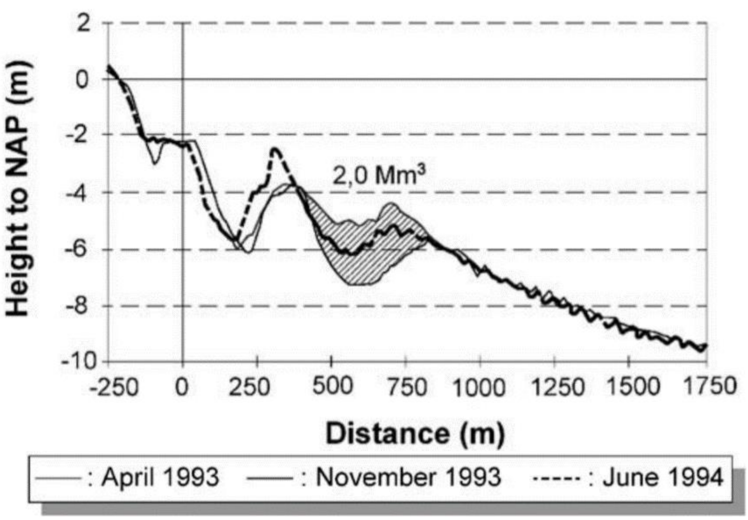


Figure 3.3 Cross-shore location of the 1993 nourishment near Terschelling. Unique for this nourishment is the cross-shore location between the inner and outer bar. (Source: Hamm et al., 2002)

Kroon et al. (1995) found that the nourished volume was quickly (over several months) incorporated into the bar system, thereby considerably raising the volumes of the inner and outer bar. Grunnet & Ruessink (2005) found that the middle and inner bar remained arrested for a period of 6-7 years. The outer bar remained uninterrupted, while the middle bar broke up and formed multiple 'drumstick' shaped rip channels. The nourishment resulted in a seaward progradation of the beach of 15 m/yr. Sedimentation landward of the nourishment amounted to twice the normal conditions. About 40% of sand gain could be subscribed to a loss of sand at the nourishment itself. All other gain could be attributed to the gradient in the longshore transport. After 1999, the alongshore migration of the outer bar resumed its longshore migration with a rate of 800 m/yr (Grunnet & Ruessink, 2005). During the study period, the nourishment itself displayed longshore migration as well, which is of particular importance for future nourishments in the Wadden Sea (Van der Spek et al., 2007).

3.2.2 Noordwijk

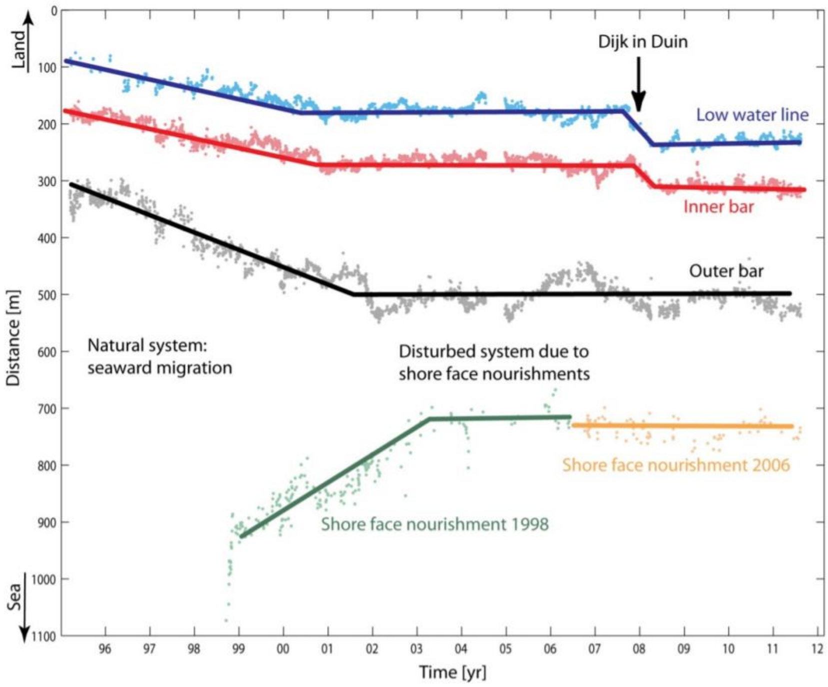


Figure 3.4 Observations of the bars at Noordwijk over the period 1995-2011, obtained with the ARGUS video monitoring system. (Retrieved from: Ruessink et al., 2012)

A second location, frequently studied for bar behaviour, is the coastal town of Noordwijk, located at 82 kilometer of the Holland coast, in the heart of the concave part (Figure 5.1). Noordwijk belongs to the part of the Holland coast which is naturally progradating and did not experience serious retreat since 1880. The bar cycle here is relatively fast with a NOM interval of 4 years. A multi barred system is present with two subtidal bars and a swash bar. In front of the town of Noordwijk two shoreface nourishments took place, plus a 'zwakke schakel' nourishment ('Zwakke schakel' means 'weak link' in Dutch). The first nourishment was placed in 1998 over a longshore stretch of 3 km, with a size of 1.7 Mm^3. By making use of the daily video imaging system of ARGUS, Ojeda et al. (2008) made a daily analysis of bar locations in the system. The nourishment was placed at 900 m seaward of the outer bar and formed a new bar seaward of this outer bar. The newly formed bar remained visible as a clear breaker bar for three years and then slowly started to dissolve. As can be seen in Figure 3.4, the nourishment migrated landward during this period until 650 m offshore, the location where bars normally decay. In the same time, the NOM of the natural bars was slowed down significantly and came almost to a halt after 2002 (Figure 3.4). With the daily images, it was possible to monitor migration patterns on a weekly, seasonal and yearly basis. As a result of the nourishment, the weekly migration rates significantly dropped. In other words: the system became less dynamic. The next nourishment in 2006 was located at the position where the 1998 nourishment ended and did not cause any significant changes to the situation (Ruessink et al., 2012).

3.2.3 Egmond

The most extensively discussed, nourished site in the Netherlands can be found near Egmond. Multiple nourishments took place here, discussed by numerous authors. Due to the strong crescent bar shapes near Egmond, a large longshore gradient is present between eroding and accreting sections: Near the horn of the bars, a sheltered zone is present, where sedimentation takes place. In between horns, the bar crest resides deeper under water, causing less wave breaking on the bar. The gradient in the longshore current causes erosion on this location. About 800 m south of Egmond, such an erosive location is present. Cohen & Briere (2007), Van Duin et al. (2004) and Van der Spek & Elias (2013) refer to this location as a 'erosion hotspot'.

For the sake of safety, the BKL position near Egmond was decided to be located more seaward than the 1990 position. This provides better protection for the Boulevard. Due to this seaward placement, nourishments are needed to maintain this more outer position (Cohen & Briere, 2007). During the period 1990-2000 multiple beach nourishments took place. The result was unsatisfying, leading to quick erosion of the nourished material (Spanhoff et al., 2004).

In order to increase the lifetime of the beach nourishments an attempt was made to protect them with a shoreface nourishment (e.g. Spanhoff et al., 2004). The first shoreface nourishment was placed around a horn located at 38.00 km, seaward of the outer bar at 680 m, thereby pushing the outer bar towards the shore. This effect only remained for 1.5 years (Cohen & Briere, 2007), but had significant impact on the system. The nourishment aligned with the outer bar in the south, thereby turning around the longshore orientation of the bar, since the bar near Egmond resided now more seaward than south of Egmond. The former bar coupled to the middle bar south of Egmond, a phenomenon which is called bar switching. Spanhoff et al. (2004) attribute this to weather conditions in the winter of 2000/2001: predominant southern waves caused crescentic shapes. Combined with the longshore difference in migration rate between the nourishment area and the southern section, a bar switch was triggered. Beside the bar switch, the protection of the horn near 38.00 km also caused strong growth of the beach on this location, enhancing erosion in the southern part of the section. This erosion was so strong that a second beach nourishment was necessary in 2000. Although in 2001 45% of the nourished sand was still present in the nourished section (Spanhoff et al., 2004), neither the intertidal beach nor the beach width did display any positive response (Cohen & Briere, 2007).

A second nourishment in 2004, extended more southward and was twice as long as the first. This nourishment caused nearshore sedimentation for a much longer period than 2.5 years, but the exact period was not clear yet when Cohen & Briere (2007) published their report. Their conclusion is that the shore near Egmond has a basic configuration, to which it naturally returns when nourishing stops. Also, the hotspot near Egmond remained present, which makes nourishing necessary in the future. The influence of the nourishment was present over 2 km south of the nourished section.

The question remains what effect nourishments have on sand waves. Crescent patterns are able to move southward or northward near Egmond depending on the wave direction with a rate 200 m/yr (Spanhoff et al., 2004). With the help of ARGUS it was possible to detect a longshore migration of 4 m/hr during storm conditions (Spanhoff et al., 2005).

Wijnberg et al. (2007) attempted to study a sand wave after implementation of the beach nourishment near Egmond of 2000. The shoreline sand wave grew as a result of the nourishment. This growth would theoretically only be possible in case of wave angle of at least 42 degrees. Wijnberg et al. (2007) also describe the bar switch episode taking place in 2001: the shoreface nourishment placed in 1999 forced the middle bar nearshore in anti-phase state. When the middle bar linked up with the inner bar it was in phase with the shoreline undulations.

3.3 Comparing nourishments

The first section of this chapter involved the study and description of single nourishments. Numerous authors, including those of the articles mentioned above, compared multiple nourishments to each other at different locations. This allows to draw more general conclusions on the impact nourishments have on nearshore systems.

Ojeda et al. (2008) compared the shoreface nourishments near Egmond, Terschelling and Noordwijk, discussed above. As already mentioned in the Introduction, he came up with three possible parameters determining bar behaviour after implementation of the nourishment:

- Cross-shore location of the nourishment
- Grain size of the nourished material
- The relative volume of nourishment

De Sonneville & Van der Spek (2012) studied five nourishments along the Holland coast, north of IJmuiden, among which also the shoreface nourishments of 1999 and 2004 near Egmond. Although conditions at the Holland coast are roughly comparable to each other, the lifetime of nourishments appeared to vary considerably. De Sonneville & Van der Spek (2012) mention five possible causes and discuss to what extent they are responsible for the observed differences:

- External forcing, such as alongshore differences in wave conditions, both in time and space, could not explain this difference, since these conditions were highly comparable.
- Grain sizes used, which according to Ojeda et al. (2008) could contribute to the longevity of a nourishment, were all comparable to the local grain sizes already present in the system and were therefore not the cause. Beside De Sonneville & Elias (2012) and Ojeda et al. (2008), also the Nourishing Guideline of Van der Spek et al. (2007) itself mentions the grain size as possible contributor to the longevity of sediments.
- The water depth at the crest of the nourishment (5 m), or the cross-shore location of implementation (±1 km) were all more or less in the same range.
- There were no significant differences in terms of relative volume (m^3/m), but in total volume there were. The second nourishment near Egmond, which became attached to a nourishment near the coastal town of Bergen in 2005 (Figure 5.4), had a total length of 4 km. Compared to the nourishment in 1999, with a length of 2 km and a size of 1 Mm^3, this difference is large. The common idea that it simply takes more time to erode a larger volume turned out to be correct.
- Differences in longshore location were not a discriminating factor either. The nourishments near Egmond in 1999 and 2004 were placed at the same longshore location, but still they displayed significant divergent behaviour.

The five points listed above could not fully explain the large differences between various nourishments. De Sonneville & Van der Spek (2013) therefore suggest that the ability of a bar to become incorporated into the local bar system is most important. If a nourishment is able to link up with neighbouring structures, such as an outer bar adjacent to the nourished site, this increases the lifetime of the intervention. In the case of Egmond, the nourishment of 2004 became coupled to a nourishment placed in 2005 near Bergen (Figure 5.4). This resulted in a more stable, and therefore longer present, bar.

The most complete study of behaviour of shoreface nourishments is carried out by Bruins (2016). He studied twenty of them, carried out along the Dutch coast, in an attempt to identify the key parameters that explain the behaviour of bars. Based on the characteristics of a bar, he was able to predict the most probable type of behaviour of the nourishment.

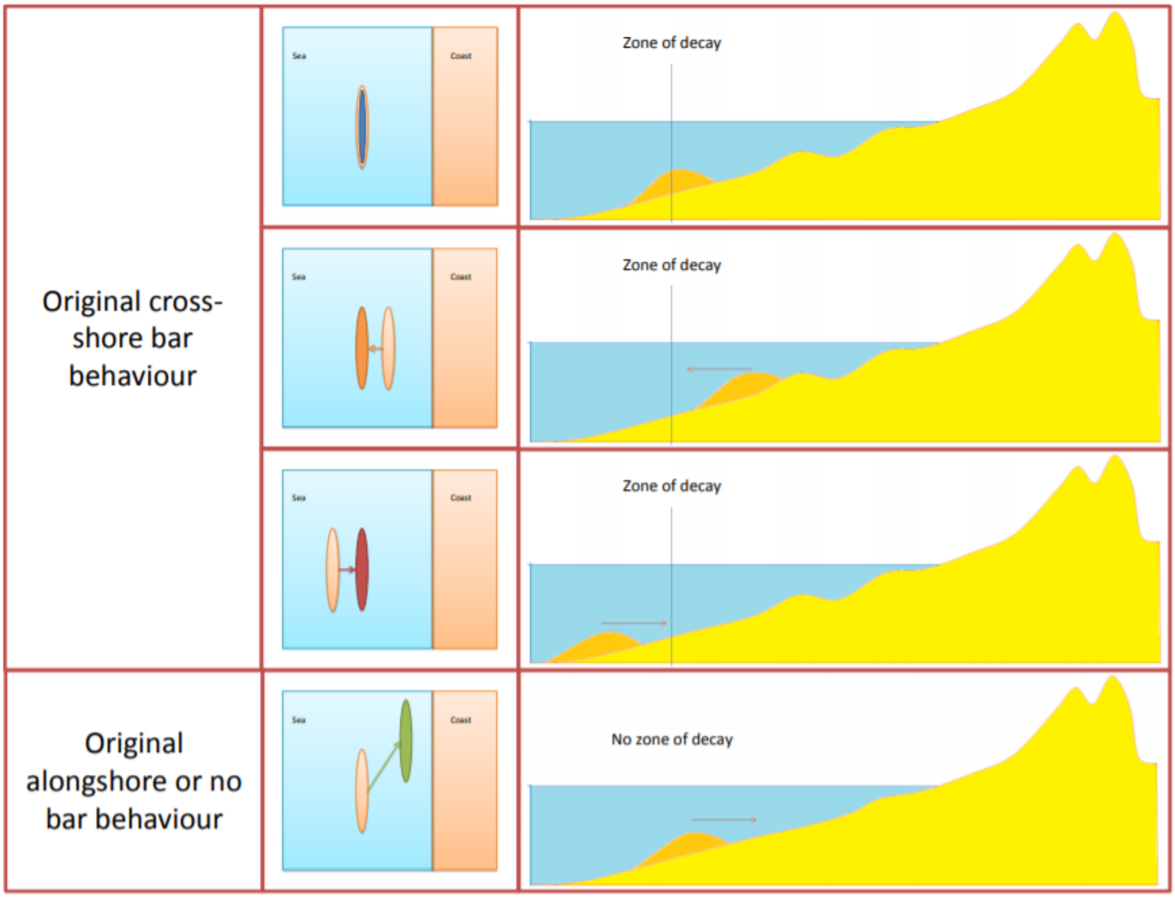


Figure 3.5 Conceptual diagram of nourishment migration after implementation. (Retrieved from: Bruins et al., 2016)

If a bar system naturally displays cross-shore migration, a nourishment located behind the outer bar will migrate towards the zone of decay, irrespective of its size or its position in the cross-shore profile (Figure 3.5). Trough formation at the landward side of the nourishment is found to develop in the case of naturally occurring cross-shore migration. In that event, the depth above the crest of the added sand is important: the higher the nourishment bar, the deeper the trough. In cases where longshore migration is dominant, or in the case of the absence of bar behaviour, the nourishment travels towards the coast in direction of the longshore current (Figure 3.5).

Bruins (2016) also studied the influence of total volume, length and relative volume (m^3/m) on the nourishment behaviour, but it appears that none of these three alter the trends in the nourishment behaviour. However, the relative volume does cause a larger increase of the nearshore volume after implementation. Secondly, the slope and the distance from the nourishment to the naturally existing bars were checked as a key parameter. However, neither did actually explain behaviour of the nourishment.

By making use of the work of Bruins (2016), it was also possible to assess the study of Lodder & Sørensen (2015). Lodder & Sørensen (2015) compared a nourished site in the Netherlands to one on the Danish shore. Since on the Danish site no clear cross-shore migration was present and the longshore transport there was 10 times larger than at the location in the Netherlands, the nourishment migrated longshore. In the Netherlands, the cross-shore transport caused landward migration of the bar.

3.4 Large-scale impact

On a larger scale, a view analyses were made by various authors, describing the large-scale impacts of nourishments. Roelse (1996) made a report on sand nourishments executed until 1991. Although beach nourishments were still a relatively new phenomenon, Roelse (1996) attributed positive changes in the sand balance to sand nourishing. He found that for every cubic meter of nourished sand, 25% extra is needed to compensate for erosion losses.

Although Wijnberg (2002) considers groins and beach nourishments as noise on a decadal scale, their influence on sediment budgets is enormous. Large amounts of artificially placed sand do have a net accreting affect, but at the same time erosion is intensified. The longshore current, transporting sand into the Marsdiep tidal inlet, received a yearly amount of 500,000 m^3/yr according to Van Rijn et al. (1997). Due to the increasing amount of nourishments since then, the latest sand budget model of Pot (2011) suggests that this number has increased towards 1,000,000 m^3/m. Rademacher et al. (2018) came to the same conclusion. They studied the behaviour of 23 nourishments along the Delfland coast and concluded that, as a result of nourishing, nearshore dynamics on this location did fundamentally change.

4. Objectives and research questions

The aim of this research is to shed light on nearshore dynamics in the surf zone as a result of nourishing, with an emphasis on volume. To be able to make a fair analysis a comparison is made with a neighbouring unnourished coast. The main question to be answered is:

> ***"What are the differences in nearshore dynamics between a nourished coast and a natural, unnourished coast?"***

First, volume changes will be described both at the nourished section of the coast and the non-nourished section of the coast. The focus will be on altered volume trends, triggered by nourishments, in both cross-shore and longshore direction.

Sub-question 1

What are the effects of nourishments on sand volume trends along a coast?

Questions to be answered with regard to the first sub-question:

- **What are the observed historical bar dynamics near Egmond?**
- **What are the historical volume trends near Egmond before nourishing?**
- **What are the new volume trends near Egmond after nourishing?**

In the second part of the thesis, the focus will be on the morphodynamical processes behind the volume trends discussed under sub-question 1.

Sub-question 2

What are the sandbar dynamics coinciding with observed volume differences/distributions?

This section contains an analysis based on the data set of the undisturbed section. The bar behaviour is studied to find the answers to the following questions:

- **What is the influence of beach nourishments on bar patterns?**
- **How do shoreface nourishments near Egmond act in terms of bar behaviour?**
- **What is the influence of nourishments on the NOM cycle near Egmond?**
- **How do nourishments affect 3D features, such as crescent bar shapes, near Egmond?**

Sub-question 3

How does long-term nourishing affect sandbar dynamics?

This last sub-question involves the synthesis of the first and second part of the analysis. The following points are examined:

- **How does nourishing affect NOM?**
- **Do nourishments trigger bar switching?**
- **Did the dynamics of the unnourished natural beach change as a result of nourishments at the bordering nourished coast?**
- **What is the extent of longshore effects imposed by nourishments?**

To answer these questions, yearly bathymetric measurements (JARKUS data) from the coast around Egmond aan Zee from 1965-2013 will be used.

5. The Holland coast and Egmond

When studying behaviour of nourishments, comparison is always a problem. To exactly figure out to what account nearshore changes can attributed to a nourishment, ideally one would do the same experiment on the same site, under the same conditions, but without nourishment. Since this is not possible, the question remains what to use as referential undisturbed coastal behaviour. In this thesis an attempt is made to remain as close as possible to the original situation. Therefore, a site near the Dutch coastal town of Egmond aan Zee (from here on simply referred to as Egmond) was chosen, located on the northern part of the Holland coast, 37.5 km south of Den Helder (Figure 5.1). What makes this site highly suitable for this study is the large contrast in coastal maintenance over a relatively short distance: in order to protect the town of Egmond, this part of the coast has been extensively nourished during the past decades (Figure 5.4). However, south of Egmond, the dune area is relatively large, and without villages in the nearby vicinity there is no need for nourishments. A 'natural' unnourished coast adjacent to an intensively nourished coast: nowhere along the Holland coast is the contrast in maintenance larger.

A secondary reason for choosing Egmond as a study location is the presence of two ARGUS locations in the past. With ARGUS video imaging, daily footage of the systems was possible, shedding light on the small-scale daily processes behind the annual observations dealt with in this research (e.g. Aagaard et al., 2005). Although these images were not used for this research, they could enable further research on this topic in the future.

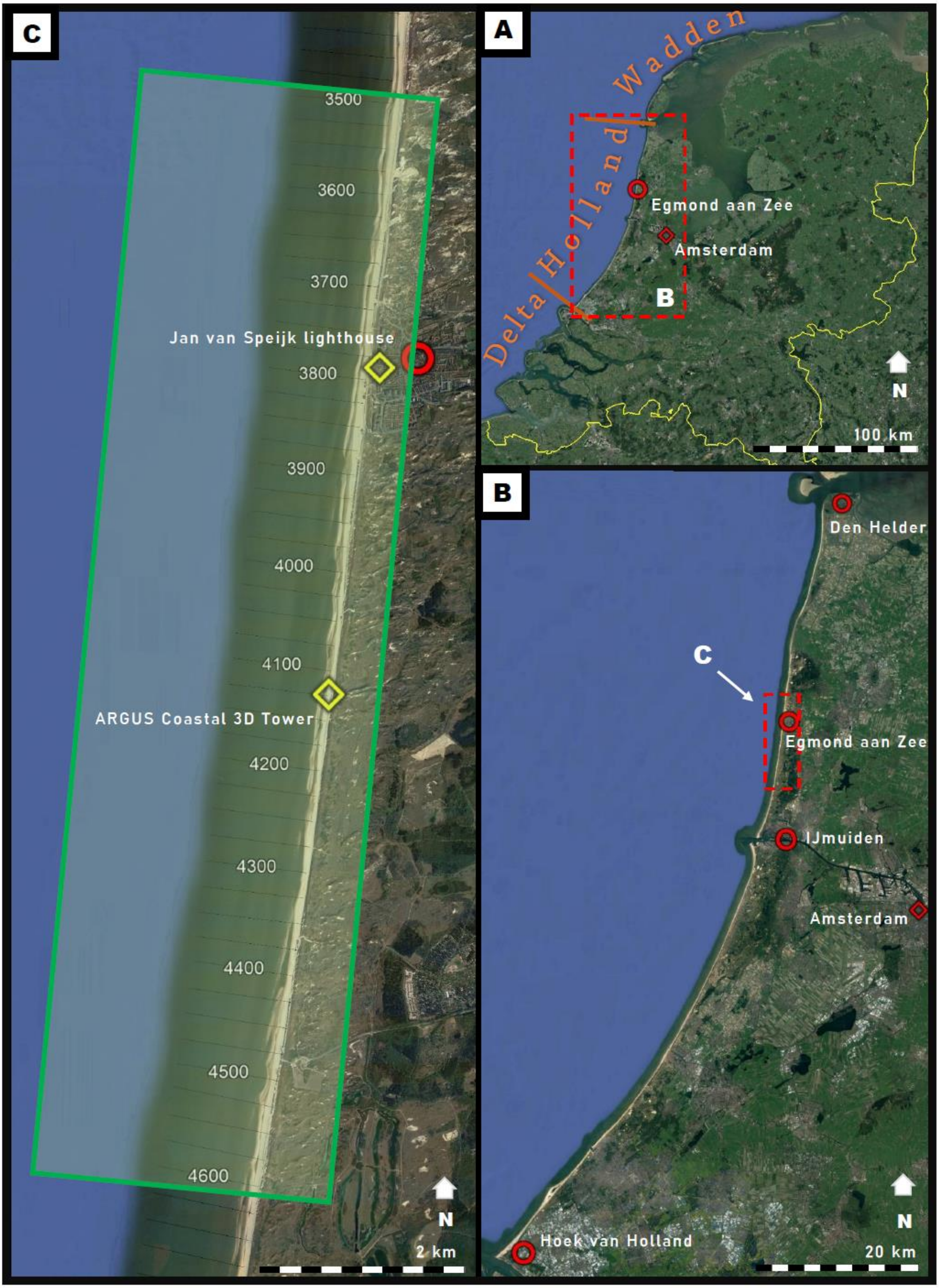
The present chapter provides all context needed for this study, starting with a description of the Dutch coast and the coast near Egmond in particular.

5.1 Holland coast

Because this study is intended to shed light on the behaviour of nourishments in the Netherlands in general, it is important to take into account the way Egmond is embedded in the Dutch coastal system. Therefore Egmond is introduced in this section, within the context of the complete Dutch coast.

5.1.1 Geographic setting

The Dutch coast is a micro-tidal system located in the south-eastern part of the North Sea. It has a total length of 432 km, of which 79 km consist of open or enclosed estuaries (Stolk, 1989). The remaining 353 km can be roughly divided into three regions: The first region is the northern Wadden coast, consisting of a barrier island system. The second region, the central Holland coast, starts at the northern tip of the Dutch mainland and is characterized by open beaches that are backed by well-developed dune systems. The southern part of the Dutch coast is the Delta Coast. (e.g. De Ruig, 1998). This part is heavily defended with largescale man-made structures, such as dikes, dams and storm surge barriers. All these different regions are indicated in Figure 5.1A.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Holland
Delta
Egmond aan Zee
Amsterdam
B
N
100 km
B
Den Helder
C
Egmond aan Zee
IJmuiden
Amsterdam
Hoek van Holland
N
20 km

Figure 5.1 Location of studied sites along the coast of The Netherlands. A) Total overview of the Dutch North Sea coast. B) The Holland Coast and C) the study site near Egmond.

The Holland Coast stretches from its northern tip, near the city of Den Helder at 0 km, towards the south near harbour moles of Hoek van Holland at 118 km (Figure 5.1). It can be seen as a wave-dominated closed beach-barrier system. On the northern edge, the Holland coast is bordered by the tidal inlet channel Marsdiep, which is the main inlet of the Wadden-sea system (Elias, 2006). The southern edge is formed by the deltas of the large river systems of Rhine, Meuse and Scheldt. Between these large channels an almost undisturbed coast of 120 km is present, with a more or less north-south orientated coastline with an orientation of 10°-190° (Sistermans and Nieuwenhuis, 2004) (Figure 5.1). The only large obstruction is formed by the harbour moles of IJmuiden near km 55. Dune systems are present along almost the whole Holland coast and vary in width between 150 m towards more than 4 kilometers (Stolk, 1989).

5.1.2 Geomorphological characteristics

Along the Holland coast, a gently sloping beach is present, with slopes varying between 1:400 and 1:135. In the shoreface slope a trend is visible from the edges of the Holland coast, where the slope is about 1:400, towards the more central laying part, where the slope is 1:150. Near IJmuiden however, the slope becomes flatter again, with a slope of 1:250 (Wijnberg and Terwindt, 1995)

The surf and breaker zone form the most dynamic part of the system and often consist of one or multiple sand bars. At most locations along the Dutch coast such sand bars are present. Their number varies between none and four (Wijnberg, 2002). The central, steeper parts of the coast contain multiple bars, while near the northern and southern tip none or just one bar is present. At these locations the coast is protected by manmade structures such as groins and dikes.

5.1.3 Sand system

As already mentioned, the Dutch coast is a sand-dominated system. Sand is mainly of fluvial origin, and brought by the Rhine and Meuse rivers. However, north of IJmuiden, part of the sediment is of Saalian origin (Van Rijn, 1995). Grain sizes in the system vary between 100 – 500 µm (e.g. Van Rijn, 1997). However, along the coast some trends are visible, such as a slightly fining trend in seaward direction (Stolk, 1989). On the beaches, a common grain size is 250-300 µm, whereas at shoreface/seafloor boundary this is between 125-250 µm. Furthermore, some alongshore variation is present. In the northern part from Den Helder towards Egmond, the sand is coarser than in the southern section (Stolk, 1989). However, drawing conclusions about trends in sediment distribution might be dangerous: Wijnberg (2002) shows the result of storm surges; after a highly energetic event the sediment appeared to be finer than before. Additionally, nourishments may also influence grainsize distribution (e.g. van de Rest, 2004).

5.1.4 Hydrodynamics

The Dutch coast is a microtidal and wave dominated system with a mean tidal range of 1.6 m Wijnberg and Terwindt (1995). The tidal wave coming in from the Atlantic Ocean propagates as a Kelvin wave northward along the Dutch coast, with the M_2 semi-diurnal lunar tide as main constituent (Elias, 2006). Along the coast a southward increase in tidal range is present from 1.4 m near Den Helder towards 1.7m near Hoek van Holland (Van Rijn, 1995). During a cycle of spring and neap tide, mean tidal ranges change 20-25 cm in magnitude (Wijnberg, 2002). Tidal currents along the coast are in order of 0.4 m/s, but reach maxima of 0.8 m/s during spring tide (Van Rijn, 1995). During the last century tidal ranges along the coast slightly increased with a rate1.5 mm/year. Especially since 1950 this trend is well visible (Hollebrandse, 2005).

Along the Dutch coast, a moderate wave climate is present, which is dominated by sea waves. The waves have two prevailing directions: north-west and south-west (Figure 5.2). Due to a longer wind-fetch, waves from the north-west tend to be slightly higher. These waves also contain small amounts of energy from swell-waves, but this contribution is difficult to detect (Wijnberg, 2002). Mean wave height along the coast is 1.1 – 1.16 m with a period of 3.7 s (Stolk, 1989). When waves reach the coast, they lose height due to energy-dissipation. Therefore, closer to the coast the actual wave height may be expected to be lower (e.g. Van Rijn, 1995). Storm surges result in waves with a height of 5 m and periods of 8-12 s (Ojeda et al., 2008). According to Van Rijn (1995), offshore wave heights larger than 2 m occur 10% of the time, while waves larger than 3 m appear 2% of the time.

5.1.5 Sediment fluxes:

Over the past decades, several overviews were compiled to describe trends along the Dutch coast. Van Rijn et al. (1995) and Van Rijn et al. (1997) studied the coastal behaviour in terms of sand budget and volumes for the period 1964-1992. The total longshore current between +3 m N.A.P. and -8 m N.A.P. is northward directed and results in a sediment loss of 500,000 m^3/yr near Den Helder into the Marsdiep tidal channel. This is compensated for by a net onshore transport of 490,000 m^3/yr and a nourishment effort of 440,000 m^3/yr (Van Rijn et al., 1997).

Table 4 Sediment fluxes in m^3/yr for different cross-shore zones (After Van Rijn, 1995; table 3.5.4)

Km ↓ Depth contour→	Dune zone (+10m - +3m)	Beach zone (+3 m - -3 m)	Surf zone (-3 m - -8 m)	Shoreface zone (-8 m - -12 m)	Total
28.00-39.00	25,000	-60,000	-20,000	-50,000	-105.000
39.00-47.00	5,000	0	-5,000	-110,000	-110.000

Table 5 Sediment fluxes in m^3/yr over different cross-shore depth contours. Positive numbers indicate onshore movement (After Van Rijn, 1995; 6.3.2)

Km ↓ Depth contour→	+ 3 m	-3 m	-8 m
28.00-39.00	25.000	50.000	50.000
39.00-47.00	20.000	50.000	50.000

5.2 Egmond

5.2.1 Geomorphological setting and hydrodynamics

To summarize the section above, specific values for Egmond are given. Wijnberg et al. (1995) divided the Holland coast into 5 regions with different Large-Scale Coastal Behaviour (LSCB-regions). Egmond belongs to the third region which stretches from 23km south of Den Helder until the Harbour moles of IJmuiden at 55 km. Most of the time there is a three-barred system present with a bar cycle of 15 years (Ojeda et al, 2008). This is relatively long compared to other locations in the Netherlands (e.g. Ojeda et al., 2008, and Wijnberg & Terwindt, 1995, describe cycles of 4 to 12 years), but also to locations abroad (Pape et al., 2010; Shand et al., 1999), where cycles of 1 to 2.5 years have been observed.

Although grain size may vary, largely influenced by nourishments or weather conditions (Wijnberg, 2002), there is a fining trend in seaward direction present. Grain sizes vary from 295 µm on the beach until less than 200 µm at 600 m offshore. A grain size of 246 µm is given as a mean for the whole coastal section (Stolk, 1989).

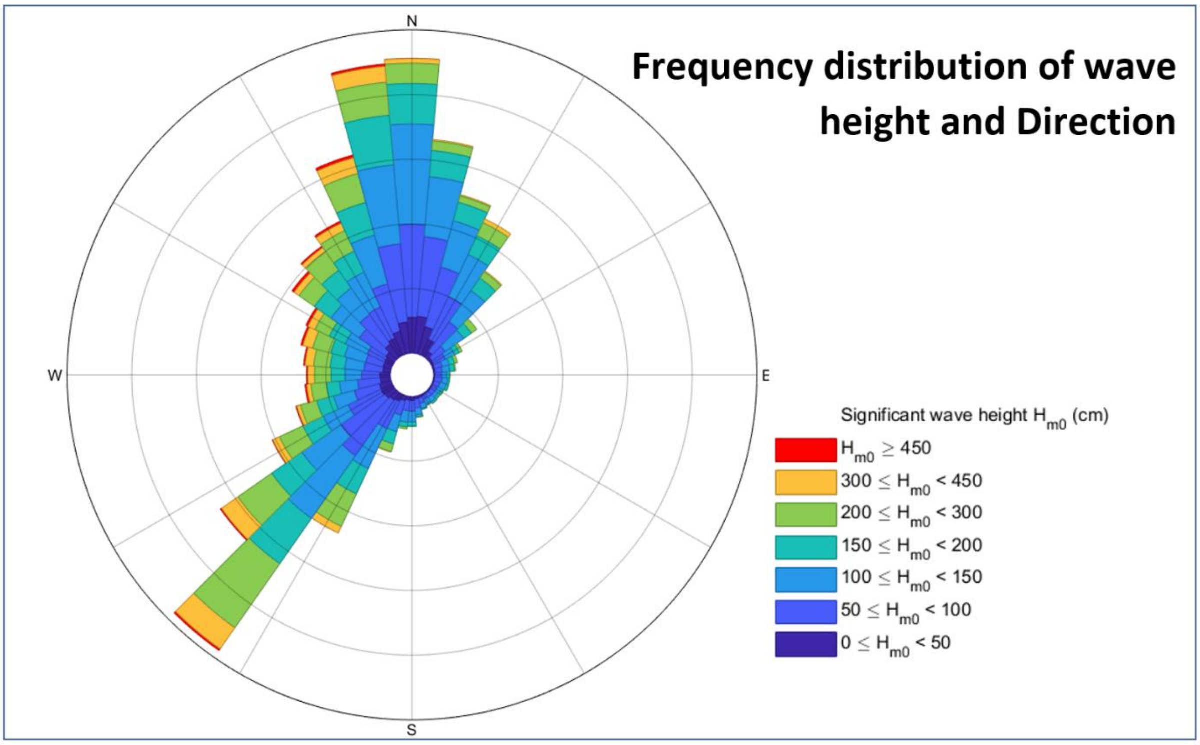


Figure 5.2 Wave data for the period 2010-2013, obtained from the Platform Hoorn Q1-A, located 50 km northwest of Egmond at distance of 30 km form the shore (Data: Rijkswaterstaat).

Wave data measured 40 km offshore is presented in Figure 5.2 for the period 2010-2013. Mean significant wave height during this period was 1.39 m with a period T_{m02} of 4.7 s (Rijkswaterstaat). The tidal range near Egmond varies between 1.2 m and 2.1 m between neap and spring tide. The peak tidal currents are northward-directed during flood and southward during ebb and their velocities vary between 0.4 m/s and 0.3 m/s respectively (Giardino et al., 2009).

Best estimates of the longshore transport near Egmond aan Zee are 360,000 m^3/yr in northward direction and 180,000 m^3/yr in southward direction (Van Rijn et al., 1995). In the cross-shore direction there is significant variation in sedimentation and erosion trends, as can be seen in Table 4 Sediment fluxes in m3/yr for different cross-shore zones (After Van Rijn, 1995; table 3.5.4)above. In this table a selection of the data of Van Rijn et al. (1995) is presented. These numbers are comparable to numbers found by De Ruig and Louisse (1991). In cross-shore direction sediment fluxes also vary, but here they have a positive landward direction (Table 5 Sediment fluxes in m3/yr over different cross-shore depth contours. Positive numbers indicate onshore movement (After Van Rijn, 1995; 6.3.2)). Although sediment fluxes are landward directed, an eroding trend is visible near Egmond. Eroding beaches lead to coastal retreat, which is found to be 70 cm/yr in the sector north of Egmond (26-38 km). South of Egmond (38-53 km) a positive accretion trend is present (Stolk, 1989).

Although Egmond aan Zee provides a very suitable location for this research, it has the steepest shoreface slope seen along the Holland coast, with a slope of 1:136 in front of the town and a slightly gentler slope of 1:163 in the southern sector. Beach slope varies between 1:39 and 1:56 along the Holland coast. With a slope of 1:45 the beach is therefore comparable to the rest of the coast (Stolk, 1989).

5.2.2 Nourishments and set-up

In the section above, the naturally occurring conditions near Egmond were provided. The next section focuses on human interventions in the area and specifically the nourishing activities. To do so, it is important to define the exact extent of the studied site. For this research, the area between 35.00 and 46.00 km south of Den Helder was studied. This section can be divided into two coastal stretches:

- The northern section, in front of the coastal town of Egmond aan Zee, which is heavily nourished. This is referred to as Section A, the 'Nourished part' or 'Northern sector' (see orange indication in Figure 5.3).
- A southern part, without nearby villages, which is not nourished at all. This site is referred to as the Southern part, the Natural beach, the Unnourished sector or Section B (see blue indication in Figure 5.3).

Egmond is considered an erosion hotspot (Van Duin et al., 2004). Besides the fact that this location is naturally eroding, nourishments at this location have a relatively short lifetime. This results in Egmond aan Zee having a relatively large record of nourishing. In sector B, however, coastal retreat is barely present, which meant that no nourishments were necessary. However, there is one exception: in 2005 a 'tiny' nourishment of just 6000 m^3 was placed between 44.5 and 45 km. Compared to the scale of other nourishments, this nourishment is negligibly small, both in terms of total and relative volumes (12 m^3/m).

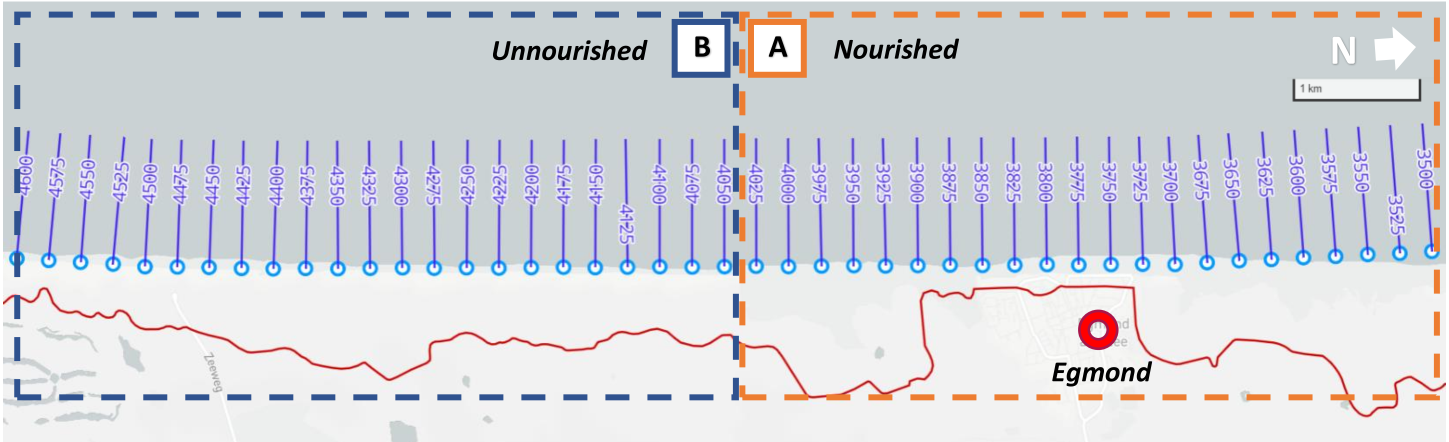


Figure 5.3 Planview of the studied site, with the longshore extent of sector A and B indicated. The purple lines indicated on the map, represent the locations of the JARKUS transects.

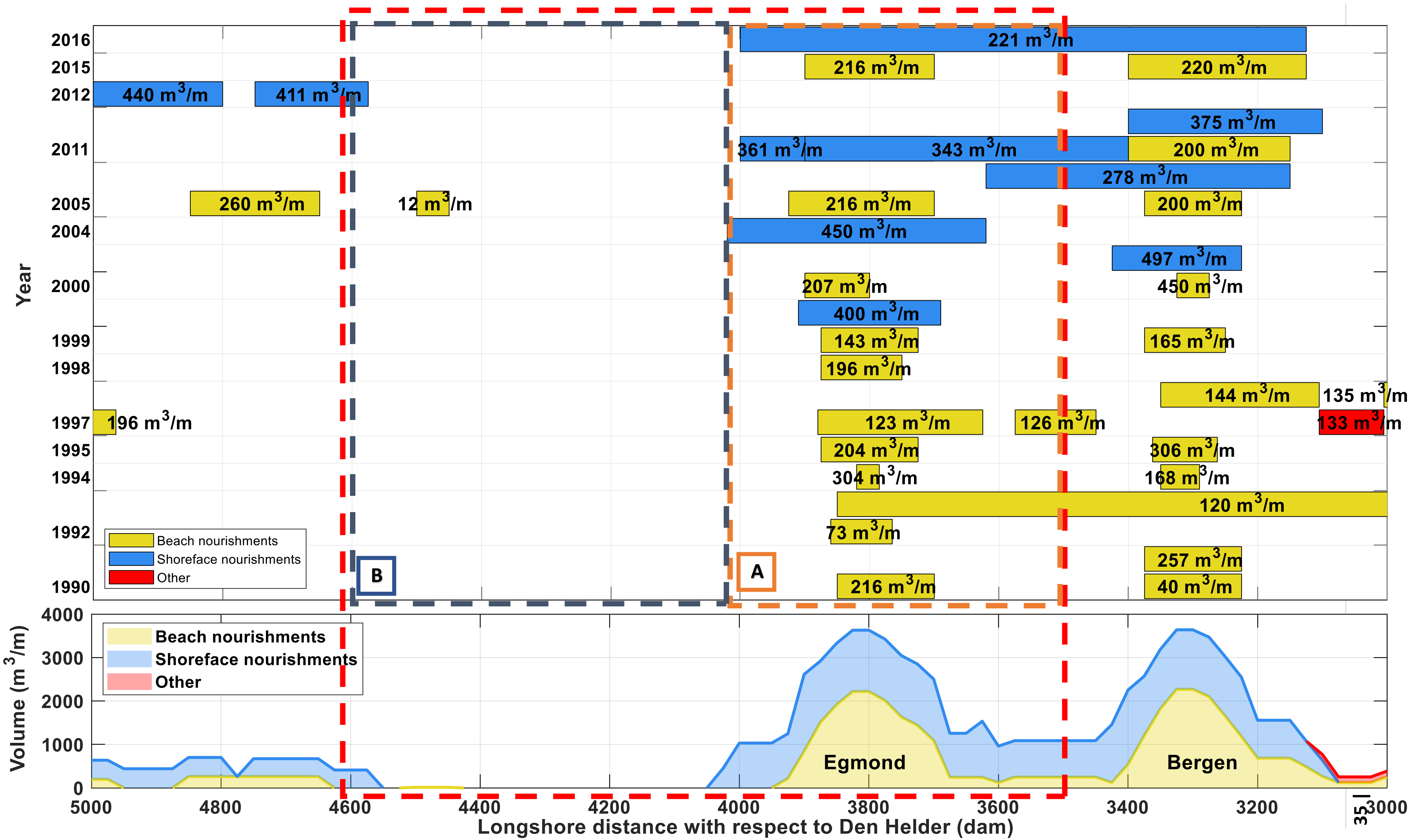
For this research, the period 1963-2013 was studied. A complete overview of all nourishments placed during this period is given in Table 6. The nourishment history of Egmond perfectly reflects the maintenance strategy of the Dutch government during the past decades. Immediately after implementation of the dynamic preservation policy in 1990 (discussed in chapter 1), beach nourishments were placed on the coast. However, it lasted until 1999 before the first shoreface nourishment was carried out, which coincides with the shift in nourishment policy in 2000 to focus on the shoreface (Mulder & Tonnon, 2010).

Table 6 Overview of the different nourishments that took place within the study area between 35.00 and 46.00 km. Note that some of the nourishments exceed the longshore range of the study area. (Data: Rijkswaterstaat).

#	Type	Date start	Date end	Location (km)	Length (km)	Total volume (m^3)	Relative volume (m^3/m)
1	Beach	5-1990	5-1990	37.00-38.50	1.50	323,318	216
2	Beach	9-1992	11-1992	37.65-38.60	0.95	69,225	73
3	Beach	5-1992	11-1992	26.20-38.50	12.3	1,472,640	120
4	Beach	6-1994	6-1994	37.85-38.20	0.35	106,343	304
5	Beach	5-1995	5-1995	37.25-38.75	1.50	306,000	204
6	Beach	5-1997	5-1997	34.50-35.75	1.25	158,000	126
7	Beach	5-1997	5-1997	36.25-38.80	2.55	314,000	123
8	Beach	6-1998	7-1998	37.50-38.75	1.25	244,442	196
9	Beach	4-1999	4-1999	37.25-38.75	1.50	214,515	143
10	Shoreface	6-1999	9-1999	36.90-39.10	2.20	880,100	400
11	Beach	6-2000	7-2000	38.00-39.00	1.00	207,445	207
12	Shoreface	6-2004	11-2004	36.20-40.20	4.00	1,800,699	450
13	Beach	6-2005	6-2005	44.50-45.00	0.50	6,000	12
14	Beach	5-2005	6-2005	46.50-48.50	2.00	519,850	260
15	Beach	4-2005	5-2005	37.00-39.25	2.25	486,023	216
16	Shoreface	8-2005	9-2005	31.50-36.20	4.70	1,306,114	278
17	Beach	3-2011	4-2011	37.00-39.00	2.00	400,000	200
18	Shoreface	8-2010	8-2011	34.00-39.00	5.00	1,713,913	343
19	Shoreface	8-2011	9-2011	39.00-40.00	1.00	360,870	361

To provide a complete overview, in Figure 5.4 all nourishments carried out near Egmond, until 2015 are plotted. In the upper panel of the figure the individual nourishments are plotted with their alongshore extent, with time on the y-axis. The lower panel provides an overview of the cumulative amount of nourished sand per meter. From Figure 5.4 It becomes clear that nourishment activities are concentrated around the coastal residences of Egmond aan Zee and Bergen. The maximum amount of sand placed near these cities total 3640 m^3/m, of which 2269 m^3/m consists of beach nourishments (Rijkswaterstaat). Towards the harbour moles of IJmuiden, coastal retreat is minimal. Accordingly, nourished amounts are rather small there, compared to Egmond and Bergen (Figure 5.4).

Figure 5.4 Graphical overview of all nourishment activities near Egmond and its surroundings. The red dotted square indicates the research area and with orange and blue sector A and B respectively are indicated. In the lower panel the cumulative volume per m is given for all nourishments. (Data: Rijkswaterstaat)



Year
2016
2015
2012
2011
2005
2004
2000
1999
1998
1997
1995
1994
1992
1990
221 m³/m
216 m³/m
220 m³/m
440 m³/m
411 m³/m
375 m³/m
361 m³/m
343 m³/m
200 m³/m
278 m³/m
260 m³/m
12 m³/m
216 m³/m
200 m³/m
450 m³/m
497 m³/m
207 m³/m
450 m³/m
400 m³/m
143 m³/m
165 m³/m
196 m³/m
144 m³/m
135 m³/m
196 m³/m
123 m³/m
126 m³/m
133 m³/m
204 m³/m
306 m³/m
304 m³/m
168 m³/m
120 m³/m
73 m³/m
257 m³/m
216 m³/m
40 m³/m
Beach nourishments
Shoreface nourishments
Other
B
A
Volume (m³/m)
Egmond
Bergen
Longshore distance with respect to Den Helder (dam)

6. JARKUS data and volume extraction methods

To investigate the impact of nourishing on the coast near Egmond, JARKUS transects were studied. Rijkswaterstaat, the executive part of the Dutch Department of Public Works, provides a database of annual measurements of the complete Dutch coast, called JARKUS ('JAaRlijkse KUStemetingen' = Dutch for 'annual coastal measurements'). These measurements consist of regularly spaced transects, perpendicular to the coast.

The following section provides insight into the measurement methods used by Rijkswaterstaat and the resulting data, used in this study.

6.1 JARKUS-raaien

Since 1963, Rijkswaterstaat surveys the entire coast on an annual basis. This is done for multiple reasons:

- Annual determination of the present coastline
- Safety checks
- Long-term study of coastal behaviour
- Providing advice on coastal management and safety

For this survey a system of beach-poles is used, called 'Rijksstrandpaallijn' (Dutch for 'beach pole line'), abbreviated as RSP. This system consists of regularly spaced beach-poles with an alongshore distance of 250 m. For the Holland coast, the northern tip of this system is located at Den Helder (Figure 5.1). Beach-poles are numbered, based on their distance in decameter to Den Helder, see Table 7.

Table 7 Overview of the studied transects between 35.00 and 46.00 kilometer from Den Helder

#	Raai ID	Distance to Den Helder (km)	#	Raai ID	Distance to Den Helder (km)	#	Raai ID	Distance to Den Helder (km)
1	3500	35.00	16	3875	38.75	31	4250	42.50
2	3525	35.25	17	3900	39.00	32	4275	42.75
3	3550	35.50	18	3925	39.25	33	4300	43.00
4	3575	35.75	19	3950	39.50	34	4325	43.25
5	3600	36.00	20	3975	39.75	35	4350	43.50
6	3625	36.25	21	4000	40.00	36	4375	43.75
7	3650	36.50	22	4025	40.25	37	4400	44.00
8	3675	36.75	23	4050	40.50	38	4425	44.25
9	3700	37.00	24	4075	40.75	39	4450	44.50
10	3725	37.25	25	4100	41.00	40	4475	44.75
11	3750	37.50	26	4125	41.25	41	4500	45.00
12	3775	37.75	27	4150	41.50	42	4525	45.25
13	3800	38.00	28	4175	41.75	43	4550	45.50
14	3825	38.25	29	4200	42.00	44	4575	45.75
15	3850	38.50	30	4225	42.25	45	4600	46.00

Perpendicular to the RSP, virtual lines, or transects, are drawn (called raaien in Dutch), which form the framework for the survey of cross-shore transects. For every transect, a profile is measured annually, with respect to the RSP. Elevations are represented in centimeters relative to NAP (Normaal Amsterdams Peil). Every JARKUS-transect is measured within a local coordinate system. However, since every beach pole has a fixed position within the RD-coordinate system (Rijksdriehoek-coördinaten) and every raai has an orientation in degrees, transects can be linked to each other in order to create a digital elevation model (DEM).

6.2 Measuring techniques

Every transect consists of two measurements: an elevation and a depth profile, also referred to as the dry and wet profiles. Elevation profiles are measured between the mean low water line (LWL) and 200 m landward of the peak of the first dune row, while depth measurements are executed between the high water line (HWL) and the end of the active zone (depth < -8 m NAP). LWL and HWL are deliberately chosen to generate overlap between the two transects, preventing empty space. Dry measurements are carried out by planes, equipped with a single beam laser, delivering a 5x5 m grid (Figure 6.1). In order to make the connection between the two profiles as exact as possible, the time lag between the surveys of the two different profiles is kept as small as possible. However, the window of execution of depth measurements is larger than for the elevation measurements. Rijkswaterstaat prescribes the period between 15 March and 15 April as the best option for elevation measurements. This is right after the storm season, while at this stage of the year vegetation is not fully grown yet (Rijkswaterstaat, 2003). For both types of measurements, the deadline is set in September. Note that this means that the time between consecutive measurements can vary between 0.5 to 1.5 years.

The depth measurements are executed using a single beam echo sounder (Figure 6.1). With a resolution of 10-20 m, data points are acquired, making use of a measuring vessel. Measurement errors for depth measurements are in the order of 10-40 cm (Rijkswaterstaat, 2005), while laser altimetry errors are in the order of 5-10 cm (Rijkswaterstaat, 2003).

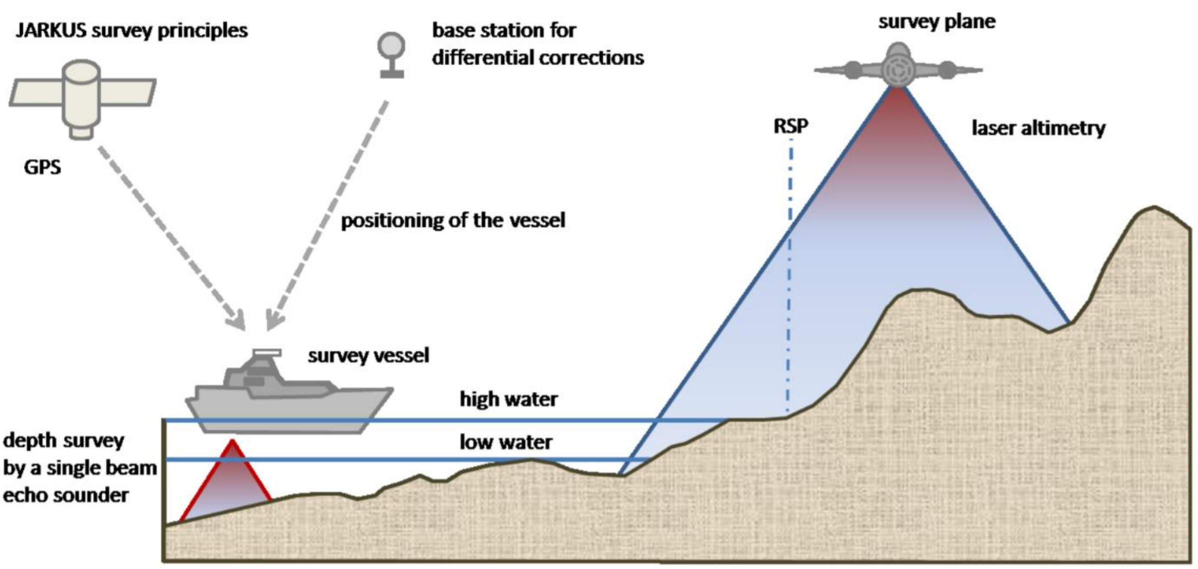


Figure 6.1 Schematized overview of survey techniques used for gathering of the data (Retrieved from: Bruins(2016)

6.3 Data extraction

For this research, 45 locations, with a longshore spacing of 250 m, along a coastal strip of 10 km near Egmond, were analysed over a total period of 50 years (Figure 5.3). With the available data it was possible to create 2250 profiles. As explained in the section above, these profiles consist of a 'dry' part, containing an elevation measurement ('hoogtebestand') of the beach and the dunes, and a 'wet' part, which contains a depth measurement of the foreshore. In order to create a complete profile, these two are combined, using the following strategy: Data is obtained from text-files and the cross-shore extent of the depth and the cross-shore extent of both transects is determined. To minimize cross-shore differences in resolution, data steps smaller than 10 m were removed. In most cases, depth measurements and elevation measurements overlap with each other. In those cases, the elevation profile was used, because of its higher accuracy (Figure 6.2A). If there is no overlap but instead a gap between the two profiles, a straight line is drawn between the two lines, as can be seen in Figure 6.2B. This may lead to wrong interpretations of bar locations and volumes.

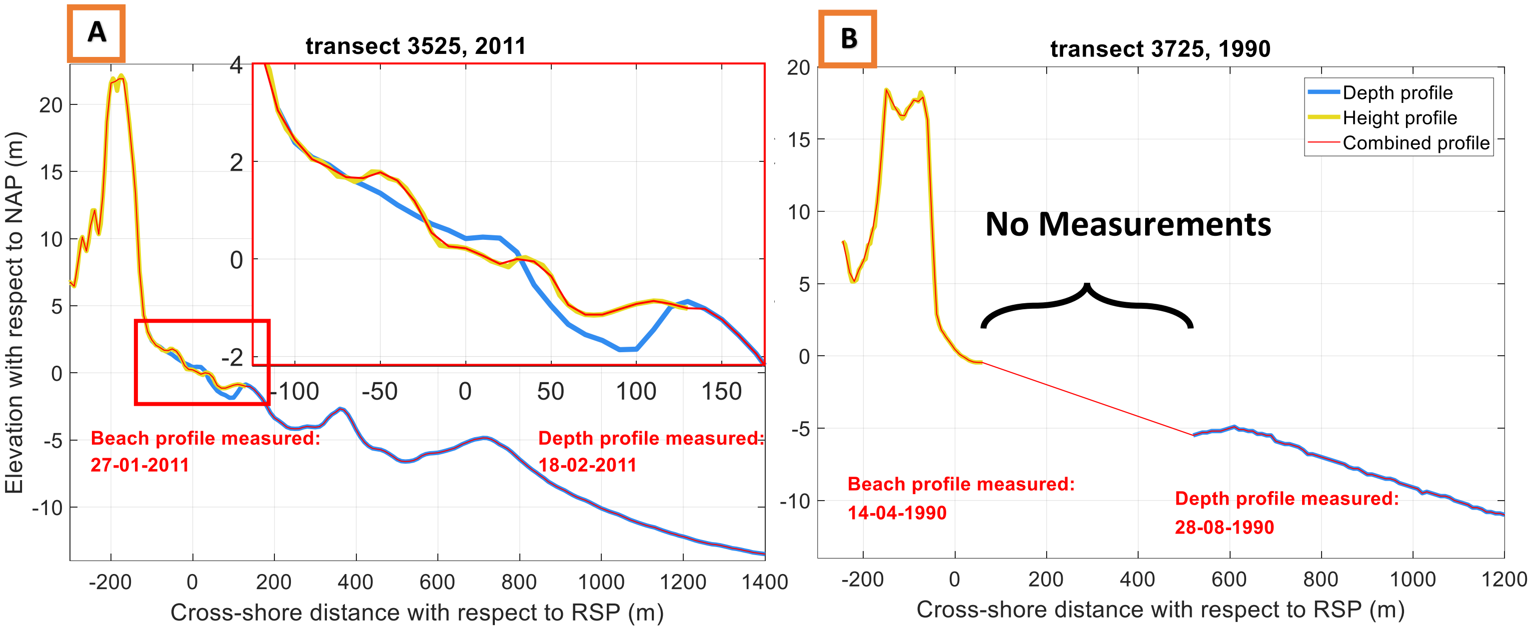


Figure 6.2 Combining of two individual transects into one profile. . A) In case parts of the two transects overlap, the beach profile is followed over the wet profile, for beach profiles are more accurate. B) If no data is available a straight line is drawn in between the two transects.

6.4 Data limits

Not in all cases data was complete, which may cause wrong estimations. In this section, missing data and other sources of error are discussed, starting with incomplete profiles. Namely, in 73 of the total 2250 transects, the profile lacked an altitude measurement or a depth measurement. These numbers are concentrated around certain years:

- All beach profiles of 2002 are missing. This accounts for all 45 longshore locations. Since there are 47 profiles lacking an elevation measurement, only 2 other transects remain with a missing beach profile.
- The same accounts for the shoreface transects: during the years 2010 and 2011, 11 locations (accounts for 22 profiles) were not measured. When subtracting these 22 profiles from the total number of missing depth transects, only 4 transects remain with a missing shoreface profile.

A second data gap has already been introduced above. In some cases, the landward minimum of a depth profile is larger than the seaward maximum of the altitude measurements. This results in an open gap, between them, as shown in Figure 6.2B, when trying to connect them. This accounts for 268 profiles, which contain a gap of 20 m or larger. A rather small number of 44 profiles have a gap that exceeds 80 m. In Figure 6.3 an overview is presented of data gaps between both types of measurement techniques. As can be clearly seen, the vast majority of gaps is present in the period 1987-1994. A data gap could be an indication for the presence of a large nearshore bar obstructing the survey vessel during the measurements. The relatively large concentration of missing data around 1990 might support this theory.

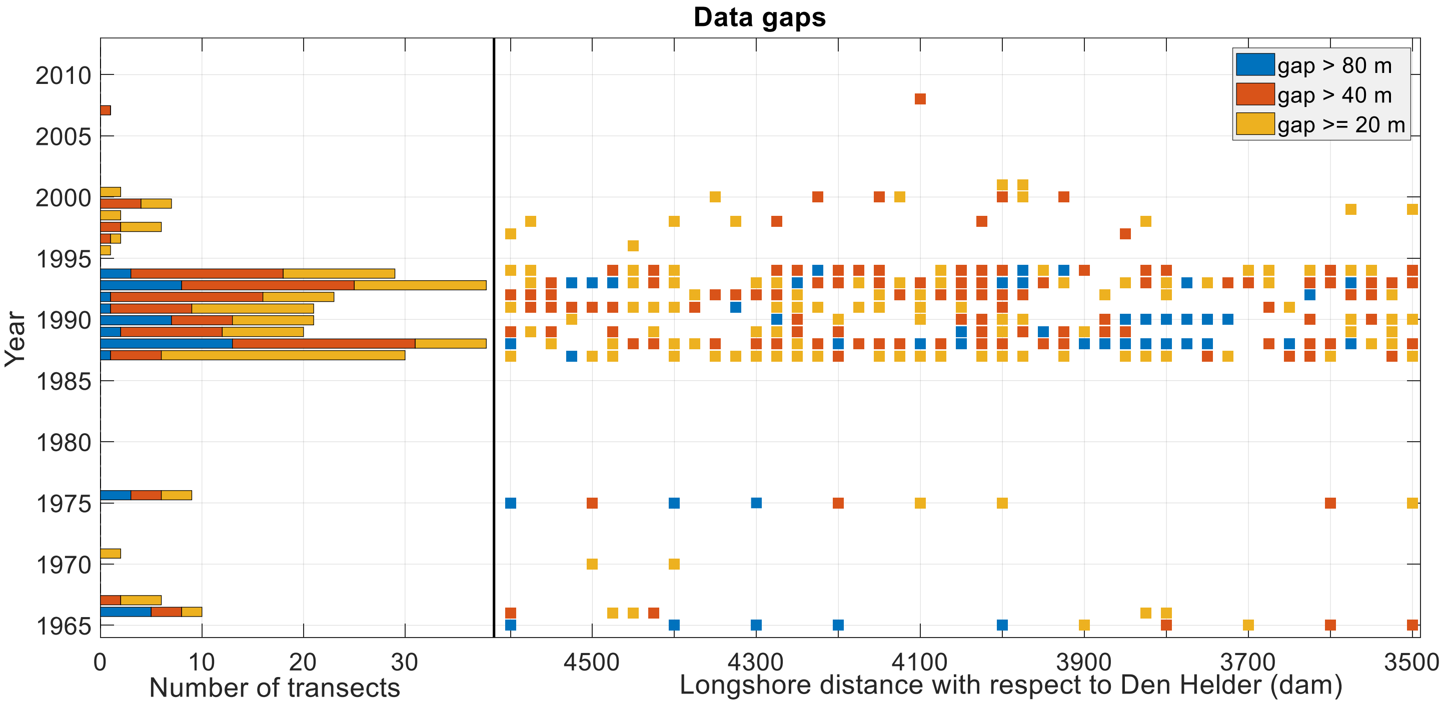
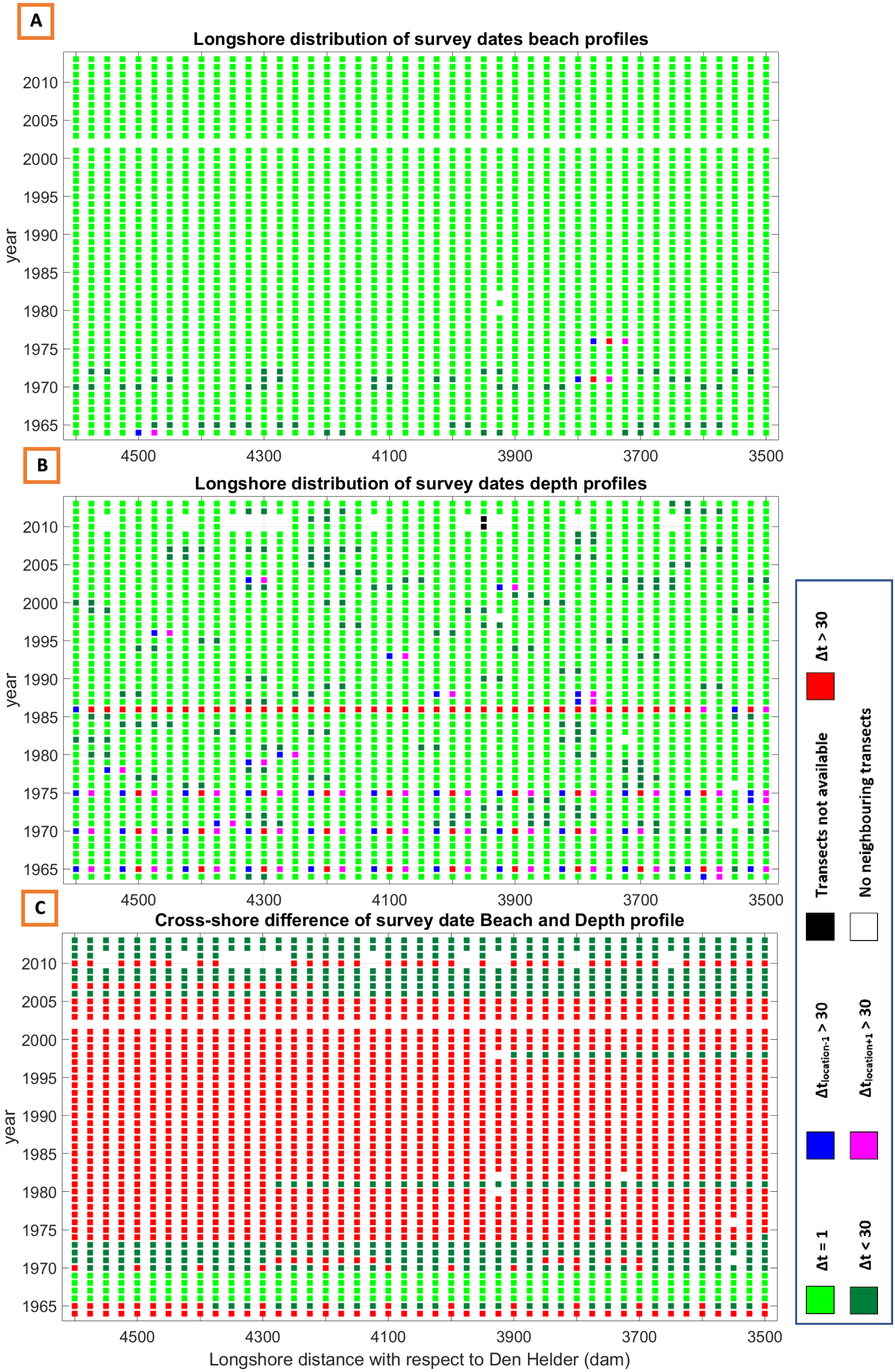


Figure 6.3 Overview of transcects, containing a data gap between the beach and wet profile. In the left panel the cumulative number per year is plotted. As can be seen the data-gaps are mainly concentrated in the period 1986-1994.

The last factor which influences the accuracy of measurements is the date on which the profile survey took place. Since one single transect consists of two different measurements, the date on which these individual profiles are obtained may differ as well. See for example Figure 6.2B, where the interval between the wet and the dry survey is multiple months. To provide insight in longshore differences in the date of profile survey, Figure 6.4 was created. The colour of each squares depicts the longshore difference in the date profile survey. Green squares indicate that the transect of interest is measured on the same day as its neighbouring profiles. Red means that this time interval is longer than a month. Purple and blue squares resemble time intervals longer than a month for either the northern profile(blue) or the Southern(purple).

When studying the squares in the upper panels of Figure 6.4 it becomes immediately clear that the vast majority of all transects were measured on the same day. The elevation transects appear to have a slightly more longshore coherence than the depth measurements. This may be caused by the surveillance techniques. The dry measurements are carried out by planes (Rijkswaterstaat, 2003). Consequently, 97.1% of all transects are measured on the same day. For the foreshore, where ships are used, this is slightly lower with a percentage of 84.4%.



A
Longshore distribution of survey dates beach profiles
B
Longshore distribution of survey dates depth profiles
C
Cross-shore difference of survey date Beach and Depth profile
year
2010
2005
2000
1995
1990
1985
1980
1975
1970
1965
4500
4300
4100
3900
3700
3500
Longshore distance with respect to Den Helder (dam)
Δt = 1
Δt < 30
Δt_location-1 > 30
Δt_location+1 > 30
Transects not available
No neighbouring transects
Δt > 30

Figure 6.4 Overview of coherence in the date, on which profiles have been surveyed.. A) Longshore coherence of beach profi B) Longshore coherence of depth profiles C) Cross-shore coherence of the combined beach and depth profiles.

On the other hand, cross-shore coherence of measurements is significantly lower. Except for the period 1966-1969, none of the two transects contributing to the JARKUS profile were measured on the same day. Time intervals of multiple months, as depicted in Figure 6.2B, are no exception. For 65.5% of all profiles the execution interval is longer than a month (Figure 6.4C).

6.5 Complete profiles

With the combined transects it was possible to make a plot of each profile. A first inspection of the newly obtained profiles learns that there is significant variation in the cross-shore extent of the transects. Incomplete profiles lacking depth data only reach to a maximum of 250 m, while largest maxima in 1993 reach over 5000 m (Figure 6.5). Cross-shore variation over time is present as well. In the earliest period of the JARKUS measurements (1964-1984), seaward maxima extended to 800 m, with a relatively small variation in cross-shore length. Also, on the landward side, median values were small with only -100 m. After 1985, measurements were expanded to maxima of at least 1000 m, with median values varying from 1110 m to 2020 m. Equivalent to the seaward expansion of the depth measurements, the dry-profile measurements were also extended in landward direction: after 1972 the landward edge moved to at least -200m. However, after the year 2000, measurements started to become less consistent, leading to major fluctuations in cross-shore extension on both the landward and seaward end (Figure 6.5).

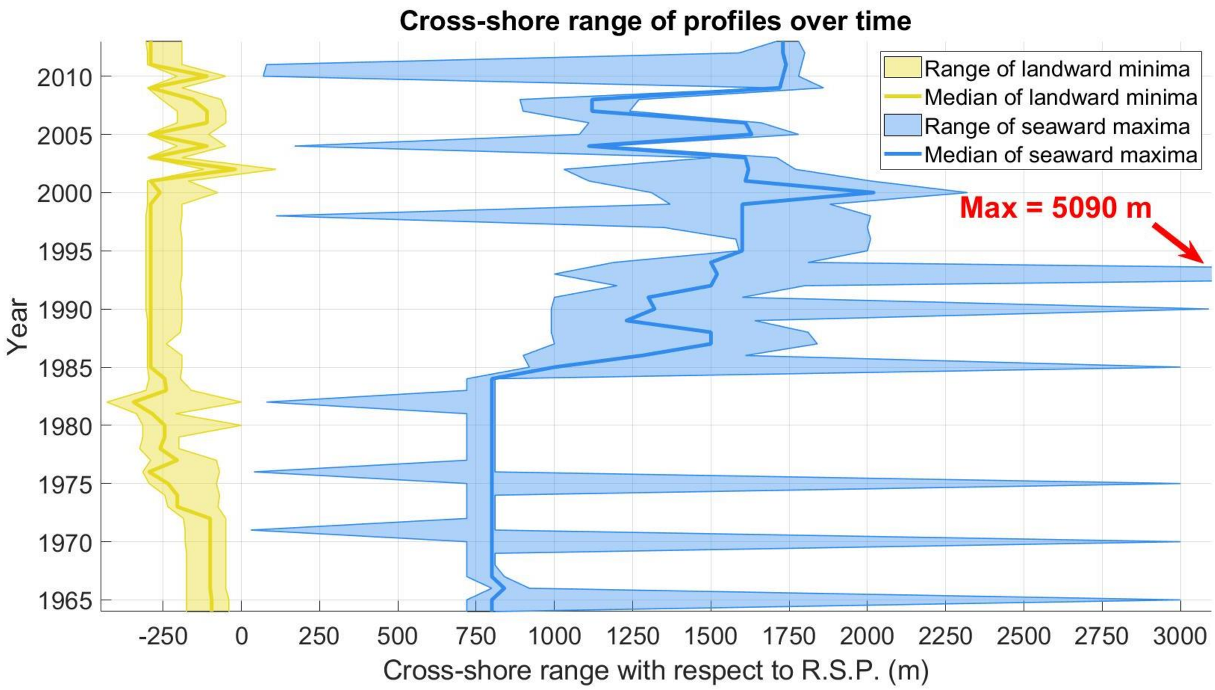


Figure 6.5 Cross-shore over of range measured transects over time

6.6 Dune crest and beach width

In Figure 6.6 the maximum elevation per profile over time is plotted. This maximum elevation should correspond to the dune crest, but due to the landward extent of the transects this is not always the case. At 43.25 km for example, the dune crest is measured for the first time in 1973, leading to a sudden change in maximum elevation, indicated with the blue circle. When analysing Figure 6.6, the

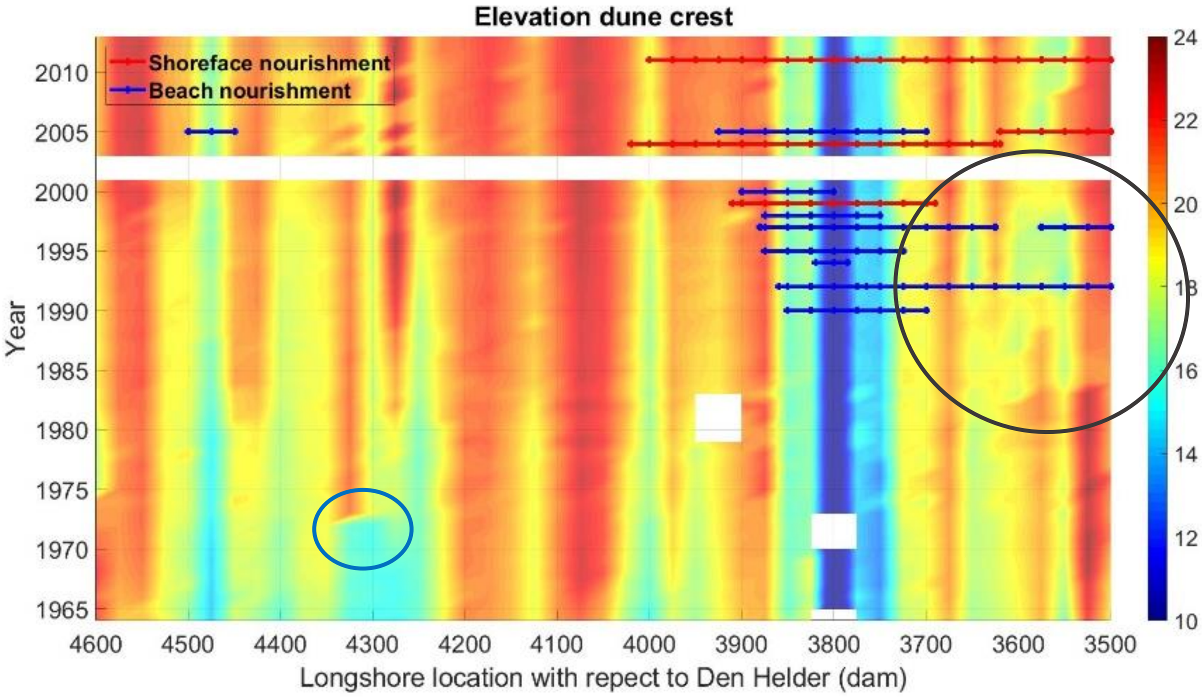


Figure 6.6 Time stacks of maximum dune crest elevation near Egmond aan Zee.

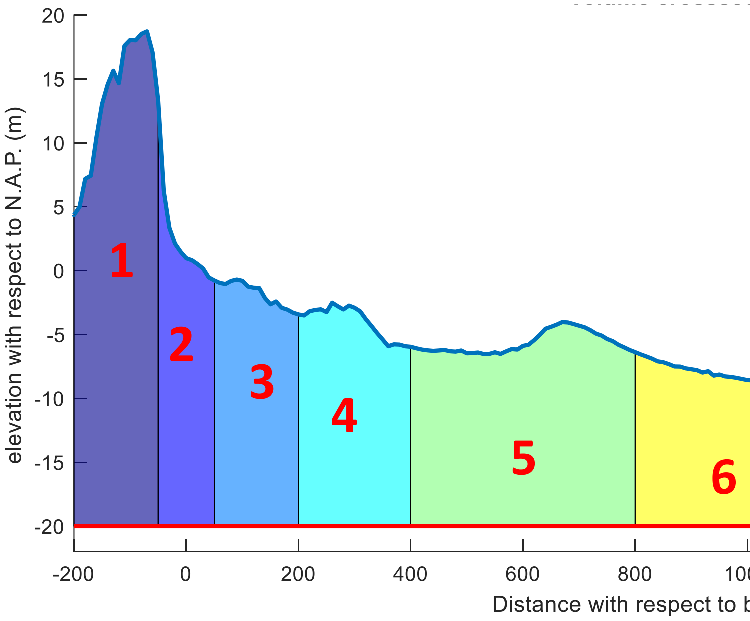
relative vulnerability of Egmond aan Zee becomes clear. The primary sea defence surrounding Egmond consists of a dune row reaching altitudes of up to 24 m. However, the lowest position along this row is the Boulevard in front of the village, where the maximum elevation is about 7.5 m, clearly visible as a blue stripe through the figure around 38.00 km. Another point of concern is dune growth. Although most of dunes show growth during the 50 years studied, in the north this growth is less pronounced, less consistent and even sometimes alternated with periods of decrease. Especially during the period 1980-1990, dune height in the north is decreasing, see the black circle in Figure 6.6**.** The width of the beach, defined as the cross-shore distance between the dune foot and the mean low water line (LWL), does not show much variation over time. With the dune foot located at an elevation of +3 m NAP and the mean low water line (LWL) at -1.6 m NAP, this beach width can be calculated. The undisturbed beach width varies from 140 m to 200 m with a mean of 173 m. Longshore differences are rather small, but beaches in the northern part around Egmond are slightly smaller. Moreover, minima reach lower values near Egmond.

6.7 Cross-shore volumes

To study nearshore volume changes induced by a shoreface nourishment near Egmond, Van Duin et al. (2004) divided the coast near Egmond into different subsections, both in cross-shore and in longshore direction. In this research this is repeated on a larger scale, over a longshore extent of 11 km (compared to 5 km in Van Duin et al., 2004). In this research the chosen longshore interval is 1 km. The cross-shore profile is also divided into different segments. These segments are to some extent arbitrary, but are chosen to represent certain parts of the cross-shore profile, as depicted in Figure 6.7. For the calculation of volume trends, the following steps were taken:

1. For every location, for every year and for every cross-shore segment, the cross-shore volumes were calculated with respect to -20 m.

2. The profiles are combined for every longshore kilometer. For each kilometer, consisting of 5 individual profiles, with a longshore spacing of 250 m, the mean is determined, for the different cross-shore sections.
3. In order to filter the long-term trends, every point on the graph is the result of the mean of 5 years: the current year, the two years before and the two years after. For instance, 1968 is the mean of the years 1966-1970.
4. To avoid a large spread in numbers, all results are presented relative to their first measurement, which is set to zero in order to create more comprehensible plots (Figure 6.8).
5. In order to provide insight in the volume changes after implementation of the nourishments, trendlines are obtained for each segment from the period until 1990 and the period after 1990.



#	Cross-shore position (m)	Year of execution
1	-200 - 50	Dune
2	-50 - 50	beach
3	50 - 200	intertidal zone
4	200 - 400	inner bar
5	400 - 800	outer bar
6	800 - 1100	End of bar zone
7	1100 - 1400	lower shoreface
8	1400 - 1700	lower shoreface
9	1700 - 2000	lower shoreface

Figure 6.7 Selection of 9 cross-shore bins

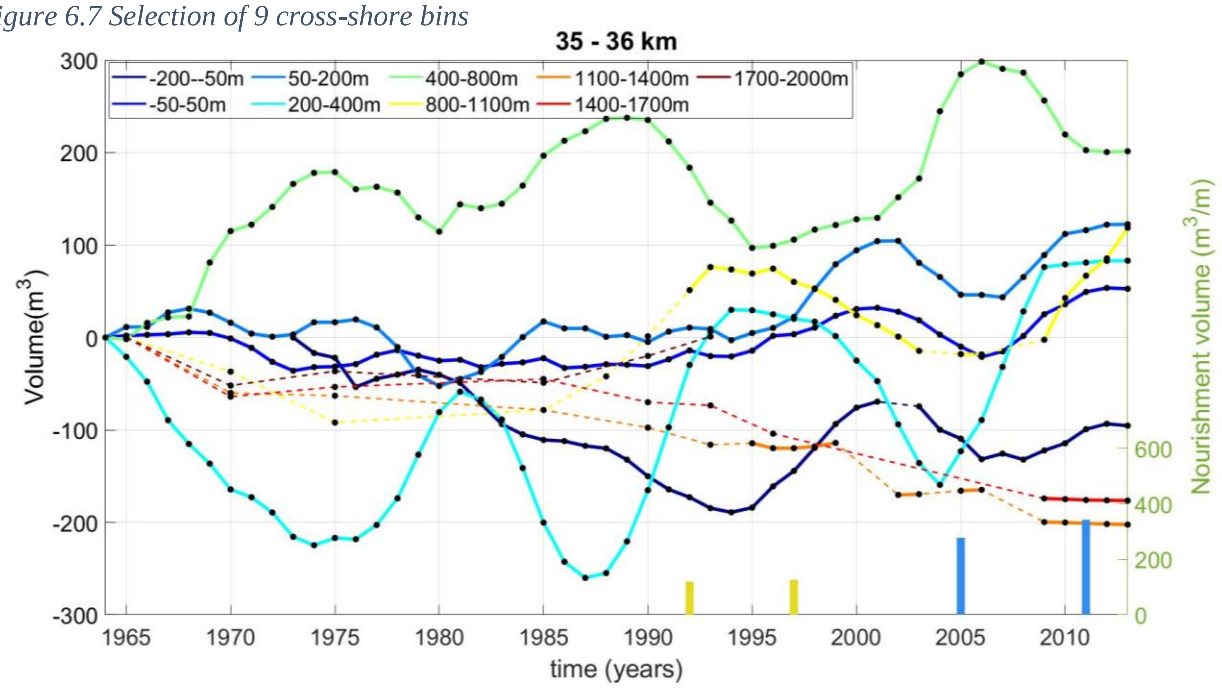


Figure 6.8 Overview of volume trends within the 9 cross-shore bins, determined in Figure 6.7. The longshore section from 35 km to 36 km, consists of 5 transects. Nourishments executed within the cross-shore section are plotted in the lower part of the figure, with yellow bars resembling beach nourishments and blue bars shoreface nourishments.

6.8 MKL-position

Rijkswaterstaat, responsible for the maintenance of the Dutch coast, developed a set of tools for monitoring purposes. Based on these monitoring tools, the coast is annually checked for safety and nourishments can be carried out if necessary. Since the coastline is highly dynamic and surveys are only executed once a year, a method was needed to obtain a representative number for a specific location. The 0 m NAP contour and the MLW position appeared to be too dynamic for trend calculations, so it was decided to use a volume instead of a specific location (Rijkswaterstaat, 1991). This led to the development of the concept Momentary Coastline (MKL = "Momentane Kustlijn"). The MKL-position is based on a volume ('Rekenschijf' or MKL-volume) instead of a static position and is therefore more stable.

To obtain the MKL-position, first, mean low water levels have to be determined ('GLW' in Figure 6.9). For the coast near Egmond this line varies between -0.77 m and -0.81 m. As upper boundary, the dune foot is used. Along almost the whole Dutch coast, the dune foot is set at an elevation of NAP +3 m. This is the case for Egmond as well. When subtracting the difference in elevation between the dune foot and MLW and detract this h from MLW, the lower boundary is found. The resulting formula for the MKL-position is:

$$\boldsymbol{x_{mkl}} = \frac{\boldsymbol{A}}{\boldsymbol{2h}} - \boldsymbol{x_{dv}} \qquad \text{with} \qquad h = MLW + 3$$

The variable A represents the area between the intersections of the upper and lower boundary with the profile and is known as the MKL-volume. The resulting MKL is compared to the Basal Coast Line (BKL = 'Basis Kustlijn'), which equals the MKL-position on 1 January 1990. This position is calculated based on an extrapolation of MKL-positions during the period 1980-1989 (Rijkswaterstaat, 1991). If MKL positions on a certain location become too low, a nourishment is implemented to restore the MKL-volume.

Deltares, the research institute cooperating with Rijkswaterstaat, provides an application for calculation of MKL-positions and coastline trends. This application, called MorphAn, was used to compute the MKL-positions for the period 1965-2015 near Egmond. Although the period 2014-2015 is

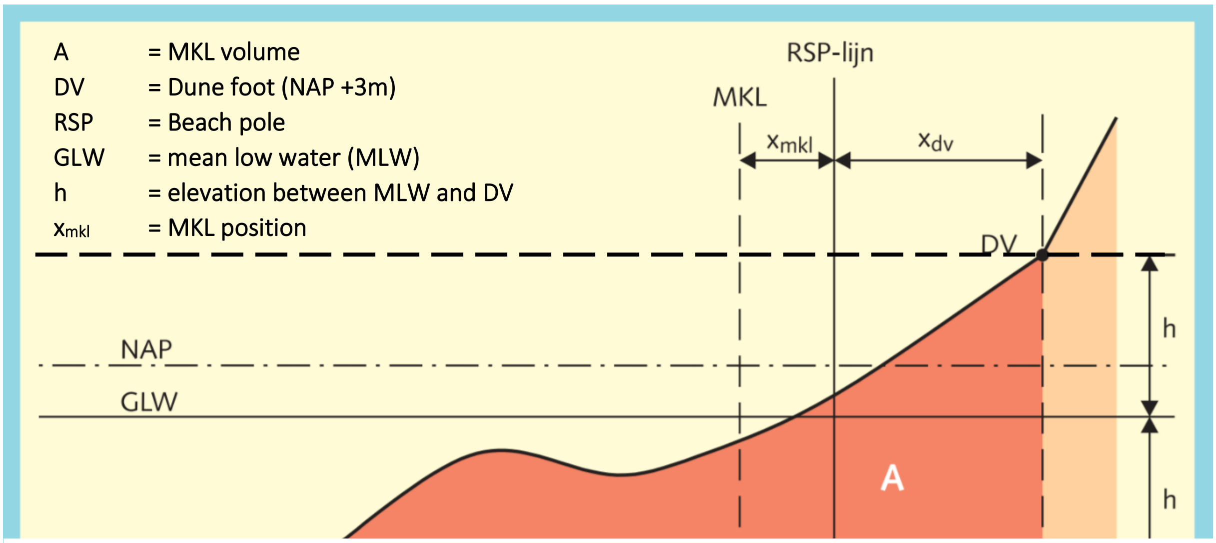


Figure 6.9 Principles of determination of the MKL-position. (Retrieved from: Leidraad Zandige Kust (1995))

beyond the range of this study, it provides more insight into further development of trends. With the help of MorphAn, MKL positions along the coastal strip near Egmond could be calculated for the period 1965-2015. This could be done for 2235 profiles of the 2295 profiles. For a total number of 60 profiles no MKL position could be obtained. The transects lacking a beach measurement from 2002 made up 44 of this number.

7. Extracting bar properties from JARKUS data

In order to study bar behaviour in the nearshore zone in terms of volume and migration, finding the bar crest was not sufficient. The landward and seaward edge had to be determined as well, to enable the calculation of volumes. Therefore, a method was developed to find every sand bar in every profile. This chapter contains a description of how sandbars were found in the JARKUS transects, how nourishments are visible in the transects and ends with the calculations of the volume of each bar.

7.1 Bar determination

In this first subsection, the techniques used to locate sand bars in a cross-shore profile are explained, including the steps that were followed to come to the principles used in this study. Different strategies were followed to obtain exact bar positions. Two techniques were tested and provided clues for bar determination. The first technique was used by Bruin (2016) and the second technique by Ribas et al. (2010) and Rademacher et al. (2018). The working of the various functions, developed for bar detection purposes, is explain in Appendix A.

7.1.1 Technique 1: mean profile

The first technique, obtained from Bruins (2016), used a mean profile. For every location a mean profile was created for the period 1964-1989, as can be seen in Figure 7.1**.** The time interval 1964-1990 was deliberately chosen to prevent deviations by nourishments, starting from 1990. However, the mean profile turned out to be an insufficient technique, since its elevation was higher than even some of the bar crests of annual profiles (Figure 7.1). Moreover, the end of the bar section, between 400 m and 600 m, is generally elevated too high, because decaying bars reside relatively long at this location. Therefore, this method was deemed incomplete and inaccurate for the purpose of this study.

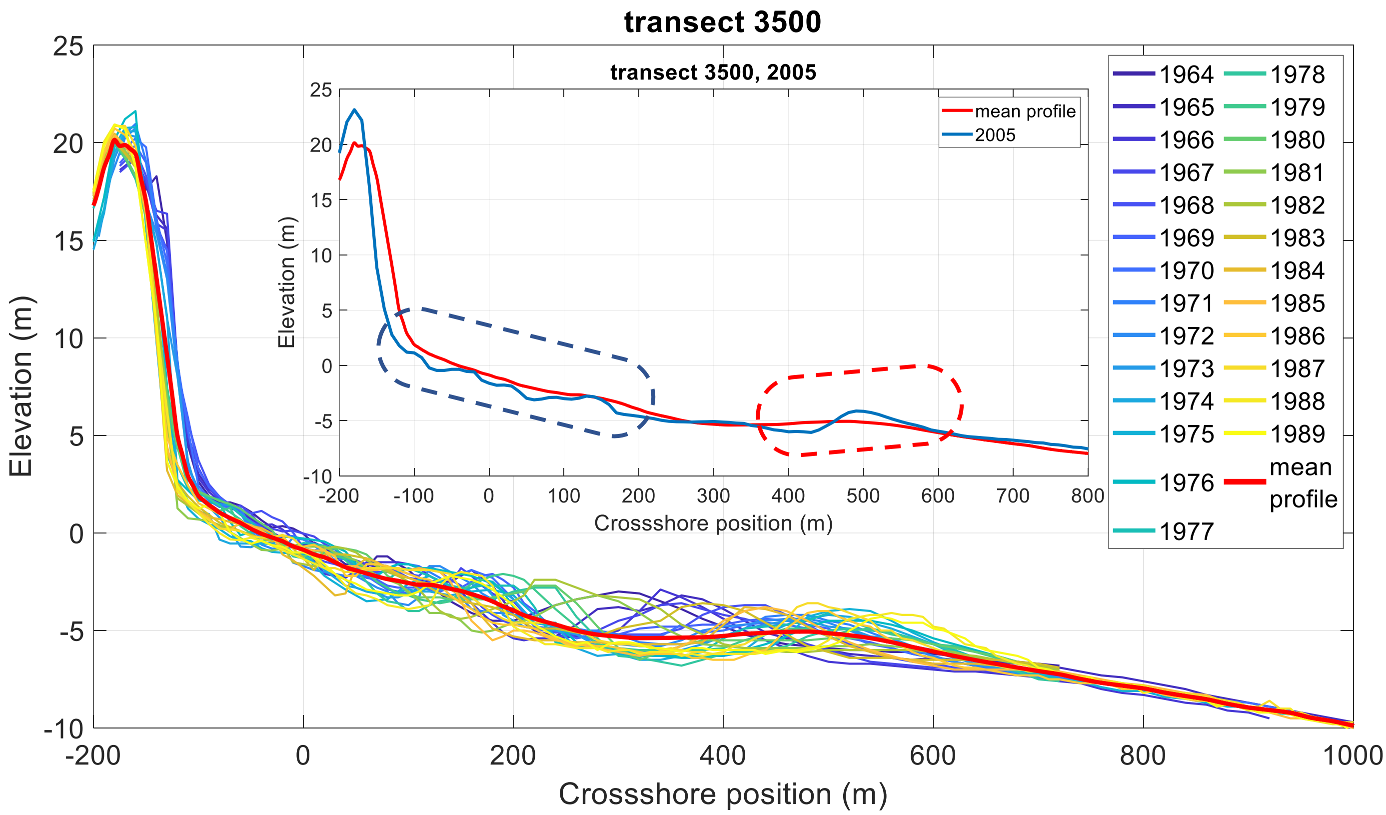


Figure 7.1 Mean profile determination. This technique is sometimes too coarse to find individual bars(blue circle) and may lead to an underestimation of a sandbar volume, on locations where bars often reside. In this case near 500 m(red circle).

7.1.2 Technique 2: derivatives

The second method is derived from a combination of Ribas et al. (2010) and Radermacher et al. (2018). Ribas et al. (2010) used a combination of the first and the second derivative of the bed profile to find the crest of a sand bar. The crest of the bar appeared to correspond to a downward zero-crossing of the first derivative, together with a negative peak in the second derivative (Figure 7.2). Radermacher et al. (2018) showed that the use of a smoothed first derivative might help to find the position in case of real field data, which has multiple peaks (Figure 7.3).

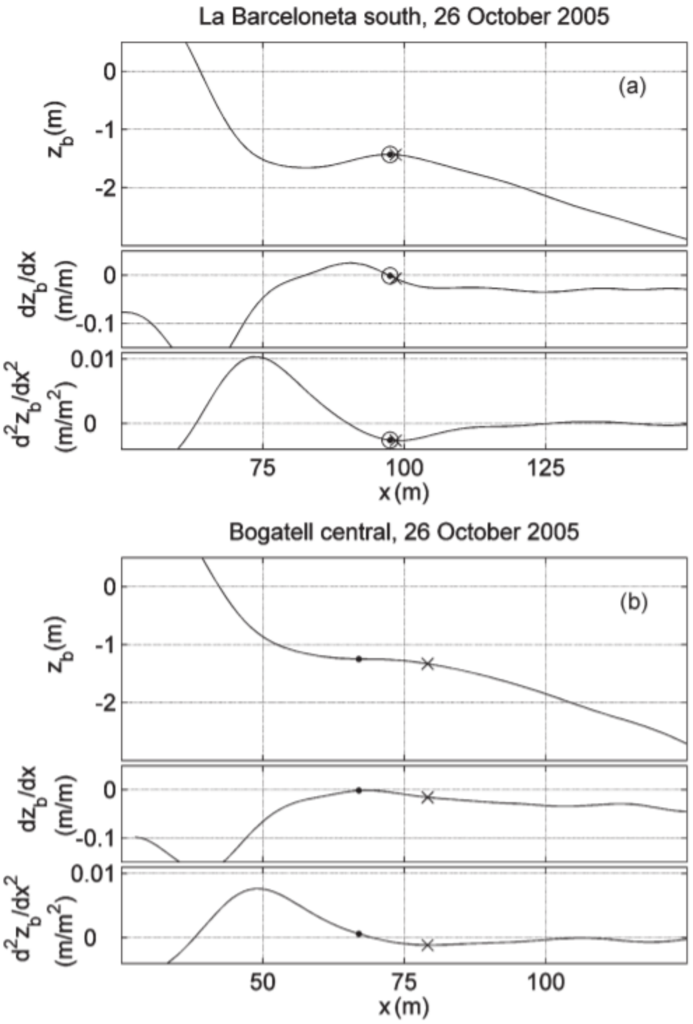


Figure 7.2 Concept of finding a bar crest by means of the first and second derivative. (Retrieved from: Ribas et al., 2010)

Another important finding of Ribas et al. (2010) was the detection of the seaward edge of a terrace by making use of the second derivative. When observing the lower panel of Figure 7.2, it becomes clear that this edge coincides with a negative peak of the second derivative.

Using both methods it appeared to be straightforward to find the bar crests. However, the application of the methods used by Radermacher et al. (2018) and Ribas et al. (2010) was only to obtain the bar position (crest position), whereas the aim of this study is to isolate the complete bar in order to derive its volume. This requires the determination of the both flanks as well, with a high level of accuracy. This turned out to be complicated.

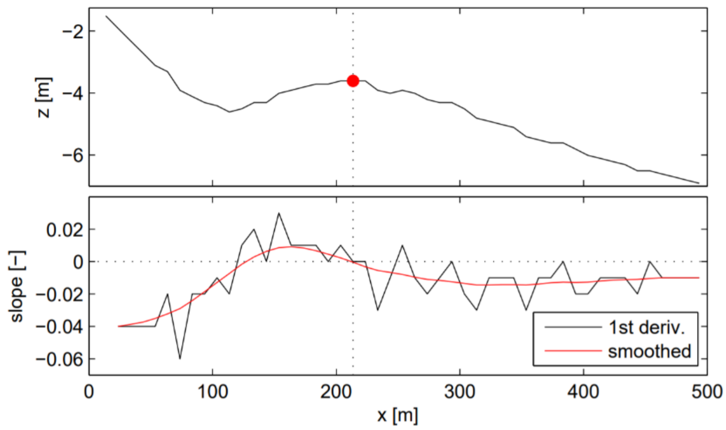


Figure 7.3 Principle of using a smoothed derivative, for crest determination (retrieved from: Rademacher et al., 2018)

In Figure 7.4 a transect measured at location 10 (3725) in 2009 is plotted in the upper panel. In the middle panel the first derivative is depicted and in the lower, the second derivative. As already stated, finding the bar crest is relatively straightforward, but the detection of the bar edges requires an additional step. When taking the derivative, the profile becomes increasingly more capricious. For example, in Figure 7.4, multiple positions left (two examples indicated with vertical blue lines) and three right (three examples indicated with vertical green lines) meet the criteria. This makes determination of specific peaks or zero-crossings increasingly complicated. However, when the profile is smoothened this leads to a decrease in accuracy. Especially the second derivative appeared too peaky or too inaccurate to determine bar edges. Therefore, in order to find the edges a new criterium was needed, which is deliberately presented in Appendix A. In summary: better results were obtained by using the intersection of the first derivative, with the mean slope as a reference (Figure A.1). In reality this concept appeared to be complex and a total number of 14 functions, divided over two phases, were needed to distillate exact bar locations.

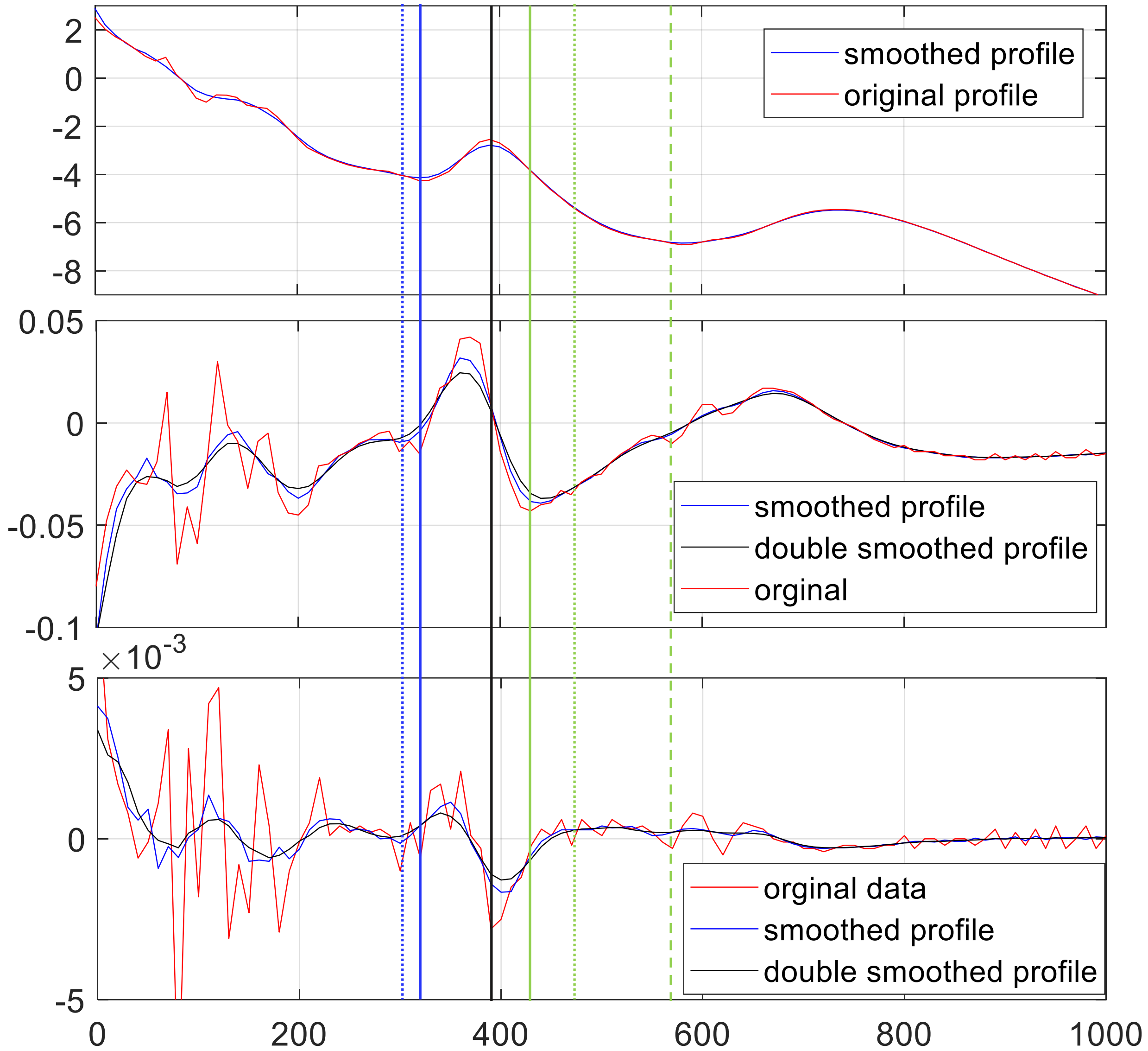


Figure 7.4 Figure showing the limitations of working with derivatives. Which peak of which derivative should be chosen? As can be seen smoothed derivatives may lead to inaccuracy, while original data may easily lead to mistakes.

7.1.3 Resulting bar locations

Altogether, 6853 bars could be located in the first round, consisting of a landward and seaward position and a crest position. By means of visual inspection, profiles were selected where the bar locations found did not deliver satisfying results. A number of 877 transects were selected, containing 1156 defects:

- Existing bars had to be combined (76 bars created)
- One or more sides of the bar had to be displaced (539 translations)
- 259 bars were wrong and had to be deleted
- At 71 locations an extra bar was found

- The program written for the first round, was not able to find terraces. With a special function, 169 terraces could be located.
- For 42 profiles all bars had to be defined manually, delivering 78 more bars.

7.1.4 Volume calculation

With all bar locations determined, it was possible to calculate the bar volumes. This was done by creating a 2D-polygon in Matlab. The volume of a sandbar is defined as the area underneath the transect and is enclosed by a straight line connecting the bar edges (Figure 7.5). Although Ribas et al. (2010) and Radermacher et al. (2018) use the bar crest as bar location, in this research the centroid is chosen to represent its position. This is in line with Bruins (2016) and may provide more details about the actual migration of the complete bar.

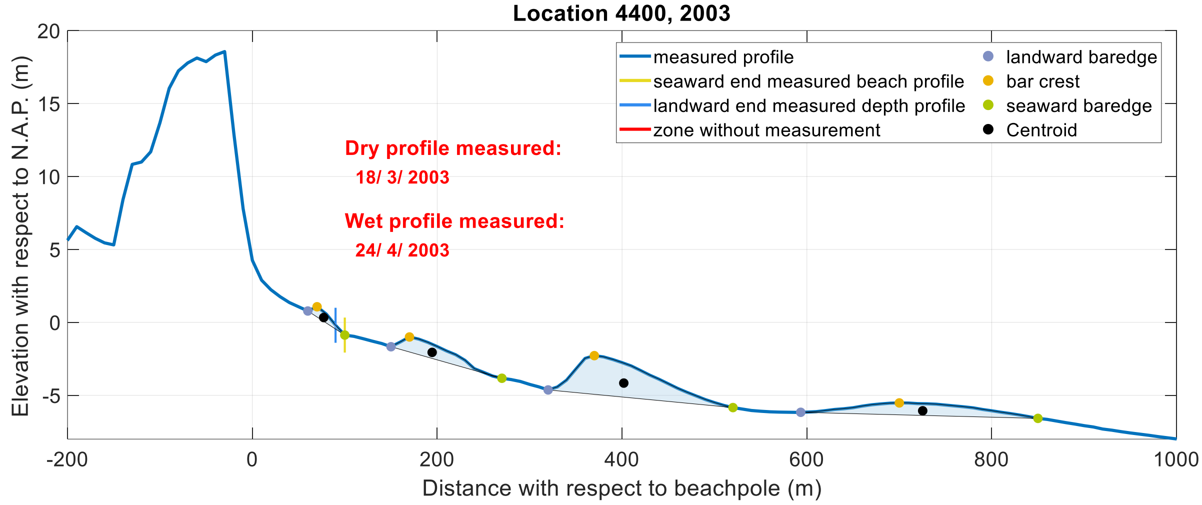


Figure 7.5 Example of a cross-shore profile with bars, as located by making use of the methods described above

7.2 Nourishments

In front of the boulevard of Egmond, multiple nourishments took place, starting from 1990. It turned out to be difficult to locate the beach nourishments. First of all because part of them took place in the period 1990-1994. In this period several large gaps between the beach profile and the depth profile where present, rendering comparison impossible. Secondly, the beach profile itself accretes or erodes each year, even without nourishment. At many locations, shoreface nourishments barely exceed this level of normal accretion. The third reason why it is difficult to study beach nourishments is the relatively short lifetime. Lifetimes of beach nourishments in this area do not exceed 2 years (e.g. Cohen et al., 2007).

Shoreface nourishments, on the other hand, have lifetimes of multiple years and are easily recognizable as an 'extra bar' seaward of the outer bar, or as an extremely accreted outer bar. On the elevation maps, shoreface nourishments appear as broad bars, with a pronounced and contrasting morphology. Since JARKUS transect measurements are mainly determined during spring and early summer, nourishments often appear in the results in the following year. After a year, the nourishment is fully incorporated in the bar system and acts as a normal bar.

In Figure 7.6 two examples of a nourished profile are given. In panel A this concerns a double nourishment of 193 m^3/m in total. As explained above, a year later this nourishment is barely visible. The shoreface nourishment of 2004 at the same location is visible as an extra bar, indicated with red in Figure 7.6B on the seaward edge of the bar zone. Also, the shoreface nourishment that was carried out in 2005 is clearly visible, as it is relatively large with 260 m^3/m.

By making use of the bar detection programs introduced above, it was possible to locate the exact location of the shoreface nourishments over time. In Table 8 some general characteristics are presented. It is important to notice that the system has been significantly enlarged during the nourishment period between 1999-2013. When studying the locations of placement and dissolvement of the shoreface nourishments, a clear seaward trend is visible, see Table 8.

Table 8 Characteristics of the 4 shoreface nourishments carried out near Egmond

#	Location	Year of execution	Year of first observation	Cross-shore position (m)	Year of last observation	Cross-shore position (m)
1	36.90 - 39.10	1999	2000	680	2003	677
2	36.20 - 40.20	2004	2005	745	2010	738
3	31.50 - 36.20	2005	2006	686	2010	727
4	34.00 - 40.00	2011	2012	819	(-)	(-)

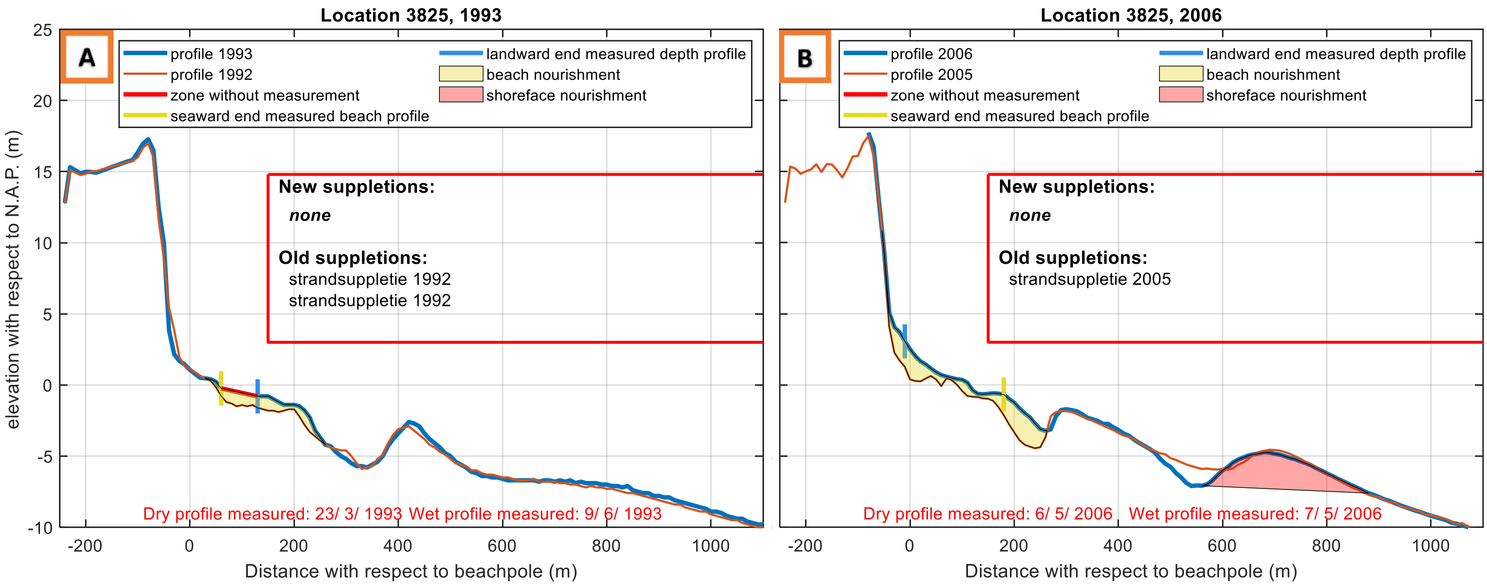


Figure 7.6 Identification of a beach nourishment (left panel) and a shoreface nourishment (right panel)

7.3 Resulting bar data

With all bars defined, plots were generated of each profile. Together with each profile the bars are plotted as 2D-polygons, including their centroids (Figure 7.7). Again note that the centroids are used as the bar location for each bar. As can be seen in Figure 7.7, the bar position is generally located at the seaward side of the crest.

To gain insight into the area near Egmond, a Digital Elevation Model (DEM) was created for each year with the available JARKUS data, see Figure 7.7. These annual elevation maps are presented in the Appendix B. On these plots the locations of the bar centroids are plotted as well. The bars are clearly visible on the map as longshore elevated structures. Again, note the good agreement between all bar locations on the map and the centroids. The DEMs are used to make a first analysis of the system.

In Figure 7.7 the DEM of 1979 is presented. This map is used to explain the observed characteristics of the studied coast. Along the shore of Egmond a multi-bar system is present, often with a shore-attached intertidal bar and two or more subtidal bars. In this particular year four longshore bars can be distinguished. In the northern part, between 3500 and 3800, the remnants of a decaying outer bar are present, indicated with a brown colour and referred to as bar 1. Note that this bar has almost vanished and is therefore not detectable in all individual transects. The new outer bar 2 is not fully grown in the north, but already serves as the outer bar in the southern sector. This leads to a major longshore difference in seaward position of the bar: the location of bar 2 is around 200 m at 3500, and near 4500 it reaches 600 m. This means that the NOM phase, discussed in the literature, has a longshore gradient: the south is further in the NOM cycle.

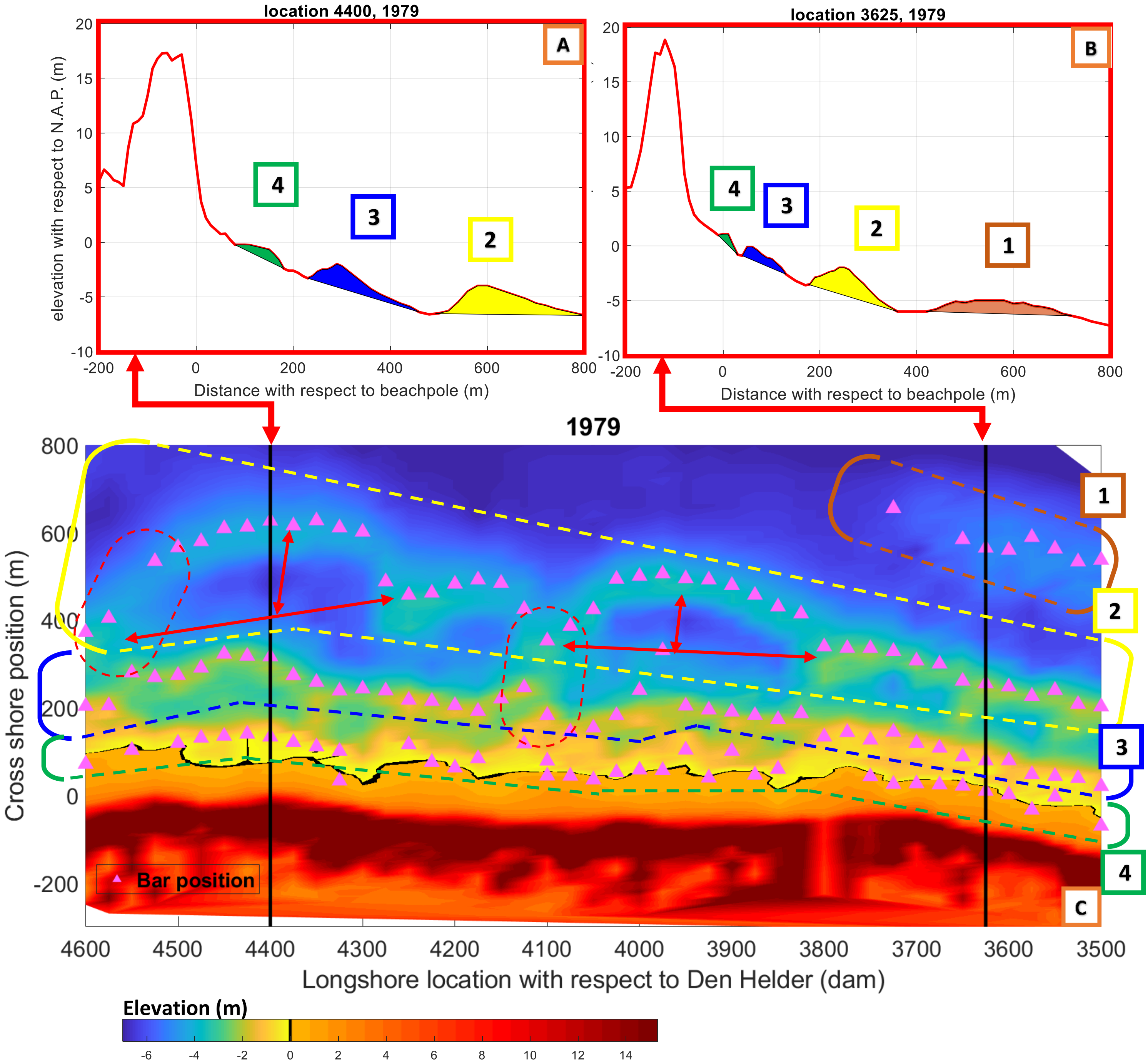


Figure 7.7 Digital Elevation Model with bars indicated. In the upper panels two example transects are enclosed.

The example used in Figure 7.7, taken from 1979, is supported by the plots of two individual transects, indicated on the map. They are taken from the southern section (location 4400) and the northern section (location 3625). Neither location is nourished yet, so they are fully comparable to each other. On both profiles an intertidal bar is present on the landward side (bar 4 on Figure 7.7). Again, however, the phase difference is clearly present. Bar 4 in the south is already a fully grown stable intertidal bar, but in the north it is only a small proto-bar residing above sea level. Bar 4 in the north completely vanished in 1980 and reappeared after 1985. Also note that bar 3 still resides in the intertidal area in the north and is already functioning as a fully submerged structure in the south.

Another important feature of the bars near Egmond is their crescentic appearance. These forms are widely present in the outer bar, with longshore wavelengths varying between 1 km and 4 km. The horns of these structures often connect to nearshore bars, especially when crescentic behaviour is more pronounced (Figure 7.7). In the middle section, between 38 and 42 km, wavelengths are often larger (2-4 km) than on either flank of the research area (1-2 km), resulting in larger cross-shore amplitudes of more than 150 m. Because of the orientation of the bar, this often leads to a break-up of the outer bar. The inner bar forms crescent patterns as well, combined with shore-attached horns. The longshore extent of these patterns is generally in the order of 1 km.

7.3.1 Summary

In this chapter, the transects created in chapter 6 were analysed in order to find bars. Including all corrections, a total of 6794 bars have been identified. The bar positions that were found seem to approximate the actual bar positions accurately. With the found positions it was possible to calculate the volume of every bar for further analysis. The results are presented in results section.

8. Results

With the methods described in the last chapter, it was possible to make a thorough analysis of the coastal system near Egmond aan Zee. Bars found in the JARKUS transects were analysed and coupled to other transects, both longshore and over time. This provides insight in the annual development of the coast, both in sector A and in sector B. The bar volumes are compared to MKL-volumes and cross-shore volumes in order to find the influence of bar volume and bar migration on total volumes. The chapter starts with a discussion of general bar behaviour with the found bars and afterwards discusses bar behaviour on a local scale. The chapter ends with an analysis of bar trends.

8.1 Cross-shore bar positions

After obtaining the exact bar locations, attempts were made to link individual bars to bars in other profiles, both in space and time. This resulted in the determination of six traceable longshore bars present in the system near Egmond in the period 1964-2013, in addition to the nourishments, which behave similar to natural bars. All bars were plotted on maps, which are enclosed in Appendix E. To summarise these results, for every year the mean was taken for all bar positions in both sector A and B, which provides insight in overall bar behaviour. In Figure 8.1 these positions are plotted.

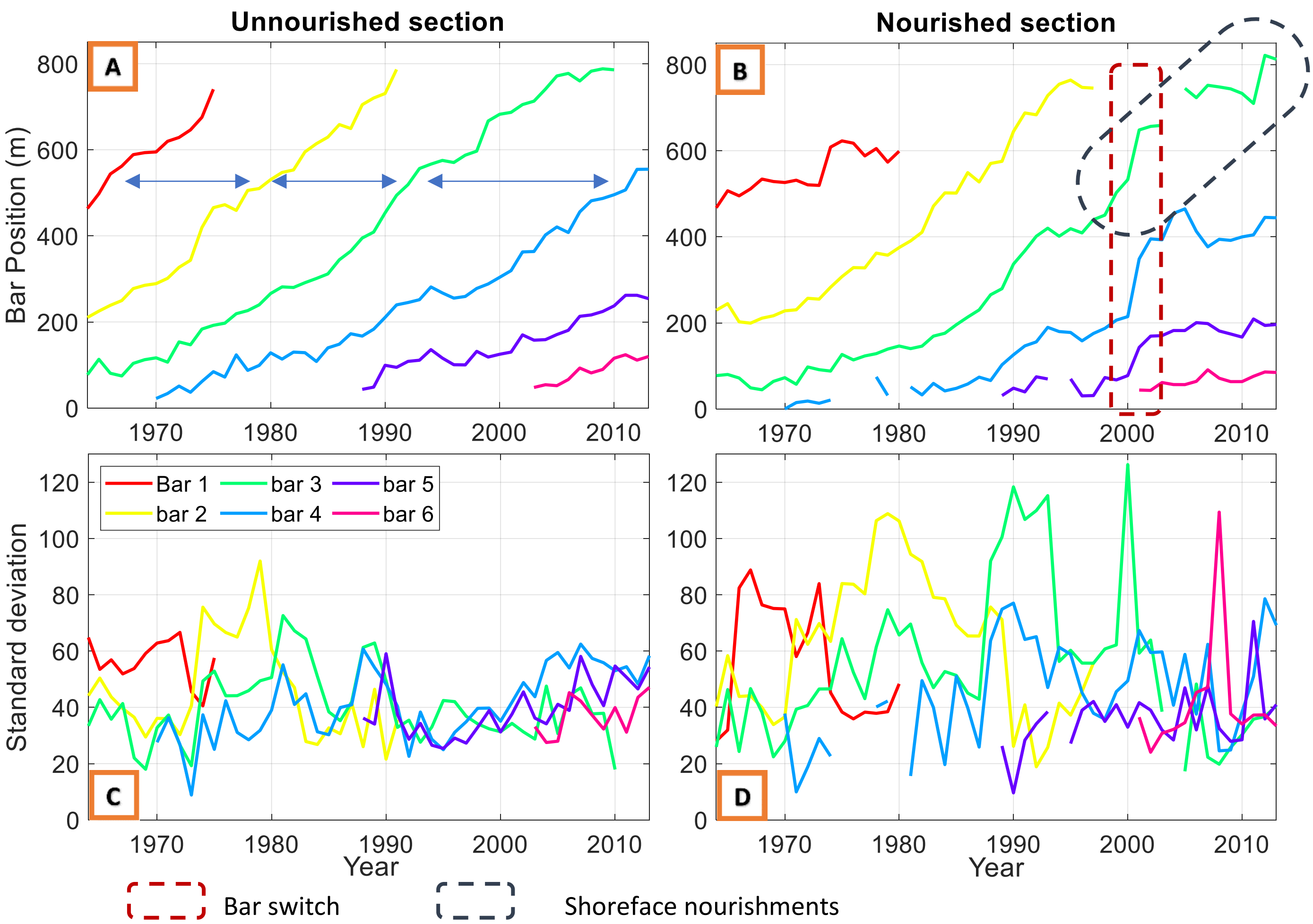


Figure 8.1 Overview of the mean positions of the bar crest during the period 1964-2013. The figure is divided into two parts, with the Unnourished section (A and C) and Nourished section(B and D). On the lower panels the standard deviation is plotted as an indicator of longshore variability of the bars. The red and blue dotted circle indicate the locations of the Bar switch episode of 2001 and the Nourishment respectively.

8.1.1 NOM cycle

In Figure 8.1, the mean cross-shore position for every bar is plotted for sector A and B. This provides insight in the development of the system near Egmond. Bars form near the shore and slowly migrate seaward and dissolve at the outer bar zone, seaward of the line 500 m. Migration rates are in the order of 10-20 m/yr, but reach maxima if the middle bar migrates offshore, after the former bar has been depleted. Although barely present, negative migration rates occur nearshore under natural circumstances during bar formation or offshore during bar decay. Onshore migration does not exceed rates larger than 10 m/yr.

From Figure 8.1, the duration of the NOM-cycle can also be determined. During the period 1964-2013, three full cycles took place, but their duration increased over time. The first two cycles have a duration of thirteen years. However, in the years 1993-1998 the migration is significantly slowed down, both in the southern sector and in the northern sector. This increases the duration towards twenty years for the third cycle.

In the lower panels of Figure 8.1, the standard deviation of the mean is plotted. The standard deviation is a measure for the longshore uniformity of the bar. Evidently, the bars in sector A are more dynamic than in sector B. This caused by the fact that bars in the north are slightly more oblique than in the south (Figure 7.7). The large peaks in the standard deviation are caused by the crescent shapes, discussed in paragraph 2.2. When these are strongly or irregularly shaped, standard deviation reaches a maximum.

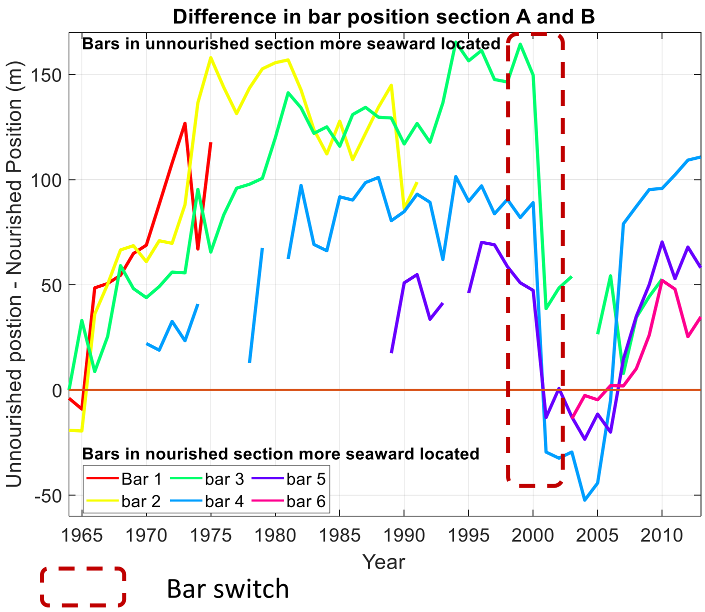


Figure 8.2 Difference in mean cross-shore position between the unnourished section and the nourished section. Positive values resemble a more seaward advanced position of bars in Sector B, while negative values indicate more seaward advanced bars in sector A.

In Figure 8.2, the mean locations for sector A and B are subtracted from each other, providing insight into cross-shore differences in bar positions between the areas. Positive values indicate more seaward advanced bar positions in the unnourished section and negative values more advanced positions in the nourished section. As expected, the southern section is generally located further offshore, due to its more advanced NOM-cycle. Also, the system in the south appears to be larger, as can be seen in Figure 8.1**.** Note the difference in maximum offshore position of bar 1 in sector A and B. Also, in Figure 8.1 a time lag in bar decay is visible: bars in the south decay earlier than their northern counterparts. During the studied period only two bars completely decayed in the study area. The time lag between complete decay in sector A and B was both times 5 to 6 years.

After 1990, nourishments were implemented in the area. Until 1999, these nourishments only took place on the beach. In this period the NOM slowed down significantly. However, this slowdown occurred in both section A and B (Figure 8.1). Therefore, the impact of these beach nourishments on the NOM cycle seems to be minimal.

Implementation of the first shoreface nourishment in 1999, however, dramatically slowed down the system in the north. The nourishment pushed the outer bar (bar 3) landward and linked up with the bar 3 in the south. This caused a major bar switch through all bars in the period 2000-2002. This bar switch is clearly visible in Figure 8.1 as a sudden seaward jump in bar position in the north. Due to the switch, bars in the northern section were more seaward located for a short period of five years. The nourishment prevented the inner bars from migrating offshore. Meanwhile, the southern section continued to migrate. Although slowed down, migration rates were sufficient to restore the more advanced position in the NOM-cycle within 6 years.

8.1.2 Bar switches

With the help of bar maps it was possible to assess bar switching. The coast near Egmond appears to be highly dynamic, especially in the intertidal zone. Bars constantly appear and disappear or interact with the inner or subtidal bars. Due to the longshore phase differences between north and south, in combination with the large-scale crescent shapes, the outer bar can easily link up with the middle bar. The middle crescent shape is often relatively large and unstable, resulting in multiple of these minor

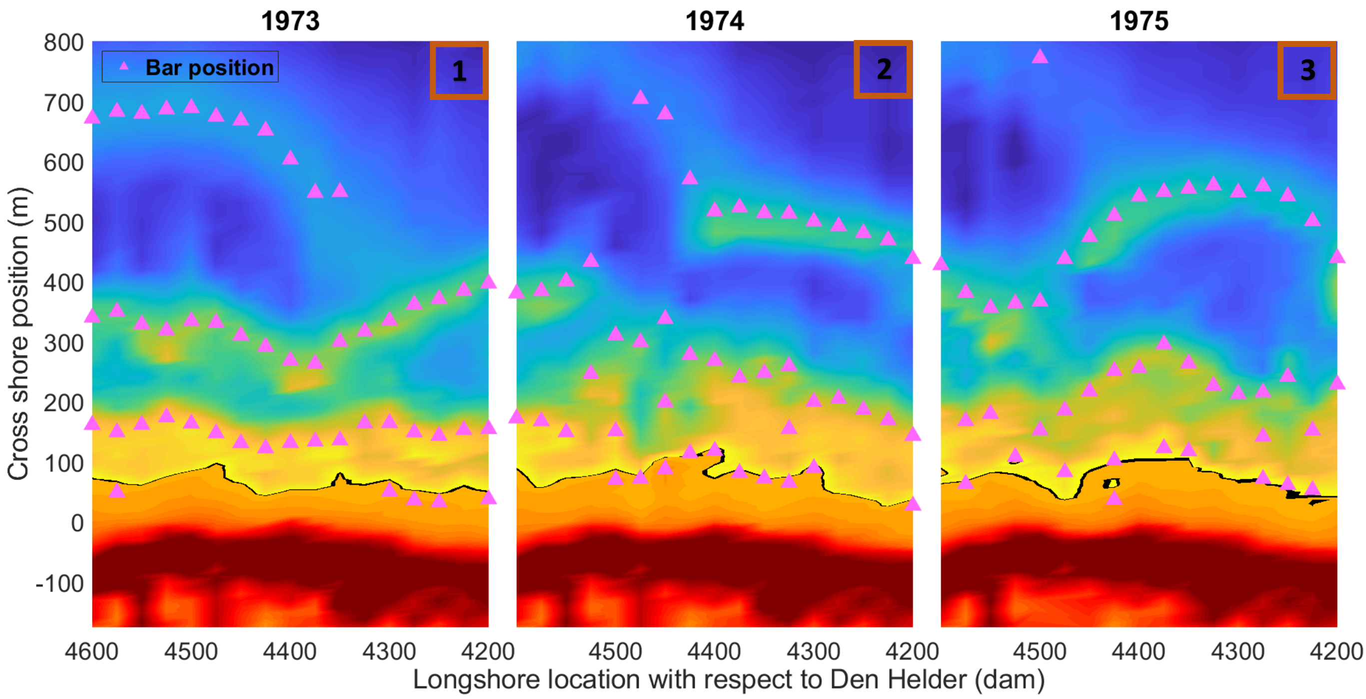


Figure 8.3 Three snapshots showing the bar switch episode of 1974. The decaying outer bar was connected to the new middle bar, causing the break-up of the middle bar. In contrast to the bar switch in 2001, this switch was temporarily and the situation recovered in 1975 (panel 3).

bar switches. This occurred on both flanks between 4200 and 4400 in the south (year 1969 and 1974) and between 3800 and 4000 in the north (year 1964, 1973, 1984, and 1987-1989). These switches were all temporal and affected the system in a minor way, so all bars kept their originally assigned number. An example is plotted in Figure 8.3. The outer bar in panel 1 connects to the middle bar, which causes a break-up of the bar near 4400. This is restored in 1975 (Figure 8.3).

8.2 Nourished vs. unnourished on a local scale

To study the behaviour of a nourishment on a local scale, location 3850 was used as an example for the complete area. This location in front of the town Egmond has been extensively nourished (Figure 5.4): between 1990 and 2011, 13 nourishments took place on this particular spot. In order to compare the nourished site with the natural site, a location from sector B was also chosen, namely location 4400. This location did not receive any nourishments and is located in the heart of the unnourished area.

8.2.1 Pre-nourishment period

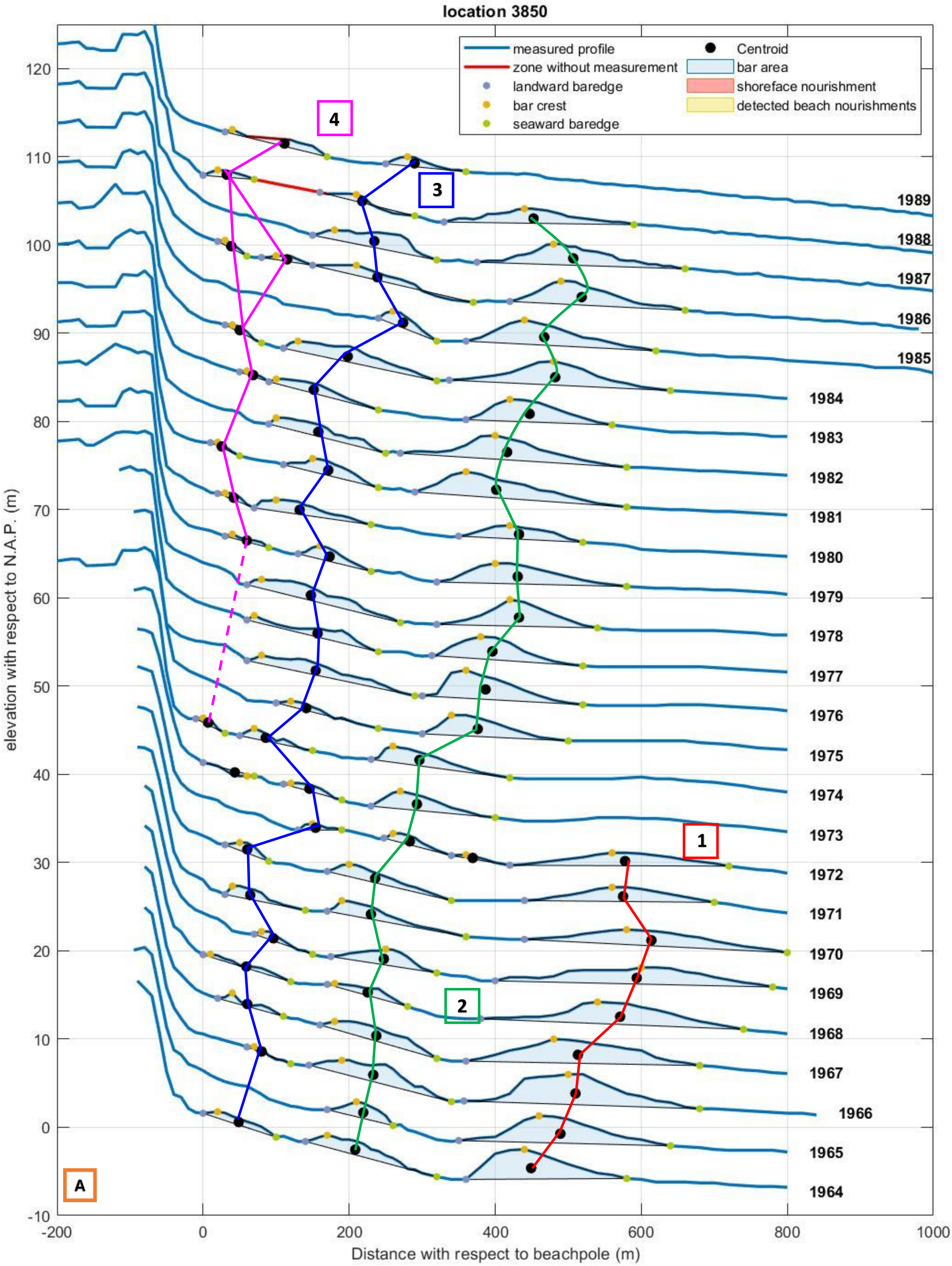
In Figure 8.4 an overview is given of all transects at locations 3850 and 4400. With the help of the bar maps, enclosed in Appendix E, the position of the bars could be tracked through time. In the pre-nourishment period, four individual bars could be isolated, which were present in both transects. Before nourishments started in 1990, both coastal sections were more or less comparable to each other. Although neither coastal system was altered yet, differences were present as well. At first sight, one can see that the system in the south is significantly larger in the period before 1990. Bar 2 does not reach further than 500 m offshore at location 3850, while in the south this line is crossed in 1978. The way the bars decay is also remarkably different: at location 4400 the bar decays in seaward direction, while in the north it decays landward. Note also that new bars form first in the south and later in the north. The southern section is permanently in a more advanced stage of the bar cycle.

8.2.2 Nourishment period

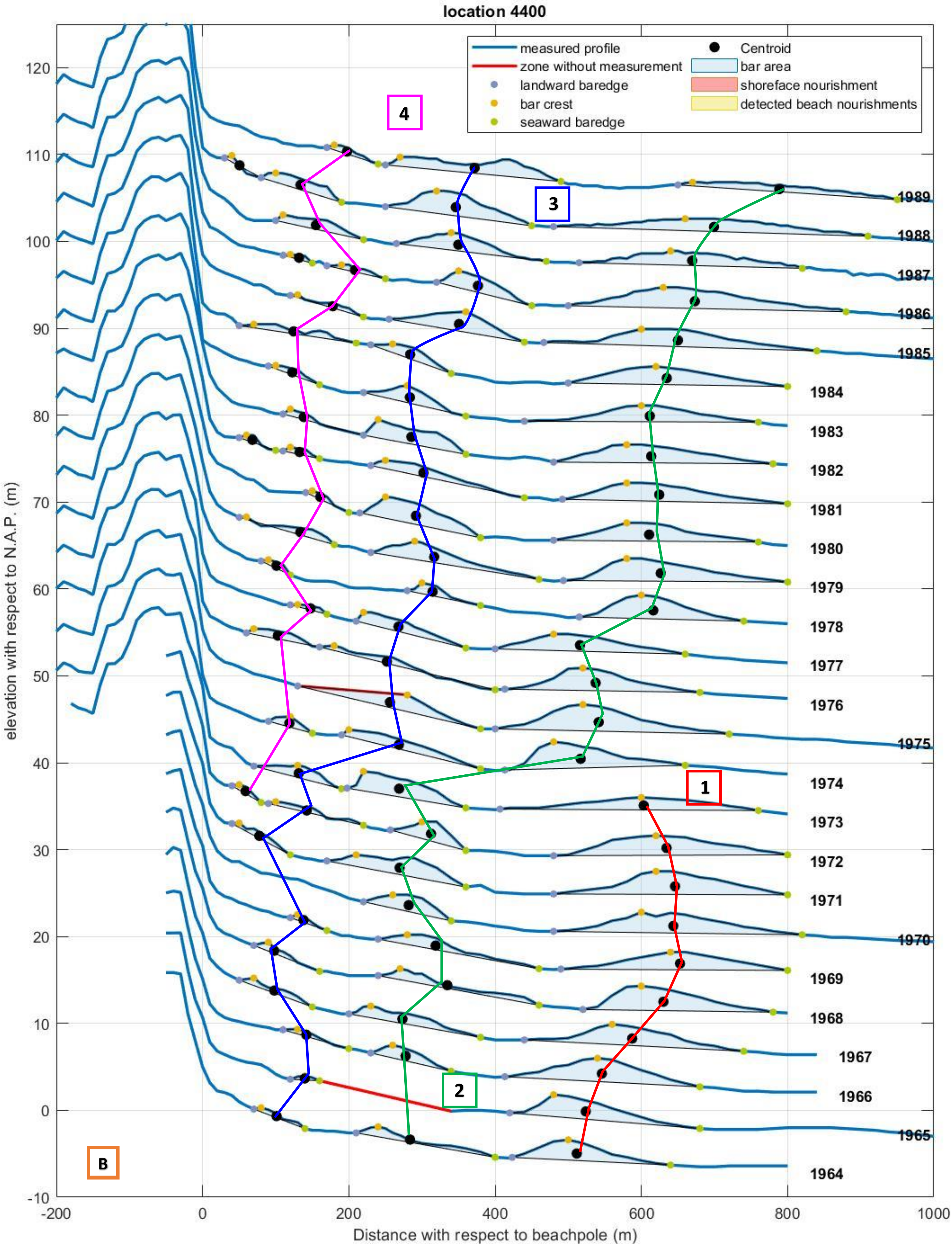
Implementation of beach nourishments after 1990 locally affected bar behaviour, as can be seen in Figure 8.4**.** Cross-shore migration at location 3850 almost ceased after 1990, while in the south it continued. When the first nourishment was placed in 1999, this nourishment pushed the outer bar landward, leading to a major bar switch, discussed in paragraph 8.1.1. All bars landward of the nourishment were pushed shoreward. The nourishment acted like a new outer bar but was only present for four years. Meanwhile, bar 4 continued growing. The moment the nourishment disappeared and bar 4 was ready to replace it, a new nourishment was placed, leading to enormous bar volumes. The nourishment bar slowly eroded, but increased again in 2011 after implementation of a third nourishment.

Meanwhile, in the south, the behaviour of transect 4400 remained natural. However, here, the outer bar reached further than before, even residing seaward of 800 m. Finally, note the large trough between the outer and the inner bar present in the south, after nourishing happened in the north.

Figure 8.4 Total overview of measured transects with bars of location 4400 and 3850. The panels are divided into a pre-nourishment part (1964-1989) and an after-nourishment part (1990-2013): A) pre-nourishment period at location 3850 B) pre-nourishment period at location 4400 C) Development of profile 3850 after start nourishment period. D) Development of profile 3850 after start nourishment period.



location 3850
measured profile
zone without measurement
landward baredge
bar crest
seaward baredge
Centroid
bar area
shoreface nourishment
detected beach nourishments
1
2
3
4
A
1989
1988
1987
1986
1985
1984
1983
1982
1981
1980
1979
1978
1977
1976
1975
1974
1973
1972
1971
1970
1969
1968
1967
1966
1965
1964
elevation with respect to N.A.P. (m)
Distance with respect to beachpole (m)
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-200
0
200
400
600
800
1000



location 4400
measured profile
zone without measurement
landward baredge
bar crest
seaward baredge
Centroid
bar area
shoreface nourishment
detected beach nourishments
1
2
3
4
B
1989
1988
1987
1986
1985
1984
1983
1982
1981
1980
1979
1978
1977
1976
1975
1974
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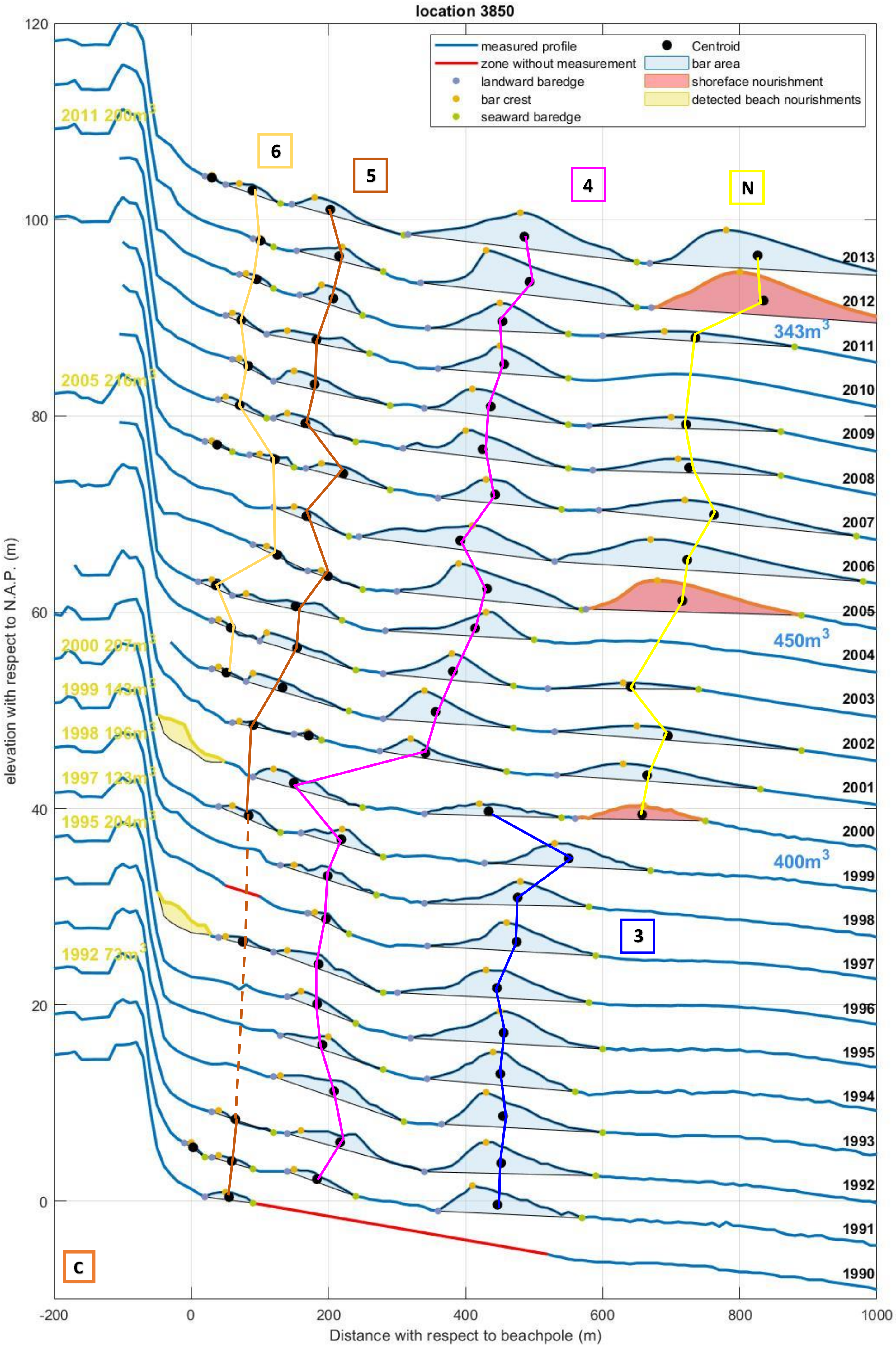
1964
elevation with respect to N.A.P. (m)
Distance with respect to beachpole (m)



location 3850
measured profile
zone without measurement
landward baredge
bar crest
seaward baredge
Centroid
bar area
shoreface nourishment
detected beach nourishments
6
5
4
N
3
C
2011 200m3
2005 216m3
2000 207m3
1999 143m3
1998 196m3
1997 123m3
1995 204m3
1992 73m3
343m3
450m3
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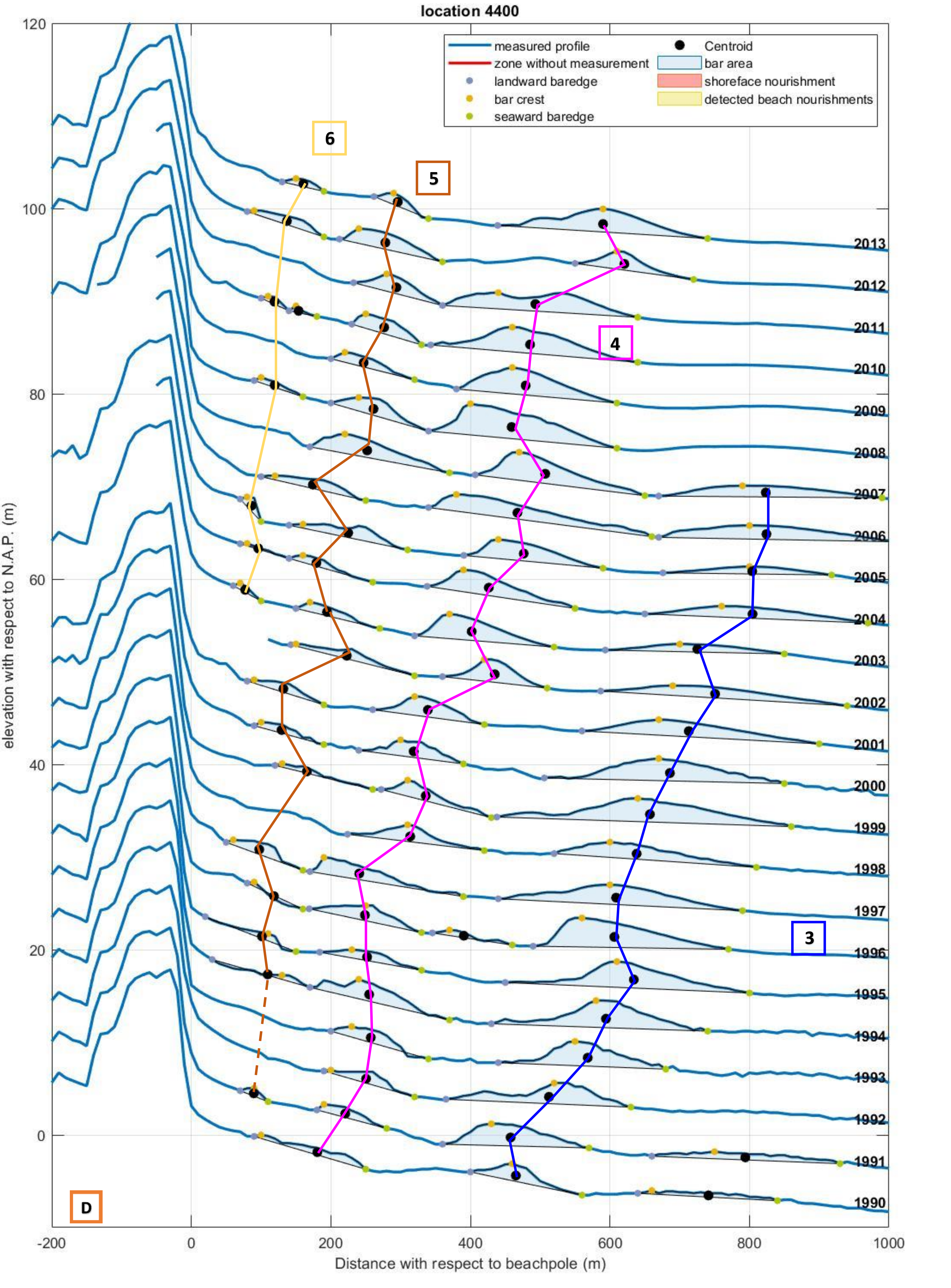
1993
1992
1991
1990
elevation with respect to N.A.P. (m)
Distance with respect to beachpole (m)



location 4400
measured profile
zone without measurement
landward baredge
bar crest
seaward baredge
Centroid
bar area
shoreface nourishment
detected beach nourishments
6
5
4
3
D
2013
2012
2011
2010
2009
2008
2007
2006
2005
2004
2003
2002
2001
2000
1999
1998
1997
1996
1995
1994
1993
1992
1991
1990
elevation with respect to N.A.P. (m)
Distance with respect to beachpole (m)
120
100
80
60
40
20
0
-200
0
200
400
600
800
1000

8.2.3 Beach nourishments

As already mentioned, beach nourishments appeared to have only a minor effect on bar behaviour and volumes. Nevertheless, in order to evaluate beach nourishments, all observations of beach nourishments at location 3825 are plotted in Figure 8.5. The first beach nourishment was carried out in May 1990, a month after measurement of the beach profile. This means that this intervention was visible for the first time in the data of 1991. However, since the profile of 1990 is incomplete (Figure 6.3) a fair comparison between nourished and unnourished sections cannot be made. Nevertheless, a seaward progradation of the dune foot is noticeable. A second and a third beach nourishment, carried out in May and November 1992, were visible in 1993. Again, the profile lacks data, but it seems that the nourished sand filled up the intertidal zone. However, it becomes clear in 1995 that beach nourishments actually do raise the beach, since in 1994 no sand was added, resulting in strong erosion to the coast. The same year a new nourishment was implemented, in order to undo the erosion. In the years 1996, 1997 and 1998 the beach was nourished annually in an attempt to fill up the trough between the beach and intertidal bar.

In 1999, the first shoreface nourishment was placed. The newly added sand formed a new bar, which pushed the former outer bar landward. At the same time a beach nourishment was placed, which pushed the intertidal bar in seaward direction. However, since there was no space for the intertidal bar to migrate seaward, the bar formed a steep terrace, indicated in profile 2000. Such terraces also form under natural circumstances, but are more frequently present after 1990.

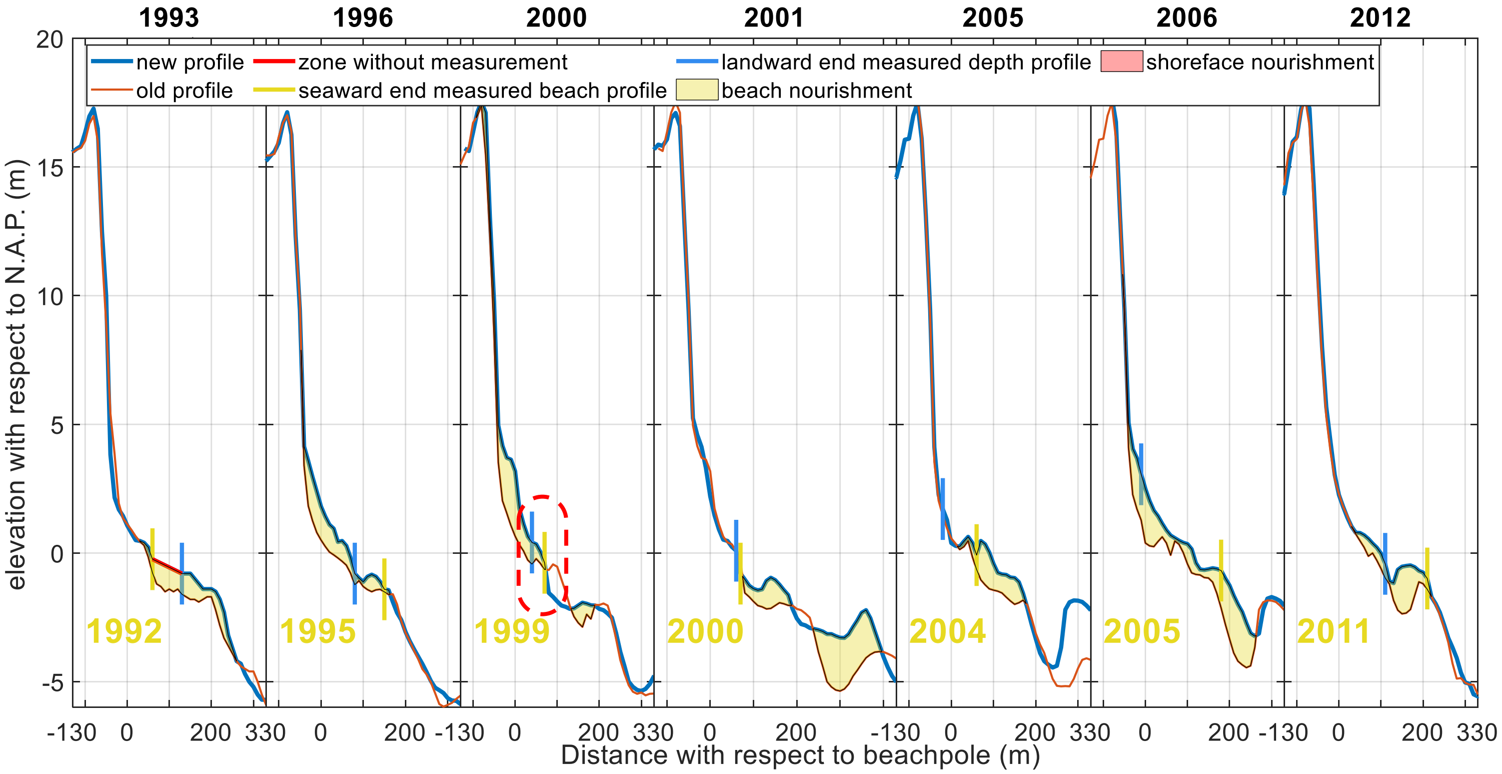


Figure 8.5 Overview of observations of beach nourishments on location 3825. The yellow number on the graph, represents the year of nourishing.

After the two large nourishments of 1999, a new one followed in 2000, filling up the trough between the beach and inner bar (profile 2001). After this nourishment, there was a period without construction work, with subsequent erosion as a consequence. This period ended in 2005, when a large new shoreface nourishment was implemented. Again, the landward bar was pushed back to the shore, to form a steep trough between the intertidal and subtidal part of the profile. Meanwhile, the beach was nourished, raising up the whole beach and filling the steep trough. Following 2006, the system was able to sustain without any nourishment or severe erosion. A newly formed bar in 2007 welded unto the intertidal part filling up the trough. The last beach nourishment of 2011 is barely visible on the JARKUS plots. Ironically, the effect of beach nourishments becomes most visible when they are absent and the beach erodes.

8.3 Bar volume

Beside the exact location, bar volumes were also calculated for every transect. These cumulative bar volumes per location are plotted in time stacks, presented in Figure 8.6. Note that the shoreface nourishments are visible in JARKUS data as 'regular' bars, thereby locally raising the total bar volume. The red colours in the upper part of Figure 8.6, therefore, reveal the presence of the nourishments. However, the increase of the total bar volume does not necessarily mean that a bar system is growing.

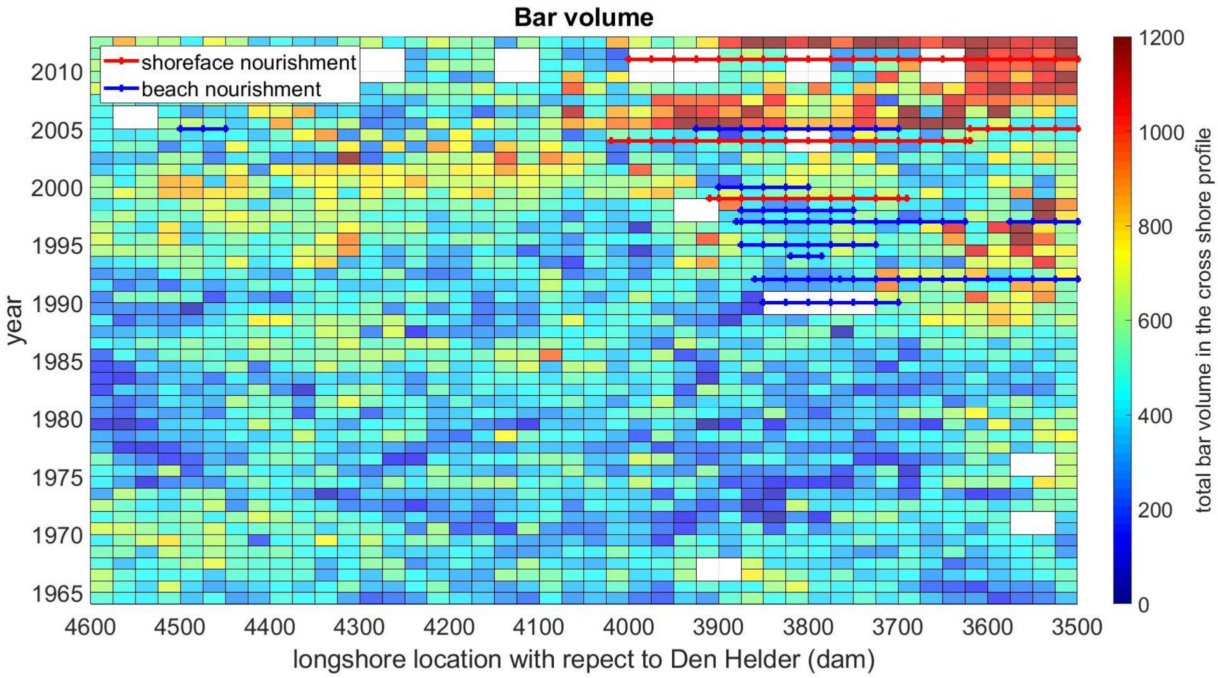


Figure 8.6 Time stacks of cumulative bar volume in cubic meter per transect.

To study the influence of nourishing on bar volume, for every location an overview has been created with bar volumes of each bar over time. Figure 8.7 consists of two of these overviews. Each of those panels consist of two sub-panels. In the upper panel, bar volume of each location is plotted over time. The grey shape in the background represents the sum of bar volumes for that specific year. In the lower panel the corresponding bar positions are plotted to gain insight in the position of each bar. Clearly visible in both panels is the relation between cross-shore position and bar volume. If a bar forms nearshore, volumes are in the order of 10-30 m^3/m. When a bar becomes subtidal, these volumes raise towards 50-400 m^3/m. When a bar continues to migrate seaward and becomes the outer bar, the volume increases further up to 750 m^3/m. However, if a bar is depleting, the volume decreases again to zero. Overall, the outer bar covers 62% of the total bar volume.

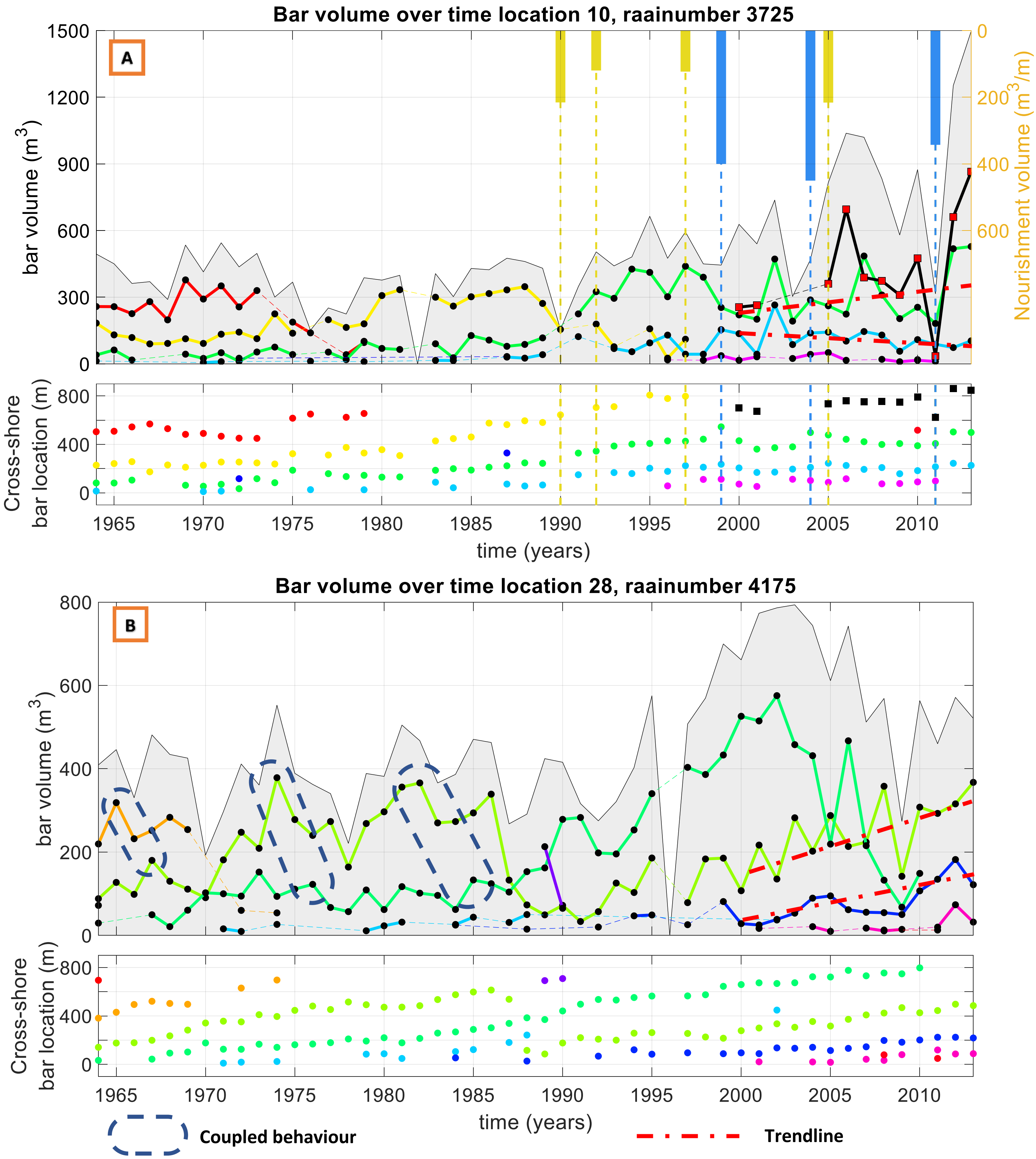


Figure 8.7 Overview of the development of bar volume on location 3725 and 4175, representing the nourished and unnourished section. In the upper panel of each sub figure the volume per bar is plotted over time. The gray background represents the cumulative bar volume and black markers represent nourishments. In the lower panel of each subfigure, cross-shore locations of every bar is plotted.

When studying Figure 8.7, a strong coupling is visible between bars. The volume of the middle bar is strongly controlled by the volume of the outer bar. Nearly all peaks, both north and south, are followed by a maximum in the middle bar within the same year or with a delay of 1 to 3 years. The same trends are present at other locations.

In the upper panel of Figure 8.7, the shoreface nourishment of 1999 becomes visible in 2000. As already discussed, the nourishment acts as a new outer bar with enormous proportions. The year after implementation, these volumes often reach values between 750 and 850 m^3/m, thereby raising the total bar volume, as stated above. Again, notice the clear coupling between the nourishment bar and the former outer bar. However, besides a sudden peak, other bar volumes are barely affected by implementation of nourishment. The middle bar is growing slower than before the nourishment and the inner bar is even decreasing in size. When comparing this to the bar volumes in the south, here, bars continue growing.

In order to place the remarks in the last paragraph into a larger context, Figure 8.8 was created. This figure is similar to Figure 8.1, but here the mean volumes per bar are plotted. From this figure the difference between a nourished and an unnourished coast in terms of volumes becomes clear. Before 1990, the bars display highly comparable behaviour, except for a time lag between the sections of several years. Noteworthy are the relatively high maximum bar volumes in sector A before 1990. Peaks in the south are more flattened, but last longer than in the north. After implementation of the beach nourishments following 1990, the behaviour in the studied section does not change.

The first major alteration in volume occurs after the first nourishment in 1999. Due to a bar switch, bar 4 suddenly becomes the middle bar and increases in volume, reaching a volume which normally belongs to the outer bar. Meanwhile, the southern sector continues to growth, conform NOM behaviour. However, the connection of bar 3 with the shoreface nourishment of 1999 enlarged the third cycle with a larger and longer peak as a result. Nevertheless, the overall behaviour of section B is fully in line with a normal NOM cycle. Nourishing in section A stopped this natural growth of the bar after 2006 and even led to a decrease of the inner bar volumes.

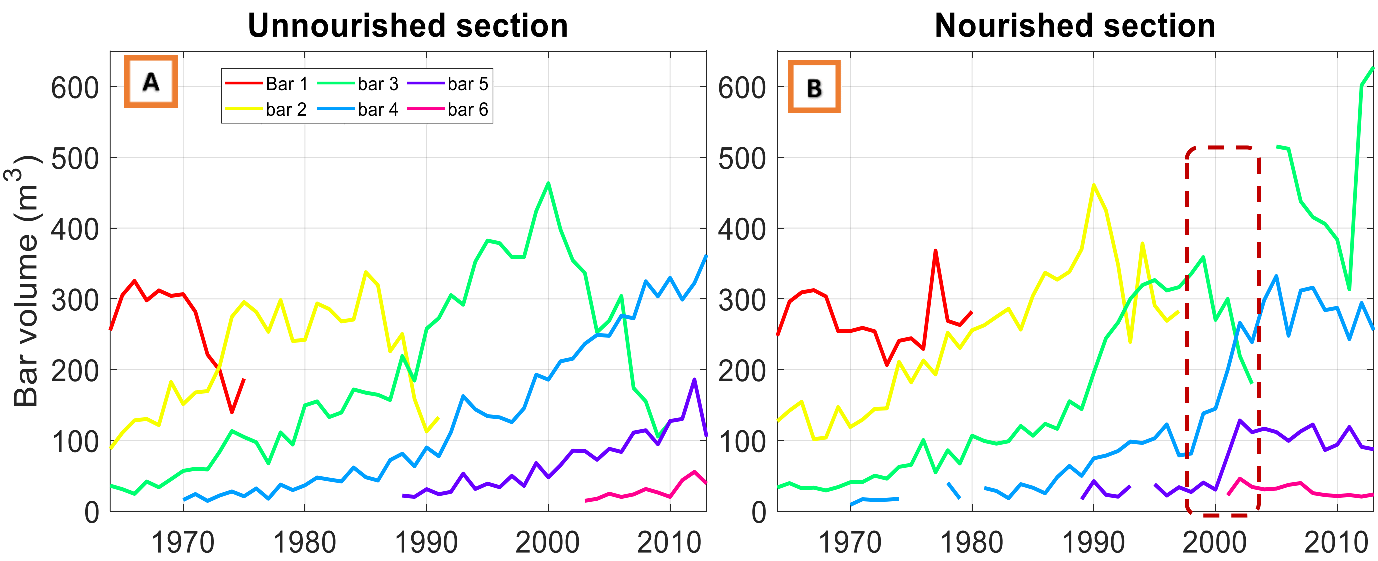


Figure 8.8 Overview of bar volume per bar over the studied period. The circle indicates the bar switch of 2001.

8.4 Cross-shore volumes

In order to compare bar volume changes in the nearshore zone with general erosion/accretion trends, an analysis of total volumes was made. To that end, the coastal section was longshore divided into 11 sections of 1 km and cross-shore divided into 9 sections with different sizes. In Appendix D.1 the plots for every kilometer are enclosed. Here, two examples are discussed. In Figure 8.10 the trends per section are plotted. In the upper panel, the natural volume trends are plotted until 1990. The middle panel depicts the situation after the start of nourishment activities, beginning in 1990, and the third panel is the difference between the two trends.

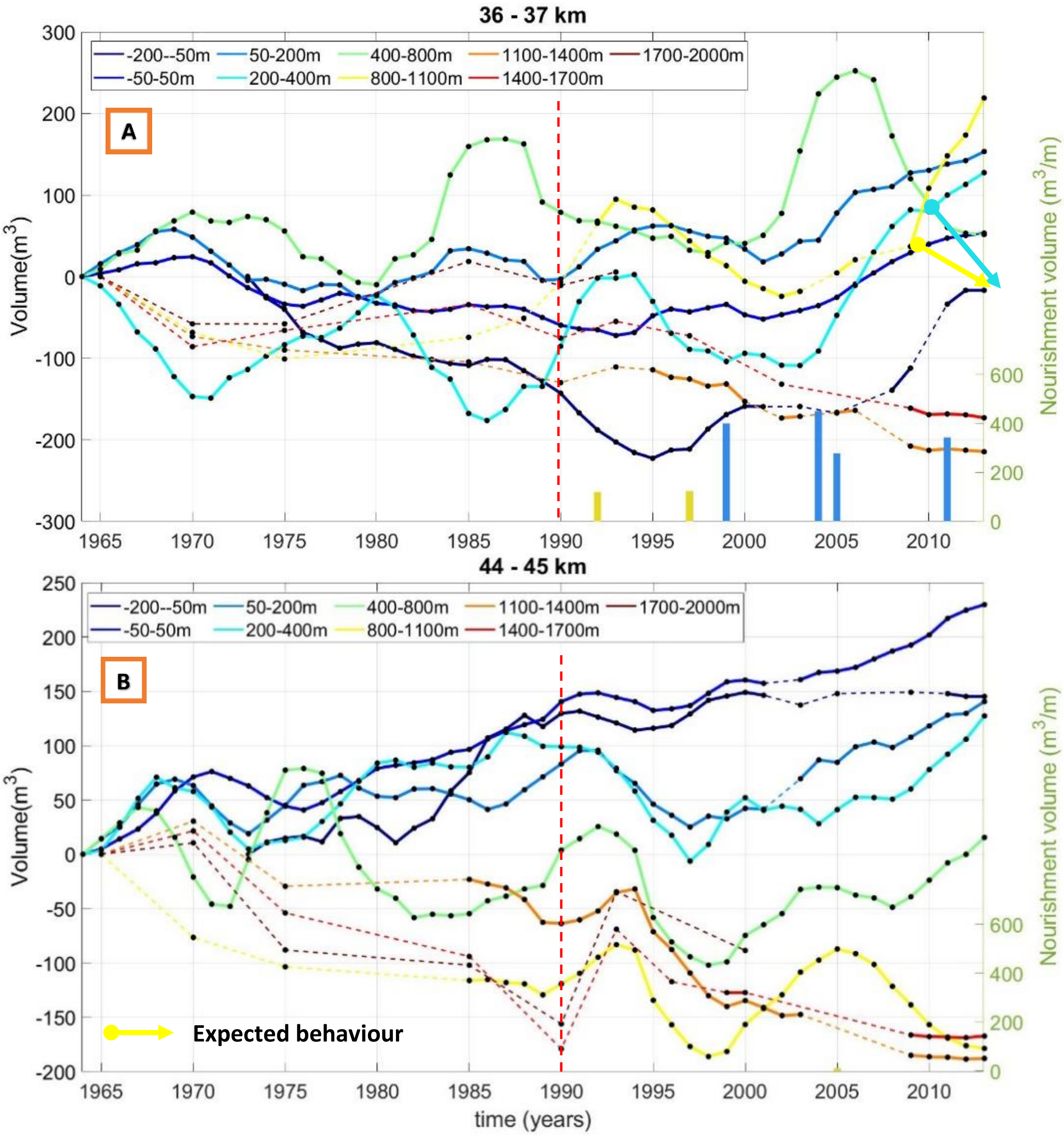


Figure 8.9 Volume trends over the study period for the cross-shore bins, indicated in Figure 6.7. Panel A) represents 5 transects from 36-37 (Nourished section) and Panel B) represents volume trends of 5 transects from 44-45 (Unnourished section). The added arrows indicate expected bar behaviour, based on the previous trends.

First note that trendlines may lead to misinterpretation of sedimentation and volume trends, because of oscillating behaviour of some of the cross-shore sections. This oscillating behaviour, mainly occurring in the sections 200-400 m and 400-800 m, is caused by bar migration. For example, the section 500-800 m is highly negative according to the middle panel of Figure 8.10, but when studying Figure 8.9, it appears that a positive peak is present right after 1990, which leads to an overestimation of the trend. Second, note that the range of the individual profiles is another source of error. Before 1990, only a small amount of transects reached further than 800 m, which makes the trends seaward of 800 m before 1990 less reliable. For this reason, the cross-shore interval 1700-2000 m was even skipped.

8.5 Erosion and volume trends

When studying Figure 8.10, it is clear why nourishments were necessary near Egmond: while most nearshore sections show accretion, in the north they are eroding. Especially in sector A, the need for maintenance was large, since constant erosion took place in the dunes (Figure 8.9A). In contrast, at other locations, such as 44-45 km (Figure 8.9B), dunes accreted over time. In general, accretion trends in the south were higher than in the north. After implementation of the nourishments in 1990, the erosive trends were reversed and the dunes started to growth in the north with rates in the order of 2-6 m^3/m per year. It becomes clear from the lower panel of Figure 8.10 that the nourishments sorted effect. The location where trends changed the most is the dune row between 35-38 km. Dunes in the south also continued growing after 1990. The middle part, between 39-43 km, showed an especially strong growing trend.

The beach area (-50 m to 50 m) appeared to be less dynamic than the dunes and displayed clear erosion trends in the north. Once again, in the rest of the sections, the opposite trend occurred and a stable, almost linear growth was present. The nourishments resulted in reversed trends in the north, as visible in Figure 8.10C. The large amount of sand nourishment led to a strong local increase between 37-38 km. Right after implementation of the first nourishment, the volume starts to growth. In the south, the trend after 1990 is one of increased accretion.

The intertidal zone (50-200 m) showed comparable behaviour to the beach zone: despite an initial negative peak in 1970 at some locations, along the whole coastal strip the intertidal zone was constantly growing. Minor oscillating behaviour was present. Also here, the growth is strongest in the northern part of the nourished section, influenced by nourishments.

The three middle sections (especially 200-400 m and 400-800 m) are the sections where the middle and outer bar reside most of the time and for that reason, they strongly reflect overall bar behaviour. The erosion trends in the cross-shore section 800-1100 m seem to alter into oscillating trends (Figure 8.9). An interesting observation concerns this oscillating behaviour of the volume. First of all, the shoreface nourishments bring all oscillating cross-shore volumes to a new maximum, which they never reached before. Secondly, they then overrule the sequence. When a new nourishment is placed, the sector 400-800 m starts to growth especially, irrespective of the bar behaviour or the expected volume trend. Two examples are marked with an arrow in the upper panel of Figure 8.9. The oscillating movement of the different sections stays more or less intact in the southern sector. However, note that the section between 400-800 m is slightly eroding there: after a maximum, reached in 1992, the following is significantly lower, a trend that is also visible in other graphs from the unnourished section (Appendix D.1 and Appendix D.2).

The most seaward sections appeared to be highly erosive throughout the whole study period. Longshore, there are small differences, but since there is only a limited amount of data available, it is dangerous to draw conclusions, especially regarding the period before 1990. After 1990, more data points are available and the behaviour of the sections appears to be slightly oscillating. As can be seen in the lower panel of Figure 8.9 the behaviour of the sections between 800-2000 is strongly coupled. However, the downward trend is still present, but slows down over time. In all longshore locations after 2009, the behaviour of the sections 1100-1700 m is slightly asymptotic Figure 8.9.

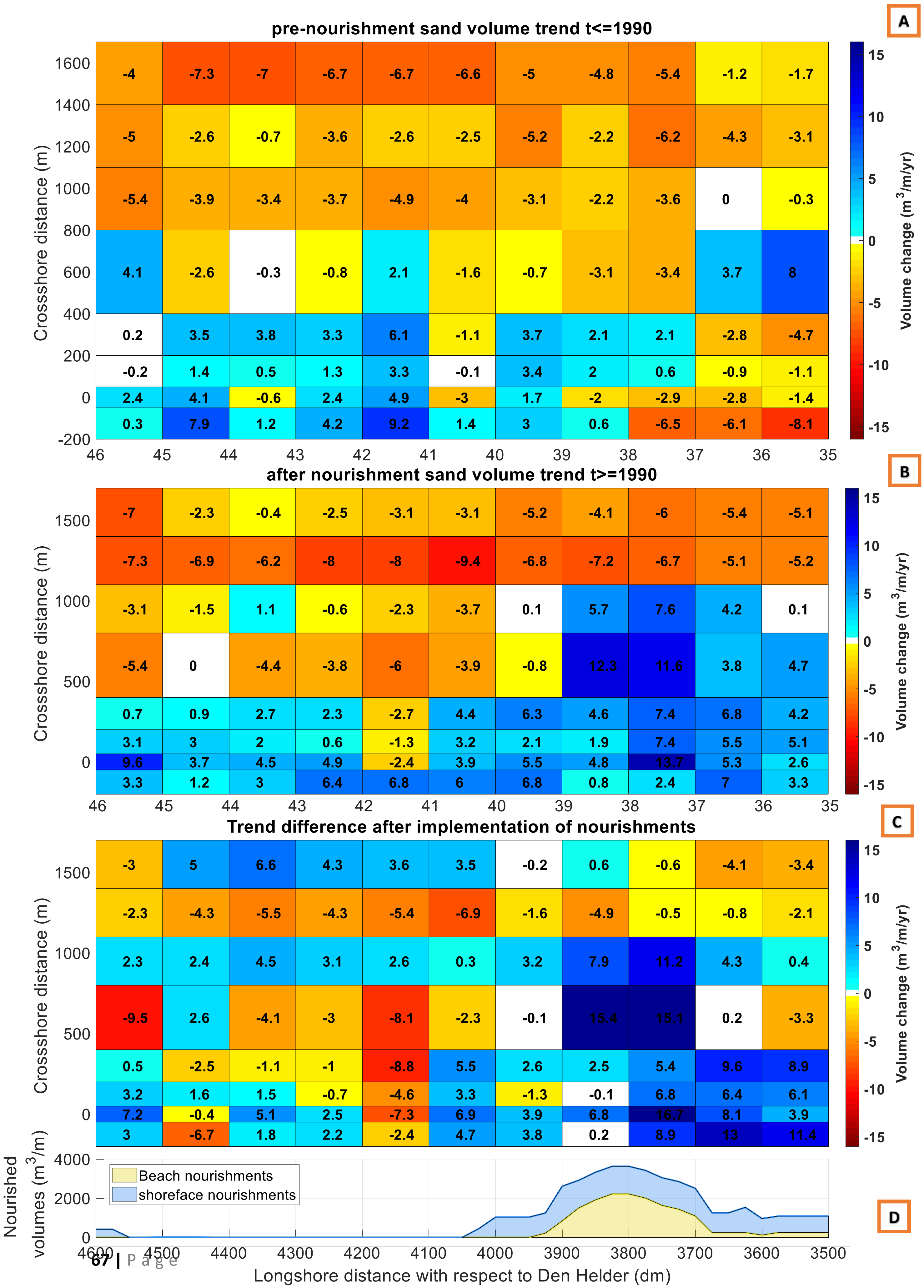

A
pre-nourishment sand volume trend t<=1990
-4 -7.3 -7 -6.7 -6.7 -6.6 -5 -4.8 -5.4 -1.2 -1.7
-5 -2.6 -0.7 -3.6 -2.6 -2.5 -5.2 -2.2 -6.2 -4.3 -3.1
-5.4 -3.9 -3.4 -3.7 -4.9 -4 -3.1 -2.2 -3.6 0 -0.3
4.1 -2.6 -0.3 -0.8 2.1 -1.6 -0.7 -3.1 -3.4 3.7 8
0.2 3.5 3.8 3.3 6.1 -1.1 3.7 2.1 2.1 -2.8 -4.7
-0.2 1.4 0.5 1.3 3.3 -0.1 3.4 2 0.6 -0.9 -1.1
2.4 4.1 -0.6 2.4 4.9 -3 1.7 -2 -2.9 -2.8 -1.4
0.3 7.9 1.2 4.2 9.2 1.4 3 0.6 -6.5 -6.1 -8.1
Crossshore distance (m)
Volume change (m³/m/yr)
B
after nourishment sand volume trend t>=1990
-7 -2.3 -0.4 -2.5 -3.1 -3.1 -5.2 -4.1 -6 -5.4 -5.1
-7.3 -6.9 -6.2 -8 -8 -9.4 -6.8 -7.2 -6.7 -5.1 -5.2
-3.1 -1.5 1.1 -0.6 -2.3 -3.7 0.1 5.7 7.6 4.2 0.1
-5.4 0 -4.4 -3.8 -6 -3.9 -0.8 12.3 11.6 3.8 4.7
0.7 0.9 2.7 2.3 -2.7 4.4 6.3 4.6 7.4 6.8 4.2
3.1 3 2 0.6 -1.3 3.2 2.1 1.9 7.4 5.5 5.1
9.6 3.7 4.5 4.9 -2.4 3.9 5.5 4.8 13.7 5.3 2.6
3.3 1.2 3 6.4 6.8 6 6.8 0.8 2.4 7 3.3
Crossshore distance (m)
Volume change (m³/m/yr)
C
Trend difference after implementation of nourishments
-3 5 6.6 4.3 3.6 3.5 -0.2 0.6 -0.6 -4.1 -3.4
-2.3 -4.3 -5.5 -4.3 -5.4 -6.9 -1.6 -4.9 -0.5 -0.8 -2.1
2.3 2.4 4.5 3.1 2.6 0.3 3.2 7.9 11.2 4.3 0.4
-9.5 2.6 -4.1 -3 -8.1 -2.3 -0.1 15.4 15.1 0.2 -3.3
0.5 -2.5 -1.1 -1 -8.8 5.5 2.6 2.5 5.4 9.6 8.9
3.2 1.6 1.5 -0.7 -4.6 3.3 -1.3 -0.1 6.8 6.4 6.1
7.2 -0.4 5.1 2.5 -7.3 6.9 3.9 6.8 16.7 8.1 3.9
3 -6.7 1.8 2.2 -2.4 4.7 3.8 0.2 8.9 13 11.4
Crossshore distance (m)
Volume change (m³/m/yr)
D
Nourished volumes (m³/m)
Beach nourishments
shoreface nourishments
Longshore distance with respect to Den Helder (dm)

Figure 8.10 Planview Erosion/sedimentation for every cross-shore section trends per kilometer. A) Old trends (1964-1989) B) Trend since implementation of nourishment (1990-2013) C) Difference in sedimentation/erosion trend after implementation of nourishments (new trend-old trend) D) Cumulative amount of nourished material.

In conclusion, in the north, the trends changed from erosion into accretion after 1990. As can be seen clearly in Figure 8.10, the location where the volume increased the most is in between 37 and 39 km, which is exactly the position where most nourishing took place. On the flank of the nourishment area, between 40 and 41 km, enhanced erosion is present. This may be a result of nourishing. The nearshore volume of the southern sections was increasing throughout the whole period. The largest longshore contrast is present in the section between 500 to 800 m. A large volume increase of the nourished coast balances a negative trend in the south. The lower shoreface was erosive during the whole period, regardless of the location. Nevertheless, this erosion seems to slow down.

8.6 Momentary Coast Line

With the help of MorphAn, MKL positions ('Momentane KustLijn' or 'Momentary Coast Line') along the coastal strip near Egmond could be calculated for the period 1965-2015. With the results, time stacks could be created of MKL positions near Egmond, which are presented in Figure 8.11. In this figure, for every profile, the MKL position is plotted as a Z-value for every year and placed in an interpolated grid. The result provides insight into the state of the coast near Egmond during the past decades. In the studied area, significant differences are present. The most northern part, between 35 and 36 km, seems to behave independently from the rest of the studied coast. The blue colours indicate the low MKL position of this location. Although the southern part seems to interact with the rest of the area, here the coast is significantly better preserved than in the middle section, where green and yellow dominate the spectrum.

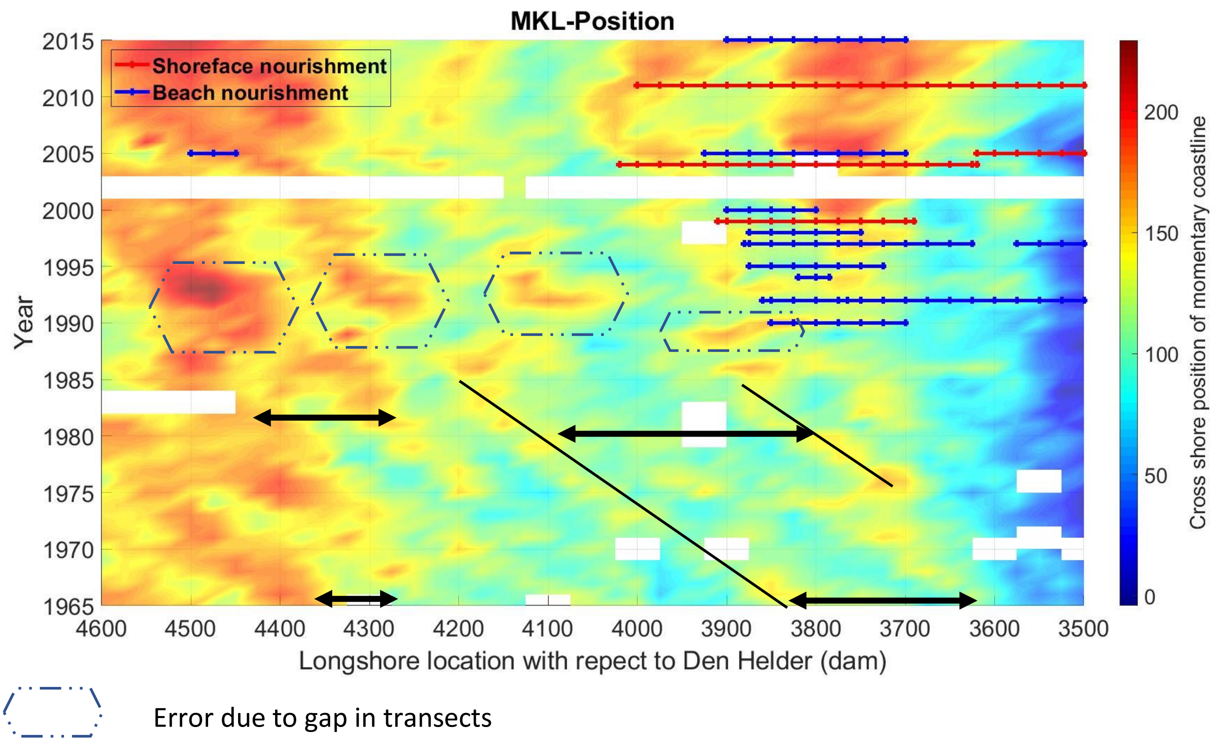


Figure 8.11 Time stacks of MKL-positions, with respect to R.S.P. (m). The red plumes around 1990, indicated with a circle, can be seen as error, caused by data gaps, discussed in section 6.4

From the MKL time stacks, it becomes immediately clear why nourishing in the southern part of the research area was not necessary. South of 4300, mean MKL positions exceed 150 m, while north of Egmond (at 3800), the mean until 1990 is 85 m. Moreover, MKL positions in the south move seaward naturally. It is important to mention that the time gaps between the two type of measurements (discussed in chapter 6) may lead to wrong estimations. This accounts especially for the red bulbs present in the period 1986-1994, outlined in Figure 8.11. All these bulbs refer to profiles containing an extremely long gap between the dry and wet transects and are therefore not useful for this study.

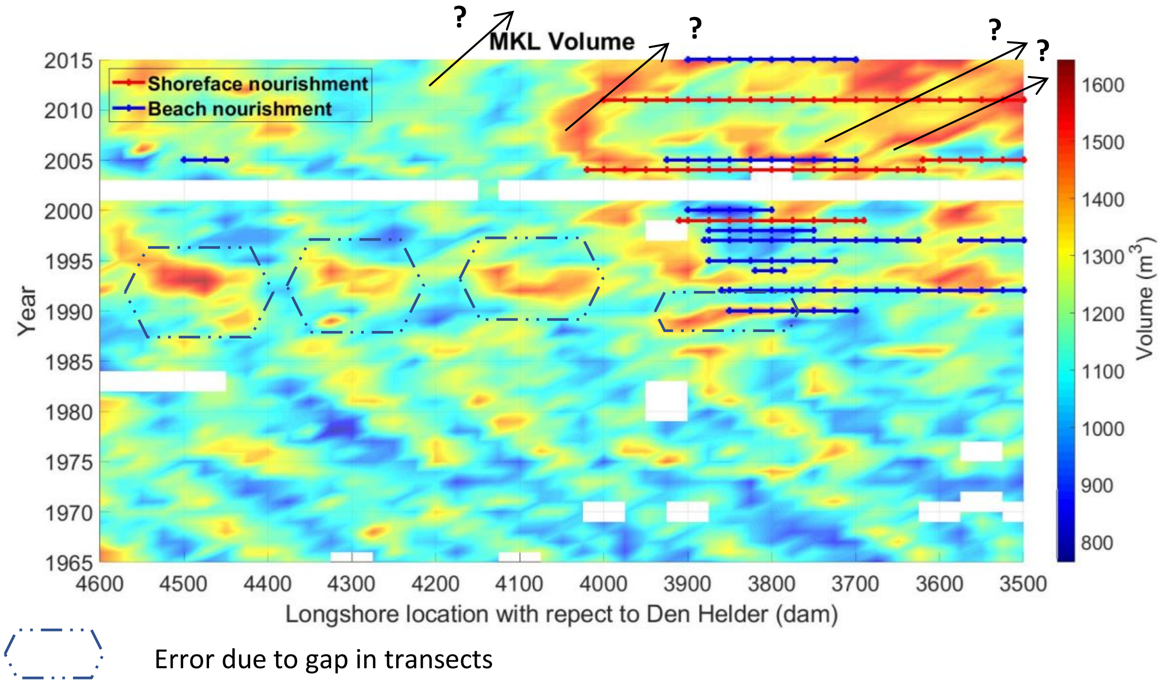


Figure 8.12 Time stacks of MKL volume. The indicated arrows represent apparent sand wave migration. The red plumes around 1990, indicated with a circle, can be seen as error, caused by data gaps, discussed in section 6.4

When carefully studying Figure 8.11**,** longshore repeating peaks in MKL position can be seen. These peaks seem to move southward over time (Figure 8.11). This could be a sign of sand waves moving southward. Accompanying celerities are around 170-180 m/yr.

Along with the MKL position, the MKL volumes have also been calculated, for the same locations. In Figure 8.12 the time stacks for MKL volume are presented. Although MKL volume and MKL position show more or less the same patterns, they differ from each other as well. The southward displacing MKL position peak, is even more pronounced in the volume. This implies an actual southward moving volume over time, called a sand wave.

After 1990, the effects of nourishing are clearly visible in both figures. MKL positions and volumes are both strongly increasing in the north, while they stay mostly unaffected in the south. Besides the expected increased values in the north, there are two other important observations. First of all, the way different sections behave within the nourished zone is remarkable. In general, the nourished section is accreting, but in the 'nourishment core' between 3800 and 3900, volumes hardly grow and even decrease. Only after a heavy nourishing campaign of annual beach nourishments, accretion can be detected in the centre of the nourished area, while at the edges of the nourishments, accretion is quite strong. The second observation is about the sand waves discussed above. Before 1990, sand waves had a southward migrating trend of 170 m/yr with a longshore wavelength of 1 to 3 km. After the start of interventions in the system, this trend disappeared in the northern section but remained present in the southern part, although less pronounced. However, after placement of the shoreface nourishment of 2004, the southward trend seemed to turn in the opposite direction, with celerities varying from 130-240 m/yr.

8.7 Bar trends and summary

This last section is intended to provide a general overview of all results discussed in this chapter. So far, three types of volumes have been examined:

1. Bar volumes
    - Show increasing trends during the NOM cycle, until they reach the outer bar zone, where bars slowly decay and bar volume subsequently becomes smaller.
    - Are kept constant in sector A, as a result of consecutive nourishments, except for the outer bar which reaches record volumes of up to 850 m^3/m.
    - Shoreface nourishments are incorporated in the bar system and become connected to the outer bar, leading to large outer bar volumes. This increases outer bar volumes in sector B as well.
2. Cross-shore volumes
    - Are the result of dividing the cross-shore profile into 9 arbitrary sections, each representing a part of the cross-shore profile (Figure 6.7).
    - Beach and dune sections in the north are eroding and accreting in the south under natural conditions.
    - The intertidal and subtidal part between 50 m and 800 m reflects bar behaviour and migration and is therefore most variable. In this section also the largest changes occurred after implementation of the shoreface nourishments.
    - The lower shoreface, seaward of the line 800 m, is barely affected by bar behaviour and is longshore constantly eroding, despite all nourishment efforts. Due to the enlargement of the system, bars (nourishments) also partly reside in the section between 800-1100 m, which raises on these locations.
3. MKL-volume
    - Provides insight into general erosion trends, and the current state of the coast.
    - Is the most ‘neutral’ way of assessing overall erosion or accretion, but has some limitations as well, which will be discussed in Chapter 9.
    - Is barely affected by bar behaviour, on first sight. Longshore fluctuations appear to correspondent to sand waves, migrating with celerities of up to 240 m/yr.

The six bars found and discussed enable research into the internal longshore differences. The bars were already checked for volume, position and, along with the latter, migration rates. In this section, the trends are combined, which reveals the most important result of a shoreface nourishment: nourishing does not only halt net offshore migration, it also obstructs natural bar growth. In Figure 8.13, volume is plotted versus cross-shore position in the system, for each bar. The grey points represent every individual observation of the bar. For both the nourished and the unnourished sector, the mean is taken for every year, which is represented by the black and red dotted lines, respectively.

The upper panels describe normal patterns of NOM behaviour for both sections for bar 1 and bar 2. Bars grow while migrating seaward, until they reach the end of the surf zone and start to decay. However, in the north these trends are suddenly interrupted after implementation of the nourishments. In the northern sector, bar 3 continues to grow after 1990, comparable to bar 2. The shoreface of 1999 leads to rapid seaward migration of bar 3, along with a slow decrease in total volume. The new shoreface nourishments in 2004 and 2005 cause a sudden jump in mean bar positions in the north. Bar observations of bar 3 form a 'cloud' in the right upper corner, which means that bar 3 does not display any trends, but remains more or less constant over time.

Similar clouds can be seen in the bar volume for bars four, five and six after implementation of the nourishments of 2004 and 2005. Compare these clouds to the still migrating and growing southern counterparts of the bars and the effect of nourishments is clear: not only does nourishing halt bar migration, but it freezes the entire system. Also note that consecutive nourishments enlarged the bar system itself. Mean values of bar 1 reached maxima of only 600 m offshore in the north, while maxima of bar 3 reside around 750. This enlargement of the system itself is also present in the southern section.

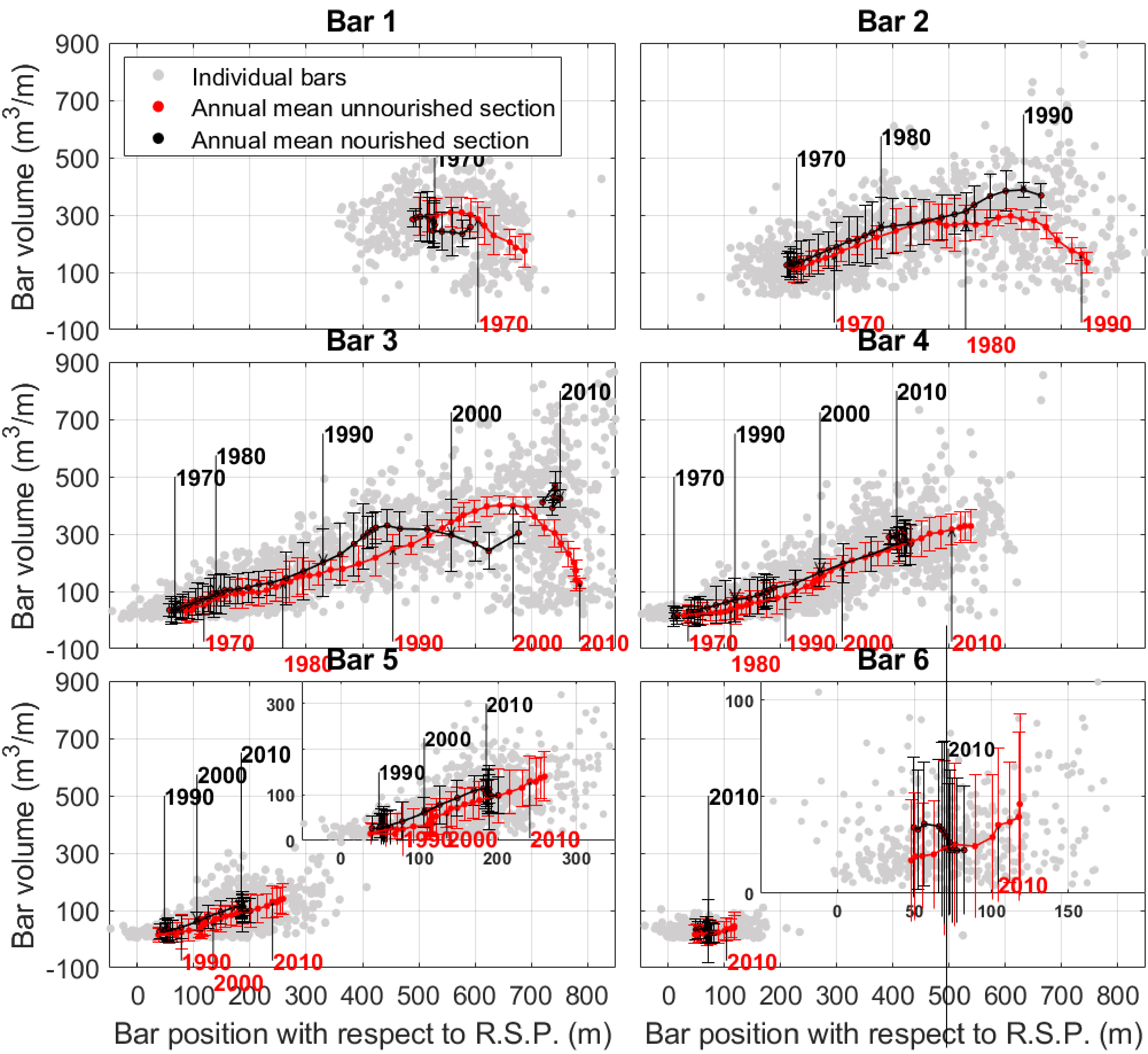


Figure 8.13 Volume vs. Bar position for bars 1 to 6. The grey dots represent individual bar observations. With black and red dots, the annual mean is plotted for the nourished and unnourished section respectively.

Since bar volumes barely change after nourishing, they play a minor role in spreading the sediment through the system. When considering shoreface nourishments as normal bars, this raises the question which roles bars play in sedimentation distribution trends along the coast. To find that out, multiple tests were done in order to find parameters explaining this behaviour. Since bars fulfil a sheltering function, the height, or actually the water depth above the crest, is very important. The shallower a bar crest gets, the larger is its wave breaker function. Of course, the cross-shore location of a bar is also important, because less erosion can take place when waves break further away from the shore. Therefore, a ratio was chosen between the outer bar position and water depth above the crest. This ratio also indirectly accounts for bar volume and height, since the perturbation of a bar must be larger when it resides further offshore than close to the beach.

In Figure 8.14, the MKL position of every transect is plotted against the location/depth ratio of the outer bar, as discussed above. These observations appear to fit a quadratic polynomial curve very well and might therefore explain a part of the sedimentation trends, covered by MKL positions. Note that the observations include the shoreface nourishments of 1999, 2004, 2005 and 2011. However, they do not alter this behaviour.

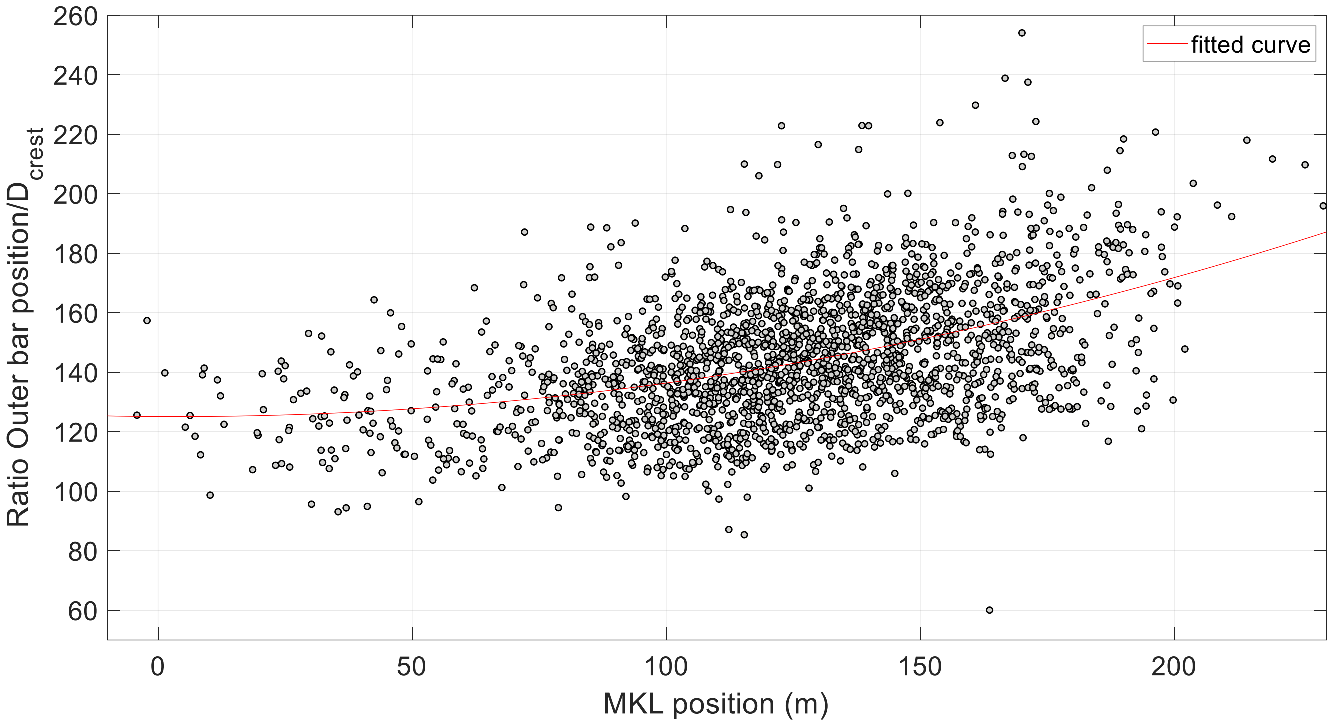


Figure 8.14 In this diagram the MKL-position is plotted vs. the ratio between the Outer bar position and water depth above the bar. A second degree polynomial curve is fitted through the data.

9. Discussion

In this thesis, a comparison has been made between two adjacent sites near the coastal town of Egmond aan Zee in The Netherlands. The northern part of this section has been frequently nourished, while the southern section remained undisturbed. The yearly measured cross-shore transects from the JARKUS database were used for an analysis of the period 1964-2013.

In this chapter, results are discussed and compared with the literature. The research questions from chapter 4 are used as a guideline for this section.

9.1 Discussion of results

Sub question 1

What are the effects of nourishments on sand volume trends along a coast?

What are the observed historical bar dynamics near Egmond?

Before elaborating on nourishments, first, a study was made of the local situation around Egmond. To that end, the period 1965 until 1990 was used. Both the northern and the southern section were completely comparable to each other, since in both areas during this period no construction works took place at all. Bar behaviour in these two areas was largely the same. With a NOM cycle duration of 13 years this part of the Dutch coast is one of the slowest in the world (e.g. Shand et al., 1999). In accordance with Cohen & Briere (2007) and Spanhoff et al. (2004), there is a longshore phase lag present in the area: the southern section before 1990 resides about 5-7 years further in its NOM cycle than the northern section. The NOM cycle itself worked as described by many authors, such as Kroon et al. (1999). Maximum mean NOM rates did not exceed 35 m/yr, which is the lowest migration rate found worldwide.

Crescent bar shapes are present near Egmond, as a part of natural bar behaviour. Locally they also cause opposite bar behaviour, as described in paragraph 8.2.1. When comparing Figure 8.4 to the Digital Elevation Models (DEMS) in Appendix C, it appears that location 3800 is located at the tip of crescentic bar, which became disconnected to the south (see year 1973 in Appendix C).

What are the historical volume trends near Egmond before nourishing?

The coastal town of Egmond is on the edge of two adjacent coastal cells, defined by Van Rijn (1997) and later used by Pot (2011). Sedimentation trends south and north of 39 km behave in exactly opposite ways. In sector A, erosion dominates in all cross-shore sections, while in sector B, accretion is predominantly present. An exception is the offshore section seaward of 800 m, where erosion dominates in both areas (Figure 8.10A). Comparing the specific numbers with the literature, however, is difficult, since longshore and cross-shore, different choices are made to set boundaries (e.g. de Ruig & Louisse, 1998; Van Rijn, 1995; Van Rijn, 1997, Pot, 2011; Van der Spek et al., 2015). Since this report is not intended as a sand budget study, the agreement between the observed trend and the literature is satisfactory.

What are the new volume trends near Egmond after nourishing?

After 1990, there is a clear contrast between north and south. Due to the nourished sand in the area until 40.25 km, the erosion trends here turn into accretion (Figure 8.10). Although accretion is present overall, a distinction can be made between the period 1990-1999 and the period 1999-2013. Annual application of sand on the beach does locally reverse the trends in the cross-shore sections between -200 and +200 m (Figure 8.9), but did not cause the intended switch towards sustainable accretion. Near Egmond, at least every two years a new nourishment was needed to prevent ongoing erosion. Moreover, in none of the transects, a beach nourishment remained for more than one year (Figure 8.5). However, after placement of the first shoreface nourishment in 1999, serious growth was established. This trend was enhanced by the shoreface nourishments in 2004 and 2005. Altogether the whole coastal section near Egmond between -200 m and 1100 m showed a positive trend (Figure 8.10B), which is in agreement with observations made earlier by Cohen & Briere (2007) and Spanhoff et al. (2004).

In the natural part of Egmond, the positive accreting trend in the nearshore part of the profile was present after 1990 as well. This trend did not alter significantly. Interesting is the section between 400 m and 800 m. When inspecting the plots in 10.D.2, it can be seen that the positive accretion trend until 1990 has turned into eroding towards 2000. Meanwhile, the section between 400 m to 800 m in the nourished section was strongly accreting. After 2000, the section in the south starts to accrete again, but with a lower rate than before.

Sub question 2

What are the sandbar dynamics coinciding with observed volume differences/distributions?

The second question involves the study of bar behaviour during the period 1965-2013.

What is the influence of beach nourishments on bar patterns?

The simple answer to this question is: almost none. Most beach nourishments did not remain visible for longer than a year, thereby not significantly changing bar behaviour. A small side note is the observation that the beach nourishments often coincide with terrace formation, as visible in Figure 8.5. The behaviour of beach nourishments is in sharp contrast with observations of Rademacher et al. (2018), who concluded that beach nourishments near the coast of Delfland (in the southern part of the Holland coast) often do transfer into a nearshore bar. The absence of a well-developed bar system at the Delfland coast could explain this difference.

How do shoreface nourishments near Egmond act in terms of bar behaviour?

The first shoreface nourishment placed near Egmond in 1999, was located closely seaward of the outer bar. The newly formed bar became the new outer bar of the system, pushing the former outer bar away, and linked up with the outer bar south of the nourishment. However, after 2001, the nourishment started to disintegrate, and became isolated. The last time this nourishment was traceable as a bar was in 2003.

The second nourishment in 2004 was placed slightly more offshore on the remnants of the last nourishment and it immediately linked up with the outer bar in section B. The nourishment in the north, placed in 2005, did also link up, creating a stable new outer bar, which gradually eroded from the south. This is in agreement with the theory of De Sonneville & Van der Spek (2012), who suggested that the ability of nourishments to link up with bars or other structures increases the lifetime of a nourishment.

By 2011, the natural bar in the south had vanished, and therefore the nourishment of 2011 became directly the most seaward part of the entire bar system. The nourishment was placed slightly seaward of the zone of decay, which might lead to landward migration, what seemed to happen between 2012 and 2013. All observations are in line with the observational tools of Bruins (2016). None of the nourishments displayed significant longshore displacement. Although the available JARKUS data did not continue after 2013, a new nourishment has been placed in 2016. The relative volume of this nourishment (221 m3/m) is quite small, which suggest that only minor maintenance was needed in 2016. This implies that the lifetime of the nourishment of 2011 is at least 5 years (Figure 5.4).

What is the influence of nourishments on the NOM cycle near Egmond?

The first shoreface nourishment of 1999 caused a halt of all seaward migration in the nourished section and even forced the former outer bar in landward direction. In Noordwijk, the sand was applied seaward of the zone of decay, which caused a period of landward migration, in which the other bars still could migrate seaward (Ruessink et al., 2012 and Ojeda et al., 2008). In Egmond, the system assumed a steady state in less than a year and all net migration was reduced to zero (Figure 8.13). The actual outer bar (bar 4 in Figure 8.1) was the first bar to respond the moment that nourishment decays.

How do nourishments affect 3D features, such as crescent bar shapes, near Egmond?

Near Egmond, bars exhibit pronounced 3D features such as crescent shapes. These structures are present in the nourishment, the middle bar, the inner bar and the shoreline. They often display a coupled behaviour, forced by the middle bar. However, since the outer bar forms larger crescent shapes than the inner bar, in most cases a longshore jump took effect from in-phase towards out-of-phase behaviour. Both types of behaviour occur in both sector A and B (see DEMs in Appendix C).

Sub question 3

***How does long-term nourishing affect sandbar dynamics*?**

How does nourishing affect NOM?

According to the guidelines for shoreface nourishments (Van der Spek et al., 2007), used by Rijkswaterstaat, a system becomes 'frozen' when a nourishment is located on the zone of decay. This is exactly what happened near Egmond. All nourishments were placed close to or on the location of bar decay, which locked the complete system in Sector A (Figure 8.1, Figure 8.8 and Figure 8.13). This did account as well for the bar volumes, which remained mostly equal: except for the nourishment itself, the bars did not increase their volume. Meanwhile, in the south, NOM continued, resulting in continuous bar growth.

Surprisingly, there is a large discrepancy between the volume of individual bars and the overall volume: near the nourishment, the overall volumes in the cross-shore sections were increasing, indicating that sedimentation took place here. However, the sand apparently did not change bar volumes. With the sandbars 'frozen' in their position, it can be concluded that they play a minor role in the distribution of sediment through the nearshore zone.

Do nourishments trigger bar switches?

Bar switching is a phenomenon which seems to repeat itself every ten years near Egmond and therefore it is not an exclusively nourishment-related issue. In 1964, the system seemed to be recovering from an episode of bar switching at the northern tip (DEM 1964 in Appendix C). Other episodes occurred in 1974, 1984, 1987, 1988 and 1989. Most of the time, this involved coupling of the outer bar to the middle bar for a period of generally a year. Except for the switch in 1974, all other switches took place between 38 and 39 km. The cause of bar switching can be found in the combination of the oblique orientation of the bar to the shore in combination with the crescent shapes of the bars.

Although bar switches occurred in different periods, one switch differs fundamentally from all other episodes: the 2001 switch was a complete switch that permanently broke through all bars. The trigger of this switch is also different, because it did not happen because of the oblique orientation of the bar, but due to its frozen position. As long as nourishing continues at the zone of decay and the bars in Sector B can migrate freely, large longshore jumps within bars will occur, leading to bar switch episodes.

Did the dynamics of the unnourished natural beach change as a result of nourishments at the bordering nourished coast?

The effects of nourishing often reach further than the edges of the nourishment. Also, in the southern sector, bar migration significantly slowed down (Figure 8.1). This is caused by the fact that bars from Zone A and B are connected. As a result, when a bar in Sector A becomes locked, the same bar in the south is slowed down in its seaward migration. Furthermore, the nourishments of 1999 and 2004, extended the lifetime of bar 3 in the south (Figure 8.1).

A last effect imposed by the nourishment was that, for the first time, bars in the north were more advanced in the bar cycle than in the south. The interannual longshore migration rate seems to have adapted to this new situation: after 2005 the migration of sand waves appeared to have turned around towards the north (Figure 8.2 and Figure 8.12).

What is the extent of longshore effects imposed by nourishments?

According to Schipper et al. (2018), side effects may be present up to 2 kilometres on either side of a nourishment. In this case we are dealing with multiple nourishments. Since the research area is limited to 35-45 km, only the southern edge of the nourishment could be checked for volume changes. In a final attempt to test the time lag between the nourishment itself and the actual maximum positive sedimentation effect in a certain cross-shore section, plots as in Figure 9.1 were created. Comparable plots are incorporated in Appendix B.

For this part, the exact longshore stretch of every individual nourishment was determined, based on the DEMs, enclosed in Appendix C. In Figure 9.1 the volume change in the nearshore section is plotted for every individual nourishment. Since none of the nourished sand was directly added landward of 500 m, this line is taken as the cross-shore border of the nearshore zone. The year of implementation is set to zero (both in time as in volume). Figure 9.1 clearly reveals the time-lag between implementation of the nourishment and an actual increase of the sediment volume in the nearshore zone. The same strategy was applied to the flanks of each nourishment. For every individual nourishment the adjacent side was determined as one kilometer next to the nourishment. These results are enclosed into Appendix C as well. Despite attempts to create the same types of plots for the beach area, the resulting graphs were too noisy and were not useful.

In order to provide a complete overview for the entire nourished area as one system, new graphs were made, comparable to those in Appendix D. These are enclosed in Appendix B.2 and make a clear distinction between the nourished and unnourished sectors. They also specifically show the volume trends in the middle section between 40 km and 42 km. Direct volume impact of the nourishments, seems to be rather limited in the south, except for a large negative erosive trend in the section 41-42 km (lower panel Figure 8.10). This can be attributed to the gradients in the longshore current (e.g. Van Duin et al., 2004). On the other hand, the effect on bar dynamics was large, extending to even 4 kilometres in the south.

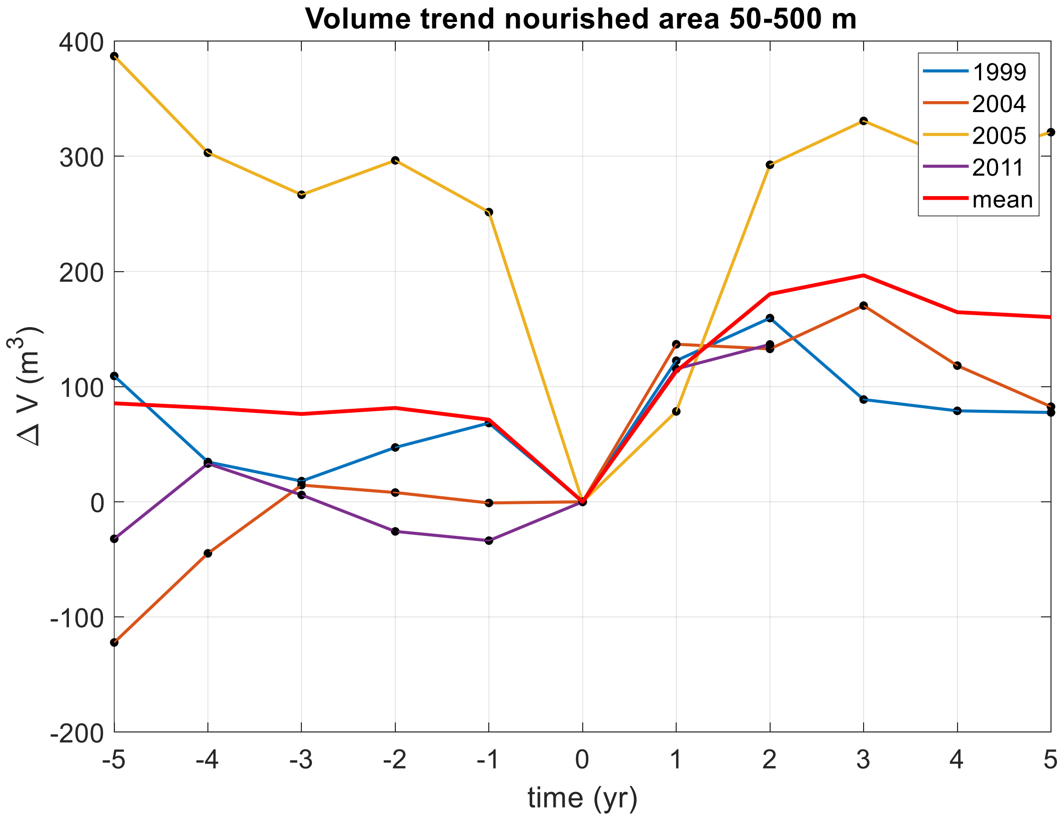


Figure 9.1 Comparison of volume trends in the nearshore area as result of execution of nourishments. Shoreface nourishments did not take place landward of 500 m, so the observed volume trends could be attributed to cross-shore spread of the nourished sand.

Table 9 Time lag between placement of a nourishment and experienced sedimentation peak in different zones around the nourishment. The adjacent site is the area residing 1 km from the flank of the nourishment. Note that it was not possible to determine the time lag on beach and dune areas with the method of Figure 9.1. Other figures, added in the Appendix B, were used.

Cross-shore section/ Location	**-175 to 50 m**	**50 to 500 m**	**500 to 1000 m**
Adjacent site (South)	6	4	1,5
Nourished area	4	3	1

General remarks

- The nourishments placed in the period 1990-2011 had a significant impact on the complete coastal stretch near Egmond. Due to repeatedly nourishing the zone of decay, the system in front of Egmond aan Zee became almost completely frozen after 2000, thereby significantly delaying the migration of the bars in the south. By keeping a constant bar at end of the bar zone in the north, after 2005, the oblique bar orientation disappeared and even reversed in northward direction. Intriguingly, in the same time, the direction of the sand wave migration reversed too, raising the question whether this could be super-imposed behaviour by the nourishment. Depending on wave conditions, longshore migration of sand waves may differ, but the coincidence in this case is striking.
- Another point is the zone of decay, discussed by Bruins (2016). When studying the locations of nourishing, the area seems to growth (Table 8 or Figure 8.13), raising the question whether the zone of decay is a fixed location within a system, or a position which may displace influenced by nourishments.
- The key parameters determining the success (sedimentation in the nearshore zone) of a nourishment aren't completely understood yet. Ojeda et al. (2008) suggest grain size, (relative) volume and position in the cross-shore section. De Sonneville & Van der Spek (2013) mention the importance of a shoreface nourishment to become incorporated into the local bar system. Near Egmond, a relation exists between the MKL position and the ratio between offshore location and water depth above the bar crest (Figure 8.14). Since water depth above a bar is directly related to its volume, this might suggest that larger shoreface nourishments create favourable conditions for sedimentation.
- In terms of coastal management, the shoreface nourishment of 1999 may be considered as inadequate (Appendix B.1). Even in the nourished section itself, the first year after implementation, a volume increase of less than 100 m^3/m was present, while the intended design was 400 m^3/ m.

9.2 Validation of method and further research

By making use of sandbar volumes, it was possible to study the impact of nourishment on bar behaviour. However, this method also contained setbacks.

JARKUS-data

The first important hiatus is the limits of working with JARKUS. Although JARKUS is a unique source of scientific bathymetrical data, it has some limitations:

- Incomplete data
- A profile consists of two measurements, often measured on a completely different moment (Figure 6.4). The implication is that the interval of measurement between two consecutive transects resides between 0.5 and 1.5 year (a difference of factor 3).
- Depth measurements and elevation measurements do not always overlap, leaving an empty gap in between the two transects. Especially in the period 1990-1995, this problem is widespread, making results from this period rather unreliable (Figure 6.3).
- Longshore and temporal differences and inconsistency in the cross-shore range of profiles (Figure 6.5).

Bar locations

The largest challenge of this thesis was to determine the exact bar locations near Egmond. This worked out perfectly, but it also raised the question of how the limits of a bar are determined exactly. In this thesis, the bottom of the trough was used as the bar edge, but in Bruins (2016) and Aleman et al. (2017) other approaches were chosen.

Cross-shore bins

Working with cross-shore bins for volume balances remains difficult, since no bar displays the same behaviour. In this thesis, static bins were used, similar to Bruins (2016) and Van Duin et al. (2004). However, Pot (2011), Van Rijn (1997) and De Ruig & Louisse (1991) used elevation contours. Both methods have their limitations and this makes it difficult to compare work to each other.

Weather

The weather impact on the system was not taken into account, but is important, since crescent bars may migrate longshore either northward or southward, influenced by the wave direction (e.g. Van Enckevort & Ruessink, 2003b; Ruessink et al., 2000; Van Enckevort et al. 2004).

ARGUS

Egmond was not only chosen based on its unique nourishment records, but also because of the presence of two ARGUS locations, enabling detailed study of the processes underlying nearshore dynamics near Egmond, including sand wave behaviour and morphological coupling between sandbars.

Future development

For this research data were available until 2013. Intuitively, this raises the question what happened to the shoreface nourishments afterwards. The nourishment of 2011 seems to have turned around the system of southward migrating crescent shapes. The question is whether this is a permanent change and what happens if an oblique system is mirrored for a longer period. Does an oblique system provide a template for interannual longshore migration of sand waves and mega-cusps? And finally: will new bar switching episodes occur near Egmond?

10. Conclusions

In this thesis, bar behaviour near Egmond was studied in order to shed light on the main question:

"What are the differences in nearshore dynamics between a nourished coast and a natural coast?"

In order to find the answer to this question, 2250 transects, measured perpendicular to the coast of Egmond aan Zee (The Netherlands), were studied. In order to enable the study of exact bar behaviour, in terms of volume, a method was developed, which could isolate bar positions from these profiles. By making use of this method, all bars present near Egmond in the period 1964 to 2013 could be found and studied, based on their cross-shore location and volume. This led to the following conclusions:

- Beach nourishments near Egmond appear to have very limited influence on nearshore volumes, due to the presence of an erosion hotspot near 38 km. Despite multiple nourishments during the period 1990-2000, no significant contribution to the MKL-position was established. Only after implementation of the first nourishment did significant sedimentation take place.
- Influenced by the shoreface nourishments, structural erosion trends near Egmond were reversed into accretion. Due to continuous nourishing, all cross-shore sections landward of the 1100 m area between 35 and 40.25 km showed accreting trends (Figure 8.10).
- Positive trends in the south continued, except for trends becoming more negative at the edge of the nourished area, between 41 and 42 km.
- Offshore erosion trends, however, remained negative both in the south and the north, and became even more negative.
- Bar migration in the north became completely frozen, forced by the shoreface nourishments. 'Frozen' does not only refer to the cross-shore bar locations, but to bar volumes as well. Meanwhile, in the south, NOM of sandbars continued, although significantly slowed down, as a result of the longshore connection with the inert bars in the north.
- Implementation of the first nourishment pushed the former outer bar towards the shore, thereby immediately forcing a bar switch episode, which cut through all bars. Bar switch episodes are a common phenomenon near Egmond (usually happening once every decade), but they mostly only comprise temporal coupling of the outer bar to the middle bar. Therefore, the bar switch as seen in 2001, can be considered a nourishment-induced phenomenon. Due to the locked bar positions near Egmond, more bar switches may be expected in the future.
- Altogether, the nourishments seem to have altered the system fundamentally: every nourishment was located more seaward, thereby enlarging the complete system. When studying Figure 8.8 one can easily see that the size of bar 3 reaches record values.
- Accretion trends were studied as a result of the shoreface nourishment. For every individual nourishment, the time lag was determined between the placement of the sand and the moment that the accretion in an area reached its maximum. This was possible for the nearshore zone between 50 m and 500 m and for the southern neighbouring kilometer of each nourishment. In these results are listed. It takes three years before nourished sand reaches the nearshore zone. In the adjacent section this is four years. For the beach and dune areas it takes four and six years, respectively. This last number is longer than the lifetime of nourishments near Egmond. Therefore, dune growth is not the result of a single nourishment, but of creating the boundary conditions enabling accretion.

- In terms of volume trends, the effects of the nourishment did not reach further than two kilometres, but the impact of the nourishments on NOM is detectable up to at least 4 km from the nourished location.
- In addition to the conclusion that bars play a minor role in dividing sediment throughout the system, the role of bars in a coastal system was studied. The second degree polynomial relation found between MKL positions and the ratio between cross-shore position and depth of the crest, suggests that a sandbar acts similar to a stable reef berm, providing a sheltered place where accretion takes place.

References

Aagaard, T., Kroon, A., Andersen, S., Sørensen, R.M., Quartel, S., Vinther, N. (2005). Intertidal beach change during storm conditions; Egmond, The Netherlands, *Marine Geology, 218 (1-4)*, pp. 65-80. DOI: 10.1016/j.margeo.2005.04.001

Aleman, N., Certain, R., Robin, N., Barusseau, J.-P. (2017). Morphodynamics of slightly oblique nearshore bars and their relationship with the cycle of net offshore migration, *Marine Geology*, 392, pp. 41-52. DOI: 10.1016/j.margeo.2017.08.014

Bruins, R.J.(2016). Morphological behaviour of shoreface nourishments along the Dutch coast, M.Sc. Report. Delft University of Technology, Delft. Retrieved from http://resolver.tudelft.nl/uuid:e7585706-571d-4b97-8b89-d7c7abd9730c

Castelle, B., Ruessink, B.G., Bonneton, P., Marieu, V., Bruneau, N., Price, T.D. (2010). Coupling mechanisms in double sandbar systems. Part 1: Patterns and physical explanation, *Earth Surface Processes and Landforms*, 35 (4), pp. 476-486. ,10.1002/esp.1929

Cohen, A.B. & Briere, C. (2007). Evaluatie van de uitgevoerde suppleties bij Egmond op basis van Argus video waarnemingen, Deltares (WL). Retrieved from http://resolver.tudelft.nl/uuid:008d440d-6535-4bd9-b100-00206bce3881

Cohn, N., Ruggiero, P., Ortiz, J., & Walstra, D. J. (2014). Investigating the role of complex sandbar morphology on nearshore hydrodynamics. *Proceedings of the 13th International Coastal Symposium*, Durban, South Africa, 13-17. *Journal of Coastal Research*, Special Issue 70, 2014, 53-58. doi:10.2112/SI65-010.1

d'Angremond, K. (2003). From disaster to Delta Project: The storm flood of 1953, *Terra et Aqua*, (90), pp. 3-10.

de Graaf, H.J.C., Oude Elberink, S.J., Bollweg, A.E., Brügelmann, R. and Richardson, L.R.A. (2003). Survey techniques for "Dry" Jarkus Profiles Along the Dutch Coast (Inwinning "Droge" Jarkus Profielen Langs Nederlandse Kust), Rijkswaterstaat AGI-GAM-2003-40

de Ruig, J.H.M., Louisse ,C.J. (1991). Sand Budget Trends and Changes along the Holland *Coast. Journal of Coastal Research*, 7(4), 1013-1026. Retrieved from http://www.jstor.org/stable/4297922

de Ruig, J.H.M. (1998). Coastline management in The Netherlands: Human use versus natural dynamics, *Journal of Coastal Conservation*, 4 (2), pp. 127-134. DOI: 10.1007/BF02806504

de Schipper, M.A., de Vries, S., Ruessink, G., de Zeeuw, R.C., Rutten, J., van Gelder-Maas, C., Stive, M.J.F. (2016).Initial spreading of a mega feeder nourishment: Observations of the Sand Engine pilot project, *Coastal Engineering*, 111, pp. 23-38, DOI: 10.1016/j.coastaleng.2015.10.011

Elias, E.P. (2006), Morphodynamics of Texel Inlet PhD thesis Delft University of Technology / IOS (under the imprint of Delft University Press) ISBN 1-58603-676-9; DUP Science / Delft Hydraulics Select Series 9/2006

de Sonneville, B., Van Der Spek, A. (2012). Sediment- and morphodynamics of shoreface nourishments along the North-Holland coast, *Proceedings of the Coastal Engineering Conference*. Retrieved from http://resolver.tudelft.nl/uuid:c96bb814-811f-4858-b1d8-a48f552904de

Giardino, A., Van der Werf, J.J., Van Ormondt, M., Brière, C.B., Walstra, D.J.R. (2009). Modelling and observations of a shoreface nourishment at Egmond (Netherlands). *Proceedings RCEM*

Conference, Santa Fe, Argentina. Retrieved from https://www.researchgate.net/publication/248701651

Grunnet, N.M., Ruessink, B.G. (2005). Morphodynamic response of nearshore bars to a shoreface nourishment, *Coastal Engineering*, 52 (2), pp. 119-137. DOI: 10.1016/j.coastaleng.2004.09.006

Hamm, L., Capobianco, M., Dette, H.H., Lechuga, A., Spanhoff, R., Stive, M.J.F. (2002). A summary of European experience with shore nourishment, *Coastal Engineering*, 47 (2), pp. 237-264. DOI: 10.1016/S0378-3839(02)00127-8

Hoeksema, R.J. (2007). Three stages in the history of land reclamation in the Netherlands, *Irrigation and Drainage*, 56 (SUPPL. 1), pp. S113-S126. DOI: 10.1002/ird.340

Kroon, A., Hoekstra, P., Houwman, K., Ruessink, G. (1995). Morphological monitoring of a shoreface nourishment nourtec experiment at Terschelling, The Netherlands, *Proceedings of the Coastal Engineering Conference,* 2, pp. 2222-2236. DOI: 10.1061/9780784400890.162

Lodder, Q.J., Sørensen, P. (2015). Comparing the morphological behaviour of Dutch-Danish shoreface nourishments Coastal Management: Changing Coast, Changing Climate, Changing Minds, *Proceedings of the International Conference*, pp. 397-406. DOI: 10.1680/cm.61149.397

Min. I&W (2007), Kustlijnkaartenboek uitgave December 2006, Ministerie van Verkeer en Waterstaat, Directoraat-Generaal Rijkswaterstaat

Min. I&W (2017), Kustlijnkaartenboek uitgave December 2016, Ministerie van Verkeer en Waterstaat, Directoraat-Generaal Rijkswaterstaat

Mulder, J.P.M., Tonnon, P.K. (2010). "Sand engine": Background and design of a mega-nourishment pilot in the Netherlands, *Proceedings of the Coastal Engineering Conference,* 10 p.. 10.9753/icce.v32.management.35

Ojeda, E., Ruessink, B.G., Guillen, J. (2008). Morphodynamic response of a two-barred beach to a shoreface nourishment, *Coastal Engineering*, 55 (12), pp. 1185-1196. . DOI: 10.1016/j.coastaleng.2008.05.006

Pape, L., Plant, N.G., Ruessink, B.G. (2010). On cross-shore migration and equilibrium states of nearshore sandbars, *Journal of Geophysical Research: Earth Surface*, 115 (3), art. no. F03008. DOI: 10.1029/2009JF001501

Planbureau voor de Leefomgeving (2010), Correctie formulering over overstromingsrisico Nederland in IPCC-rapport. Retrieved from https://www.pbl.nl/correctie-formulering-over-overstromomgsrisico

Pot, R.(2011). System-description Noord-Holland Coast, M.Sc. Report. Delft University of Technology, Delft. Retrieved from http://resolver.tudelft.nl/uuid:ae808e51-7d9f-464a-a7d6-07703f4240e8

Price, T.D., Rutten, J., Ruessink, B.G. (2011). Coupled behaviour within a double sandbar system, *Journal of Coastal Research*, (SPEC. ISSUE 64), pp. 125-129. , https://www.jstor.org/stable/26482146

Price, T.D., Ruessink, B.G., Castelle, B. (2014). Morphological coupling in multiple sandbar systems - A review, *Earth Surface Dynamics*, 2 (1), pp. 309-321. DOI: 10.5194/esurf-2-309-2014

Radermacher, M., de Schipper, M.A., Price, T.D., Huisman, B.J.A., Aarninkhof, S.G.J., Reniers, A.J.H.M. (2018). Behaviour of subtidal sandbars in response to nourishments, *Geomorphology*, 313, pp. 1-12. DOI: 10.1016/j.geomorph.2018.04.005

Hillen, R., & Roelse, P. (1995). Dynamic preservation of the coastline in the Netherlands, *Journal of Coastal Conservation*, 1 (1), pp. 17-28. DOI: 10.1007/BF02835558

Ribas, F., Ojeda, E., Price, T.D., Guillén, J. (2010). Assessing the Suitability of Video Imaging for Studying the Dynamics of Nearshore Sandbars in Tideless Beaches, *IEEE Transactions on Geoscience and Remote Sensing*, 48 (6), art. no. 5415649, pp. 2482-2497. DOI: 10.1109/TGRS.2009.2039576

Roelse, P., 1996. Evaluatie van zandsuppleties aan de Nederlandse kust 1975-1994, Rijksinstituut voor Kust en Zee , RIKZ-96.028. Retrieved from http://repository.tudelft.nl/islandora/object/uuid:124344c6-151c-4e31-bb5b-95eb2e63f5c5?collection=research

Ruessink, B.G., Kroon ,A. (1994). The behaviour of a multiple bar system in the nearshore zone of Terschelling, the Netherlands: 1965–1993, *Marine Geology*, Volume 121, Issues 3–4, pp. 187-197, https://doi.org/10.1016/0025-3227(94)90030-2

Ruessink, B.G., Van Enckevort, I.M.J., Kingston, K.S., Davidson, M.A. (2000). Analysis of observed two- and three-dimensional nearshore bar behaviour, *Marine Geology*, 169 (1-2), pp. 161-183. DOI: 10.1016/S0025-3227(00)00060-8

Ruessink, B.G., Grinten, R.M., Vonhögen-Peeters, L., Ramaekers, G., and Lodder, Q.J. (2012). Nearshore evolution at Noordwijk (NL) in response to nourishments, as inferred from Argus video imagery. *Proceedings of the 25th NCK days*. Retrieved from https://proceedings.utwente.nl/194/

Ruessink, B.G., Coco, G., Ranasinghe, R., Turner, I.L. (2007). Coupled and noncoupled behavior of three-dimensional morphological patterns in a double sandbar system, *Journal of Geophysical Research: Oceans*, 112 (7), art. no. C07002. DOI: 10.1029/2006JC003799

Rutten, J., Ruessink, B.G., Price, T.D. (2018). Observations on sandbar behaviour along a man-made curved coast, *Earth Surface Processes and Landforms*, 43 (1), pp. 134-149. DOI: 10.1002/esp.4158

Shand, R.D., Bailey, D.G., Shepherd, M.J. (1999). An inter-site comparison of net offshore bar migration characteristics and environmental conditions, *Journal of Coastal Research*, 15 (3), pp. 750-765.

Short, A.D. (1992). Beach systems of the central Netherlands coast: Processes, morphology and structural impacts in a storm driven multi-bar system, *Marine Geology*, 107 (1-2), pp. 103-132. DOI: 10.1016/0025-3227(92)90071-O

Sistermans, P., Nieuwenhuis, O. (2004). Holland Coast (the Netherlands). *Eurosion Case Study*. Retrieved from http://databases.eucc-d.de/plugins/projectsdb/project.php?show=378

Spanhoff, R., Walburg, A.M., Biegel, E.J.(2004), Evaluatie onderwatersuppleties Egmond en Bergen Januari 2004, Den Haag : Rijkswaterstaat, Rijksinstituut voor Kust en Zee, Den Haag, RIKZ/OS/2004112W. Retrieved from http://publicaties.minienm.nl/documenten/evaluatie-onderwatersuppleties-egmond-en-bergen

Spanhoff, R., Kroon, A., De Keijzer, S. (2006). Shoreface nourishments as a natural laboratory with emphasis on the Egmond Case, *Coastal Dynamics 2005 - Proceedings of the Fifth Coastal Dynamics International Conference*,1-14. 10.1061/40855(214)61.

Stive, M.J.F., De Schipper, M.A., Luijendijk, A.P., Aarninkhof, S.G.J., Van Gelder-Maas, C., Van Thiel De Vries, J.S.M., De Vries, S., Henriquez, M., Marx, S., Ranasinghe, R. (2013). A new alternative to saving our beaches from sea-level rise: The sand engine, *Journal of Coastal Research*, 29 (5), pp. 1001-1008, 10.2112/JCOASTRES-D-13-00070.*1*

Stolk, A., 1989. Zandsysteem kust ^ Een morfologische karakterisering. Kustverdediging na 1990, Technisch Rapport 1. Rep. GEOPRO 1989-02, Department of Physical Geography, Utrecht University

Taal M., Mulder J., Cleveringa J., Dunsbergen D. (2006), 15 years of coastal management in the Netherlands; Policy, implementation and knowledge framework. The Hague, Rijkswaterstaat, National Institute for Coastal and Marine Management/RIKZ.

van der Grinten, R.M., Ruessink, B.G. 2012. Evaluatie van de kustversterking bij Noordwijk aan Zee - De invloed van de versterking op de zandbanken. Retrieved from http://publicaties.minienm.nl/documenten/evaluatie-van-de-kustversterking-bij-noordwijk-aan-zee-de-invloe

van der Spek, A.J.F., Kruif(de), A.C., Spanhoff, R. (2007). Richtlijnen onderwatersuppleties, *Ministerie van Verkeer en Waterstaat, Rijkswaterstaat, Rijksinstituut voor Kust en Zee (RWS, RIKZ)*, 2007.012. Retrieved from http://publicaties.minienm.nl/documenten/richtlijnen-onderwatersuppleties

van der Spek, A., Elias, E., 2013. The effects of nourishments on autonomous coastal behavior. In Coastal Dynamics, *Proceedings of the 7th International Conference on Coastal Dynamics*; pp. 1753–1763

Van der Spek, Ad & Lodder, Quirijn. (2015). a new sediment budget for the netherlands; the effects of 15 years of nourishing (1991-2005). *Coastal Sediments*. 10.1142/9789814689977_0074.

van Duin, M.J.P.,Wiersma, N.R.,Walstra, D.J.R., van Rijn, L.C., Stive, M.J.F., 2004. Nourishing the shoreface: observations and hindcasting of the Egmond case, The Netherlands. *Coastal Enginering* 51 (8–9), 813–837. DOI: 10.1016/j.coastaleng.2004.07.011

van Enckevort, I.M.J., Ruessink, B.G. (2001). Effect of hydrodynamics and bathymetry on video estimates of nearshore sandbar position, *Journal of Geophysical Research: Oceans*, 106 (C8), art. no. 1999JC000167, pp. 16969-16979, DOI: 10.1029/1999jc000167

van Enckevort, I.M.J., Ruessink, B.G., Coco, G., Suzuki, K., Turner, I.L., Plant, N.G., Holman, R.A. (2004). Observations of nearshore crescentic sandbars, *Journal of Geophysical Research C: Oceans*, 109 (6), pp. C06028 1-17, DOI: 10.1029/2003JC002214

van Enckevort, I.M.J., Ruessink, B.G. (2003a). Video observations of nearshore bar behaviour. Part 1: Alongshore uniform variability, *Continental Shelf Research*, 23 (5), pp. 501-512, DOI: 10.1016/S0278-4343(02)00234-0

van Enckevort, I.M.J., Ruessink, B.G. (2003b). Video observations of nearshore bar behaviour. Part 2: Alongshore non-uniform variability, *Continental Shelf Research*, 23 (5), pp. 513-532, DOI: 10.1016/S0278-4343(02)00235-2

van Koningsveld, M., Mulder, J.P.M. (2004). Sustainable coastal policy developments in the Netherlands. A systematic approach revealed, *Journal of Coastal Research*, 20 (2), pp. 375-385, DOI: 10.2112/1551-5036(2004)020(0375:SCPDIT)2.0.CO;2

van Rijn, L.C., 1995. Sand budget and coastline changes of the central Dutch coast between Den Helder and Hoek van Holland. Report H2129. Delft Hydraulics, The Netherlands. Retrieved from http://resolver.tudelft.nl/uuid:6837af90-6f12-4f14-ac73-4d6978f72f47

van Rijn, L.C. (1997). Sediment transport and budget of the central coastal zone of Holland, *Coastal Engineering*, 32 (1), pp. 61-90, DOI: 10.1016/S0378-3839(97)00021-5

van Rijn, L.C., Walstra, D.J.R. (2004). Analysis and modelling of shoreface nourishments, Rijkswaterstaat, Rijksinstituut voor Kust en Zee. Retrieved from http://resolver.tudelft.nl/uuid:8d3509b9-8b95-

4b3b-a995-c643fa19388b

Walstra, D.J.R., Reniers, A.J.H.M., Ranasinghe, R., Roelvink, J.A., Ruessink, B.G., (2012). On bar growth and decay during interannual net offshore migration, *Coastal Engineering*, 60 (1), 190-200. DOI: 10.1016/j.coastaleng.2011.10.002

Wijnberg, K.M., Terwindt, J.H.J. (1995). Extracting decadal morphological behaviour from high-resolution, long-term bathymetric surveys along the Holland coast using eigenfunction analysis, *Marine Geology*, 126 (1-4), pp. 301-330, DOI: 10.1016/0025-3227(95)00084-C

Wijnberg, K.M. (2002). Environmental controls on decadal morphologic behaviour of the Holland coast, *Marine Geology*, 189 (3-4), pp. 227-247. , DOI: 10.1016/S0025-3227(02)00480-2

Wijnberg, K.M., Aarninkhof, S.G.J., Spanhoff, R. (2007). Response of a shoreline sand wave to beach nourishment, *Proceedings of the Coastal Engineering Conference*, pp. 4205-4217. DOI: 10.1142/9789812709554_0353

Wright, L.D., Short, A.D., Green, M.O. (1985). Short-term changes in the morphodynamic states of beaches and surf zones: An empirical predictive model, *Marine Geology*, 62 (3-4), pp. 339-364. DOI: 10.1016/0025-3227(85)90123-9

Data acknowledgements

JARKUS data	*Rijkswaterstaat (the Dutch Department of Public Works) is responsible for measurement and collection JARKUS data into the JARKUS database. The data, used for this thesis, was provided by the Utrecht University.* Nourishment data can be requested via: https://www.helpdeskwater.nl/
Nourishment data	*Data on nourishments, is collected by Rijkswaterstaat, and stored in the form of Excel sheets. Nourishment data, used in this study was delivered by Utrecht University.* Nourishment data can be requested *via: https://www.helpdeskwater.nl/*
Wave data	Wave data, used in this thesis, is collected by Rijkswaterstaat, and is free available via https://waterinfo.rws.nl/

Image acknowledgements

Google. *Egmond aan Zee*. Retrieved from: *https://www.google.nl/maps/place/Egmond+aan+Zee/@52.6224178,4.6216436,4183m/data=!3m1!1e34m5!3m4!1s0x47cf589bc95193fb:0x760cbfa174620855!8m2!3d52.6186114!4d4.6302431*

***Deltares**. Coastviewer, retrieved from: https://www.openearth.nl/coastviewer-static/.*

Appendix

A. Determination of bar edges
B. Sedimentation trends after implementation of nourishments
C. Digital Elevation Models
D. Longshore volume trends
E. Bar maps per year

Appendix A Determination of bar edges

A.1 Bar edge determination

Although the methods used by Ribas et al. (2010) and Radermacher et al. (2018) did not work out completely, their work contained multiple clues that led to the development of the technique used in this study to derive the bar edges. First of all, the concepts of peaks and zero-crossings in the derivative were used again. However, when studying the transects carefully, it appeared that not the zero-crossing was the key, but the crossing of the derivative with the mean slope. Here, the mean slope is defined as the mean of the first derivative between NAP 0 m and x = 1150 m (Figure A.1). In summary, the following definitions of the bar positions were used:

1. In order to find out whether a bar is present, a clear peak in the double smoothed first derivative must be present.
2. The landward edge is defined as the first point after the crossing of the original first derivative with the mean slope (green vertical lines in Figure A.1).
3. The seaward edge is determined using the landward edge of the neighbouring seaward bar as a reference. From this position the seaward bar edge is backward determined. The seaward edge is located at the last data point before the bar reaches the mean slope, see blue vertical lines.
4. With the two edges determined, the bar top is simply the maximum elevation of the bar.

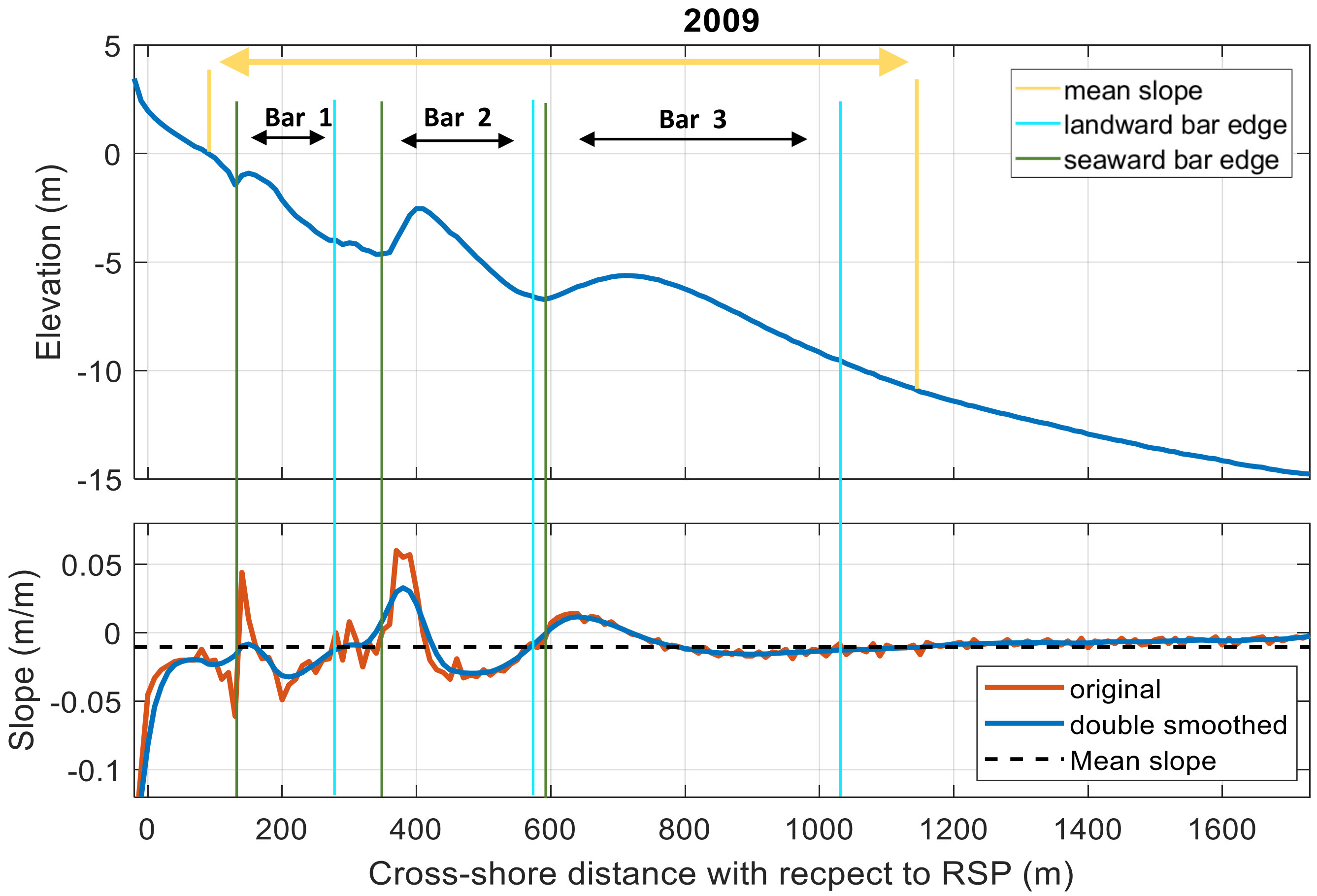


Figure A.1Example of finding the cross-shore position of the edges of a bar. As becomes clear from this figure the landward edge of a bar interferes with the first point after the crossing of the original derivative with mean slope. The same accounts for the seaward bar edge: the first point after the ascending crossing of the original derivative with the mean slope, corresponds to the seaward end

A.2 Description of programs

Determination of the bars required multiple steps and numerous minor tests. To provide insight into the way they are found, in the next section, the working of the main programs is explained. In Figure A.2 a schematised overview of all programs and functions involved is presented. To prevent endless summations of statements and checks, the programs are only briefly discussed.

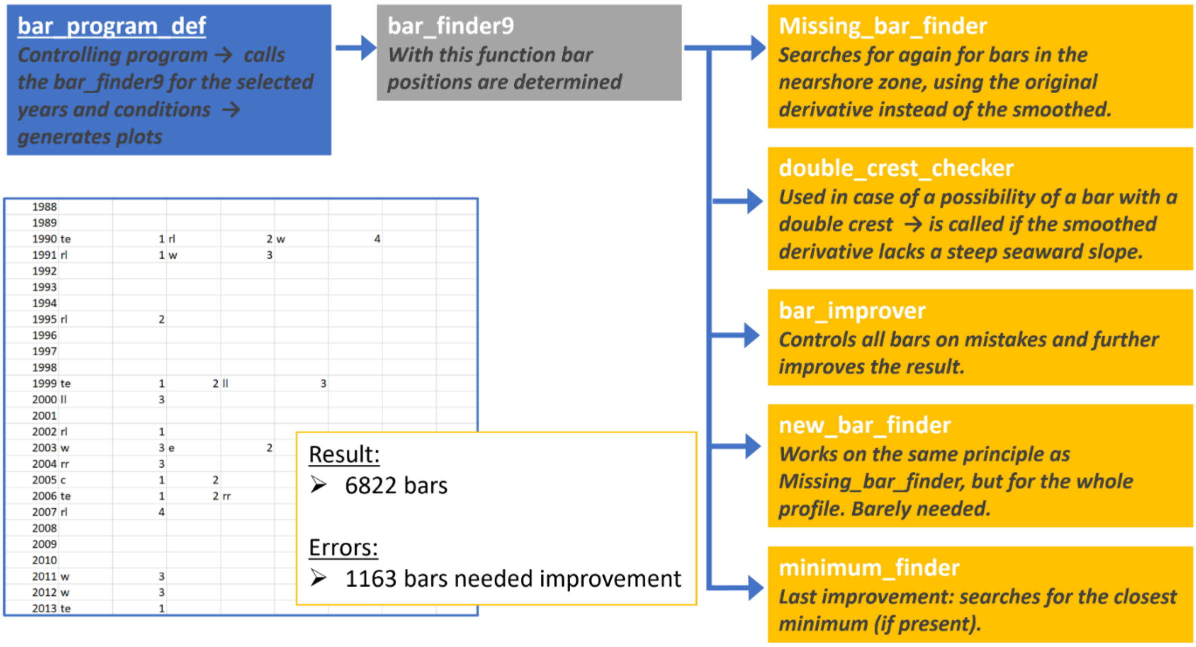


Figure A.2 Diagram representing the main functions, needed to identify bars in the JARKUS-transects.

A.3 Bar_finder9

A total number of nine attempts were needed to find the correct manner of determining the correct bar position. The first derivative plays a key role in this process. The intersections of the double smoothed derivative with the mean slope are used as the main indicator of a bar, see X6 and X7 in Figure A.3. Especially in the nearshore zone, a bar where slopes are steep and negative, peaks in the derivative often do not reach the mean slope. Therefore, on this part of the transect a check is

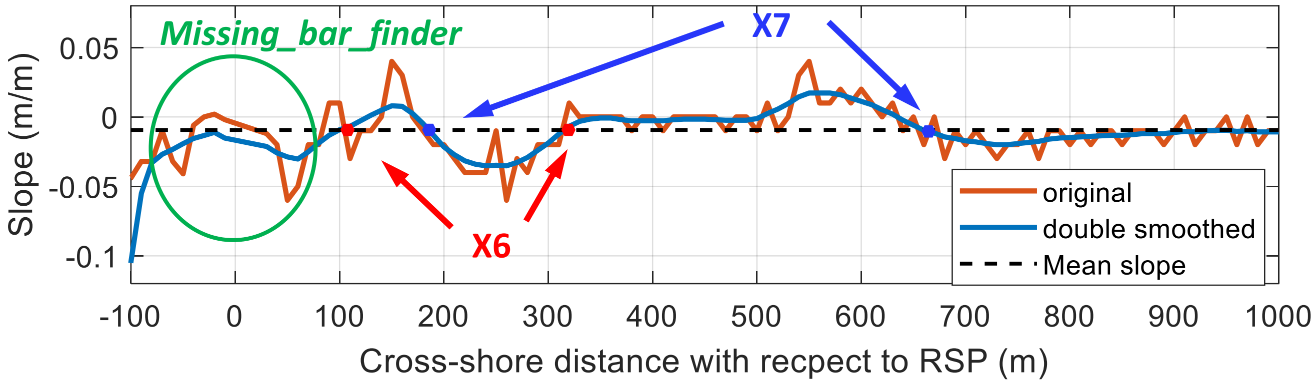


Figure A.3 The principle of bar detection by the Bar_finder9. The areas between X6 and X7 are possible bars. If in the nearshore part of the profile no intersections are present between the smoothed derivative and the mean slope(as indicated with the green circle) the Missing_bar_finder is activated.

performed, making use of the original derivative. The function *new_bar_finder* makes use of the same principle and is used when no bars are found on large parts of the profile.

A.4 Double_crest_checker

In some cases, a bar has two peaks, see Figure A.4. This often coincides with a less pronounced negative peak in the double smoothed derivative, clearly visible in the lower panel. When such a peak is absent, the *Double_crest_checker* function is activated, checking whether there is a double crested bar or not. When this is true, the new actual edge of a bar is determined, moving it beyond the second bar crest towards the seaward flank of the bar.

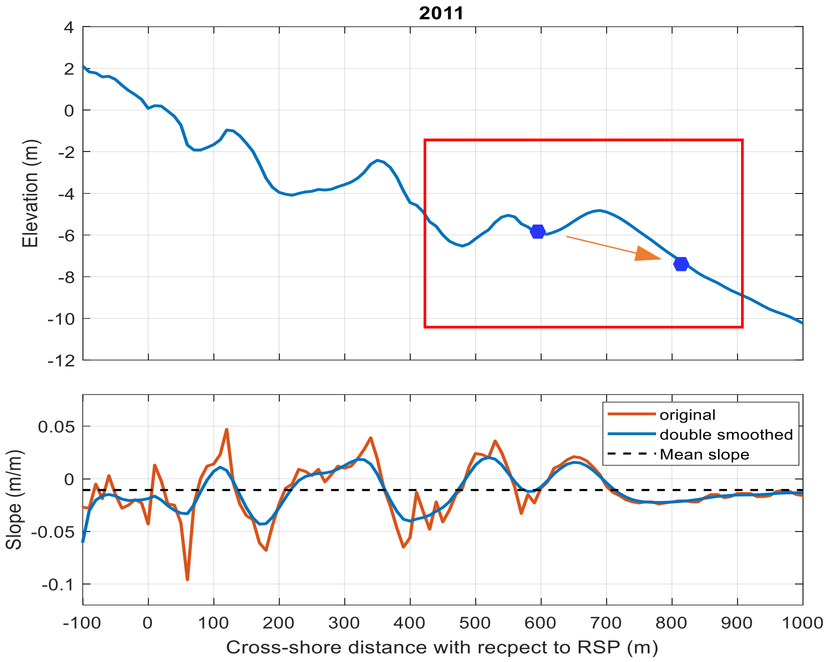
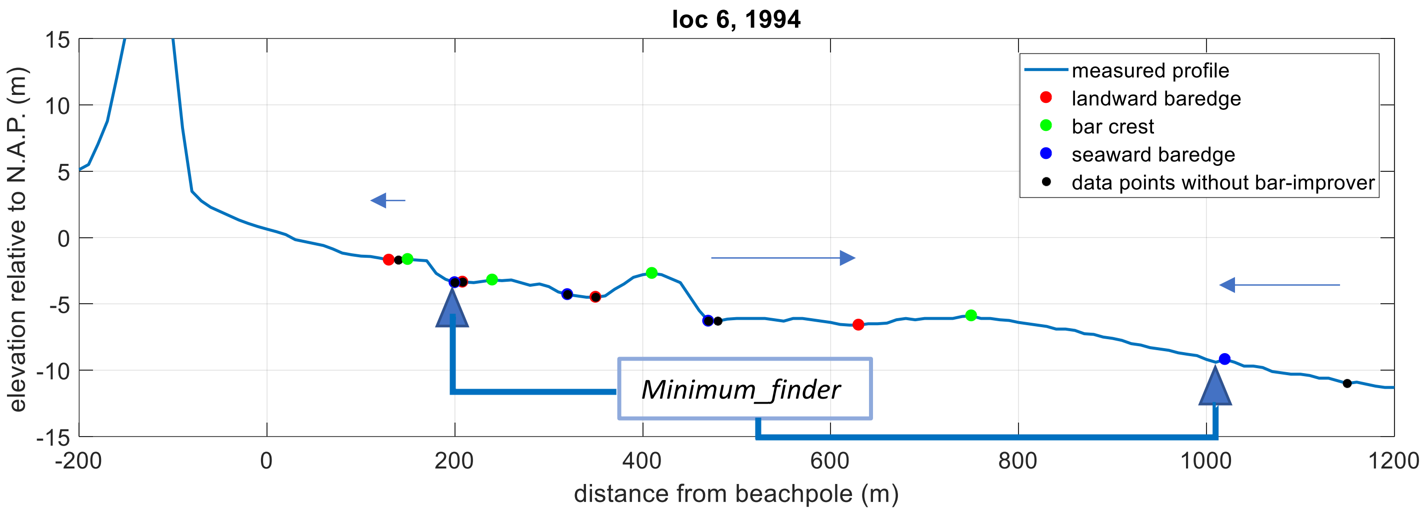


Figure A.4 Graphical representation of the Double_crest_checker. As can is visible in the lower panel, the negative peak in the double smoothed derivative around 500m is smaller than other peaks.




```
1994
slope = -0.0097515
bar added between 1156.6667 and 1198.8889 with help of the second derivative
bar between 1156.6667 and 1198.8889 deleted >> too little elevation
landward side bar 4 seaward displaced (loop A.1.2.1)
landward side bar 1 landward displaced (loop B.1)
seaward side bar 4 landward displaced because of small slope part 2
```

Figure A.5 Mutations in the bar positions, imposed by the Bar_improver and the Minimum_finder.

A.5 Bar_improver

After the bar locations are obtained, the flanks are checked again on their correctness. Small undulations or flat parts in the profile could cause major mistakes of up to several hundreds of meters. Therefore, especially bars with long flanks are checked for incorrect slopes on irregularities in slope. If the mean slope of a flank is too low or opposite of the trend and this is not an exception, a bar edge could be replaced. Another problem facing bar determination is the asymptotic behaviour of the seaward flank of the outer bar. This leads to unrealistically long bars, as depicted in Figure A.5. In Figure A.5, the complete profile of location 6, from the year 1994, is depicted, with the bar locations along with the model output. In black, the old data points are visible before the bar locations were checked by the *bar_improver*. When observing Figure A.5 thoroughly, one can see that local minima should correspond to bar edges. One of these minima can be seen around x = 1000 m and is indicated with an arrow in Figure A.5. To ensure that the lowest option is chosen as the bar edge, the function *minimum_finder* is written, searching for a local minimum within 20 m.

A.6 Improving the results

Altogether a number of 6853 bars could be located in the first round, consisting of a landward and seaward position and a crest position. By means of manual inspection profiles were selected, where the found bar locations did not deliver satisfying results. A number of 877 transects were selected, containing 1156 defects:

- Existing bars had to be combined (76 bars created)
- One or more sides of the bar had to be displaced (539 translations)
- 259 bars were wrong and had to be deleted
- At 71 locations an extra bar was found
- The program written for the first round, was not able to find terraces. With a special function, 169 terraces could be located.
- For 42 profiles all bars had to be defined manually, delivering 78 more bars.

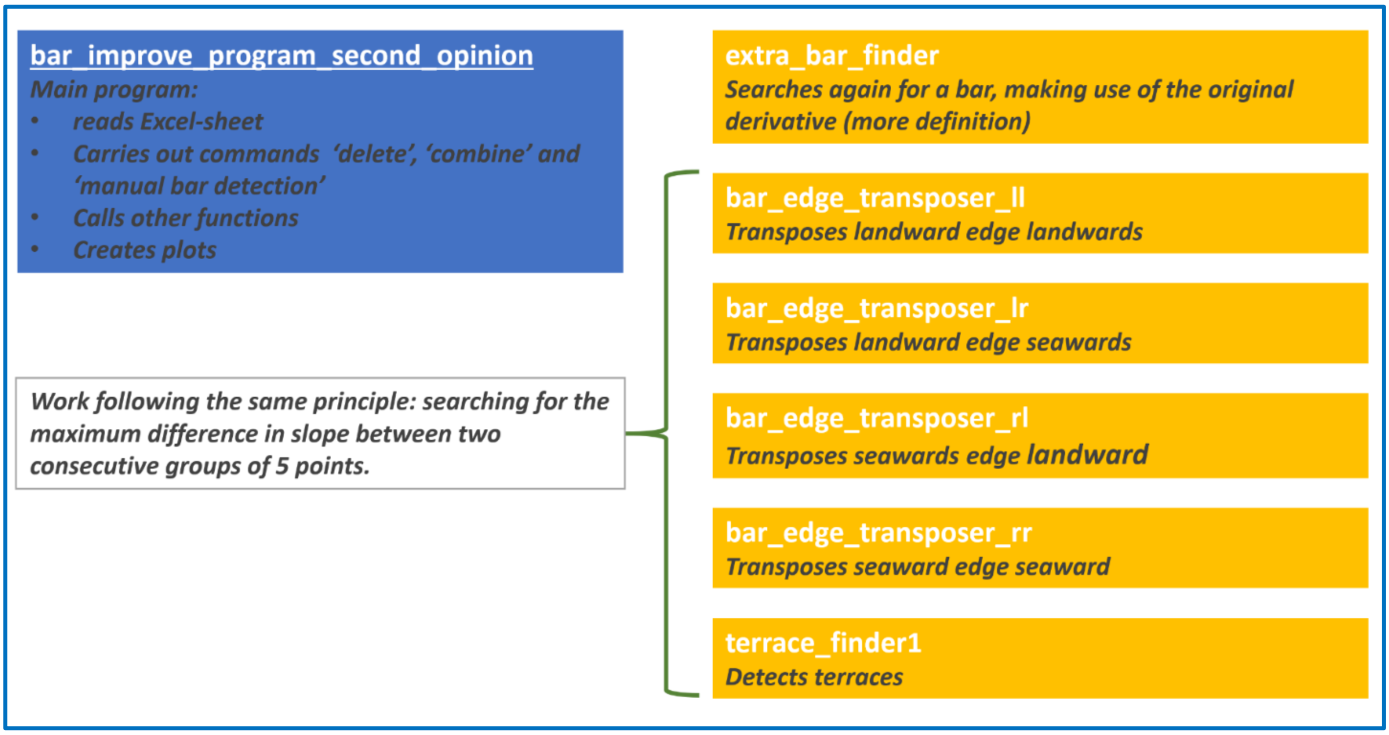


Figure A.6 Schematized overview of all functions involved in the second phase of bar detection.

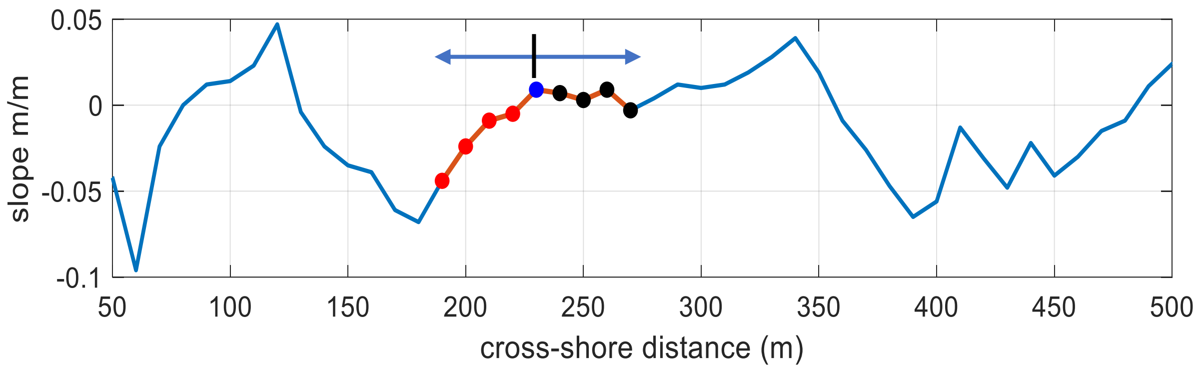


Figure A.7 The new principle of bar edge detection. The purpose of this strategy is to find the location where the difference between the points left and right of the studied point (blue in this example) is maximum.

In Figure A.6 the structure of the second phase is shown. For this phase an excel sheet containing all the wrong transects, was created (Figure A.2), which was used as a starting point for this section. In an attempt to improve the results of the first phase, six new functions were created. First of all, a function that could locate bars that were not found during the first round was created, called *extra_bar_finder*. This function searches within the correct part of the profile for a new extra bar. This function accounts for bars, which have less regular shapes, such as long flanks or terrace-like shapes.

The other functions work based on the same principle. Instead of looking for peaks, the largest contrast is determined. By making use of loops, for every location the difference in the slope is determined between the four landward points and the four seaward points (Figure A.7). The maximum position is saved and represents the correct bar edge. In Figure A.8 examples are presented of improved results after the second phase.

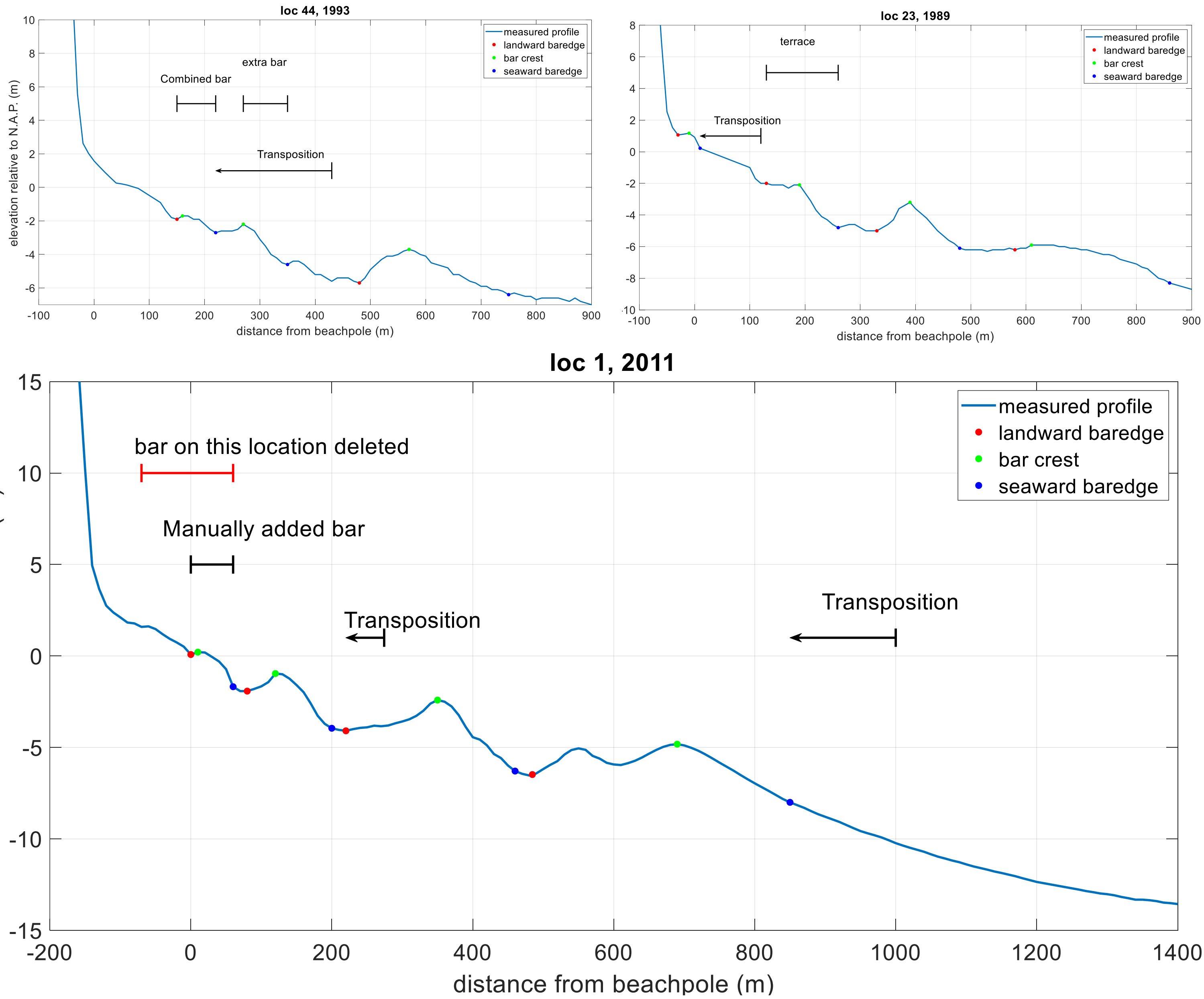
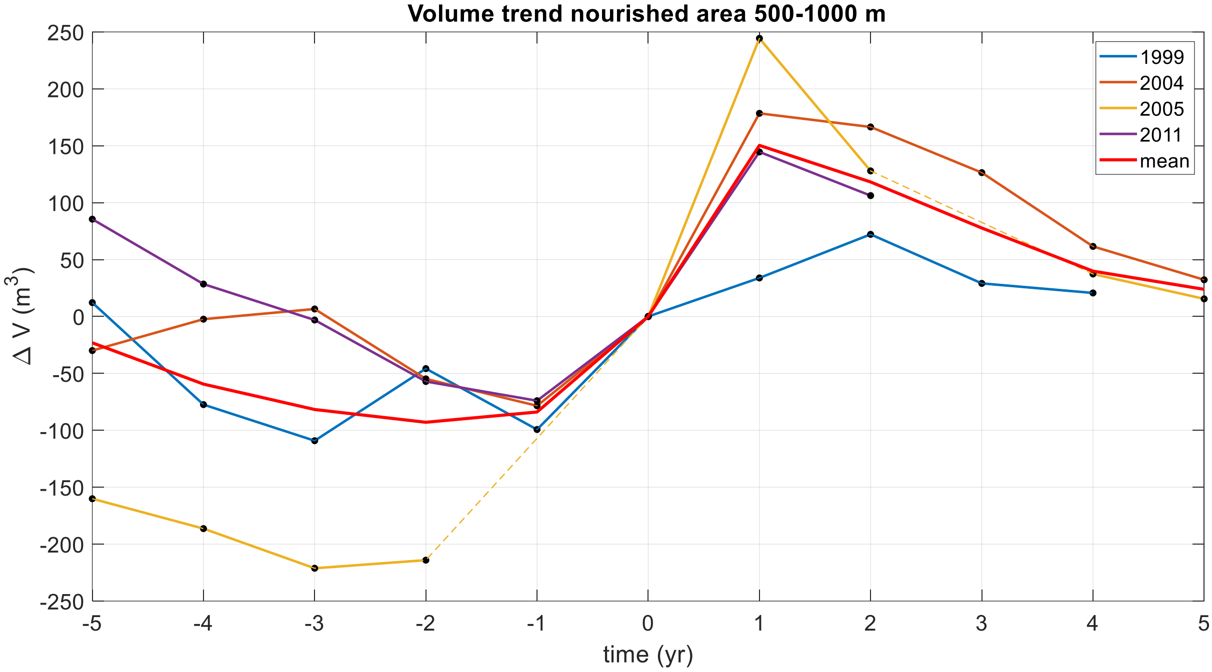
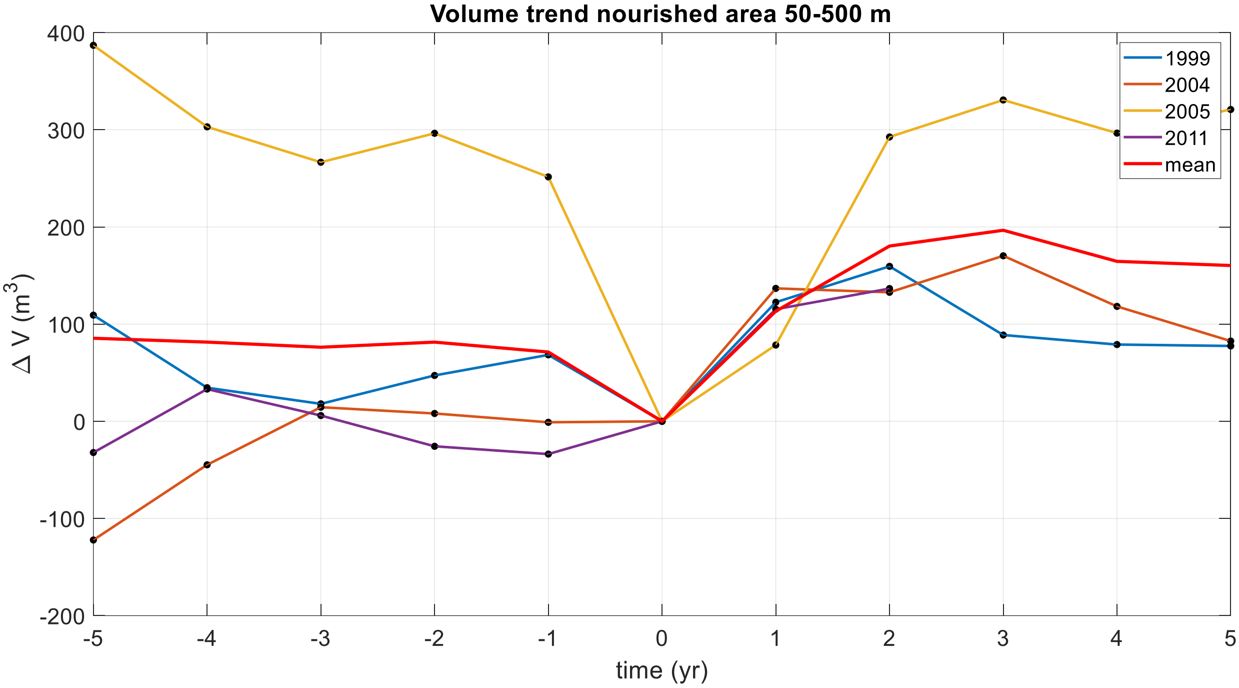


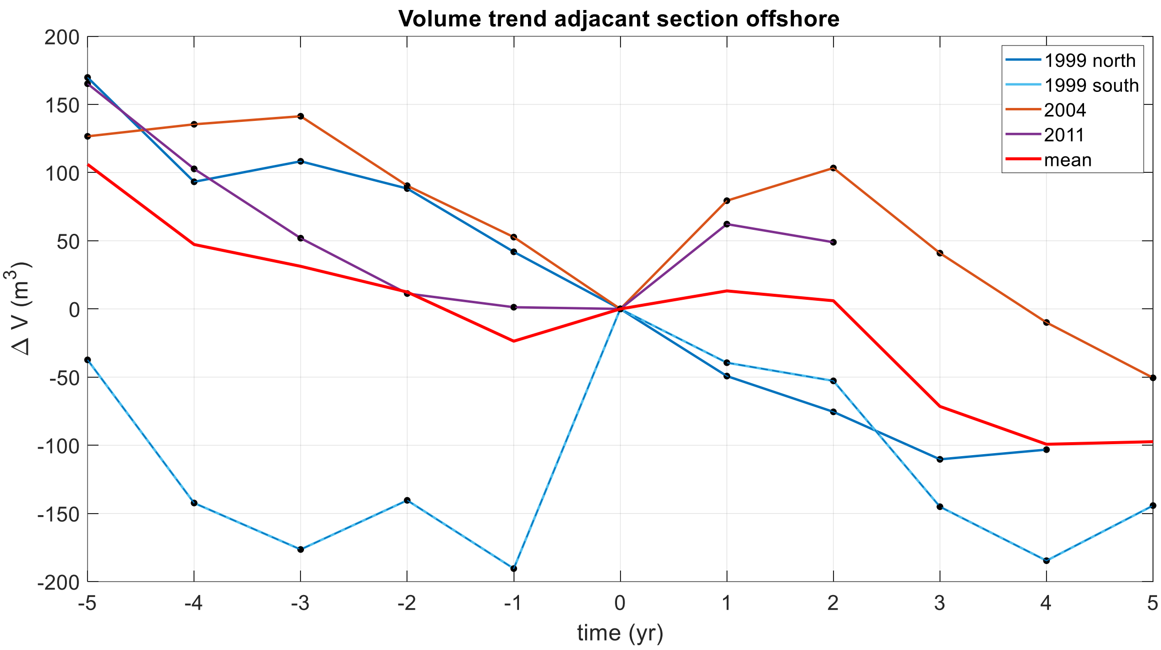
Figure A.8 Corrections resulting from the second phase. Corrections consist of: Bar edge transpositions, deletion of bars, manually added bars, terraces, extra bars and combined bars.

Appendix B Sedimentation trends after implementation of nourishments

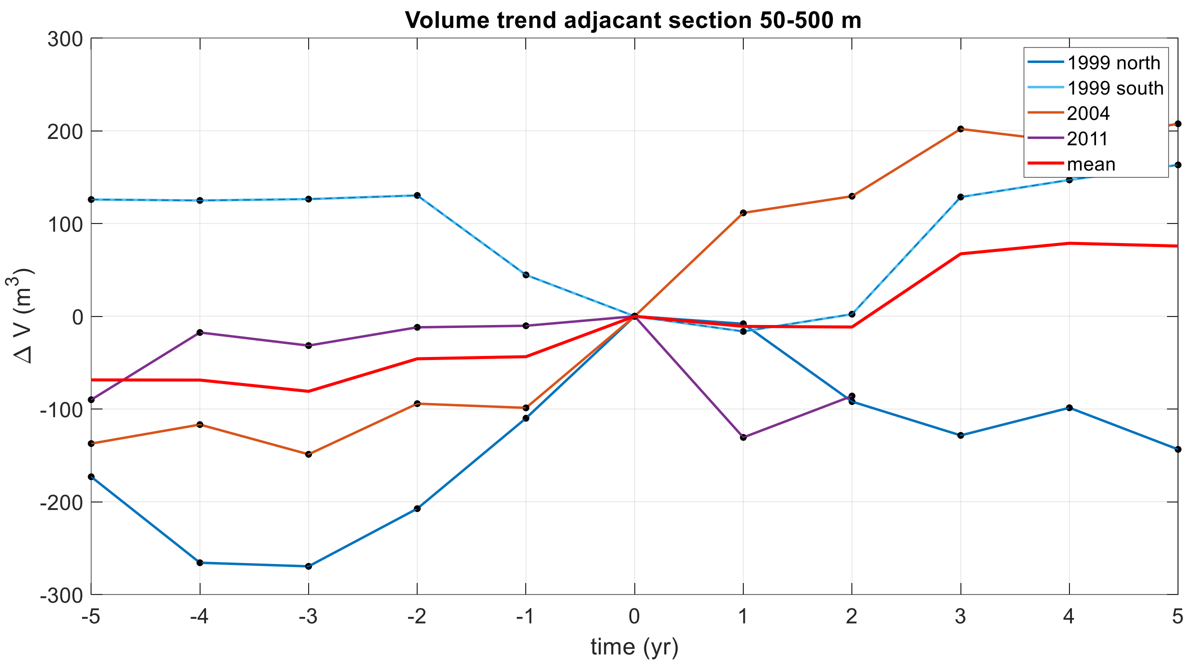
B.1 Figures used for determination of maximum positive sedimentation peak after nourishing





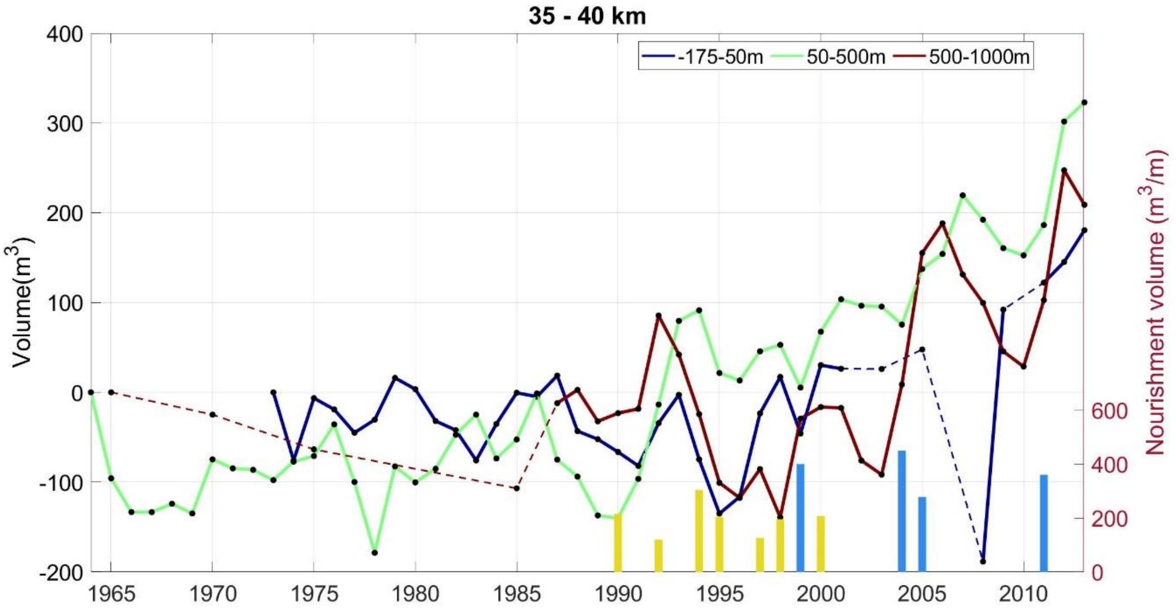


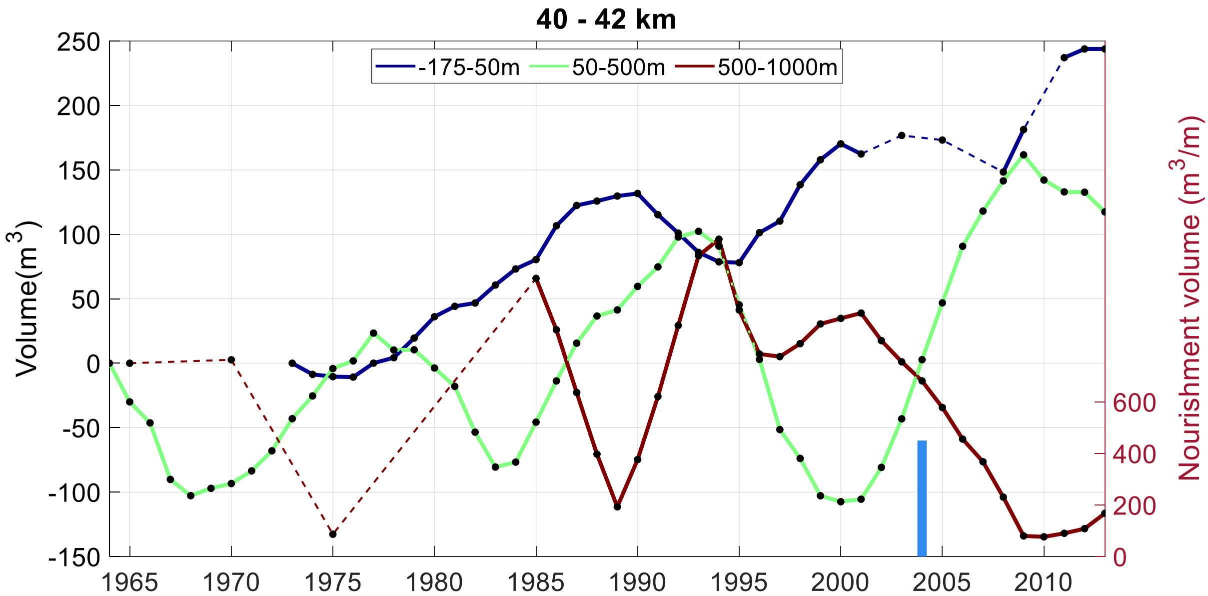
Volume trend adjacant section offshore
200
150
100
50
0
-50
-100
-150
-200
-5
-4
-3
-2
-1
0
1
2
3
4
5
time (yr)
Δ V (m3)
1999 north
1999 south
2004
2011
mean

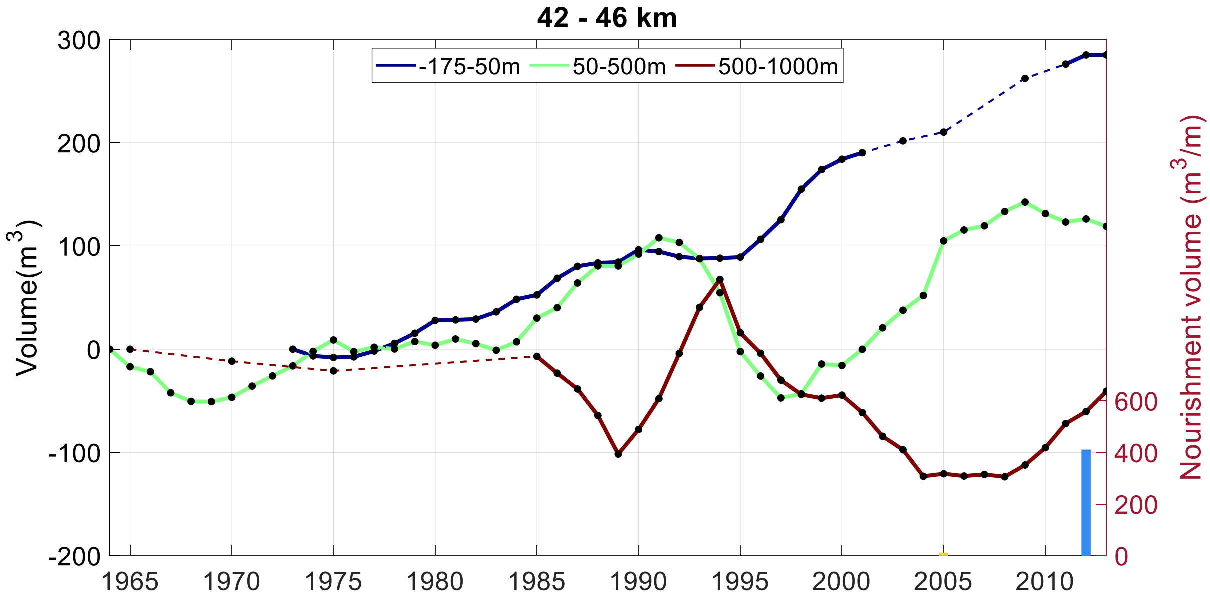


Volume trend adjacant section 50-500 m
300
200
100
0
-100
-200
-300
-5
-4
-3
-2
-1
0
1
2
3
4
5
time (yr)
Δ V (m3)
1999 north
1999 south
2004
2011
mean

B.2 Figures used for finding the beginning of positive influence on the beach/dune system as result of nourishing



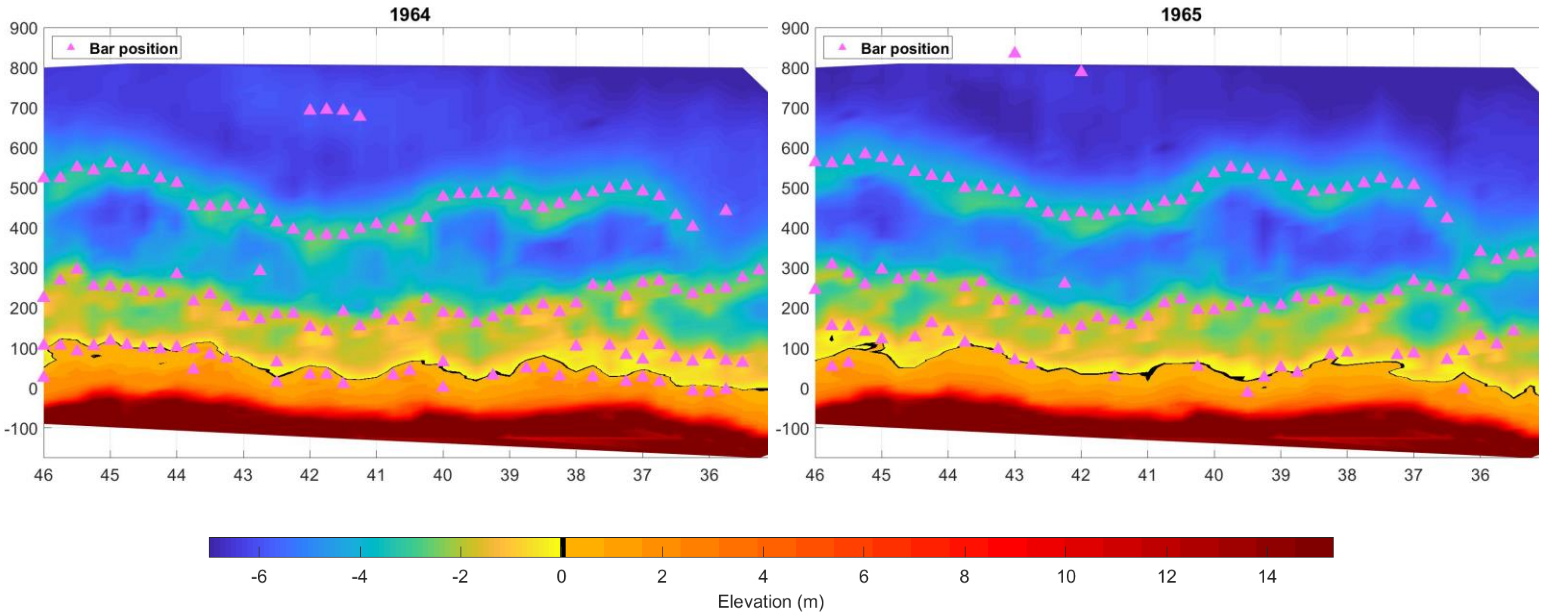


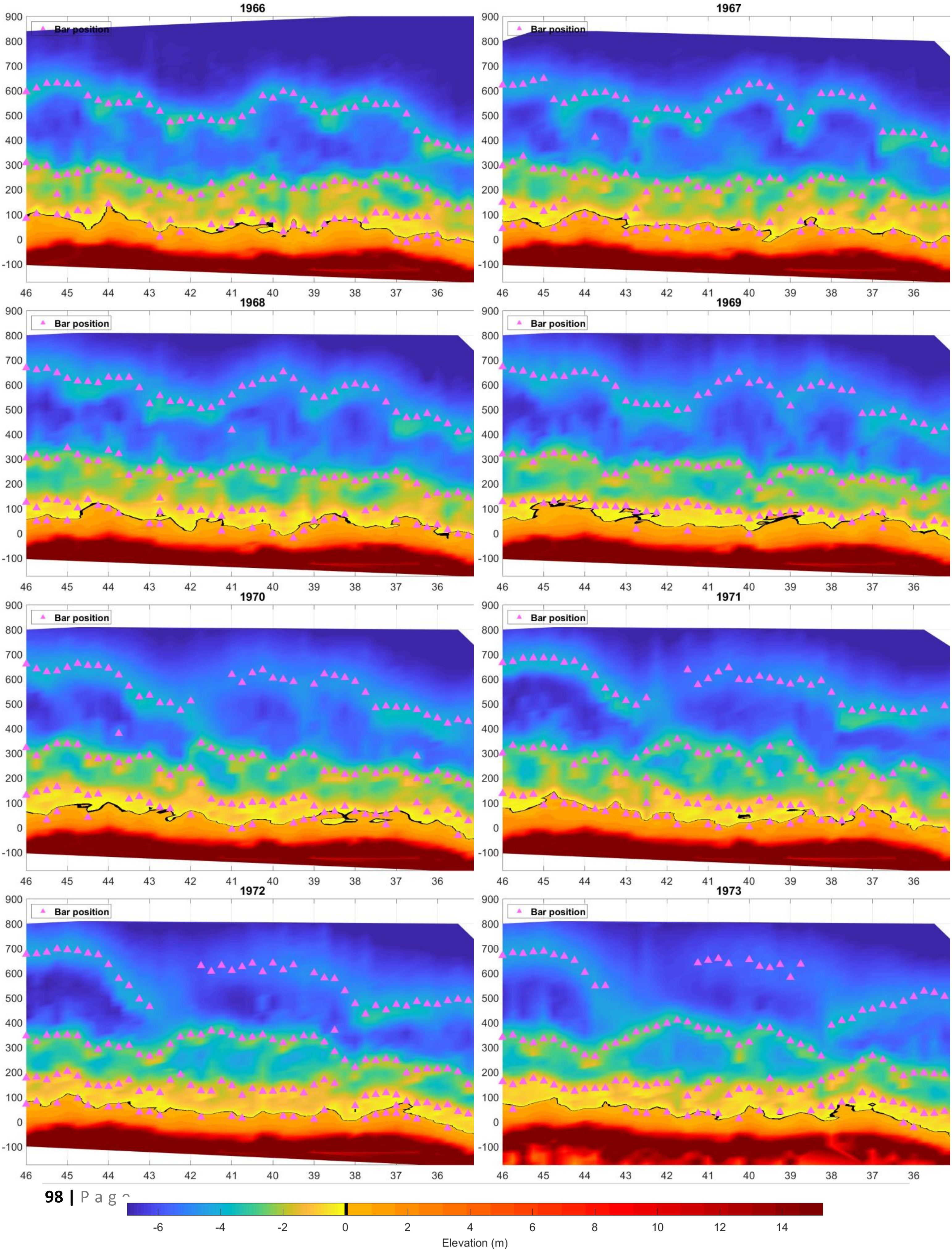


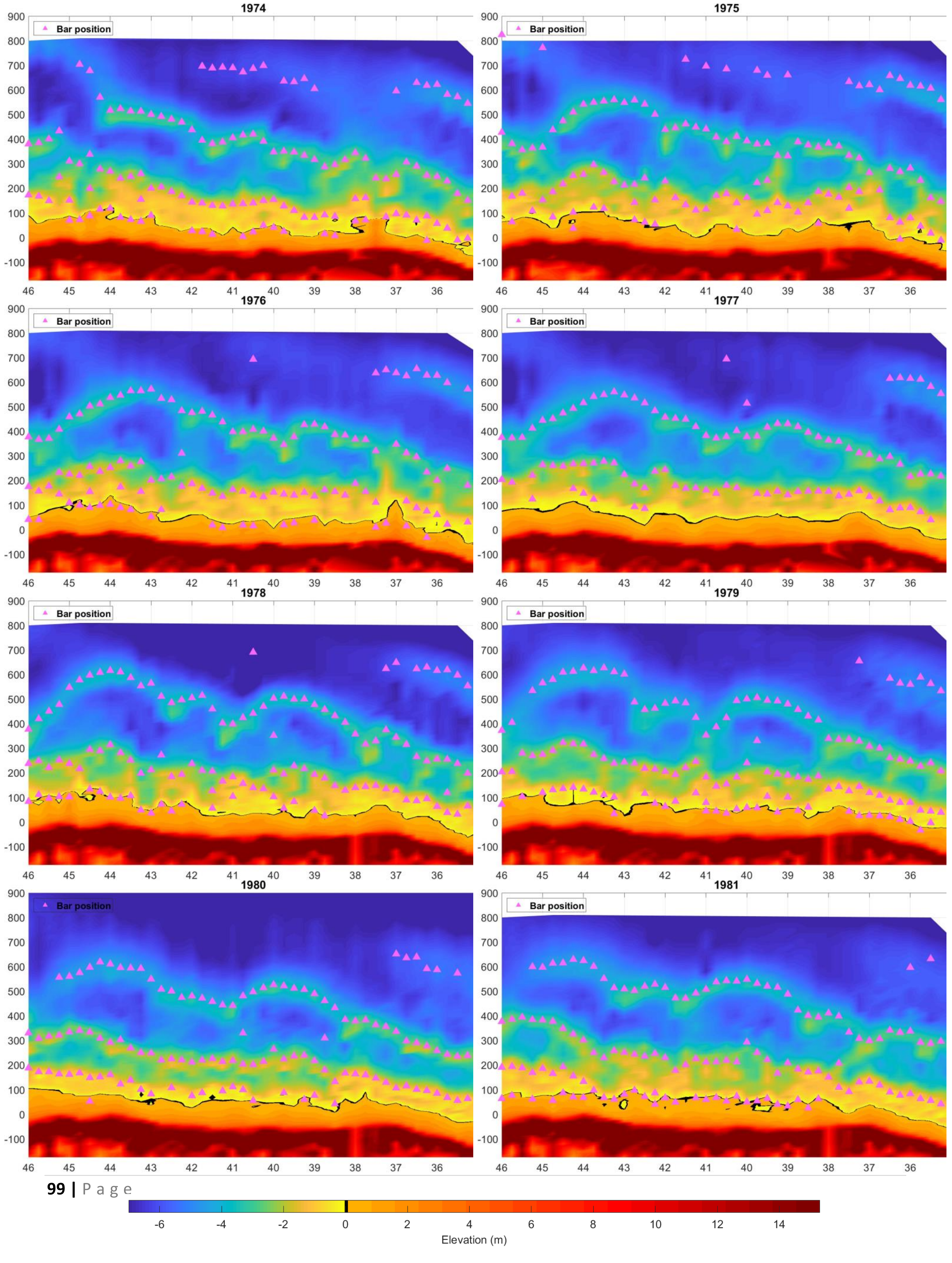
Appendix C Digital Elevation Models

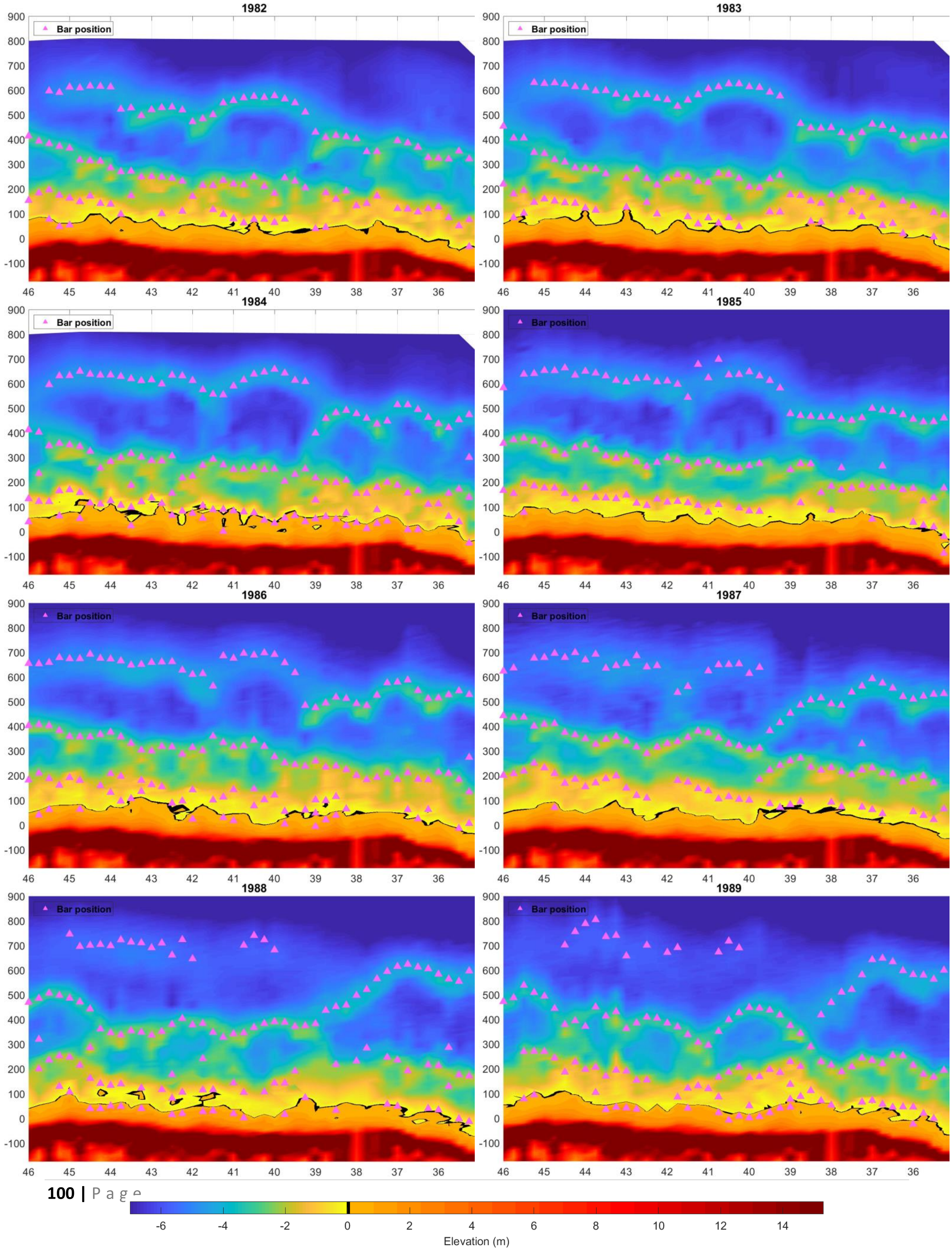
In this appendix all Digital Elevation Models created for this study are presented. In order to save space, the X and Y labels were removed from the graph.

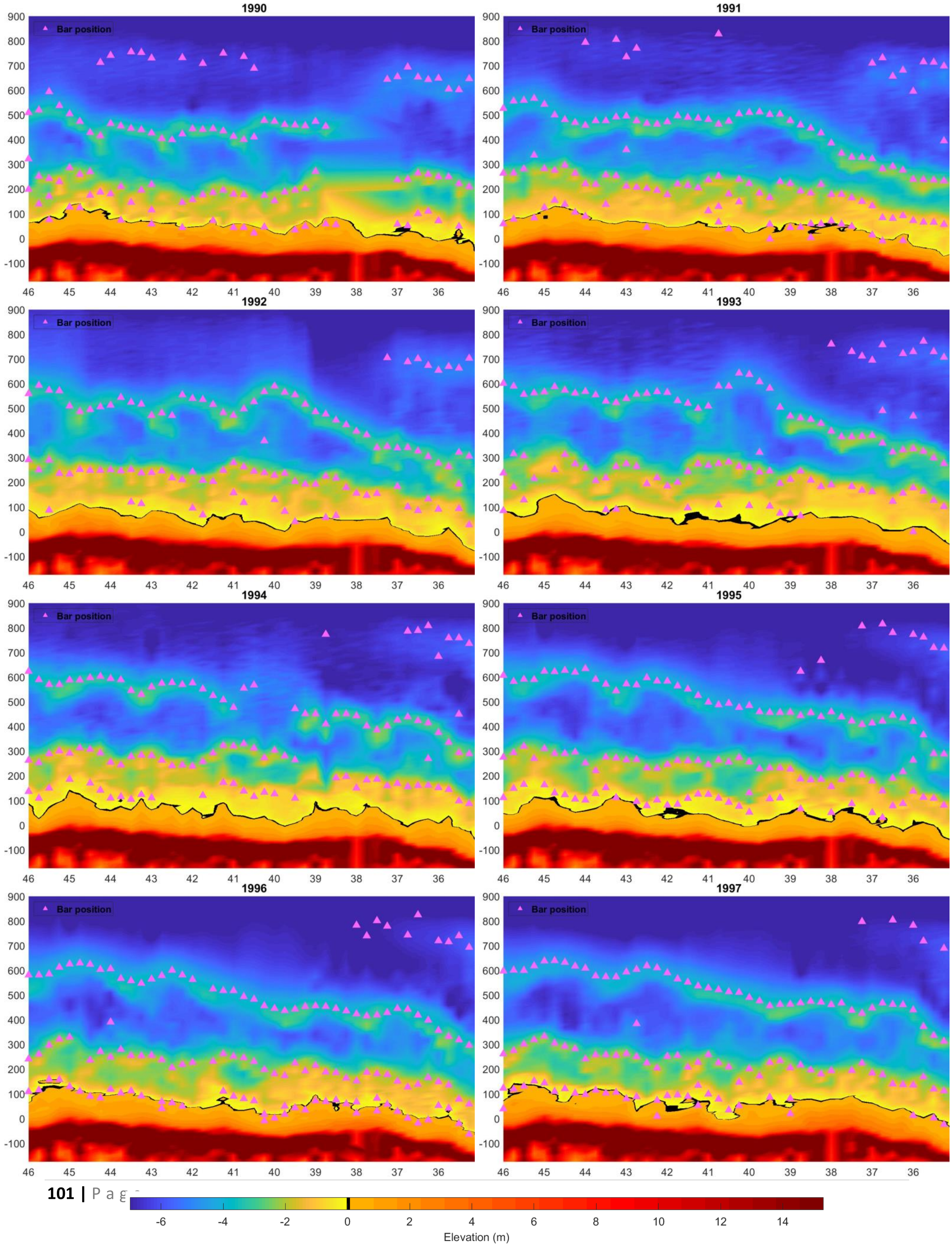
X-axis: distance from Den Helder (km)
Y-axis: distance with respect to the beachpole (m)

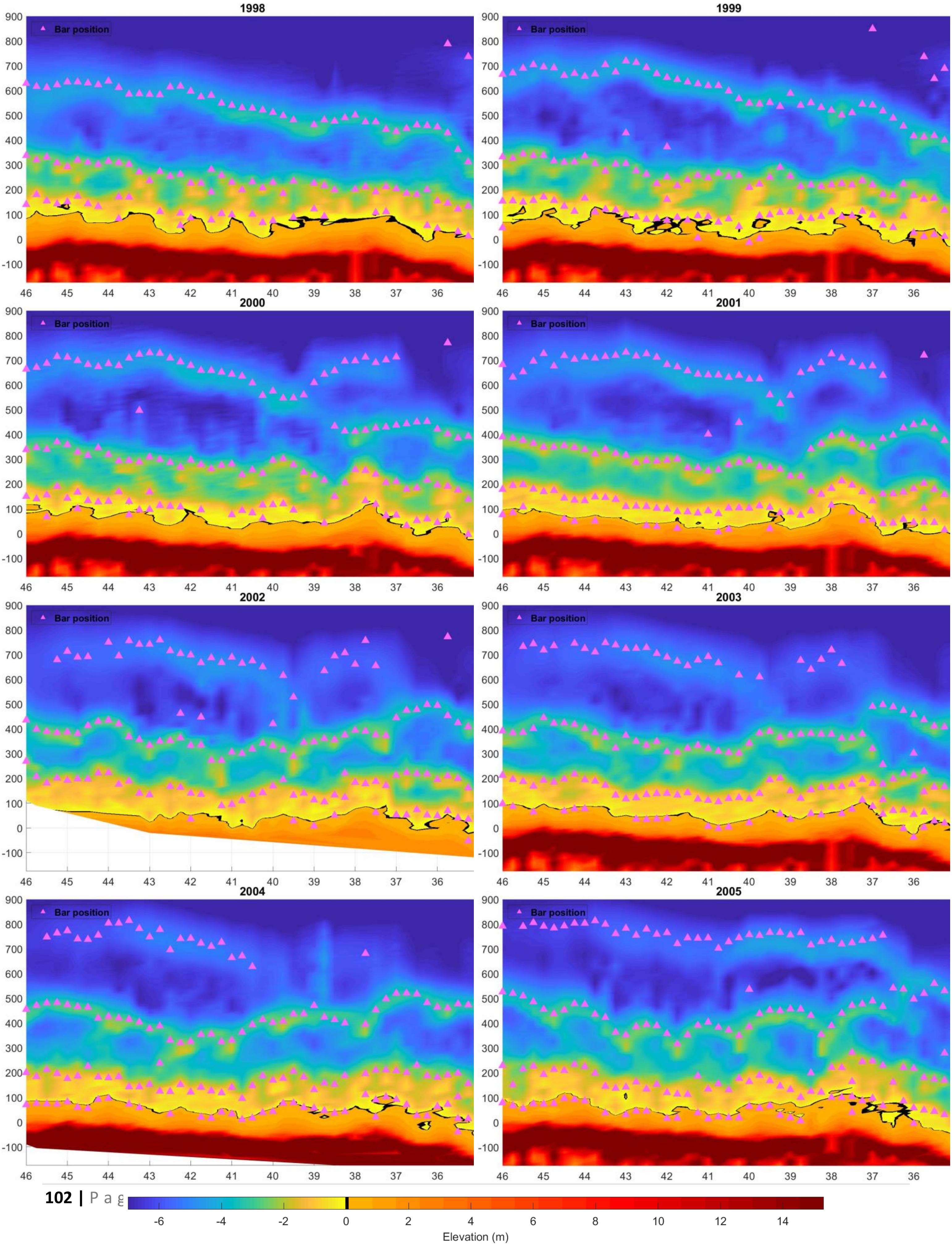


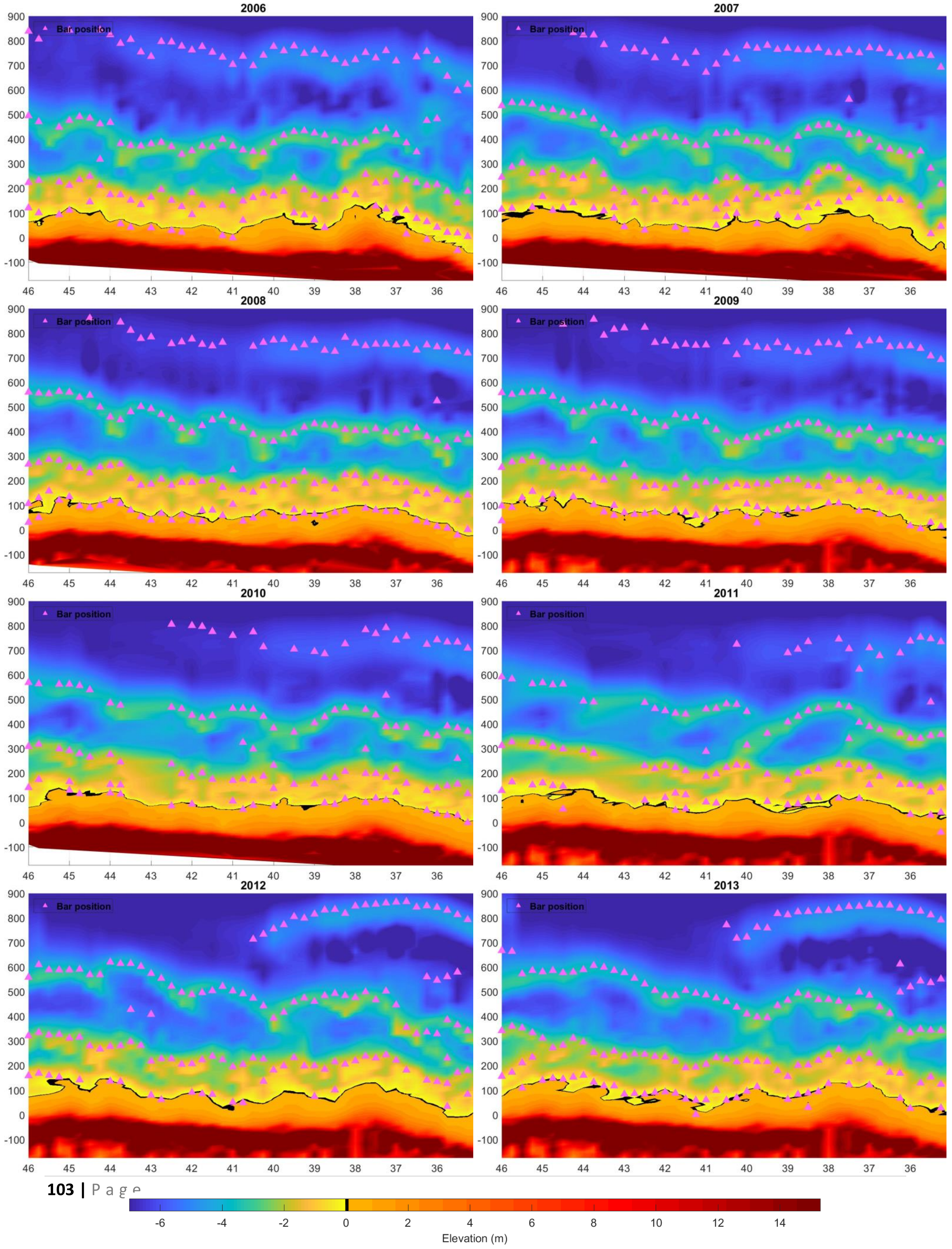

1966
1967
1968
1969
1970
1971
1972
1973
Bar position
900
800
700
600
500
400
300
200
100
0
-100
46
45
44
43
42
41
40
39
38
37
36
-6
-4
-2
0
2
4
6
8
10
12
14
Elevation (m)


1974
1975
1976
1977
1978
1979
1980
1981
Bar position
900
800
700
600
500
400
300
200
100
0
-100
46
45
44
43
42
41
40
39
38
37
36
-6
-4
-2
0
2
4
6
8
10
12
14
Elevation (m)


1982
1983
1984
1985
1986
1987
1988
1989
Bar position
900 800 700 600 500 400 300 200 100 0 -100
46 45 44 43 42 41 40 39 38 37 36
-6 -4 -2 0 2 4 6 8 10 12 14
Elevation (m)


1990
1991
1992
1993
1994
1995
1996
1997
Bar position
Elevation (m)

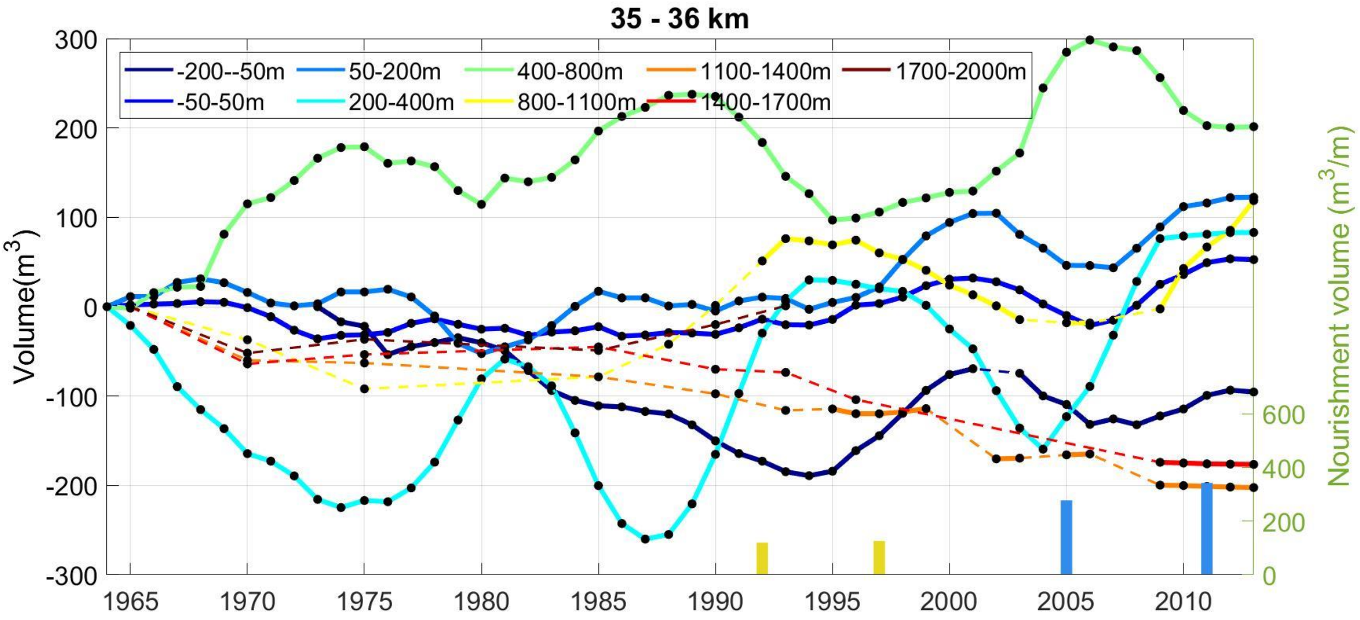

1998
1999
2000
2001
2002
2003
2004
2005
Bar position
900
800
700
600
500
400
300
200
100
0
-100
46
45
44
43
42
41
40
39
38
37
36
-6
-4
-2
0
2
4
6
8
10
12
14
Elevation (m)

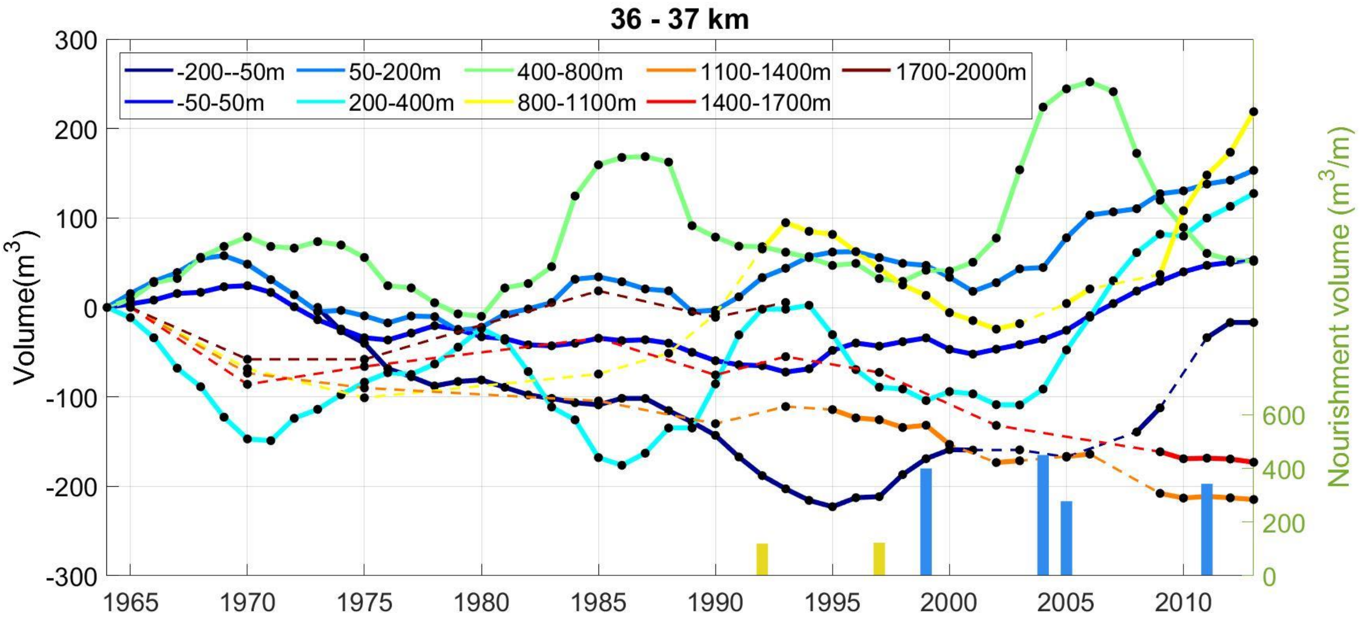

2006
2007
2008
2009
2010
2011
2012
2013
Bar position
900
800
700
600
500
400
300
200
100
0
-100
46
45
44
43
42
41
40
39
38
37
36
-6
-4
-2
0
2
4
6
8
10
12
14
Elevation (m)

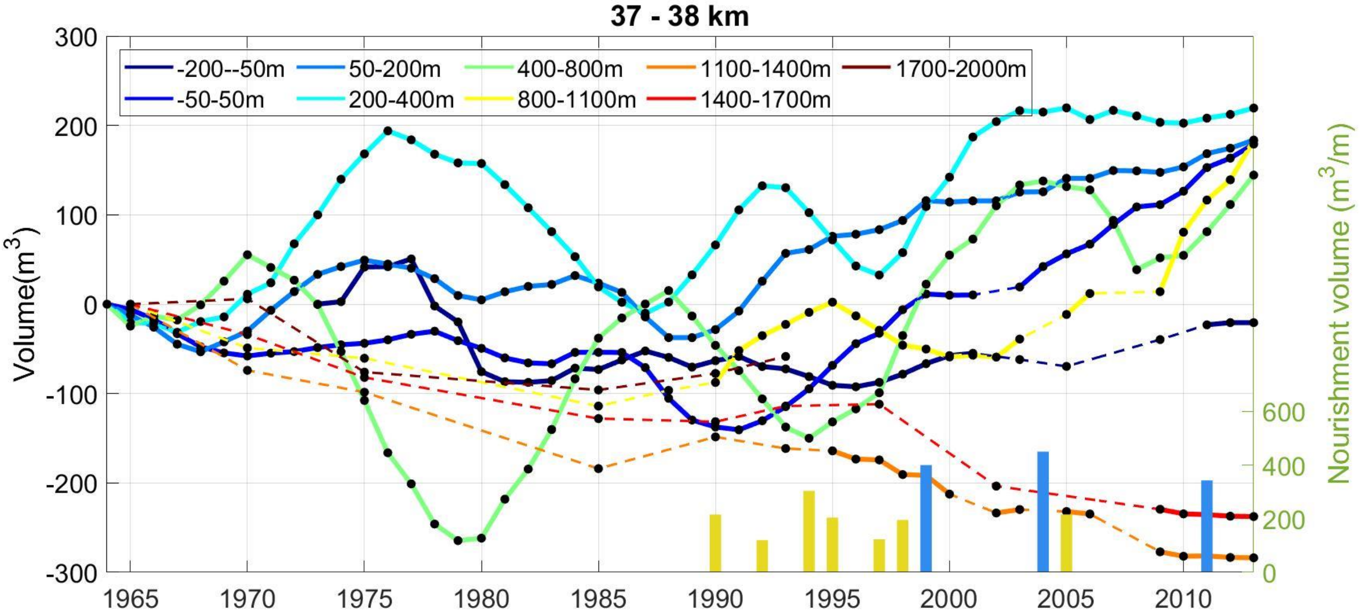
Appendix D Longshore volume trends

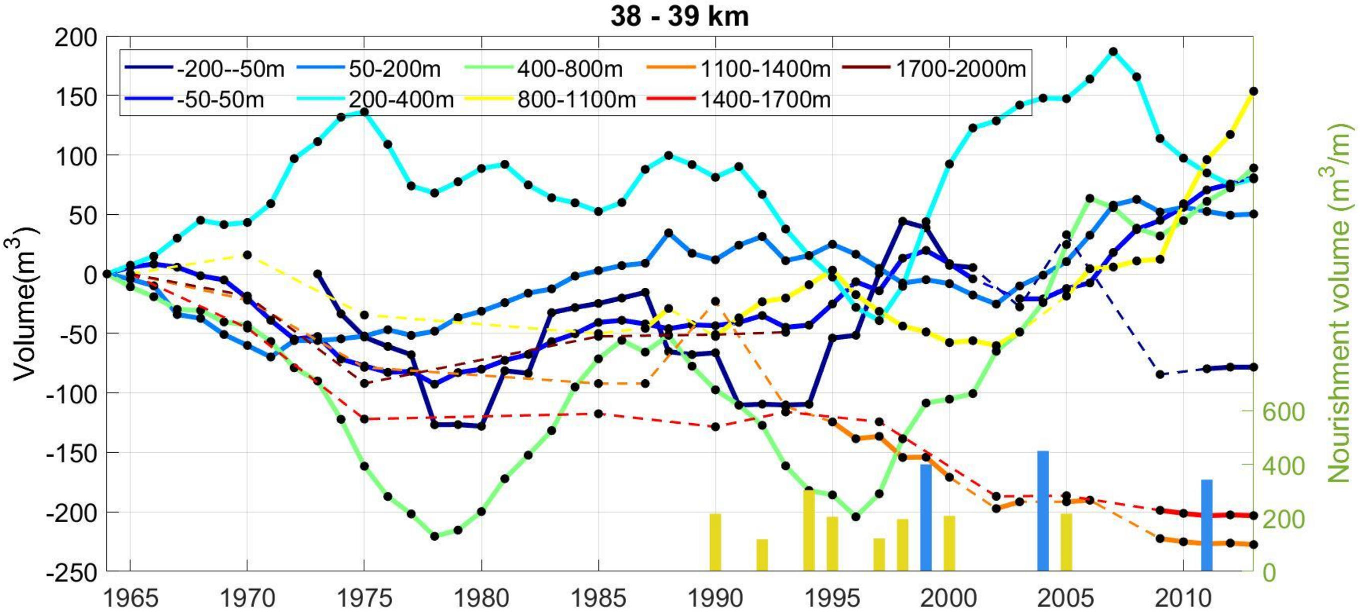
Overview of volume trends within 9 cross-shore section for the period 1965-2013 for various longshore sections. The relative volumes (m^3/m) of nourishments executed within the specific longshore section are plotted in the lower part of the figure, with respect to the right y-axis. Yellow bars resemble beach nourishments and blue bars shoreface nourishments. In section D.1 the longshore measurement interval is 1 km. In section D.2 the entire nourished section is compared to the entire unnourished section.

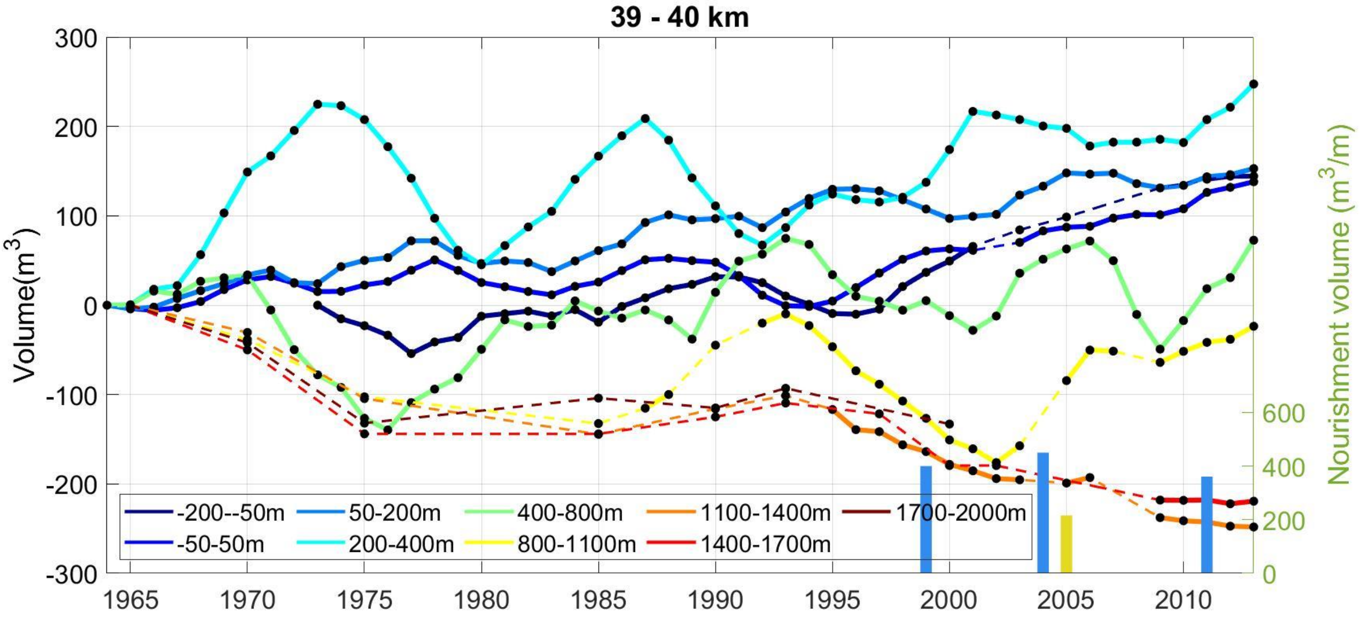
D.1 Per longshore kilometer

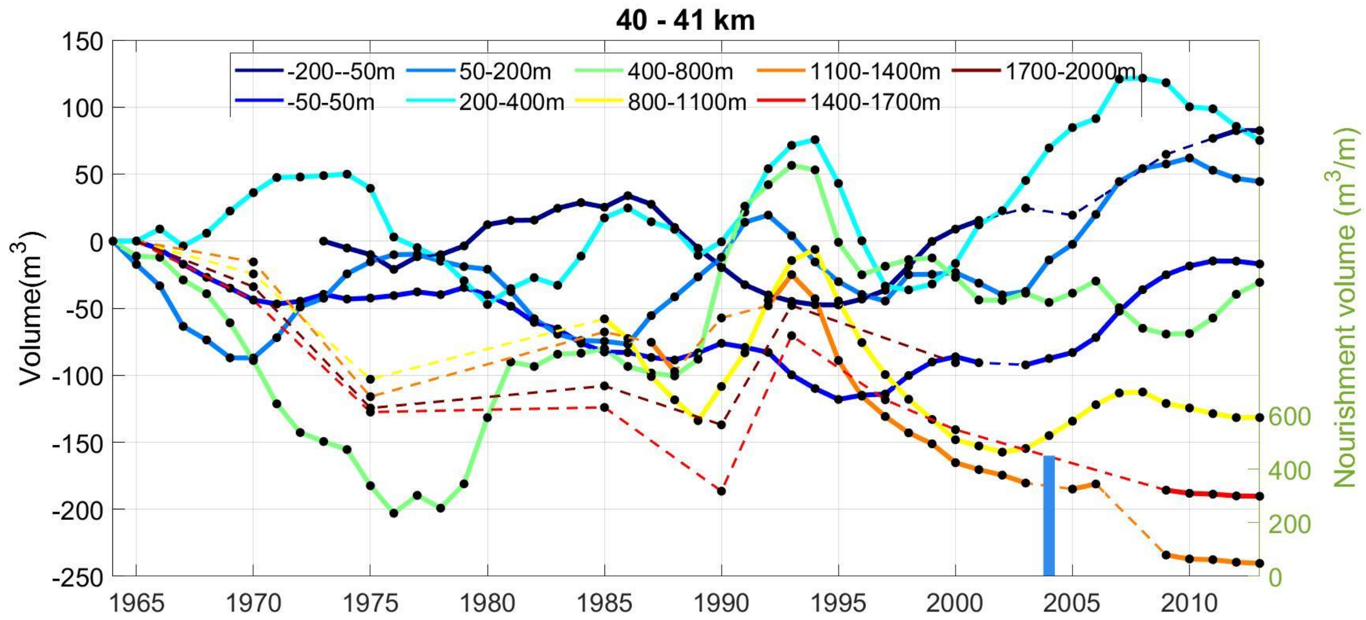


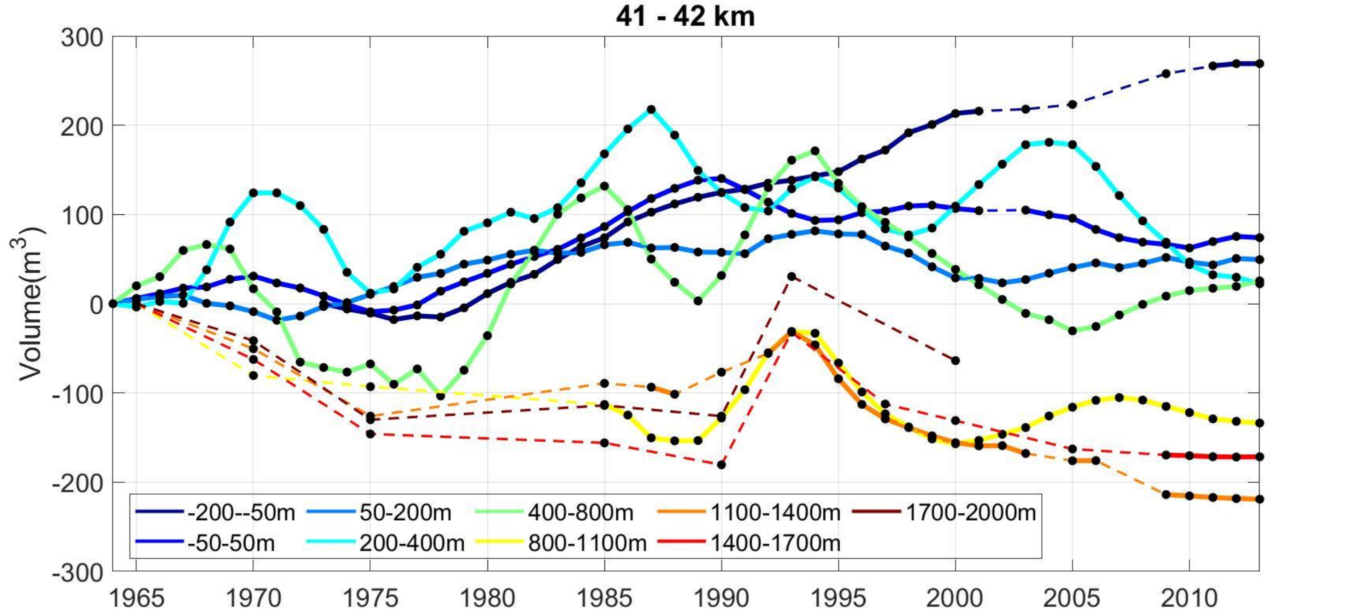


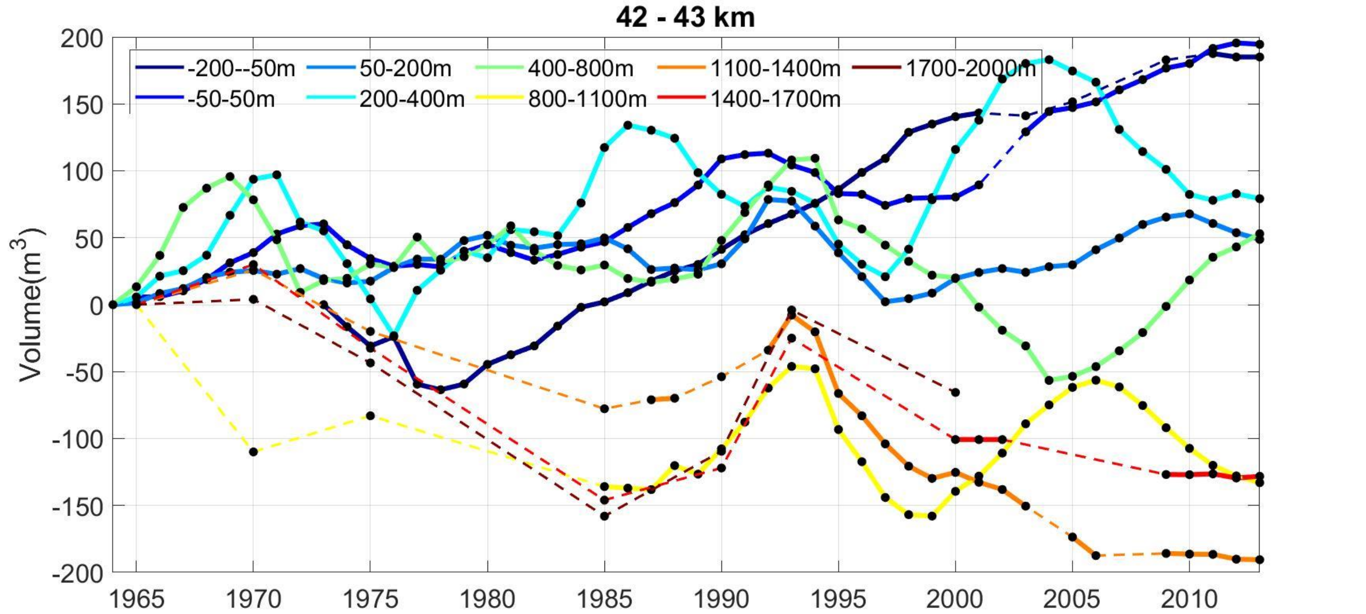

37 - 38 km
-200--50m
50-200m
400-800m
1100-1400m
1700-2000m
-50-50m
200-400m
800-1100m
1400-1700m
Volume(m3)
Nourishment volume (m3/m)

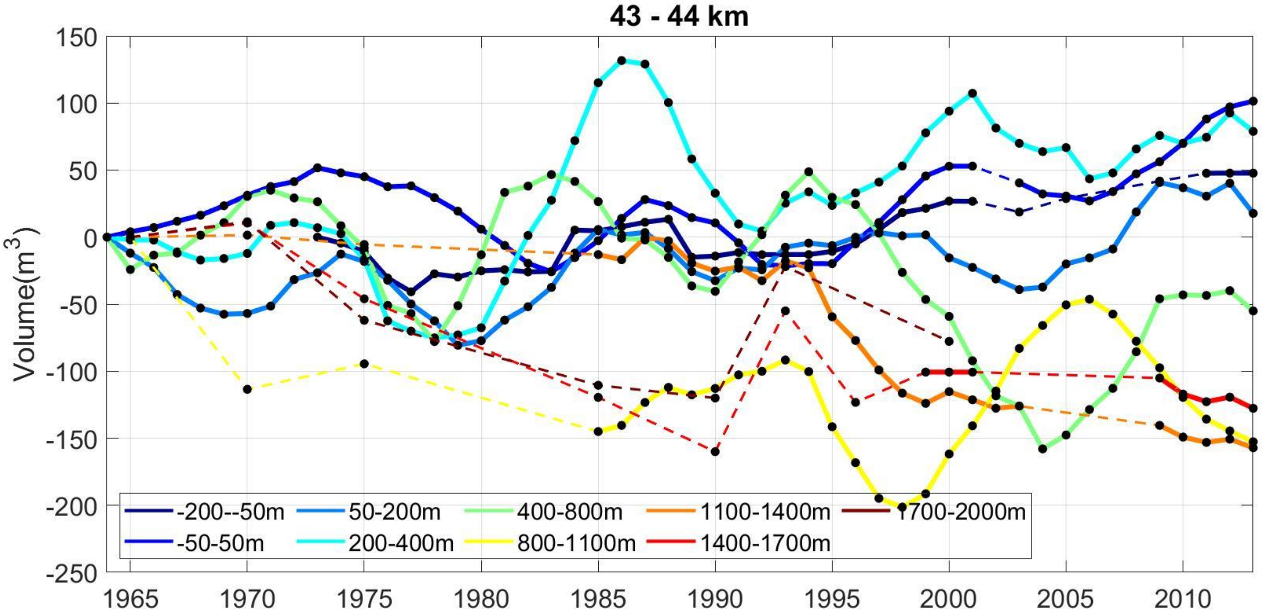

38 - 39 km
-200--50m
50-200m
400-800m
1100-1400m
1700-2000m
-50-50m
200-400m
800-1100m
1400-1700m
Volume(m3)
Nourishment volume (m3/m)

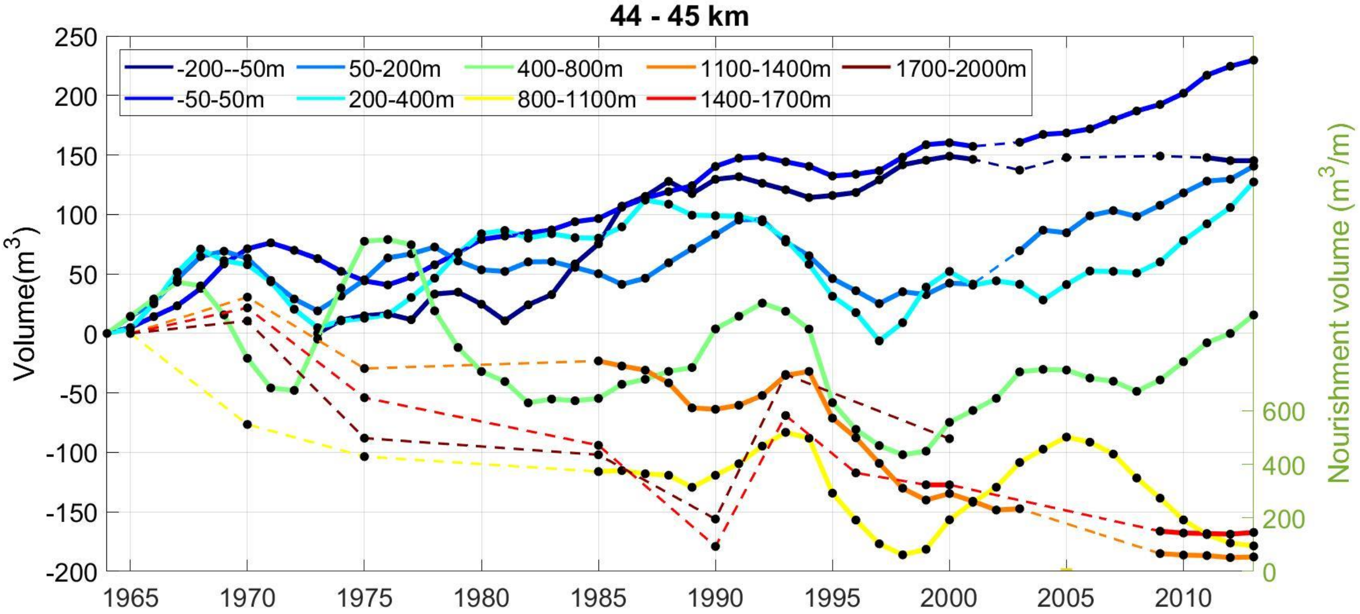

39 - 40 km
-200--50m
50-200m
400-800m
1100-1400m
1700-2000m
-50-50m
200-400m
800-1100m
1400-1700m
Volume(m3)
Nourishment volume (m3/m)

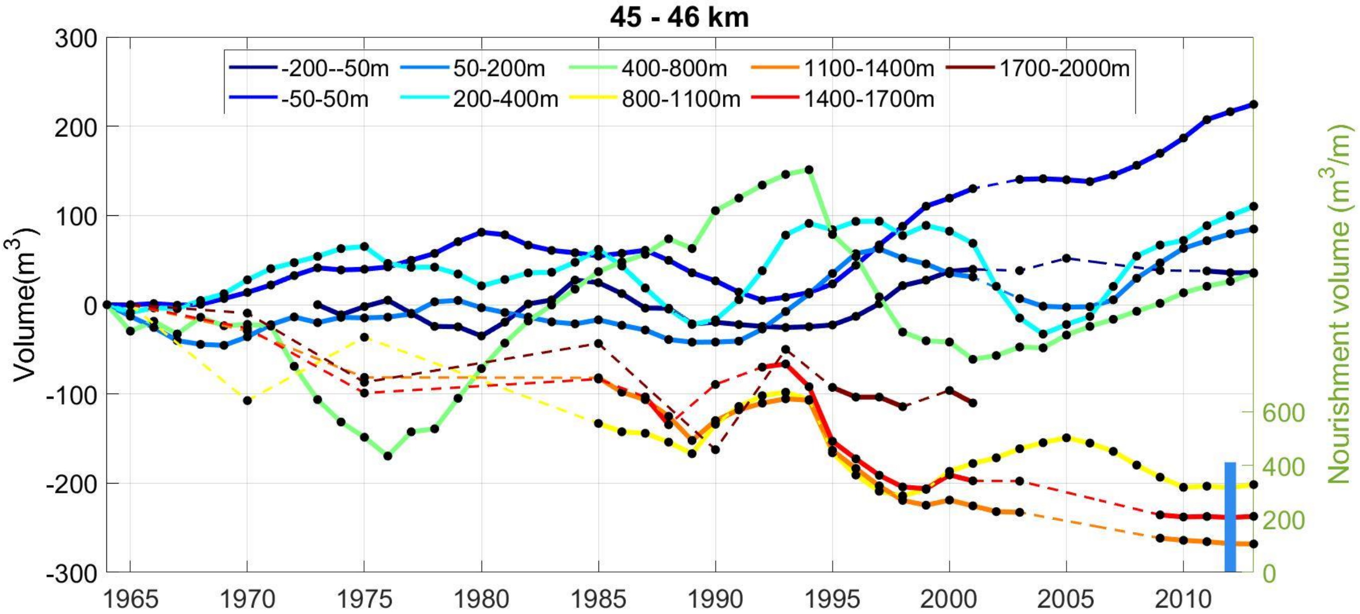

40 - 41 km
Volume(m3)
Nourishment volume (m3/m)
-200--50m
-50-50m
50-200m
200-400m
400-800m
800-1100m
1100-1400m
1400-1700m
1700-2000m


41 - 42 km
Volume(m3)
-200--50m
-50-50m
50-200m
200-400m
400-800m
800-1100m
1100-1400m
1400-1700m
1700-2000m


42 - 43 km
Volume(m3)
-200--50m
-50-50m
50-200m
200-400m
400-800m
800-1100m
1100-1400m
1400-1700m
1700-2000m

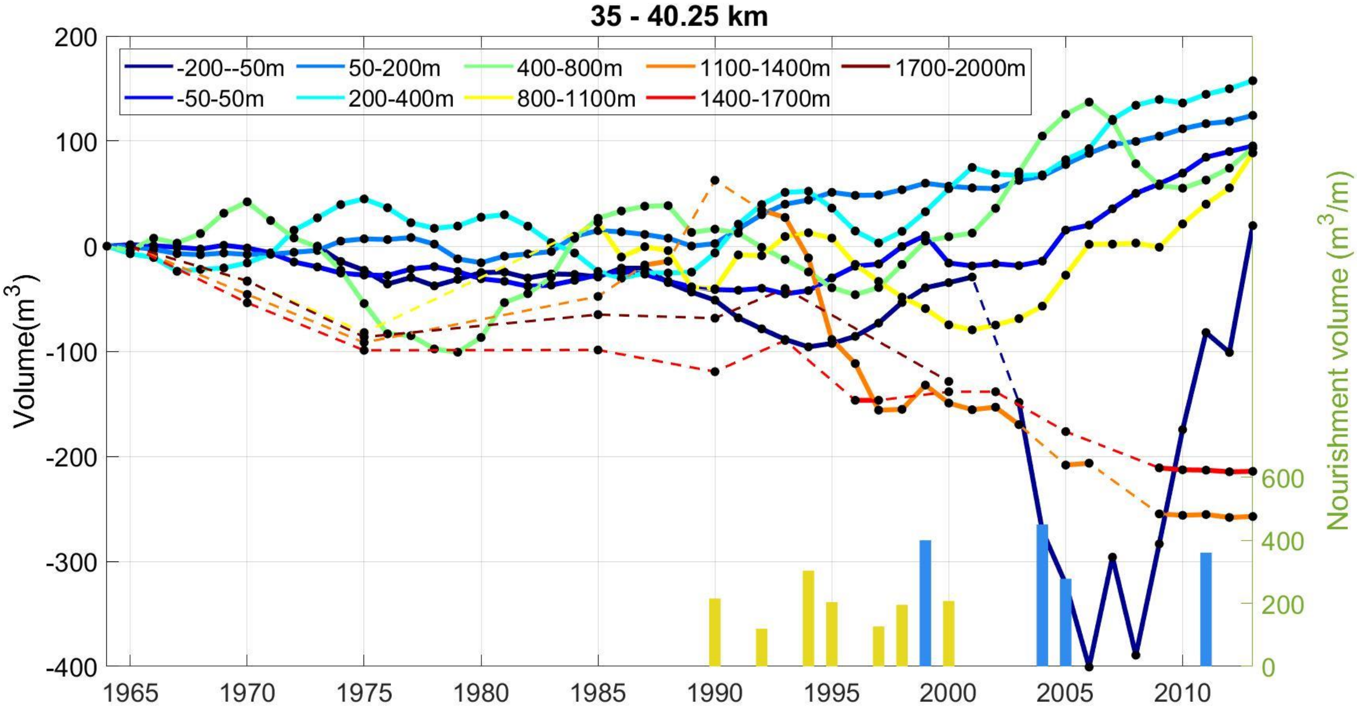

43 - 44 km
Volume(m3)
-200--50m
-50-50m
50-200m
200-400m
400-800m
800-1100m
1100-1400m
1400-1700m
1700-2000m


44 - 45 km
Volume(m3)
Nourishment volume (m3/m)
-200--50m
-50-50m
50-200m
200-400m
400-800m
800-1100m
1100-1400m
1400-1700m
1700-2000m

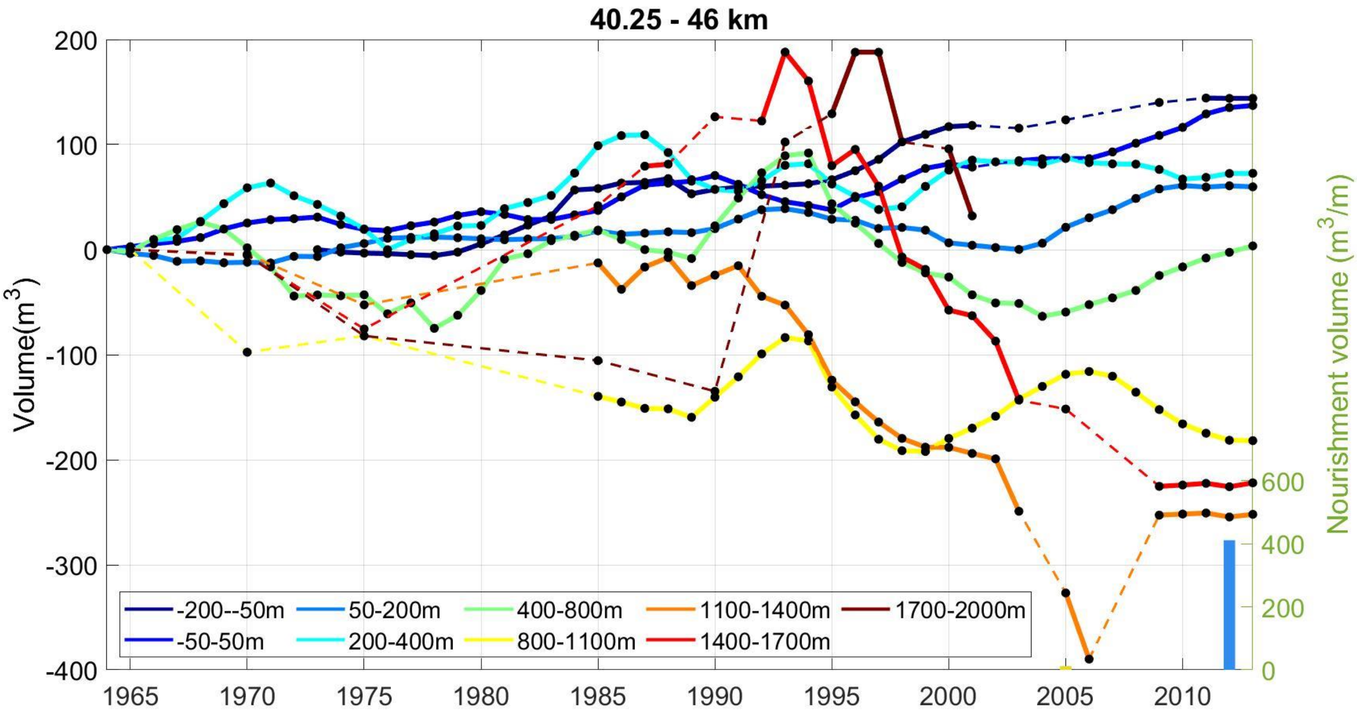

45 - 46 km
Volume(m3)
Nourishment volume (m3/m)
-200--50m
-50-50m
50-200m
200-400m
400-800m
800-1100m
1100-1400m
1400-1700m
1700-2000m

D.2 Nourished vs. Unnourished

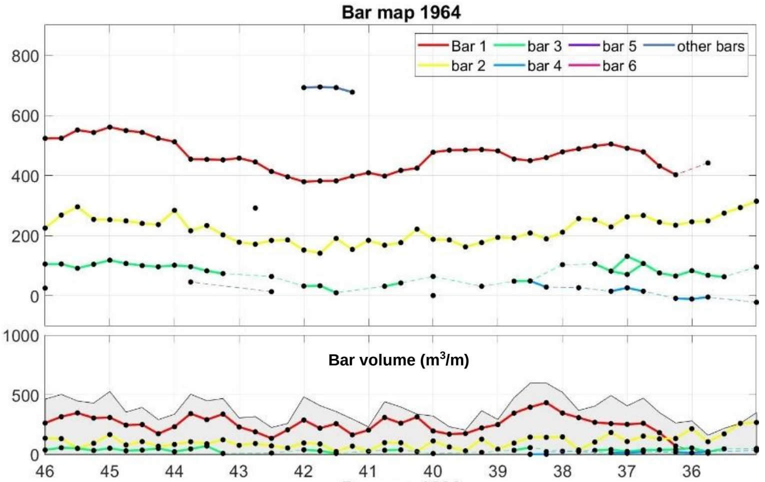
Nourished part:

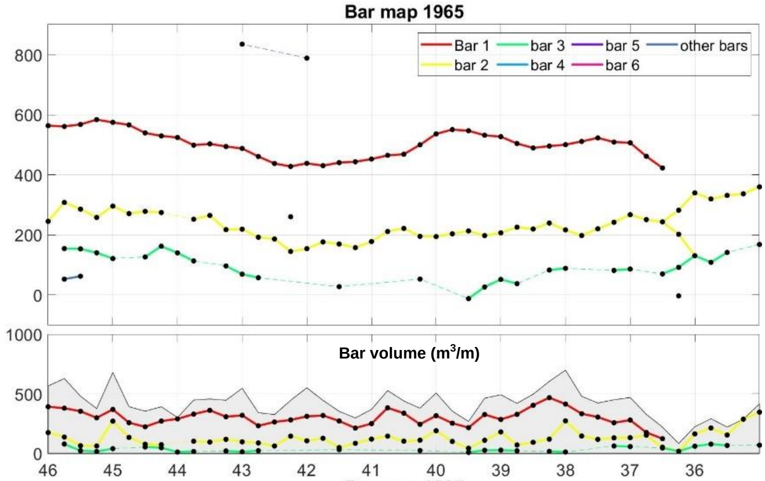


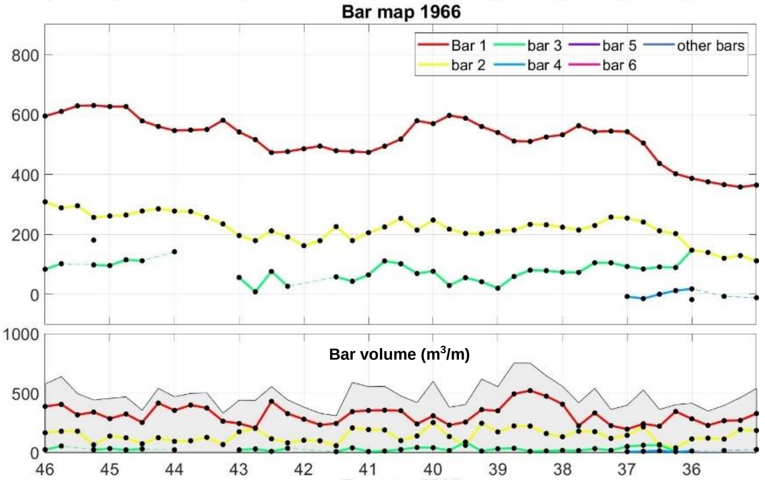
Unnourished part:

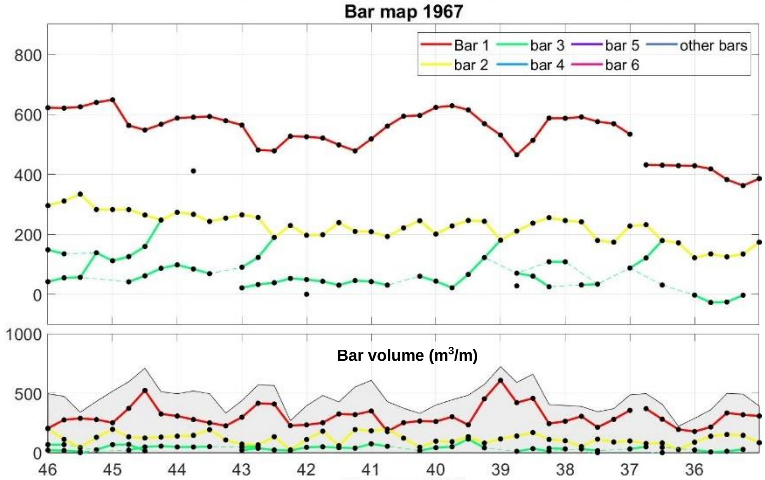


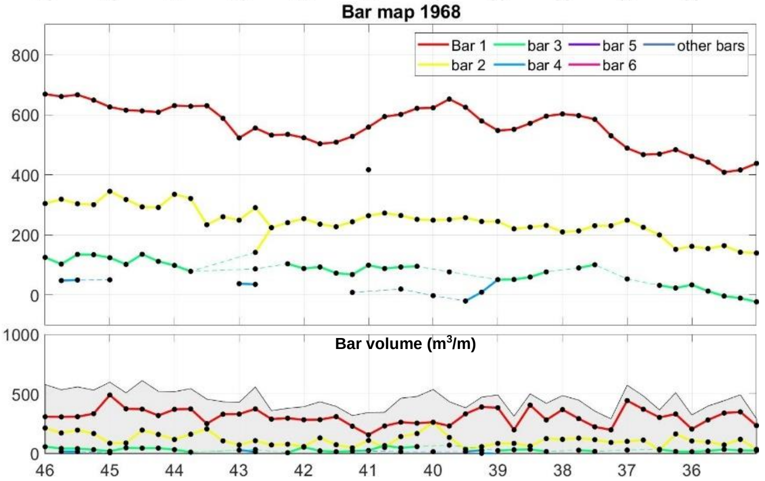
Appendix E Bar maps per year

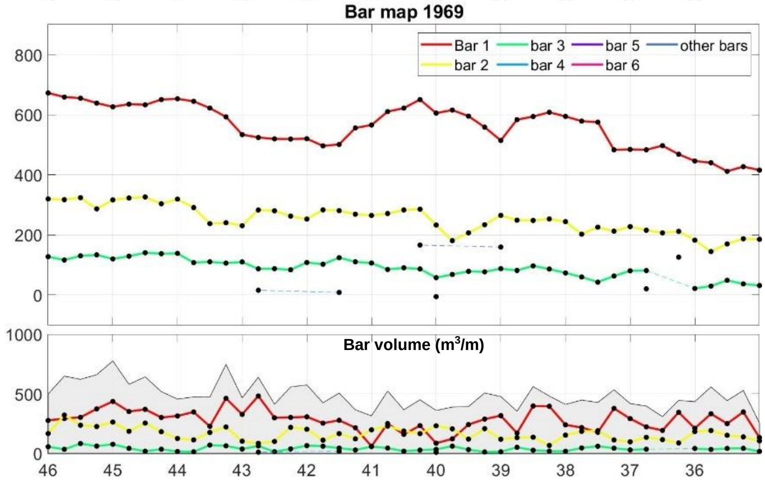


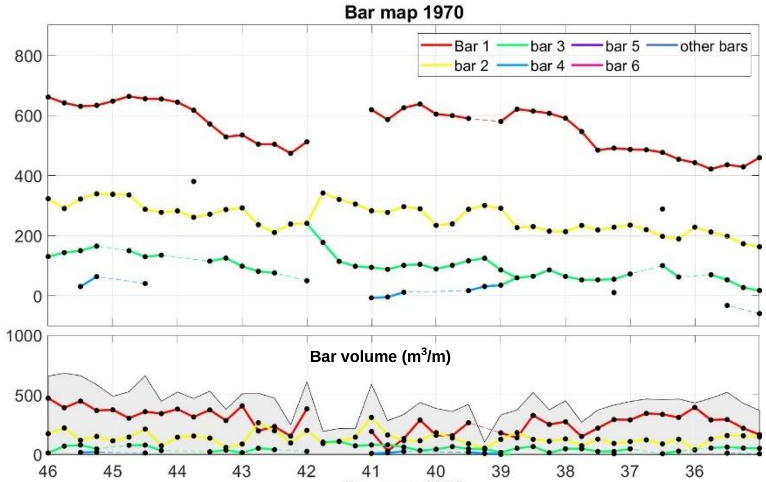


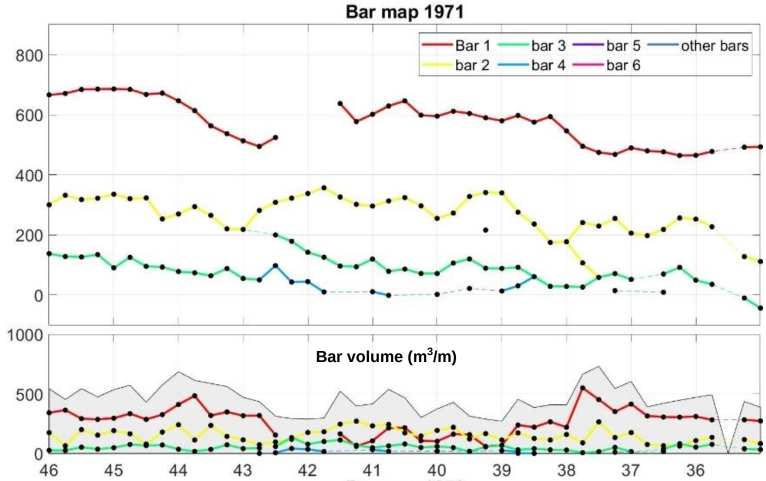


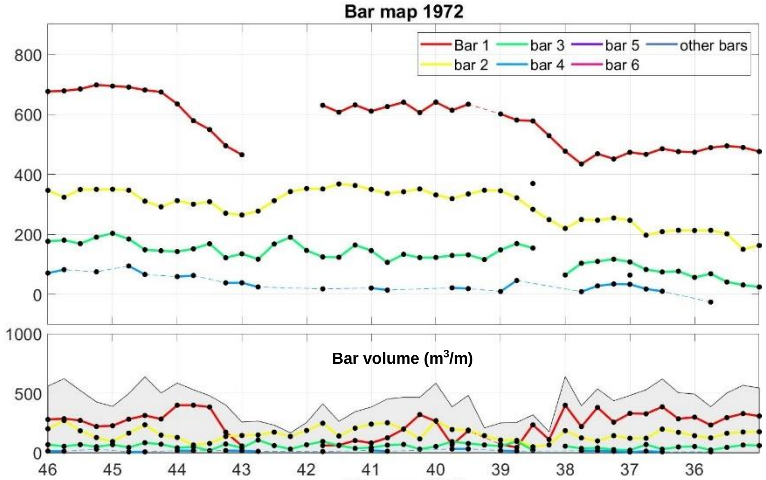


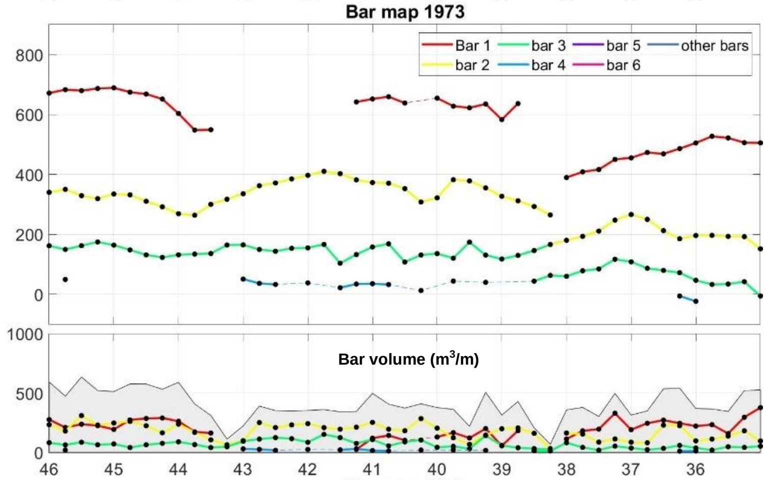


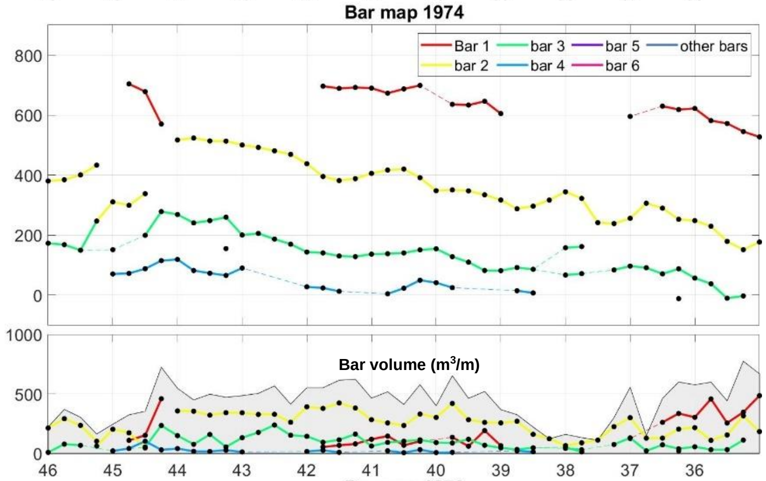


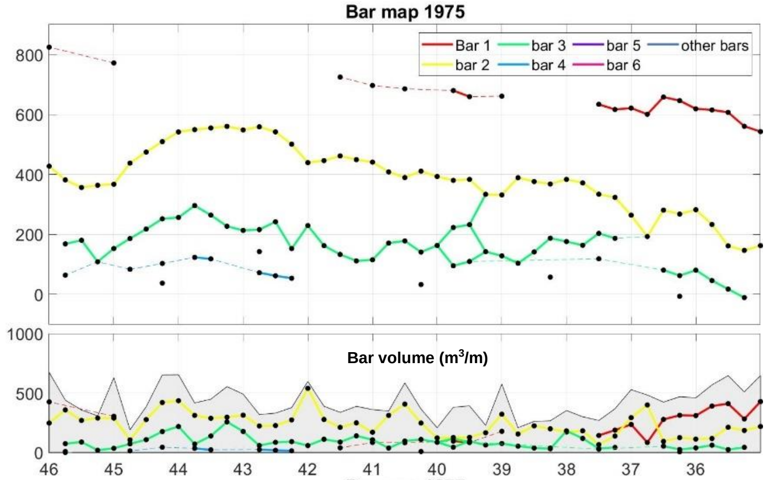

Bar map 1970
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m^3/m)

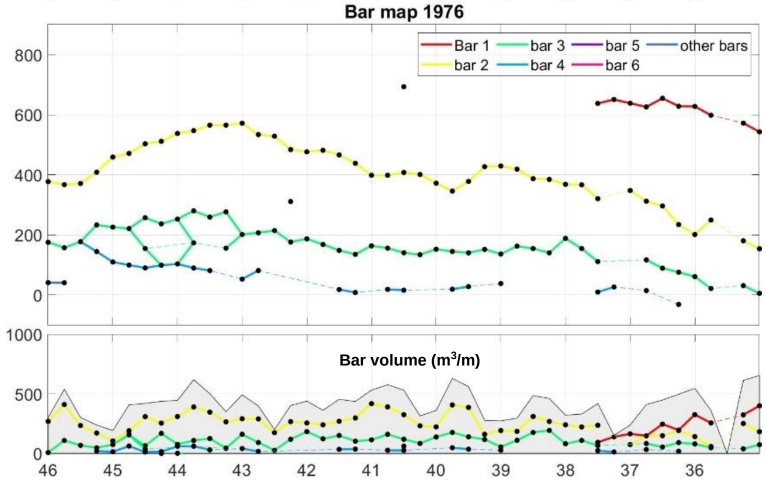

Bar map 1971
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m^3/m)

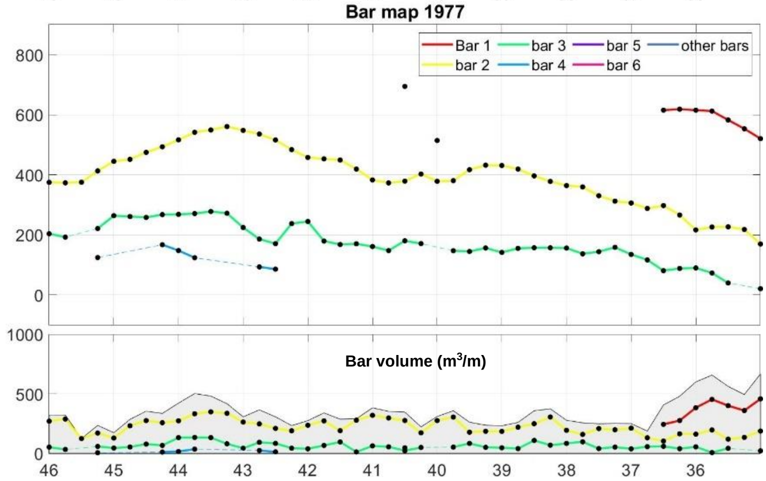

Bar map 1972
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m^3/m)

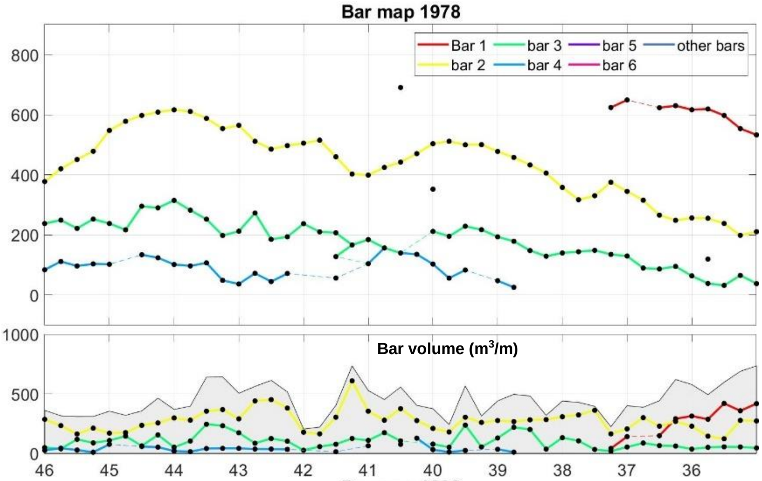

Bar map 1973
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m^3/m)

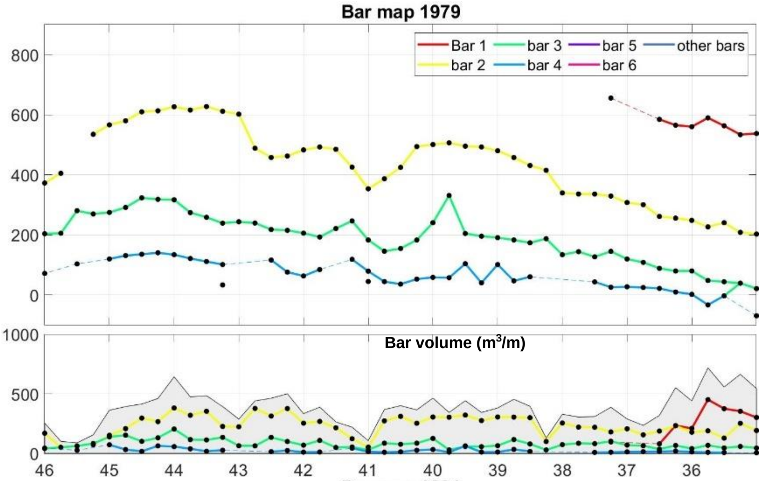

Bar map 1974
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m^3/m)

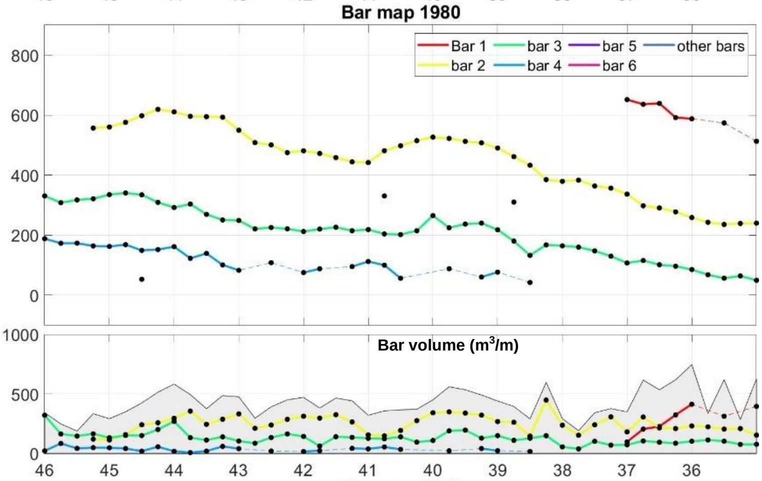

Bar map 1975
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m^3/m)

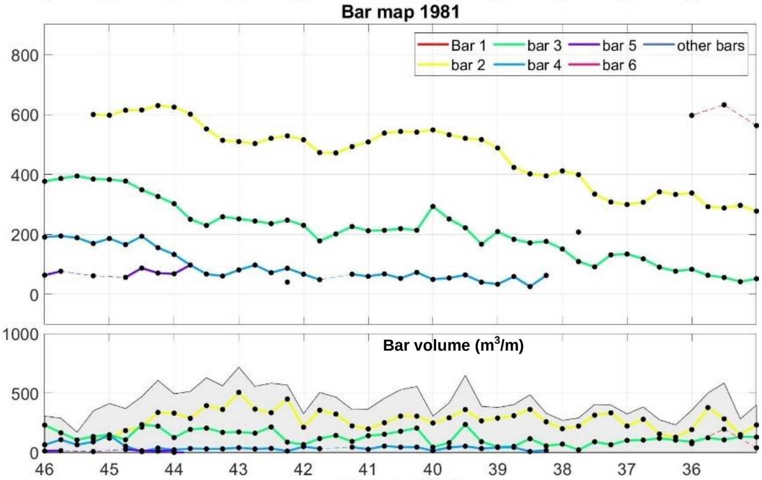

Bar map 1976
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m^3/m)

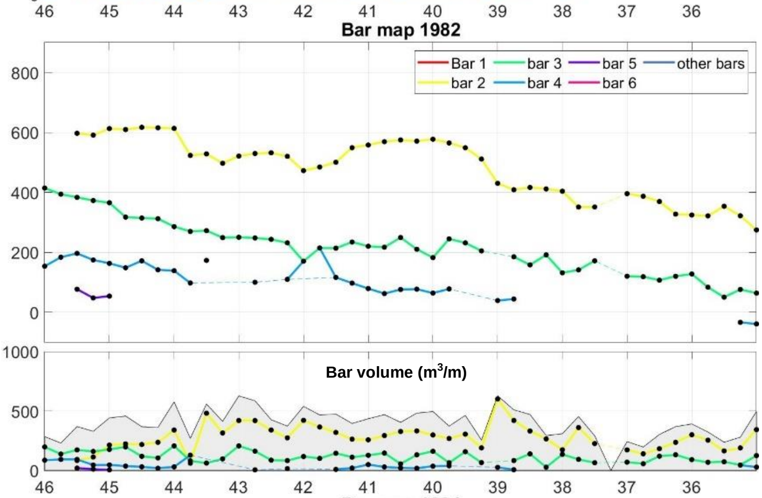

Bar map 1977
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m^3/m)

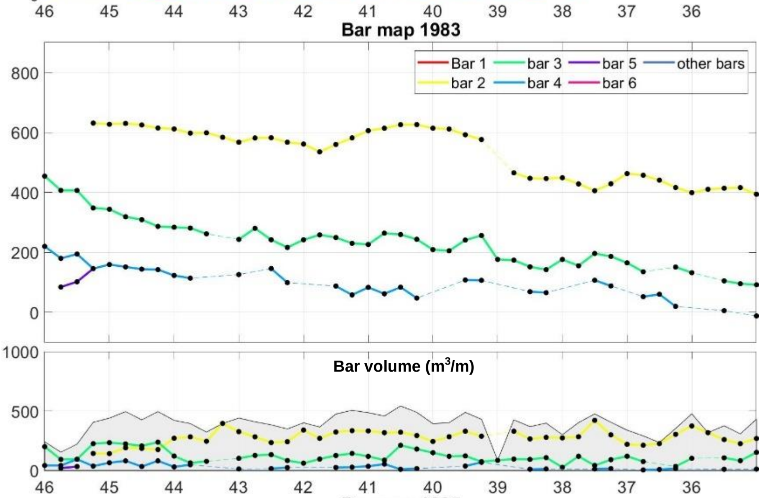

Bar map 1978
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m3/m)

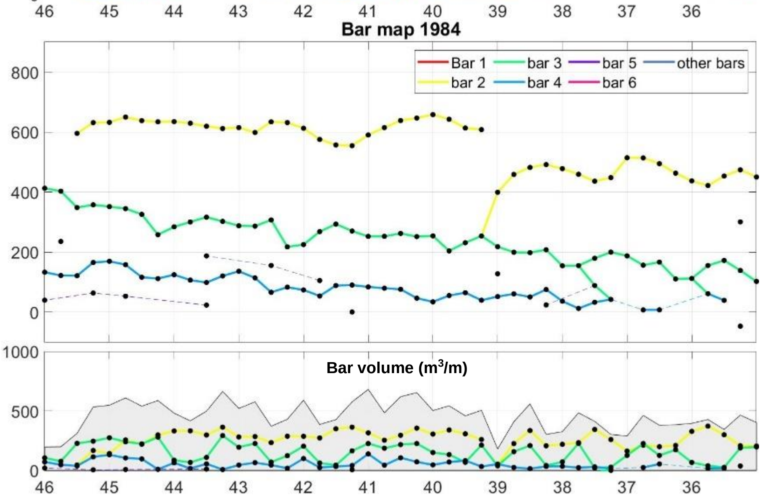

Bar map 1979
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m3/m)

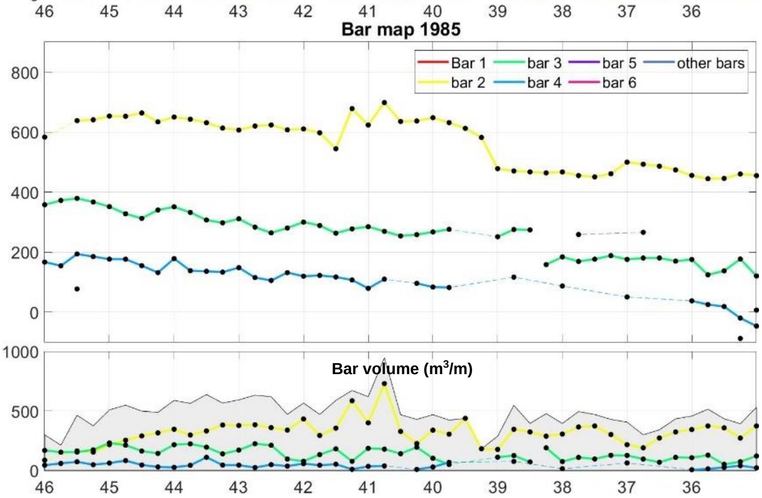

Bar map 1980
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m3/m)

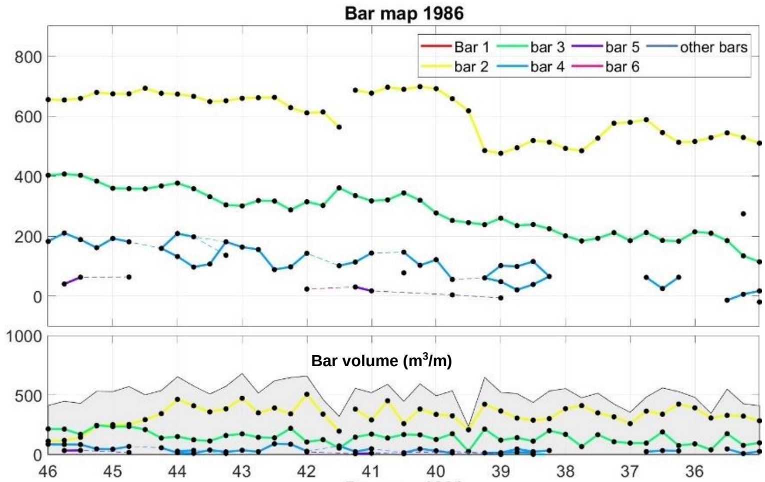

Bar map 1981
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m3/m)

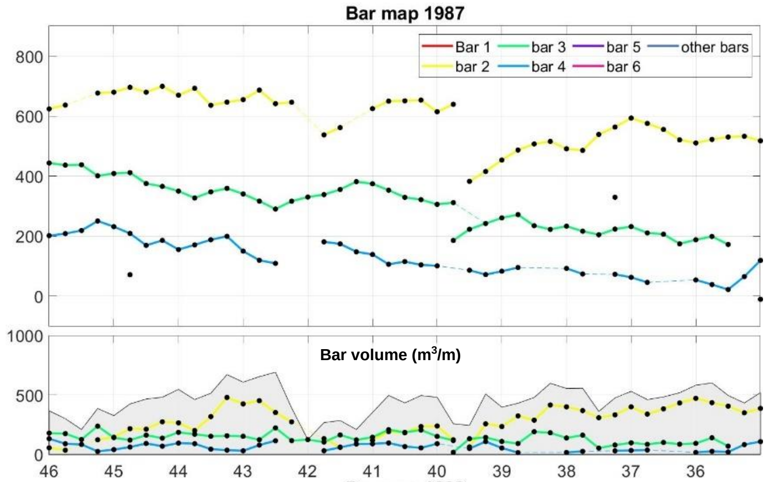

Bar map 1982
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m3/m)

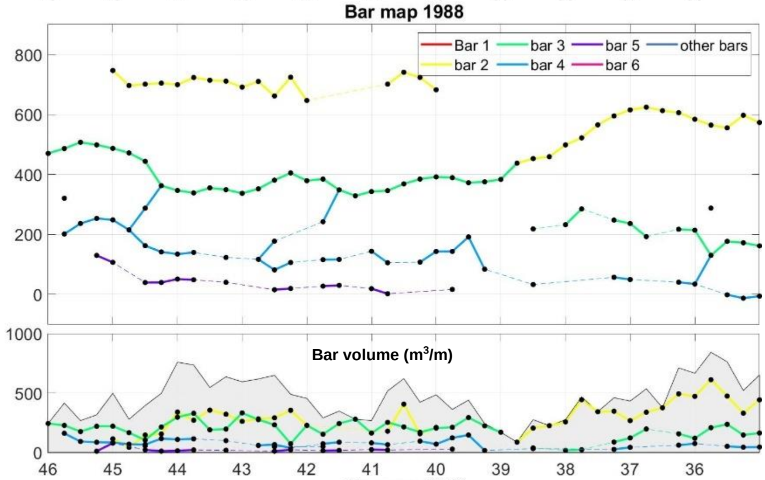

Bar map 1983
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m3/m)

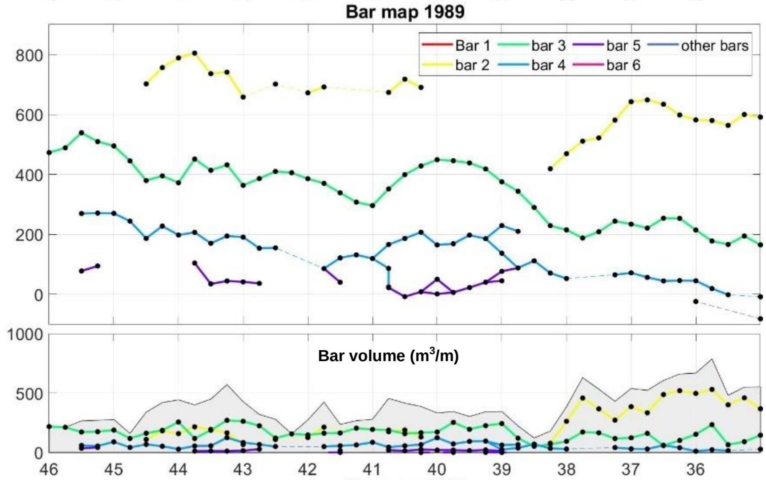

Bar map 1984
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m3/m)

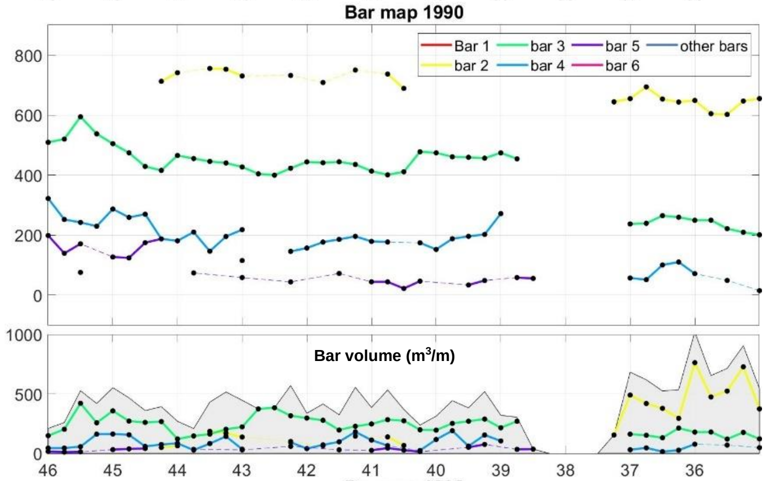

Bar map 1985
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m3/m)

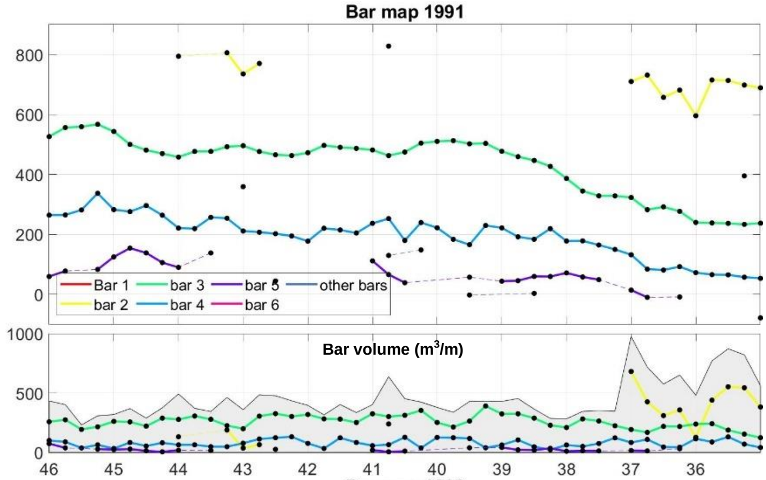

Bar map 1986
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m^3/m)

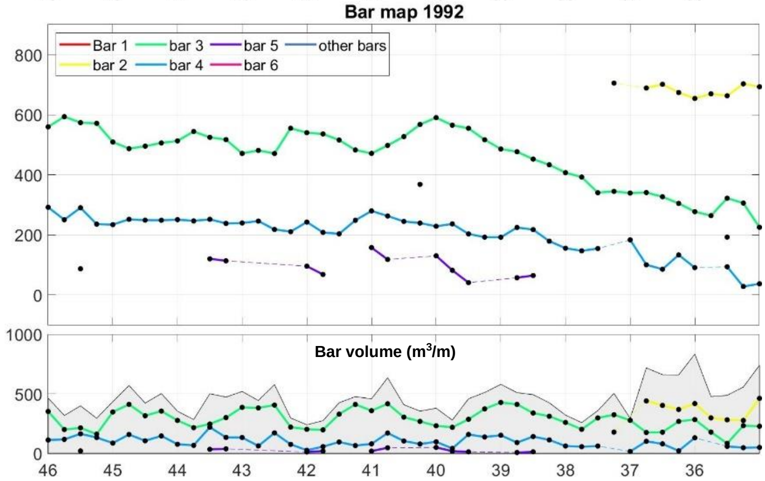

Bar map 1987
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m^3/m)

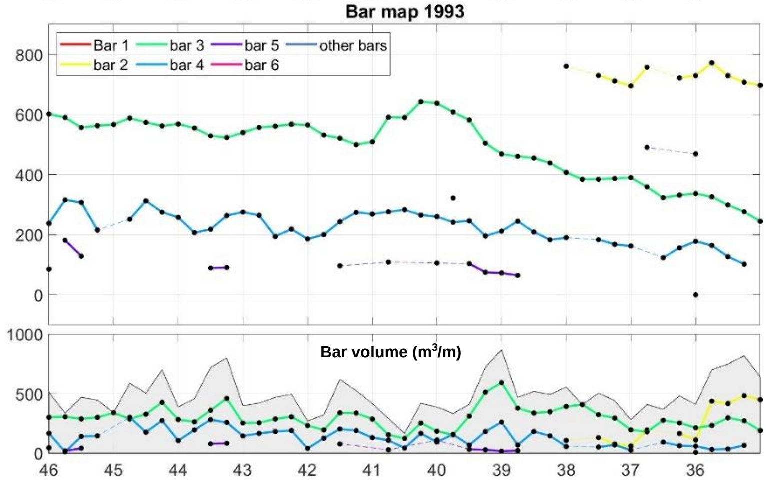

Bar map 1988
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m^3/m)

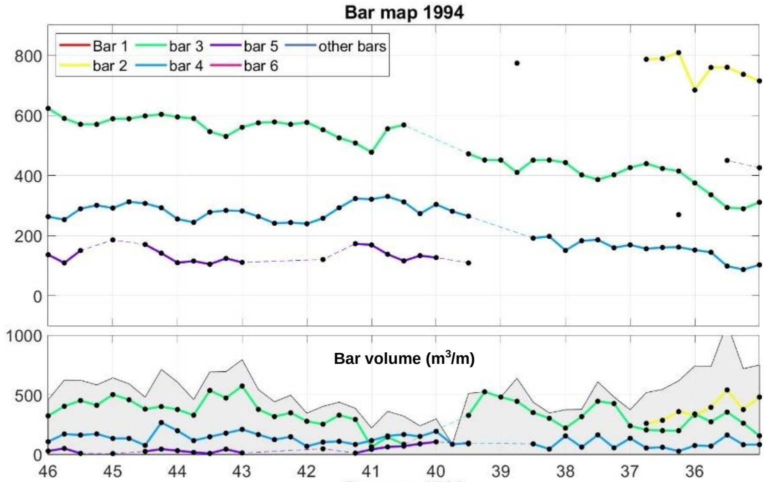

Bar map 1989
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m^3/m)

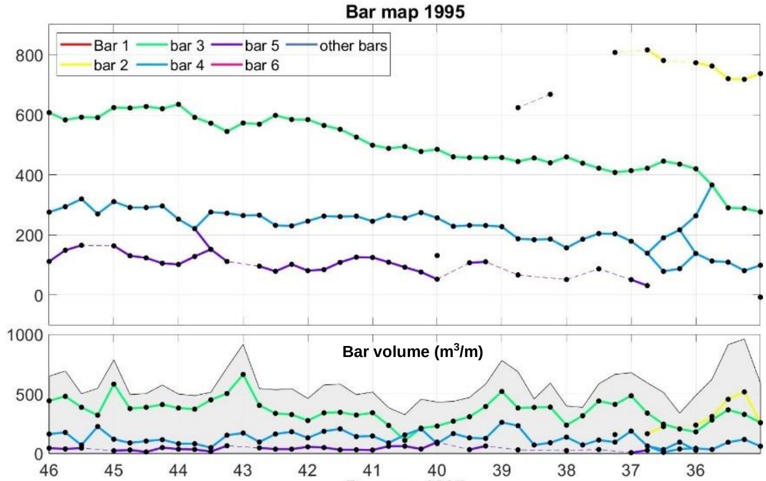

Bar map 1990
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m^3/m)

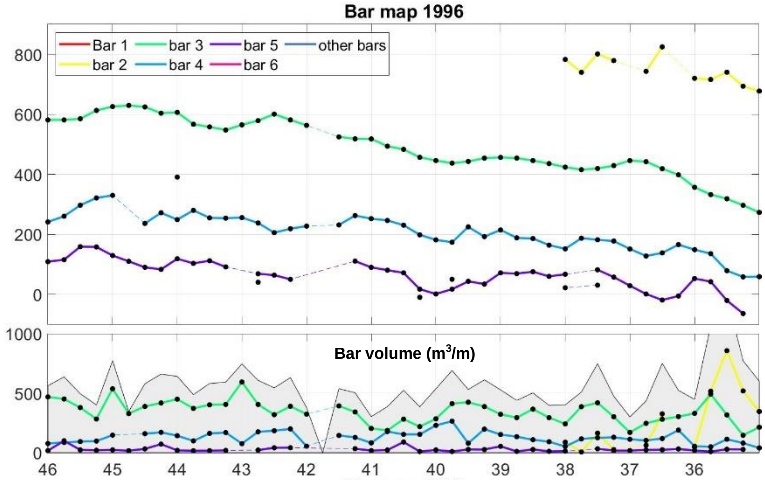

Bar map 1991
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m^3/m)

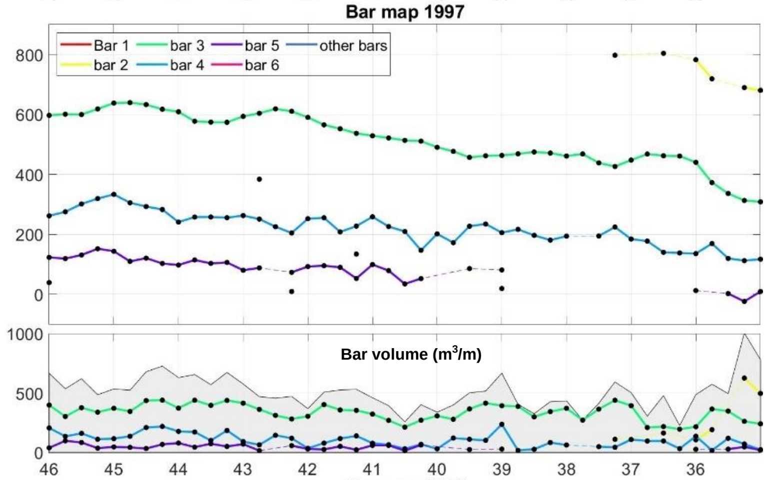

Bar map 1992
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m^3/m)

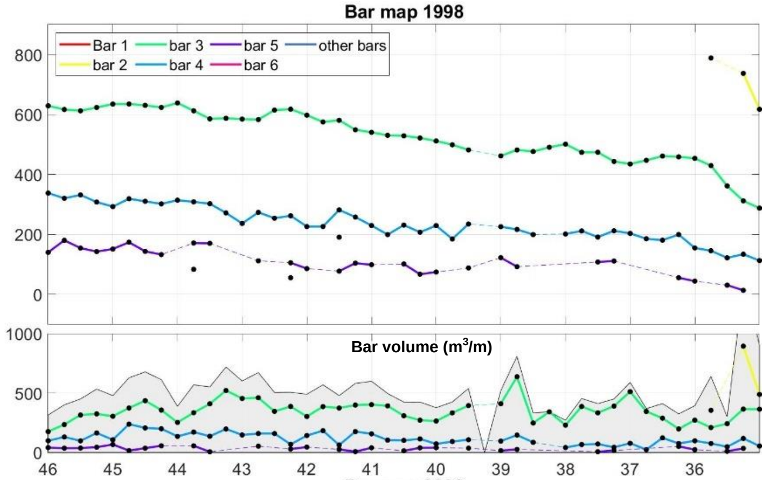

Bar map 1993
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m^3/m)

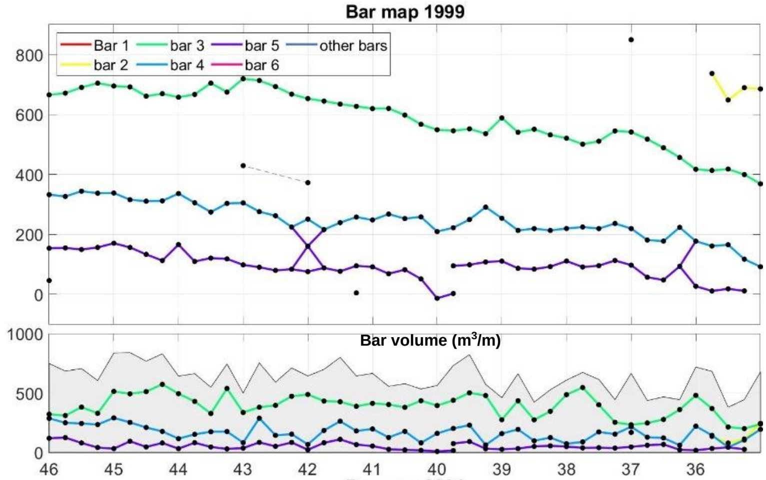

Bar map 1994
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m3/m)

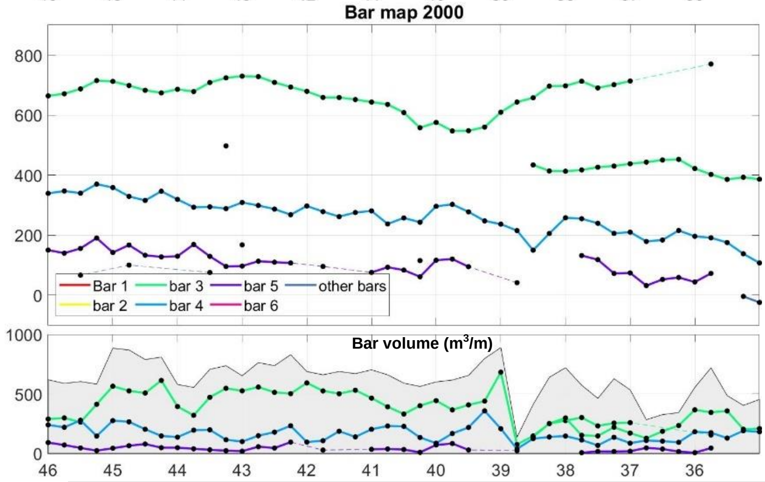

Bar map 1995
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m3/m)

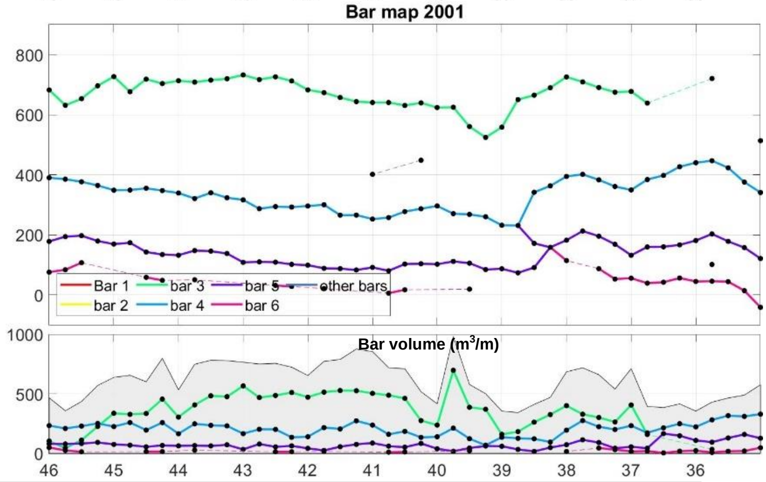

Bar map 1996
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m3/m)

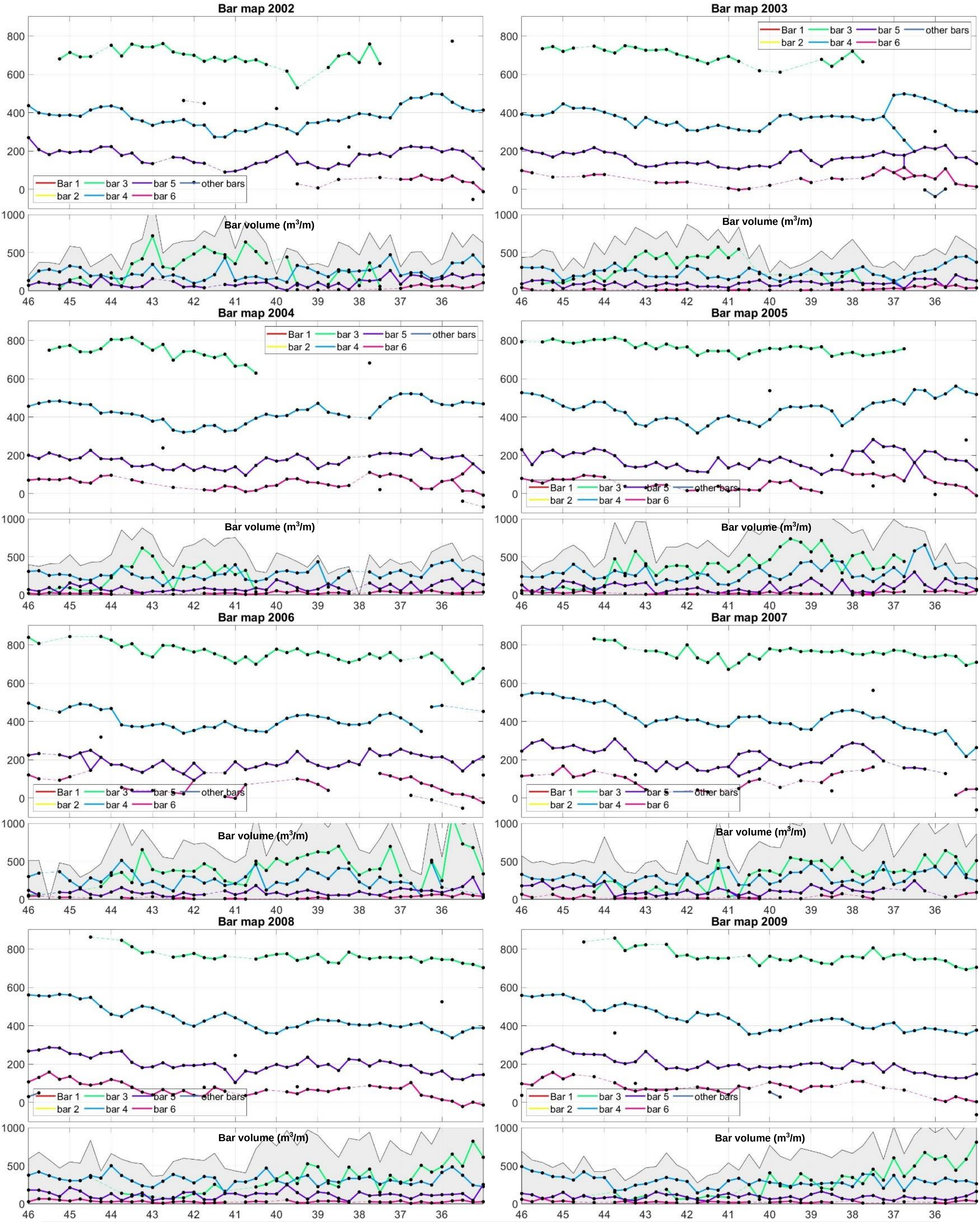

Bar map 1997
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m3/m)

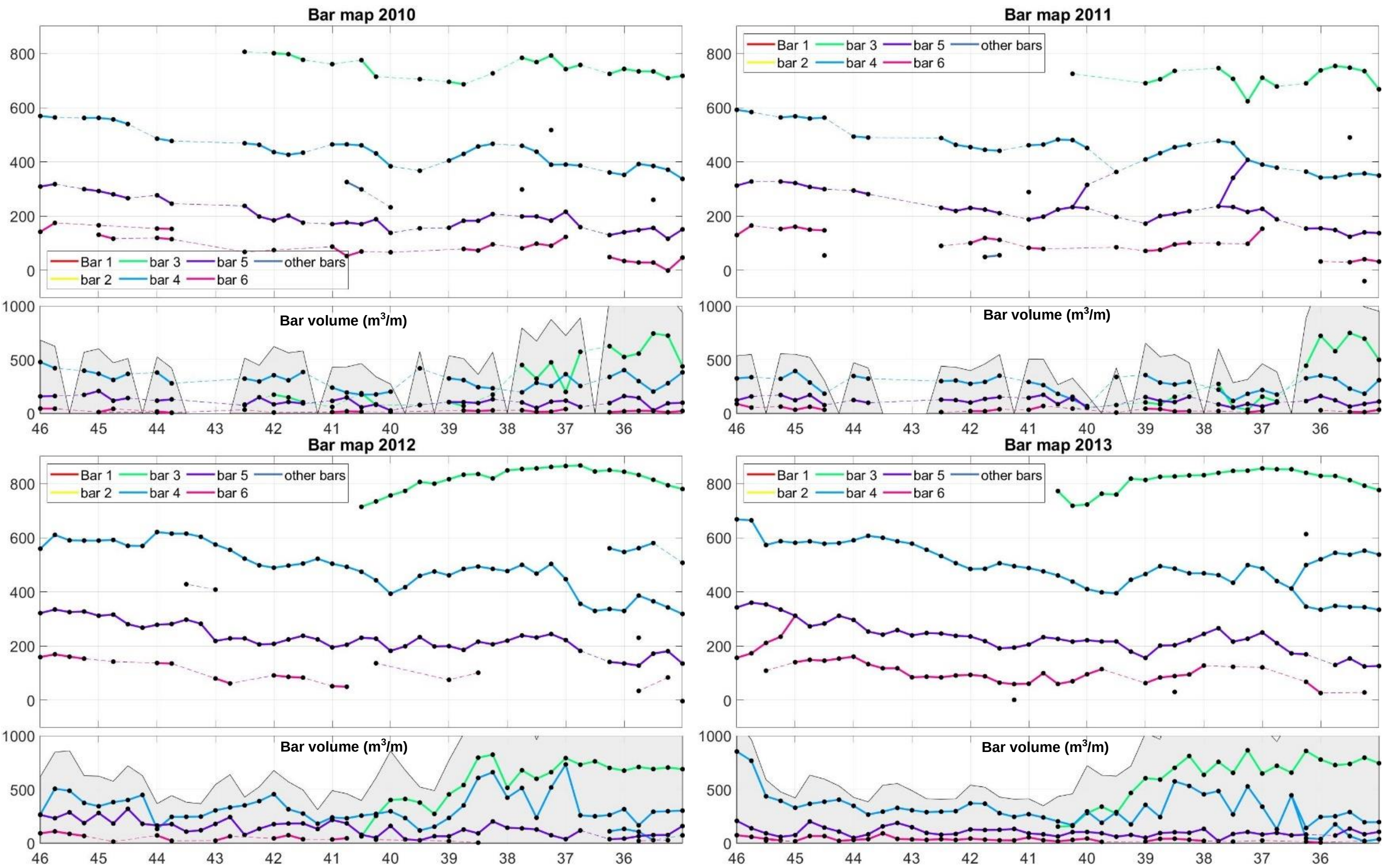

Bar map 1998
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m3/m)


Bar map 1999
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m3/m)


Bar map 2000
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m3/m)


Bar map 2001
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m3/m)


Bar map 2002
Bar map 2003
Bar map 2004
Bar map 2005
Bar map 2006
Bar map 2007
Bar map 2008
Bar map 2009
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m3/m)


Bar map 2010
Bar map 2011
Bar map 2012
Bar map 2013
Bar 1
bar 2
bar 3
bar 4
bar 5
bar 6
other bars
Bar volume (m3/m)