Ecobeach Project Phase II

Evaluation of the effect of the PEM on the nearshore morphology at Egmond (The Netherlands)

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Summary
The study aims at providing qualitative and quantitative insight into the impact that the Ecobeach system (also called PEM for Pressure Equalizing Modules) has on the morphological development at Egmond between Rijks Strand Palen 37 and 49 (km). In this area the PEM have been present for the period 2007-2010 in the framework of an experiment by BAM and Rijkswaterstaat.
The evaluation is primarily based on a temporal comparison of the evolution of Coastal State Indicators (CSI) observed in the test area before and after the Ecobeach (PEM) installation. Furthermore, an area adjacent to the test site is used as a reference to enable a spatial comparison of the observations.
The nourishments that were carried out in 2004 and 2005 just North and South of the test and reference areas are clearly influencing the local morphology for about two years after placement. Since 2008 no obvious feeding of sand towards the test and reference areas is observed. The longshore coherent gradual offshore migration and decay of the outer bars dominate the morphological behaviour of the outer regions. The influence of the bar dynamics on the observed accretion of the Dune and Beach regions in the Test and Reference areas is, similar to the impact of the nourishments, difficult to establish.
The quantification of changes in the CSI behaviour (by application of statistical fitting approaches through the CSI time series) confirms that the temporal development of the CSI for the period 2007-2010 exhibits a change of behaviour in both the Test and the Reference areas. The increase in beach volume with respect to the natural development for the period 2007-2010 is estimated to be about 8 m^3/m/yr for both the Test and the Reference areas.
As both areas exhibit similar trend breaks, the evidence for identifying and quantifying a possible effect of the Ecobeach system is inconclusive.
The possible influence of the PEM on the local beach and dune morphology falls within the range of natural variability in the study area.

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	Nov 2012	C. Brière		J.A. Battjes		L. Janssen	
		L. Vonhögen		L.C. van Rijn			
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1 Introduction

1.1 Context

The Dutch government is challenging companies to be more innovative. This has led to a proposal by BAM (largest construction firm in The Netherlands) to the Ministry of Public Works (Waterdienst) to protect the Dutch coast in an innovative way with the Ecobeach system (see Appendix A for details). The easily installable Pressure Equalizing Modules (PEM) have been developed in Denmark by the Skagen Innovation Centre (SIC) and consist of vertical, passive drainage pipes that are regularly spaced on the beach (every 10 m in the cross-shore direction and every 100 m in the alongshore direction). There is no physical understanding yet of how the system functions.

The Ministry of Public Works is now investigating the potential value of the proposed system under the framework of the WINN program (WAter INnovatiebron). To that end, a field experiment has been carried out in Egmond aan Zee (The Netherlands), from November 2006 to December 2010. Two test areas (Jan van Speijk and Coast 3D) were selected where the Ecobeach modules were installed. The Ministry of Public Works is interested in the functioning of the system and its effects on the coast. For better understanding, good and thorough monitoring is needed, in order to quantify the possible effects of the system, and to separate these from natural variations of the coast.

Deltares – WL|Delft Hydraulics was requested by the Waterdienst to assess the impact the PEM may have on the local morphological development. To that end, first a monitoring strategy for the field experiment in Egmond was set up, referred to as Phase I (Cohen and Grasmeijer, 2007). In Phase II, a study approach was developed which formed the basis for annual data analysis studies (Brière *et al.,* 2007, Brière *et al.,* 2008, Brière and Van den Boogaard, 2009, and Brière, 2010). The present report describes the final data analysis and assessment of the effectiveness of the PEM based on the entire period (2007-2010) the PEM were present.

1.2 Objectives and research questions

The overall objective of the study is to provide qualitative and quantitative insight into the impact that the Ecobeach system may have on the morphological development at Egmond in the area where the system has been installed. This study does not address the working principles of the Ecobeach system. As the Ecobeach system is installed on the beach, there is a particular focus on the beach and dune regions. The overall objective is sub-divided into a number of sub-objectives that relate to more specific research questions. These sub-objectives are:

- To identify and quantify errors in the data that are used for the analysis
- To identify the natural (as opposed to that influenced by the Ecobeach system) development of the Egmond coastal zone.
- To assess the influence of beach and shoreface nourishments on the morphological behaviour of the Egmond coastal zone.
- To quantify statistical parameters representing the changes in the morphological behaviour of the Egmond coastal zone, thus enabling the evaluation of the influence

of the Ecobeach system in the beach and dune regions where the PEM have been installed.

To reach these sub-objectives, research questions are more specifically addressed.

- To identify and quantify data errors
  - Q1A: How is the interpolation between the sub-aerial part and the sub-aqueous part of Jarkus measurements performed? Can we quantify the impact on the resulting data?
  - Q1B: which errors and inconsistencies in the Jarkus dataset affect the present study?
  - Q1C: Are errors introduced when interpolating raw dGPS data on the provided RWS grids?
  - Q1D: For which types of analysis is the dGPS dataset appropriate?
  - Q1E: Can we aggregate the survey data as indicators of the state of (parts of) the morphology at Egmond?

- To identify the natural development of the Egmond coastal zone
  - Q2A: How does the longshore averaging affect the variability in the result?
  - Q2B: What is the long-term evolution of the morphology?
  - Q2C: What is the long-term alongshore variability of the morphology?
  - Q2D: Can we identify seasonal variations in the aggregated data?

- To assess the influence of beach and shoreface nourishments on the morphological behaviour of the Egmond coastal zone
  - Q3: What is the impact of the recent nourishments on the morphological development of the Test and Reference areas?
  - Q4: What is the influence of the cyclic bar behaviour on the development of especially the beach and dune volumes?

- To quantify statistical parameters representing the changes in the morphological behaviour of the Egmond coastal zone
  - Q5A: Can we quantify the alongshore coherence of the observed cross-shore sediment exchange?
  - Q5B: Can we quantify the volume changes of the coastal system?

- To evaluate the influence of the Ecobeach system on the beach and dune regions where the PEM have been installed.
  - Q6: Can we identify and, if possible, quantify the effect of the PEM on the coastal system?

1.3 Study approach

The research questions are addressed using available annual Jarkus surveys and dGPS survey data collected at smaller time intervals at Egmond. The data evaluation consists of four main components:

1) Overview of the available data and of the accuracy with which it has been collected and subsequently processed;
2) Definition of cross-shore aggregated parameters (so-called Coastal State Indicators or CSI) that describe the state of the coastal system, and analysis of profile data;

3) Morphological analysis of the observed coastal zone development at Egmond, especially to evaluate the influence of beach and shoreface nourishments on the morphological behaviour;
4) Quantification of indicators representative of changes in the morphological behaviour of the coastal system at Egmond;
5) Evaluation of the Ecobeach system based on the observed and analysed morphological development of the Egmond coast.

The evaluation is primarily based on a comparison of the temporal evolution of Coastal State Indicators observed at a test site (so-called “Test area”) before and after the Ecobeach installation. Furthermore, an area adjacent to the test site is used as a reference to enable a spatial comparison of the observations (this area is referred to as the “Reference area”). Given the large natural variability in the coastal zone in general and the major anthropogenic influences at Egmond in particular, it is imperative to consider both aspects in the final evaluation of the system. Moreover, the Egmond coast has been studied extensively (a.o. Van Enckevort and Ruessink, 2003a,b; Wijnberg, 1995; van Duin et al., 2004). From these studies, it is apparent that since the 90’s, the Egmond coast is significantly influenced by the beach and shoreface nourishments. The study area is therefore extended northward (Egmond area) and southward (Heemskerk area) to include areas that have been recently nourished. This allows for full coverage of the coastal cell where morphological developments might be linked to the development of the area where the Ecobeach system has been tested.

A morphological analysis attempts to isolate the effects of the PEM by addressing the influence of the nourishments and of the cyclic bar behaviour on the morphological behaviour of the Egmond area. A top-down approach is adopted in which the analysis starts at the largest considered spatial scales. The next step is to zoom in on smaller scales to estimate cross-shore sediment exchange and to assess the impact of the nourishments on the beach and dune volumes.

The quantification of changes in the coastal system at Egmond is performed through the quantification of changes in the Coastal State Indicators (CSI). To that end, three distinct statistical fitting approaches are applied, that consist of 1) a linear fitting through the 1990-2006 data, 2) a linear fitting through the 1965-2006 data, and 3) a linear fitting with a harmonic component through the 1965-2006 data. The residuals (i.e. observations minus the fits) are then evaluated for the periods before and after the installation of the Ecobeach experiment. Quantities that indicate a change in the morphology of the coastal system are computed. The averages of the residuals obtained over the four years before and after the Ecobeach installation, and of the corresponding standard deviations are calculated. These parameters indicate to which extent the observations differ from the model hindcasts (period 2003-2006) and from the model forecasts (period 2007-2010), as well as provide insight on the variability of the residuals.

1.4 Organisation of the report

This report is a continuation of Brière *et al.* (2007, 2008), Brière and van den Boogaard (2009), and Brière (2010). During these previous studies, minor changes of the methodology were made.

Chapter 2 presents the site characteristics. The general morphological behaviour at Egmond is presented, as well as the forcing conditions (wave, wind) acting on the coastal stretch from

2006 up to 2010. Finally, the motivation for the selection of four areas (Egmond, Test, Reference and Heemskerk) is given.

Chapter 3 deals with the data processing and its possible influence on the accuracy of the aggregated data. This section summarises various aspects of the Jarkus and dGPS data sets such as data coverage, temporal distribution, comparison between raw data and grids. Finally, Chapter 3 presents the Coastal State Indicators that are derived from the Jarkus and dGPS sources.

Chapter 4 and Appendix B present the results of the profile-data analysis, including a sensitivity analysis of the CSI aggregated over different longshore distances, a description of the patterns in the CSI, and a discussion on the seasonal variability and on the longer-term natural variability.

Through a morphological analysis, Chapter 5 and Appendix C provide a discussion on the influence of beach and shoreface nourishments on the morphological behaviour of the Egmond coast, as well as on the influence of the bar system dynamics on the volume changes.

Chapter 6 presents the quantification of the statistical parameters representing the changes in the CSI's behaviour by applying several fitting approaches. Such quantification enables the evaluation of the impact of the Ecobeach modules on the coastal and dune systems.

The project has been carried out by C. Brière, L. Vonhögen, D.J.R. Walstra and H.F.P. Van den Boogaard. The content of this report has been reviewed by prof. J.A. Battjes, prof. L.C. van Rijn, and J.G. de Ronde.

2 Physical settings

2.1 Egmond Coast

The coastal zone of the Netherlands is often divided into three major regions that differ both in morphological appearance and in the dominance of related physical processes, viz. the Delta area, situated in the south-western part of the Netherlands and consisting of a number of former islands, separated by tidal basins, inlets and an estuary, the Wadden area, situated in the northern part of the Netherlands and consisting of barrier islands alternating with tidal inlets and their related ebb tidal deltas at the seaward side, and finally the Holland coast in the central part of the Dutch coast, between Den Helder in the north and Hoek van Holland in the south. The latter is about 120 km long and mainly consists of sandy beaches and multiple barred nearshore zones. Four major artificial works are situated in the area, the harbour moles at Hoek van Holland, Scheveningen and IJmuiden and the Hondsbossche Sea Defence near Petten. Egmond (Figure 2.1) is located on the Holland Coast, between the harbour moles of IJmuiden and the Hondsbossche Seadyke.

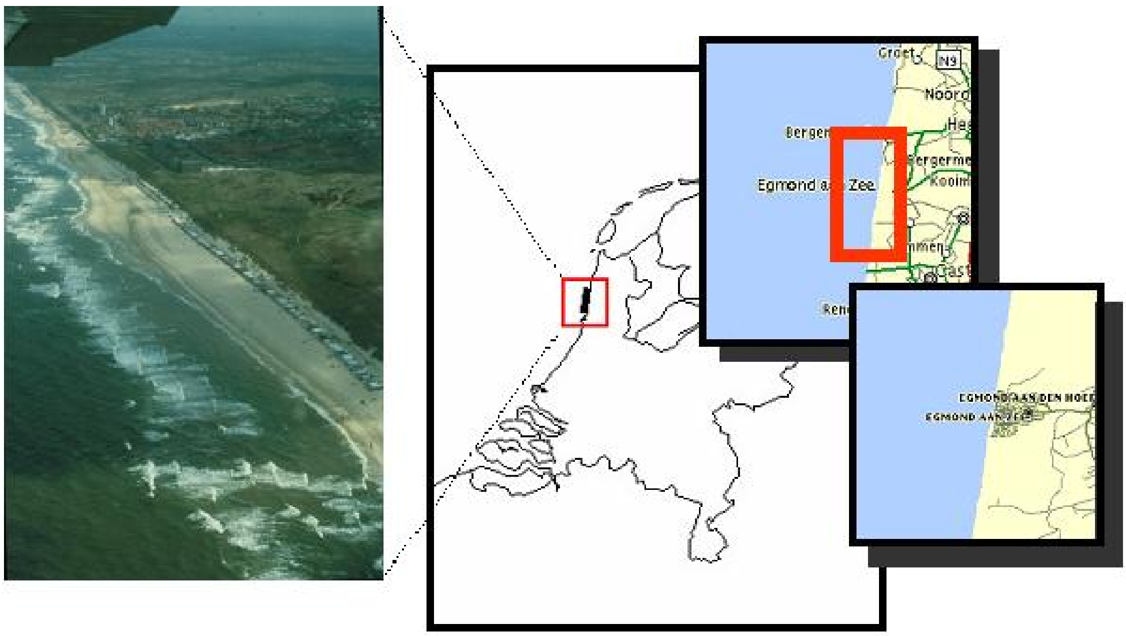

Figure 2.1 : The location of the Egmond site

2.2 Geomorphology and sediment characteristics

The shoreface of the Holland coast has a concave profile and can be divided into three regions (Van Alphen and Damoiseaux, 1989): (1) a southern region and (2) a northern region with a slope of 1:400, and (3) a central area with a slope of 1:170.

The lower shoreface below NAP – 8m is smooth and does not show any barred features (NAP is Dutch Ordnance Level, NAP 0 m is about mean sea level). The upper part of the shoreface is the nearshore zone. This area is characterised by multiple nearshore bars (Wijnberg, 1995). At Egmond, the nearshore bed profile is characterised by a double subtidal bar system. The crest of the outer bar is almost straight and lies 3.5 m to 4 m below the mean water level. The crest of the inner nearshore bar has an irregular alongshore plan view with a mainly crescentic appearance, and lies below NAP – 1.5 m to NAP – 2.5 m. Sometimes rip channels appear in the inner nearshore bar, with an alongshore spacing of about 500 m. The cross shore spacing between bar crests is fairly constant in time at about 300 m.

The beaches at the Holland coast have a width of 100 to 200 m from the dune foot to the low water line and have an average slope between 1:35 and 1:60 (Stolk, 1989). The morphology of the beach is often characterised by a swash bar.

The dune area at Egmond has a cross shore width of about 2.5 to 3 km. The maximum height of the foredune ridge is about 16 m and has an artificial straight alignment. At Egmond, the foredunes are partly natural. In the past, management strategies consisted mainly of enlarging the dune body by means of sand fences and plantation of marram grass. This part of the coastline is now managed less strictly, and the foredunes are developing more or less freely and naturally. Most of the landward-located dunes are well developed parabolic features.

The sediments at Egmond Jan van Spijk are well sorted and composed of fine to medium sand with a mean grain size between 250 and 350 μm. Most of the sediments of the bed surface in the nearshore bar troughs and near the swash area contain shells or shell fragments. Overall, there is a coarsening of the sediment from deep water to the intertidal beach and a fining from the intertidal beach to the dunes.

Short (1992) used the results of Kohsiek (1984), Van Bemmelen (1988) and Van Alphen (1987) to characterize the dune, beach and surf sediments, respectively. Short showed that the dune sands are relatively uniform alongshore with an overall mean grain size of 226 μm. On the other hand, the beach sands exhibit a coarsening around 12 km, 18 km, 42 km and 60 km from Den Helder southwards.

2.3 Environmental conditions

The Holland coast is a mixed energy coast, according to the classification scheme of Davis and Hayes (1984). A mixed energy coast implies that both wind waves and tides act on the sandy sediments and influence the morphology.

According to Stolk (1989), the prevailing wind direction is southwest (23%), followed by west (16%), east (13%) and northwest (12%). The northwest storm winds cause the largest wind set up along the coast.

During the Ecobeach experiment, the maximum daily mean wind speed occurred in January 2007 with magnitudes up to 12 m/s. The spring was usually characterized by strong winds of magnitudes up to 10 m/s (e.g. 2008). On the other hand, the winter 2008-2009 was characterized by milder wind conditions. The prevailing wind directions were southwest, followed by west. The southwest wind had a higher occurrence during the winter. The north-easterly wind (less than 10%) occurred mainly during the early summer period but was also found from September to December (e.g. years 2007 and 2008). Finally, a south-easterly wind occurred from January to March 2009, which is characterized by mild wind conditions.

Waves drive beach change and are therefore essential for any assessment of beach morphodynamics. At the beginning of the experiment (November 2006), a strong north-westerly storm occurred with significant wave heights up to 5 m. The remaining days of the year (in November and December) showed regular winter conditions. In January 2007, two major westerly storms occurred with significant wave heights of approximately 4 m. Wave conditions then returned to moderate, until two major storms occurred in March 2007. The conditions returned to low-energy until the beginning of July when another storm occurred with significant wave heights of about 3 m. The remaining days in July and August showed regular summer conditions. In September, conditions became slightly stronger with a storm with significant wave heights of approximately 3 m. October was characterized by low-energy wave conditions.

Similar to 2006, strong north-westerly storms occurred in November 2007 with wave heights of up to 6 m. In December, wave conditions were mild with significant wave heights lower than 1 m. A storm occurred in the beginning of February 2008 with significant wave heights of approximately 5 m. After 1 month of low-energy wave conditions, waves became much more energetic in March (with significant wave heights of about 3 m), persisting until the 25th. Since then, 2008 showed regular summer conditions.

Autumn and winter 2008-2009 are characterized by moderate conditions, with only two strong storms occurring, the first one at the beginning of October with significant wave heights up to 3.5 m and the second one at the end of November with significant wave heights up to 4.75 m. January and February 2009 showed low-energy conditions for the winter period; only one storm occurred at the end of March, with significant wave heights of about 2.5 m. The following period April to August 2009 showed regular summer conditions, except in July which was characterised by very low-energy conditions.

North-westerly storms again occurred in September and October 2009 with much more energetic ones occurring at the end of November (with significant wave heights up to 5 m). Afterwards, wave conditions became more moderate, until storms occurred in February 2010. The rest of the spring was characterized by moderate conditions, and the summer showed regular summer conditions, until September 2010 when a storm occurred (with significant wave heights of about 4 m). The remaining October to December months showed regular winter conditions except for a major storm in November (with significant wave heights of about 5 m).

The wave conditions occurring from 2006 to 2010 are consistent with the analysis of Short (1992). The winter period (November to January) experienced the highest waves increasing in size each month to a peak in January. While November and December had relatively low variance, January has the highest variance with extreme storminess in 2007. The years 2008 and 2010 are characterized by more moderate wave conditions. On the other hand, 2009 can be seen as a period with low-energy winter wave conditions.

2.4 Short term morphology

On a small scale (1 km) and on the short time scale of a storm, longshore non-uniformities may develop as local disturbances that are superimposed on the overall straight regular system resulting in a three-dimensional morphological system. Rip channels (with length of 200 to 300 m and depth of 0.5 to 1 m) are generated in the crest zone of the inner bar on a time-scale of a few days during minor storm conditions, and are generally washed out during major storm conditions. Overall, it can be concluded that the net changes on the inner bar and the beach are relatively small, but larger changes can be observed at the outer bar. The bars show a long-term migration of about 20 to 40 m/yr in seaward direction (Van Rijn et al., 2003).

Spatial variations in beach width and volume are due to sand waves. Quartel and Grasmeijer (2006) found variations in beach width of about 40 m over a distance of roughly 300 m, although these variations were not always present. A sand wave crest (largest beach width) may contain 5000 m^3 of sand. Sand waves were found to migrate with an alongshore velocity of roughly 250 m/yr, but not necessarily in one predominant direction.

2.5 Short-term evolution of the intertidal beach

Bars on the intertidal beach at Egmond can be divided into two types: the low tide swash bar and the high tide swash bar. The low-tide swash bar is positioned near the low-tide water line, where it is influenced by swash processes during low tide and by (breaking) wave processes during high tide. The high tide swash bar is positioned near the high-tide water line, where it is influenced by swash processes during high-tide only.

Beach states at Egmond range between an alongshore bar trough system and a reflective system, based on the classification of beach types by Wright and Short (1984). Kroon (1994) is more specific, distinguishing three phases in high-tide swash behaviour: (1) the initial generation and growth of the swash bar, (2) its stabilisation or shoreward migration, and (3) its destruction. Phases 1 and 2 take place during low to moderate wave-energy conditions, whereas phase 3 is related to high wave-energy conditions. The stabilisation or migration in phase 2 is strongly related to conditions when the water levels are higher than the swash bar crest. From spring to neap tide, the bar stabilises, whereas from neap to spring tide it moves in the landward direction.

2.6 Short term evolution of subtidal zone

The short term evolution of the nearshore bars has been studied by Wolf (1997). He found that in case of low to moderate wave-energy conditions, the sediment fluxes were onshore directed, resulting in onshore migration of the inner bar and an accretion of the beach. In case of high-energy storm wave conditions, the sediment fluxes were offshore directed, causing the inner bar to migrate offshore and the beach to erode and flatten. Irregularities in onshore and offshore movements of the inner bar system were also observed by Kroon (1994).

2.7 Long term morphology

On the larger longshore scale (10 km) and in the long term (years), the behaviour of the outer and inner bars at Egmond is two-dimensional in the sense that the bars are continuous and of the same form in the longshore direction and show the same overall pattern (onshore and offshore migration).

Wijnberg (1995) studied the behaviour of nearshore bars along the Holland coast and concluded that it can be separated into distinct regions of bar behaviour. Two of these regions are characterised by cyclic offshore directed bar movement, which is described in greater detail in Ruessink and van Rijn (2002). South of IJmuiden, the cycle return period is about 4 years, whereas north of IJmuiden (including Egmond) the bar cycle takes about 15 years. Causes for this remarkable difference are unknown.

2.8 Characteristics of the PEM

The Ecobeach system consists of vertical drainage pipes, called pressure equalizing modules (PEM), with a length of 2 m and a diameter of 0.06 m (Figure 2.2). Only the lowest 1.30 m part of the pipes is permeable and there is a filter at the top enabling air flow. The PEM are placed in rows, with the tops about 0.25 m beneath the surface, from the mean high water line to the mean low water line, at a distance of 10 m from each other. The rows, which contain mostly about 6-9 PEM, have an alongshore spacing of 100 m.

Figure 2.2 : Example of a drain that has been installed in the beach

The description provided in annex A describes the claimed functioning of the Ecobeach system. The mechanisms involved are not discussed in this project and are therefore considered outside the scope of this report.

2.9 Selection of sites

The field experiment with Ecobeach modules has been carried out in Egmond for two areas (Jan van Speijk and Coast 3D) from November 2006 (Figure 2.3) until the end of 2010. Drains were installed along two coastal stretches of 3 km in front of the town of Egmond (from Rijks Strand Palen (RSP) 36.00 to 39.00, marked in red in Figure 2.3) and south of the town (from RSP 40.00 to 43.00, marked in yellow in Figure 2.3). RSP refers here to a permanent base line of beach poles used in The Netherlands.

The approach detailed in Brière et al. (2007) is adopted in which:

- The analysis is focusing on the southern test area, as the natural behaviour of the northern test area is difficult to describe due to the extensive nourishments carried out in the past in front of the town of Egmond
- A reference area is considered for spatial comparison of morphological developments
- A fixed longshore distance is chosen over which the morphological developments will be described and quantified
- The analysis is extended to southern and northern areas for full coverage of the coastal cell

The southern test area for the Ecobeach system (Coast 3D site, marked in yellow in Figure 2.3) is supposedly quite undisturbed by nourishments. More specifically, this section has not been nourished directly, except in 2004 (see section 2.10). The southern test area is therefore considered as a relatively “natural” coastal stretch for testing the Ecobeach system. This southern area has been consequently selected by RWS for the analysis of the effects of the Ecobeach modules on the natural behaviour of the beach and dune systems. The southern area will hereby be referred to the “Test area”. Still, it should be borne in mind that artificial nourishments that have taken place near to the test site in the years prior to the experiments might unacceptably influence the results. The potential influence will be discussed in Chapter 5. Finally, the US patent of the Ecobeach system mentions the importance of physical processes and site characteristics relevant for the functioning of the PEM. To our knowledge, these physical processes and characteristics were not specifically considered when RWS selected the sites for testing the Ecobeach system.

By comparing the morphological trends before and after the installation of the Ecobeach modules, the analysis provides insight in the behaviour of Coastal State Indicators for the specific area in question. Such a temporal analysis does not enable the distinction between potential trend breaks due to particular events (e.g. stormy season) and deviations induced by the Ecobeach system. Therefore, a so-called “Reference area” has also been considered. The Reference area has been chosen south of the Test area, and stretches from RSP 43 to RSP 46. No influence of the Ecobeach system is expected in the Reference area as well as a limited influence from nourishments. This choice will be discussed further in Chapter 5.

The northern section is located in front of the town of Egmond in an area that has been strongly affected by nourishment activities. The combination of nourishments with the installation of the PEM is supposedly beneficial to the coastal system. However, due to this combination, the impact of the PEM on the coastal system cannot be isolated. The so-called “Egmond area”, from RSP 37 to RSP 40, is still used in the analysis for a full coverage of the coastal cell in which morphological developments might have affected the area where the Ecobeach system has been installed.

Finally, the analysed area is extended to a fourth control section (so-called “Heemskerk area” from RSP 46 to 49), southward of the Reference area, for full coverage of the coastal cell in which morphological developments might have affected the area where the Ecobeach system has been installed.

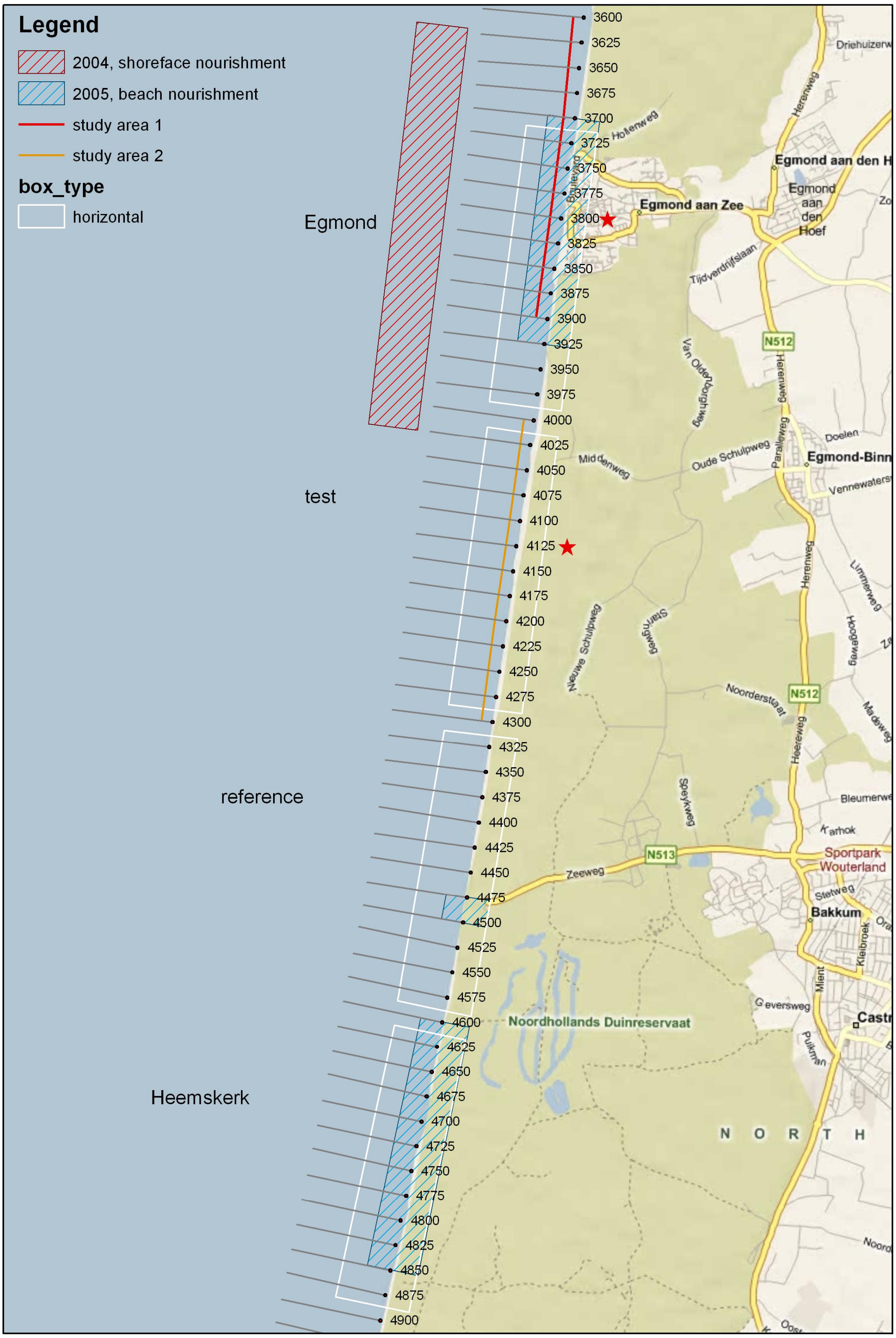

Figure 2.3 : Map of the coastal stretch considered for the analysis showing the locations of the areas where the PEM have been installed and the location of the nourishments. Horizontal boxes used in the analysis (see chapters 4 and 6) are displayed in the figure.

2.10 Nourishment history

Beach and shoreface nourishments have been carried out in the sections adjacent to the Test and the Reference areas, and to a smaller extent in the two areas themselves. As these activities might have induced a disturbance in the Test and Reference areas, it is crucial to evaluate the impact of the nourishments on the development of the coastal system. This evaluation will be described in Chapter 5.

Figure 2.4 shows the location of the beach and shoreface nourishments that have occurred in the Egmond region. It shows that the Reference area might be influenced by a nourishment at Heemskerk in May-June 2005 (250 m^3/m from RSP 46.50 to RSP 48.50). Moreover, a nourishment in Castricum, that is not registered in the RWS database, has been performed. To our knowledge, a total amount of 6 600 m^3 has been applied in May-June 2005 from RSP 44.75 to RSP 45.00. On the other hand, the Test area is located next to a region where successive beach and shoreface nourishments have been applied. In particular, the interventions performed in Egmond in 2004 and 2005 (shoreface nourishment of 450 m^3/m from RSP 36.2 to RSP 40.2 and beach nourishment of 216 m^3/m from RSP 37 to RSP 39.25, respectively) might influence the behaviour of the selected test area after the installation of the PEM.

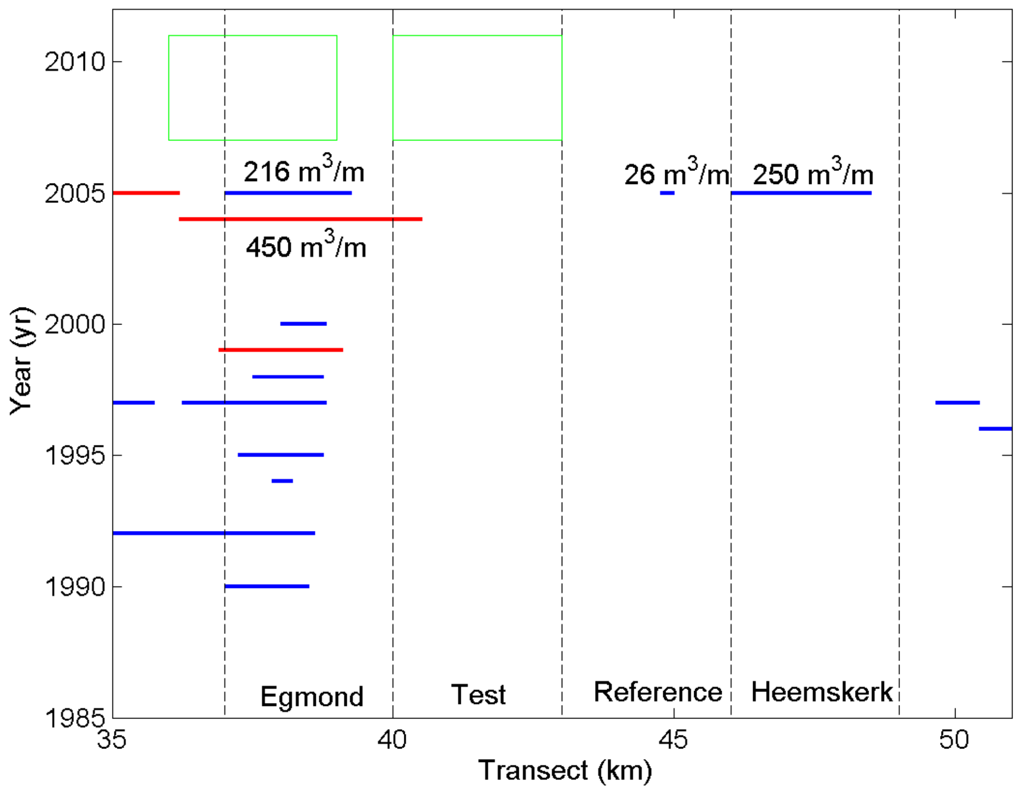

Figure 2.4 : Location of nourishments in time. The blue and red lines correspond to beach and shoreface nourishments, respectively, and show their extent along the coastal stretch of interest (x-axis). The green boxes show the location of the Ecobeach test areas, as well as they define the time interval during which the PEM were present in the beach.

3 Description of datasets and data aggregation methods

3.1 Introduction

This chapter describes the datasets and the data aggregation methods that form the basis of the present study. Two types of datasets are being used. The well-known Jarkus data set comprises annual measurements along the Dutch coast from various sources. In addition, site specific high resolution dGPS data, collected from 2002 to 2009, is introduced. The evaluation of the PEM is based on an analysis of the temporal evolution of various cross-shore aggregated parameters derived from the measured topography and bathymetry. These so-called Coastal State Indicators (CSI) are described in section 3.3. Finally, section 3.4 discusses the coastal areas over which the CSI are longshore averaged.

3.2 Datasets

In the following sub-sections, various attributes (e.g. coverage, methods of interpolation) of both Jarkus and dGPS datasets are described. In particular the influence of the interpolation methods used to combine the data is discussed and quantified.

3.2.1 Jarkus

The Jarkus dataset consists of annual surveys of the entire Dutch coast (see Figure 3.1) carried out by the Dutch Department of Public Works (Rijkswaterstaat). The monitoring started in the southern part in 1963 (km 99 – km 118, with origin km 0 located at Den Helder and for increasing kilometres counted southward). From 1964, the remaining part of the Holland coast (km 0 – km 99) was included in the monitoring program.

The coastal profiles are measured every 250 m alongshore, from the foredune to approximately 1 km seaward (near the NAP – 8 m depth contour). The alongshore position of cross-shore survey lines is marked by a permanent base line of beach poles (RSP system). The cross-shore resolution of the profiles ranges from 5 m near the shoreline to 10 m offshore.

The sub-aerial and the sub-aqueous parts of the coastal profile are measured separately. The sub-aerial part of the profile data (from the dunes to the momentary water line) was initially gathered by levelling. Since 1977 aerial photographs (stereography) were used followed by laser altimetry (Lidar) since 1997. The sub-aqueous part of the data is gathered by single-beam echo sounding, up to the momentary water line.

The survey dates of both parts of the Jarkus profile are available in the RWS database for most (but not all) surveys. The time gap between the sub-aqueous and the sub-aerial parts of the Jarkus data can reach up to 6 months. The average period between both surveys is about 2.5 months, in which the sub-aerial part is generally measured earlier (spring) than the sub-aqueous part (summer or autumn).

The two parts of the coastal profile are combined into one Jarkus transect.

- Q1A: How is the interpolation between the sub-aerial part and the sub-aqueous part of Jarkus measurements performed? Can we quantify the impact on the resulting data?

The representative Jarkus profile is obtained by interpolation between the sub-aerial and the sub-aqueous parts. If there is a spatial gap between the two parts, the z-levels of the missing points are obtained by interpolation. If the two parts are overlapping, a weighted average is calculated. The weights allocated to the sub-aerial points are ranging from 1 for the most landward point of the interpolated section to 0 for the most seaward point of the interpolated section. The weights allocated to the sub-aqueous points are ranging from 0 for the most landward point of the interpolated section to 1 for the most seaward point of the interpolated section. In case of overlap, the sub-aerial part is usually above the sub-aqueous profile. The difference in the integrated sediment volume between the sub-aerial part and the interpolated section is about 5 m^3/m on average and 25 m^3/m as the largest observed difference, in the Test area. The Reference area shows comparable values.

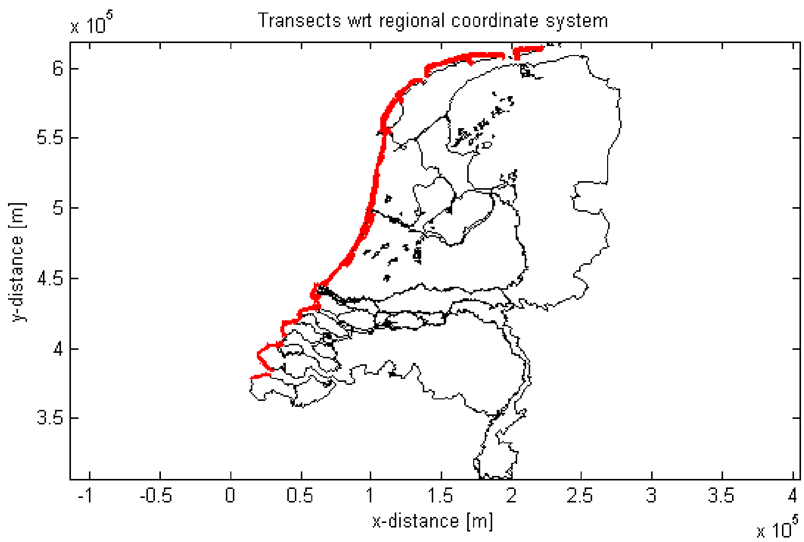

Figure 3.1 : Location of Jarkus transects along the Dutch coast

- Q1B: which errors and inconsistencies in the Jarkus dataset affect the present study?

The Jarkus dataset contains some inconsistencies and data gaps (Table 3.1)

Table 3.1 : Missing data in the Jarkus transects

year(s)	Remark
all	Data for Transect 5175 are unavailable
2002	NAP + 3m not measured at all (LIDAR not measured)
1993	South of 5150 no data at all
1983	South of 4450 no data at all

Molendijk et al. (2008) pointed out that both the 1992 and 1993 surveys contained severe errors in profiles at RSP 40.50, 40.75, 41.00 and 45.25. In 2006, transect RSP 45.50 showed similar errors. The values and the volume calculations for these years should therefore be excluded from the analysis.

The time interval between two successive profile soundings at a particular location may vary between 0.5 and 1.5 year. In combination with the average 2.5 months with which the sub-aerial part of the Jarkus is precedes than the sub-aqueous part, the profile sampling may have a seasonal bias. This topic will be addressed in Chapter 4.

Several beach restaurants are located especially around transects RSP 44.50, RSP 44.75 and RSP 45.00 (left-hand plot in Figure 3.2). However, the restaurants are not visible in the Jarkus transects (right-hand plot in Figure 3.2). These transects can therefore be used in the analysis.

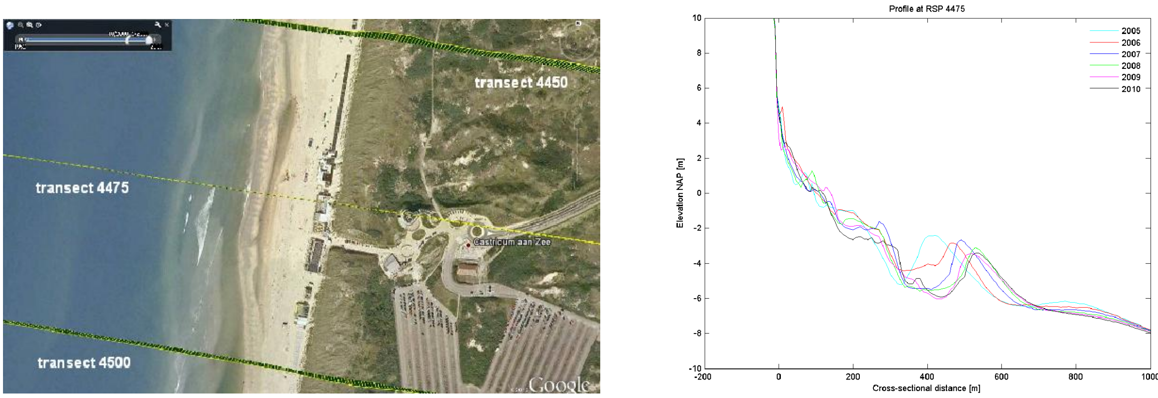

Figure 3.2 : Location of beach restaurants and corresponding Jarkus transects

3.2.2 dGPS measurements

Between the 15th May 2002 and the 1st July 2009, additional bed levels were surveyed more frequently than the Jarkus measurements. These additional measurements are referred to as “dGPS measurements”, as a differential Global Positioning System instrument was used. In Figure 3.3, the spatial and temporal coverage of the dGPS surveys is represented.

Between May 2002 and June 2004, topographic beach measurements were carried out around low spring tide (typical range 1.8 m) every 4 weeks. Data was collected along approximately 20 cross-shore transects with a 50 m alongshore spacing. In addition, ad-hoc measurements between transects have been carried out to capture details of small rip channels. Each transect stretches from just below the momentary water level to well above the dune foot at NAP + 3m. The lowest bed levels, about NAP – 1.5 m, were reached during low-energy wave conditions. During this period no measurements were performed in deeper water.

Unfortunately, the spatial coverage varied over the years (as is also obvious from Figure 3.3). More specifically, between May 2002 and September 2002 (5 surveys), the measurements covered the area enclosed by RSP 40.75 and RSP 41.75. From October 2002 to June 2004 (20 surveys), the data was collected from RSP 40.10 to RSP 41.10. From March 2006 onward, a motor-quad was used, enabling the coverage of a wider area, from RSP 37.00 to RSP 43.00. These measurements were obtained by Utrecht University and carried out within the framework of a PhD project.

From March 2007 onward, the measurements were carried out by Rijkswaterstaat, both on the beach and offshore. In 2007 and 2008, the data was collected from RSP 35.00 to RSP 45.00, and in 2009 from RSP 40.00 to RSP 46.00. Measurements were taken along the Jarkus transects, with 3 or 4 transects in between on the sub-aerial part of the profile, and 1 transect in between on the sub-aqueous part. The alongshore spacing is therefore 50-62.5m on the beach and 100-150m offshore. The surveyed profiles were not methodically carried out during low water, so the beach surveys did not always extend to the Mean Low Water line at NAP – 0.78m.

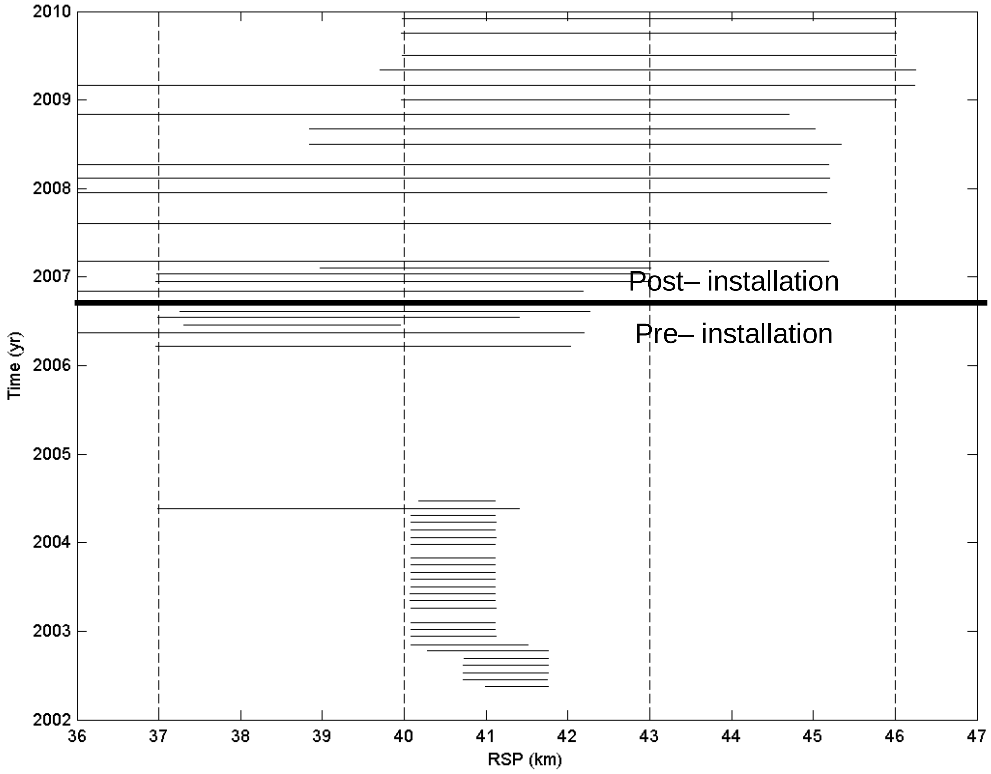

Figure 3.3 : Coverage of the dGPS surveys used for the data analysis

3.2.3 Processing dGPS data

The dGPS transect data were interpolated on 10mx10m grids, which were provided by Rijkswaterstaat (Waterdienst).

- Q1C: Are errors introduced when interpolating raw dGPS data on the provided RWS grids?

The extent of the dGPS grids coincides with the coverage of the dGPS surveys perfectly. Therefore, it is assumed that all raw data points have been used to generate the dGPS grids.

The interpolation was performed using the DIGIPOL program. This software has advanced algorithms which can include the effect of the orientation of (morphological) features in the raw data points as part of an iterative linear interpolation. DIGIPOL has a given precision of about 40 cm.

Still, the interpolated z-levels at the dGPS grids and the raw dGPS data reveal some differences. These differences are generally present at the dune front. The differences between the interpolated values and the raw dGPS data range from 1 mm to 0.5 cm. The errors introduced when interpolating the raw data on grids are therefore judged as minor.

- Q1D: For which types of analysis is the dGPS dataset appropriate?

The incomplete spatial coverage of the dGPS surveys does not allow an analysis which is based on the comparison of the evolution of morphological indicators representative of both the Test and Reference areas.

The difference in temporal survey resolution is also an important issue. The added value of the dGPS data is primarily its high temporal resolution which would enable the evaluation of seasonal effects. However, the gap of almost two years (2004-2006) prevents the temporal analysis. The dGPS data gathered in the years 2002-2004 can only be used to describe the natural behaviour of a confined coastal stretch, whereas the dGPS data gathered after the installation of the PEM have been obtained at a lower temporal resolution but covering almost the entire Test and Reference areas.

The dGPS data can therefore only be used to address one specific research question (Q2D, see section 4.4).

3.3 Coastal State Indicators

- Q1E: Can we aggregate the survey data as indicators of the state of (parts of) the morphology at Egmond?

The data analysis is based on the bathymetric information relevant for the description of the morphological features that change in time and space. To that end, the bathymetric data are aggregated into a limited number of variables (referred to as Coastal State Indicators or CSI). The most compact way to summarise the above mentioned type of information is in terms of sediment volumes and budgets.

A main characteristic of a nearshore profile is considered to be its “cross-shore position”. This information deals with the accretive or retreating nature of a coast. For example, along an accretive part of a coast the nearshore profile shifts seaward. Therefore, a profile’s behaviour can be expressed in terms of change in cross-shore position of the profile.

To account for the “cross-shore position”, the volumes and the sediment budgets should be defined with respect to a geo-referenced landward location.

The identification (Chapter 4) and quantification (Chapter 6) of changes in the behaviour of the morphology is based on the analysis of several Coastal State Indicators (CSI), which describe several parts of a cross-shore profile. This section defines the CSI that are used in the subsequent analyses.

The CSI are based on the definition of a referenced (fixed) shoreward boundary as well as an upper and lower boundary level. These CSI are presented in Figure 3.4.

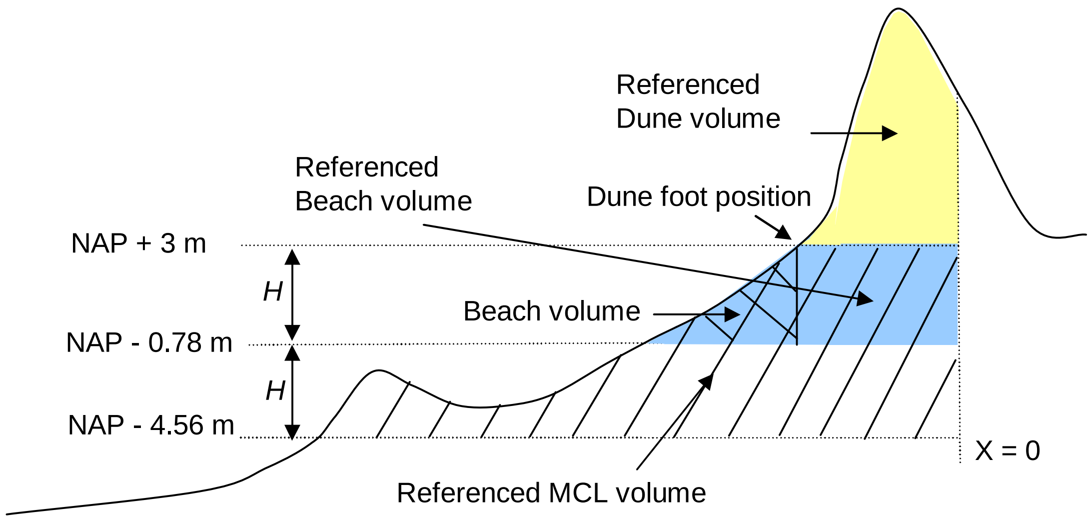

Figure 3.4 : Sketch of Coastal State Indicators used for the identification and quantification of changes in the behaviour of the morphology at Egmond

The CSI are based on the following characteristic elevations:

1. the dune foot chosen arbitrarily at NAP + 3m. The corresponding position or dune foot position is calculated with respect to a geo-referenced origin (x = 0). The origin corresponds to the position situated 250 m landward from the location of the NAP + 3m z-level obtained from the Jarkus dataset for the year 2005. This landward reference position is chosen at a location where the dune system is stable.
2. the mean low water level at NAP – 0.78m. The corresponding position or shoreline position is calculated with respect to the geo-referenced origin.
3. the lower elevation level of the “Momentary CoastLine” or MCL at NAP – 4.56m (Van Koningsveld and Mulder, 2004). The corresponding position is calculated with respect to the geo-referenced origin.

The volumetric CSI that are used in the analysis are defined as follows:

1. Beach volume (between NAP + 3 m and NAP – 0.78 m, and with the dune foot position as the landward boundary),
2. Referenced Dune volume (upward of the NAP + 3 m elevation, and with the geo-referenced origin as the landward boundary),
3. Referenced Beach volume (between NAP + 3 m and NAP – 0.78 m, and with the geo-referenced origin as the landward boundary),
4. Referenced MCL volume (between NAP + 3 m and NAP – 4.56 m, and with the geo-referenced origin as the landward boundary).

Besides the above presented CSI, it was suggested by RWS and BAM during the course of the project to use several additional CSI. Table 3.2 summarises the characteristics of all the CSI that were considered in the present study. However, the analysis is primarily based on the above mentioned ones. For completeness sake, Appendix B provides plots of the CSI that were not of direct relevance for the analysis provided in the main report.

Table 3.2 : Coastal State Indicators used for the identification (chapter 4) and for the quantification (chapter 6) of changes in the morphological behaviour at Egmond

Coastal State Indicators	Dataset	Boundaries
Referenced MCL volume	Jarkus	NAP + 3 m, NAP – 4.56 m, wrt. x = 0 m
Referenced Beach volume	Jarkus	NAP + 3 m, NAP – 0.78 m, wrt. x = 0 m
Referenced Dune volume	Jarkus	NAP + 3 m, wrt. x = 0 m
Dune foot position	Jarkus + dGPS	NAP + 3 m, wrt. x = 0 m
Shoreline position	Jarkus	NAP – 0.78 m, wrt. x = 0 m
Beach width	Jarkus	Horiz. dist. btw dune foot and shoreline
Beach volume	Jarkus + dGPS	NAP + 3 m, NAP – 0.78 m, wrt. $x_{(NAP\ +3m)}$

3.4 Longshore-averaging of Coastal State Indicators

On small scale (1 km) and on the short time scale of a storm, longshore non-uniformities develop as local disturbances that are superimposed on the overall alongshore coast yielding a three-dimensional morphological system. In particular, rip channels (with length of 200 to 300 m and depth of 0.5 to 1 m) are generated in the crest zone of the inner bar on the time-scale of a few days during minor storm conditions. Rip channels generally are washed out during major storm conditions. Spatial variations in beach width and volume are also due to sand waves. Quartel and Grasmeijer (2006) found variations in beach width of about 40 m over a distance of roughly 300 m, although these variations were not always present. A sand wave crest (large beach width) may contain 5 000 m^3 of sand. Sand waves were found to migrate with an alongshore velocity of roughly 250 m/yr.

Spatial aggregation by averaging the CSI along the longshore direction is performed in order to minimize the noise, induced by these local features, from the long-term Jarkus or medium-term dGPS time series.

By averaging the CSI in the longshore direction within each of the four areas defined in section 2.9 (Egmond, Test, Reference, Heemskerk), the reported analysis is performed in an area-specific manner. A buffer zone of 250 m between the four selected adjacent areas is considered, and aggregation is performed for each pre-defined area over a stretch of 2.75 km (11 transects). The extent of the four areas used for the analysis in Chapter 4 and in Chapter 6 is displayed in Figure 2.3 as white boxes.

4 Analysis of profile-data

4.1 Introduction

The CSI, described in section 3.3, are aggregated to merge data and reduce possible noise. The length of the coastal stretch over which data is aggregated might affect the (natural) variability remaining in the results. This influence is investigated in section 4.2 prior the identification of the behaviour of the CSI. Section 4.3 gives a description of the temporal evolution of the aggregated CSI, before their quantification (Chapter 6). Besides, the influence of seasonal variations in the CSI is discussed in section 4.4. The research questions specified in section 1.2 are answered through a description of the analysis, followed by the observations resulting from the analysis.

4.2 The effect of aggregation

- Q2A: How does the longshore averaging affect the variability in the result?

The longshore variability is closely related to the temporal variation of the CSI in the different transects. Scatter plots of the Referenced Beach volumes in the Test area are shown in Figure 4.1 for several transects. To gain insight in the bandwidth of the aggregated values the envelopes of the maximum and minimum values are plotted as well. The bandwidth of the Referenced Beach volume and of the Referenced MCL volume (see Appendix B) is about 200 m^3/m and about 400 m^3/m, respectively.

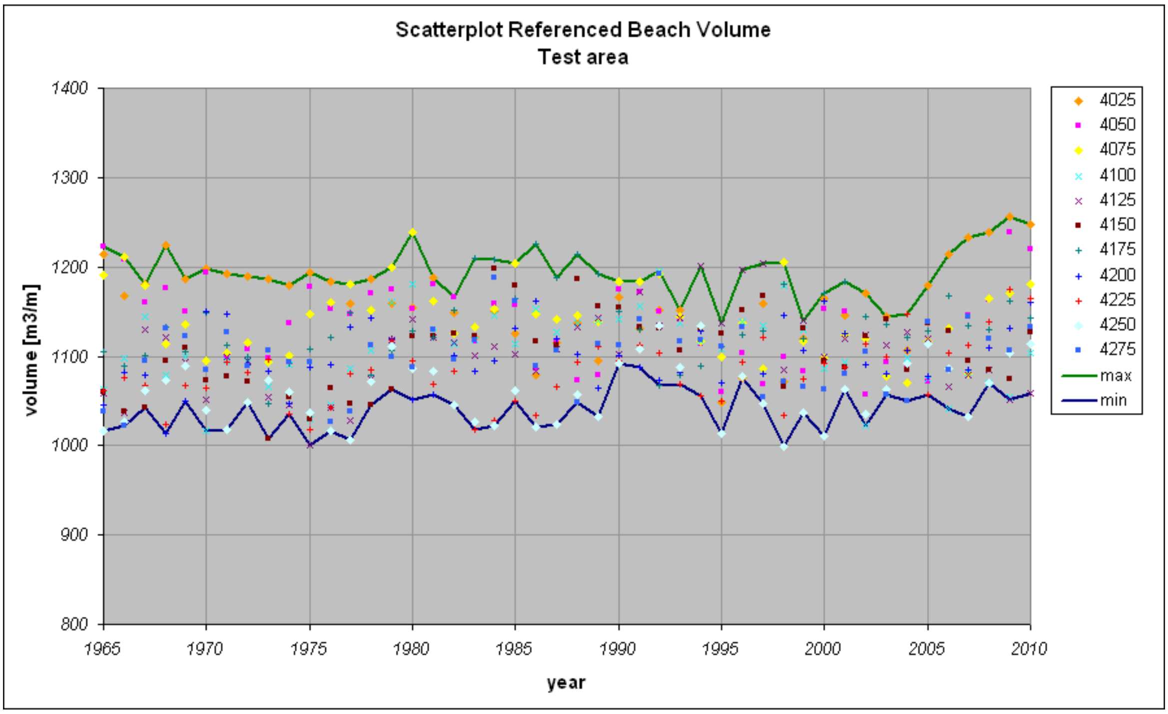

Figure 4.1: Example of scatterplot of Referenced Beach volume

In addition, a sensitivity analysis of the Referenced Beach volume and of the MCL volume is performed by averaging these CSI over a different number of transects (Figure 4.2 and Appendix B). The volumes of these different aggregations are slightly dissimilar. However, these differences become smaller with increasing number of transects, as local features are averaged out.

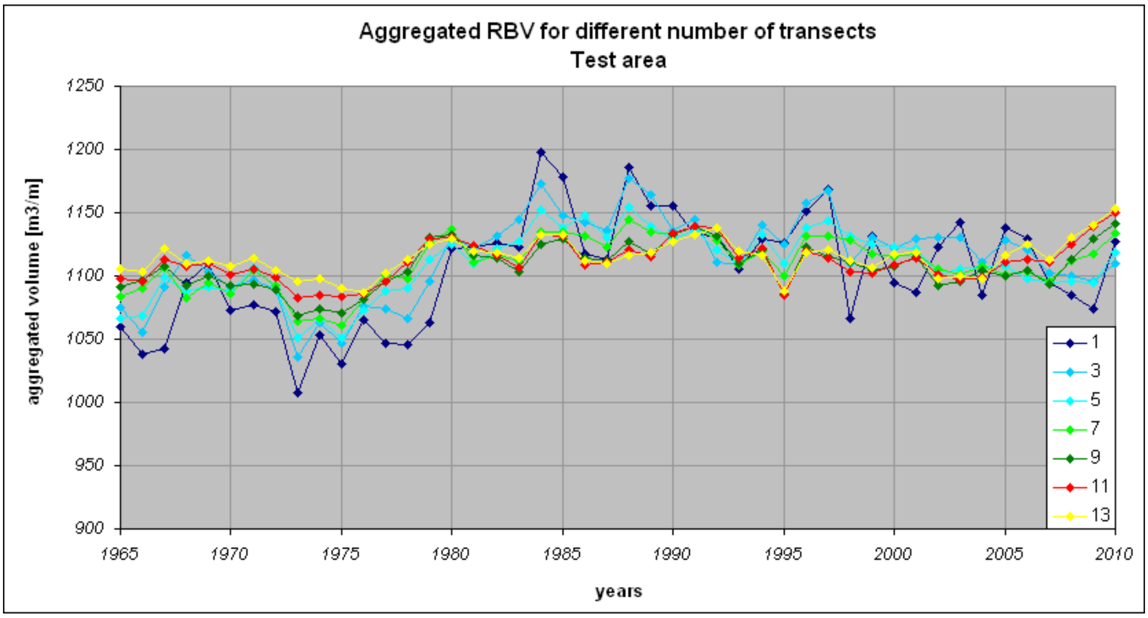

Figure 4.2: Referenced Beach volume averaged over a different number of transects

Figure 4.3 displays, for the Referenced Beach volume, the difference in volume obtained when aggregating using different numbers of transects. For instance, the difference in volume is about 10-15 m^3/m, if using 11 and 13 transects for the aggregation. In the following analysis, the CSI averaged over 11 transects have been used, allowing for the inclusion of all transects of the considered area, and accounting for a buffer zone of 500 m between areas.

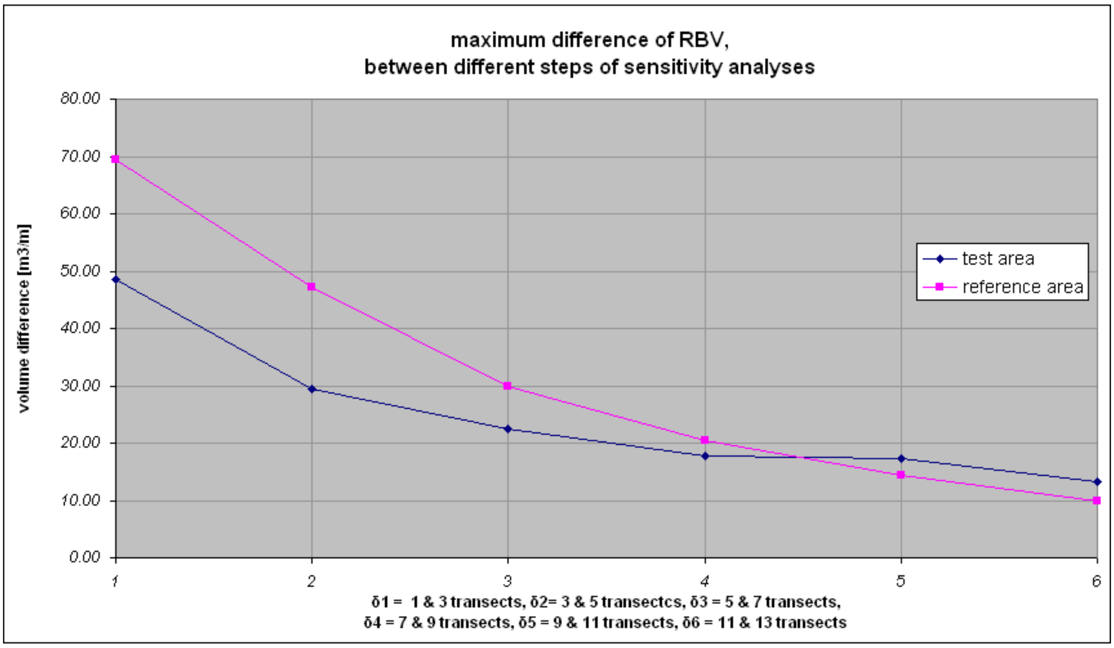

Figure 4.3: Sensitivity analyses of the Referenced Beach volume [m3/m] in the Test and Reference areas

4.3 Description of alongshore and temporal variations

4.3.1 Temporal variations

- Q2B: What is the long-term evolution of the morphology?

Since 1965, the Referenced MCL volume, the Referenced Beach volume and the Referenced Dune volume have increased in both the Test area (Figure 4.4) and the Reference area (Figure 4.5).

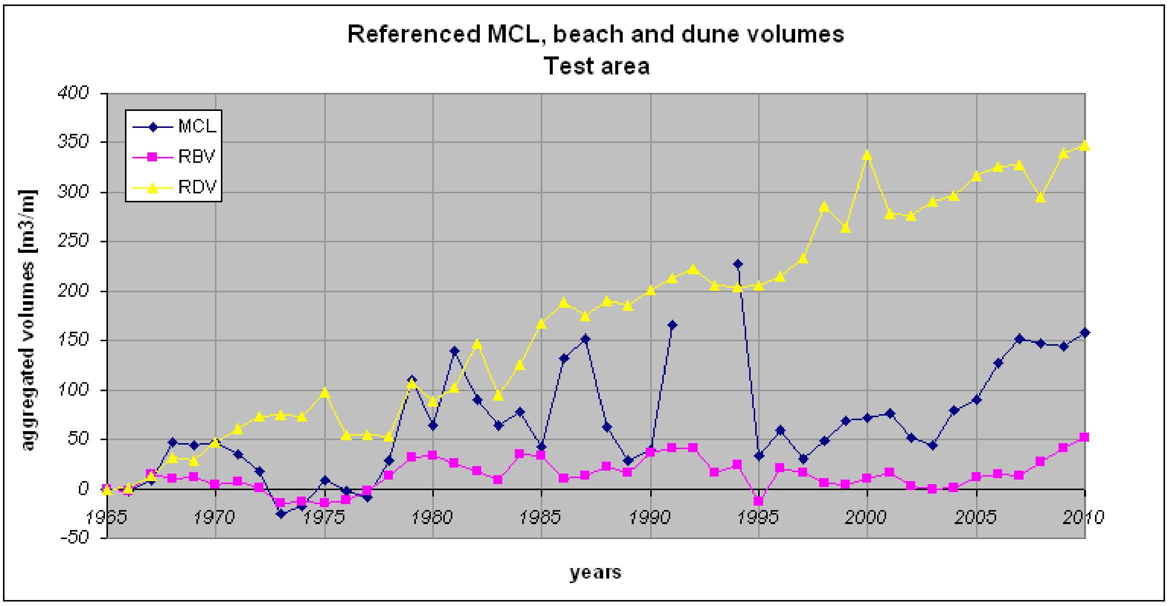

Figure 4.4: Aggregated Referenced MCL, Beach and Dune volume in the test area [m3/m]

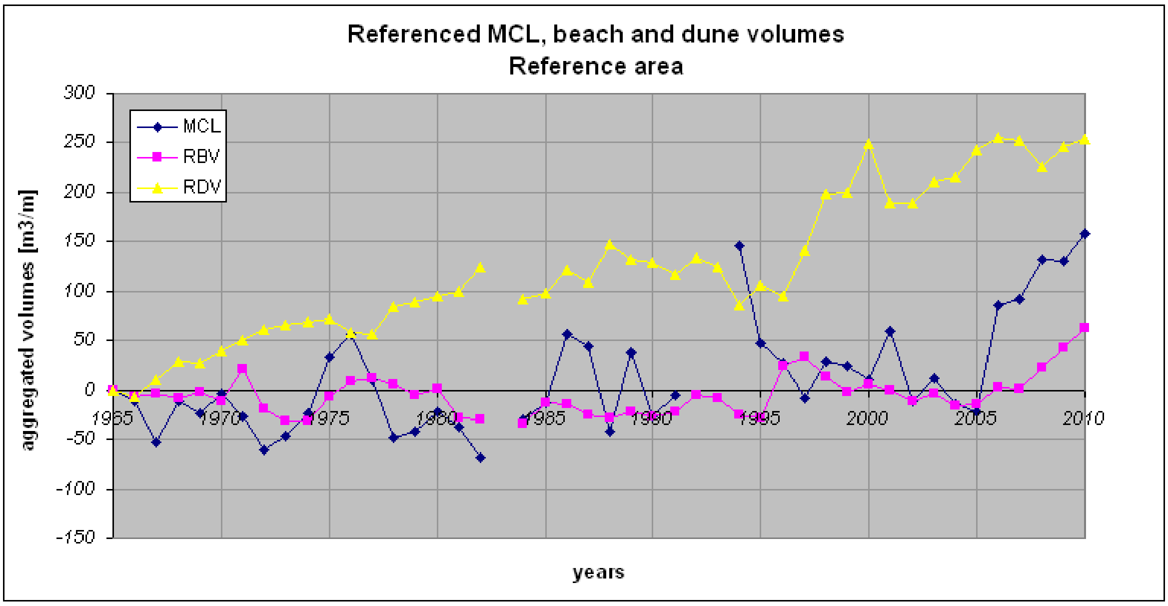

Figure 4.5: Aggregated Referenced MCL, Beach and Dune volume in the reference area [m3/m]

The volume of the dunes has increased the most, up to 350 m^3/m in the Test area and 250 m^3/m in the Reference area since 1965. The slight decrease in both areas in 2008 is due to a storm surge that occurred in November 2007. The Referenced MCL volumes show large variations throughout time, with differences up to 75-100 m^3/m per year. The Referenced Beach volume shows the lowest increase in time with a maximum of 50-60 m^3/m in one year.

4.3.2 Alongshore variations

- Q2C: What is the long-term alongshore variability of the coastal system?

A linear trend analysis applied to the CSI can also give insight in several research questions. First it may indicate breaks in the development of the coastal system due to nourishments. Secondly, it provides an opportunity to explore the data for seasonality, and finally it gives an idea about the overall longshore variability. The trend analysis is performed for the Referenced Beach volume for one, two and three time periods (Figure 4.6).

To investigate the overall alongshore variability, the linear trend is estimated for the entire period (1965-2010). To evaluate whether the start of the large scale nourishments in 1990 introduced a trend break and a change in coastal behaviour, the linear trend is estimated for two shorter time periods as well (1965-1990 and 1991-2010).

To investigate whether the installation of the PEM is capable of introducing a break in the regression lines, the linear trends are estimated for three periods (1973-1989 (17 yrs), 1990-2006 (17 yrs), 2007-2010 (4 yrs)). The latter analysis did not add any additional information compared to the previous two analyses, as the third period was relatively short and therefore very vulnerable to outliers (not shown here for the sake of brevity).

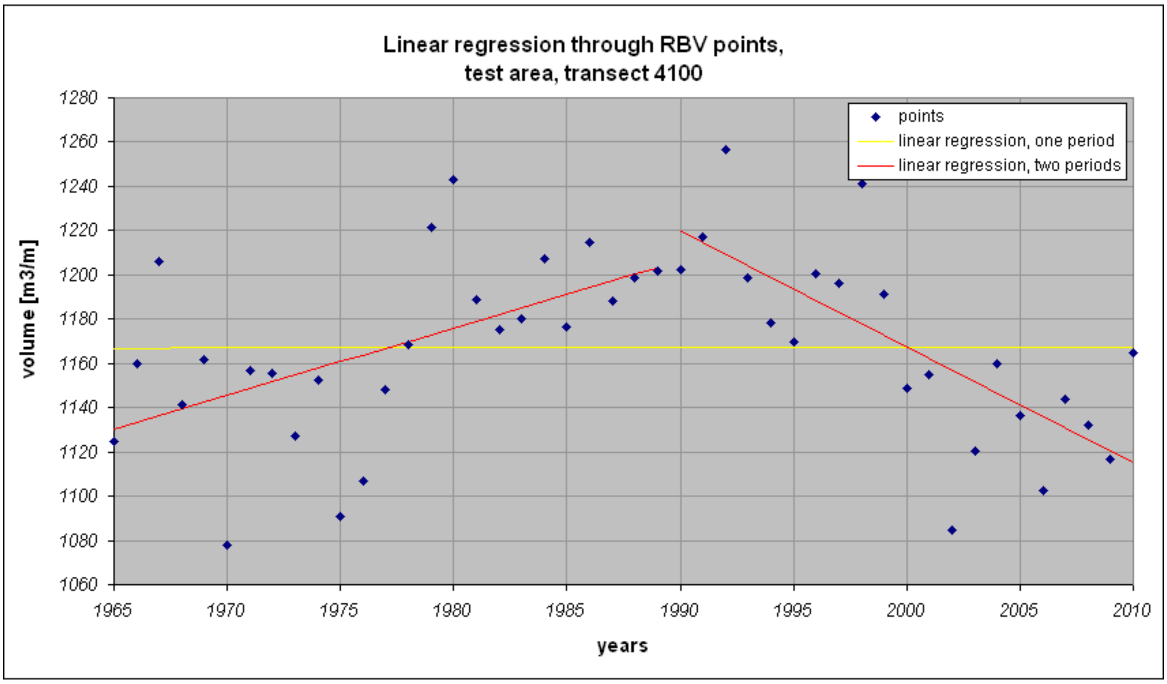

Figure 4.6 : Example of linear regression through Referenced Beach volume points.

The slope of the linear regression line of the Referenced Beach volume for the entire period varies in the longshore direction (Figure 4.7). In general, this slope is positive, indicating an increase in the Referenced Beach volume. An exception is the Heemskerk area from transect RSP 47.25 onwards, which indicates a retreat of the coastal system.

The slopes of the linear regression lines of the Referenced Beach volume for the two periods analysis show a very clear break for the transects 35.00 to 39.00. Before 1990, the trend is negative, with a decrease in volume, whereas after 1990 the trend is positive. The Test and Reference areas do not reveal a distinguishable break. Switches from positive to negative and vice versa occur in both areas. This alongshore variability in the Test and Reference areas has a spatial extent of about 1 to 1.5 km.

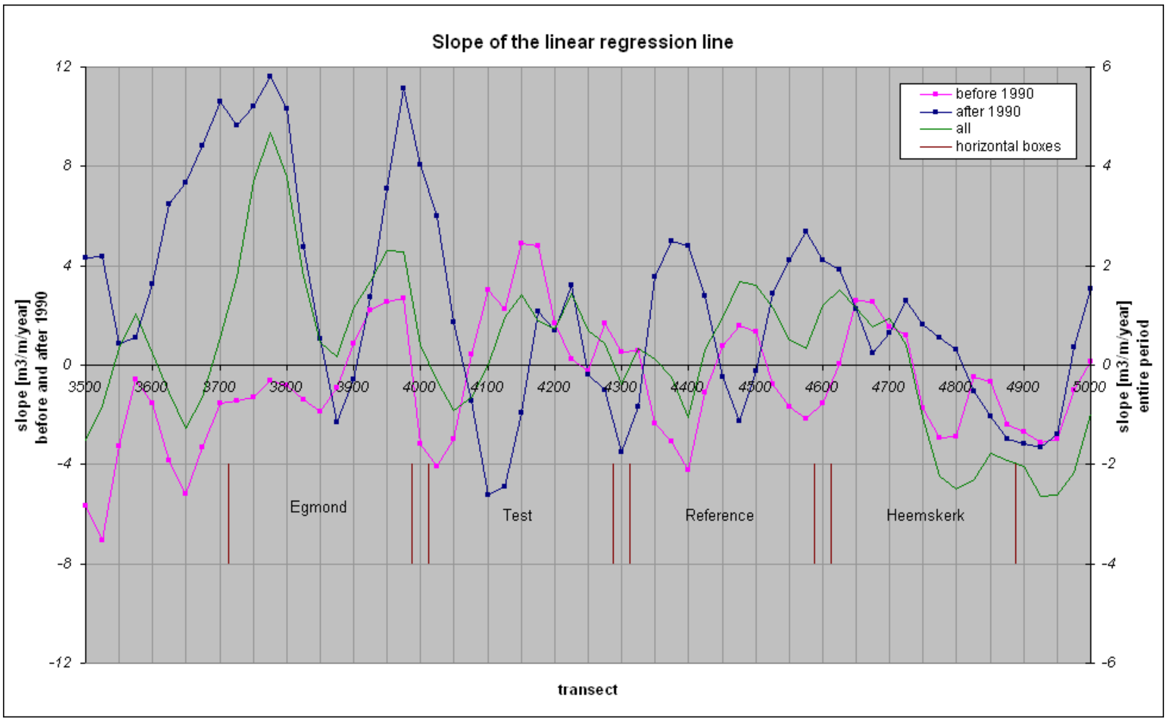

Figure 4.7 : Slope of the one and two periods linear regression analysis of the Referenced Beach volume [m3/m/year] versus the alongshore position

In the years 1965-2010, both the Referenced Beach volume (Figure 4.8) and the Referenced MCL volume (Figure 4.9) increase in all the areas except for a mild decrease of the Referenced Beach volume in the Heemskerk area.

The Referenced Beach volume loss in the Heemskerk area is about 40 m^3/m over the entire period. The Referenced Beach volume in the Egmond area decreases from 1965 until 1995. After 1995, it increases significantly. This switch is probably due to the nourishments carried out since the 1990's.

The MCL volume increases gradually from 1965 onward and does not exhibit a distinctive trend break around 1990 or afterwards. Considering the Egmond data for the entire time interval, an increasing trend with (increasing) oscillations is visible. This pattern does not change when considering the period from 2005 onwards.

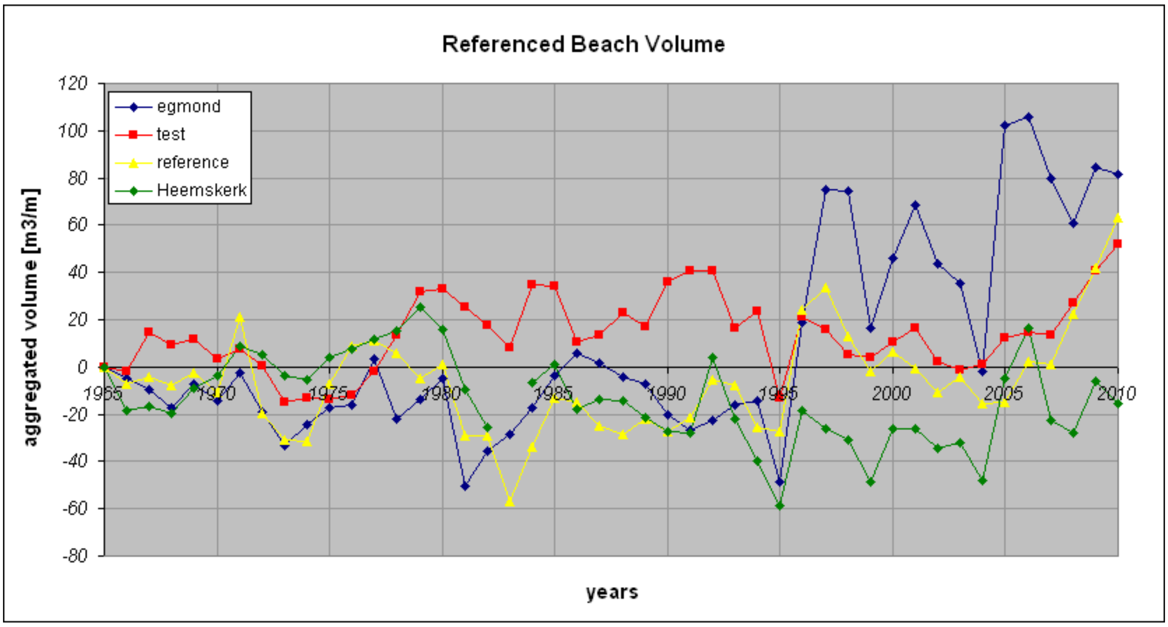

Figure 4.8 : Change in aggregated Referenced Beach Volume since 1965 for all four areas [m3/m].

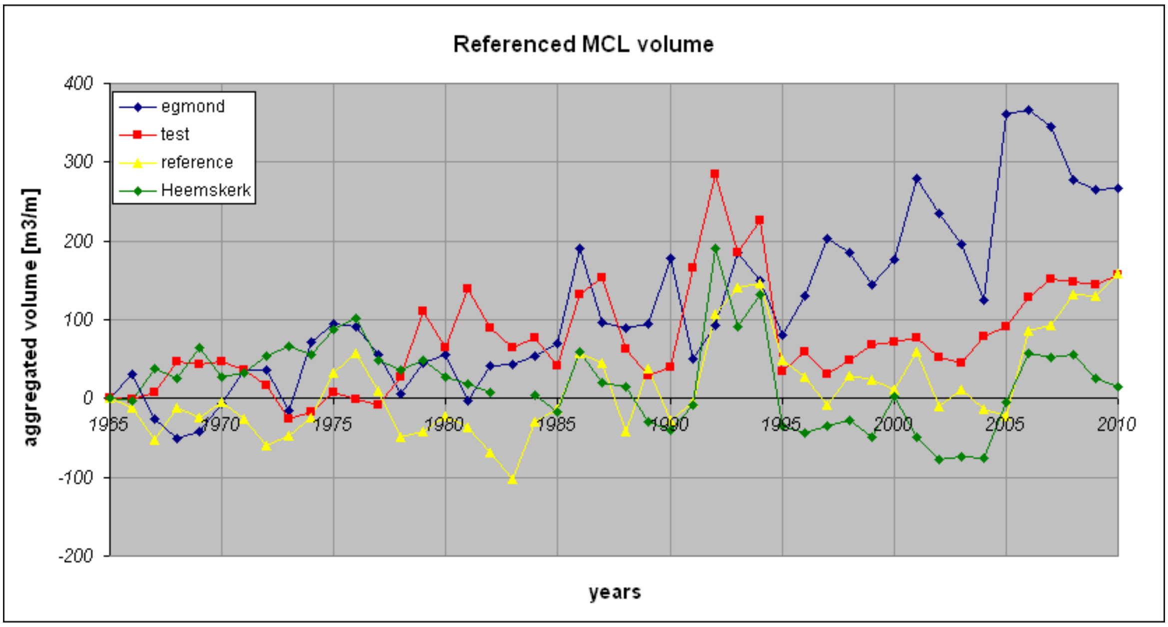

Figure 4.9 : Change in aggregated Referenced MCL volume since 1965 for all four areas [m3/m].

4.4 Identification of seasonal variations

- Q2D: Can we identify seasonal variations in the aggregated data?

The CSI are computed using Jarkus data. This is due to the limited extent of the dGPS data in time and space. In particular, the incomplete spatial coverage of the dGPS surveys does not allow an analysis which is based on the comparison of the evolution of indicators representative of both the Test and Reference areas.

The advantage of the Jarkus data is that it is a long regular time series; however, it is not clear if seasonal variability of the coastal morphology is represented by the annual Jarkus measurements. The dGPS data are measured throughout the year and might shed light on the seasonal effects on the calculated CSI.

By plotting the temporal evolution of the CSI calculated with dGPS data, seasonality in the coastal morphology can be investigated. Figure 4.10 displays the Beach volume (Table 3.2) at transects 4075-4105 for the period 2002-2004 during which the elevations were measured 8 to 11 times each year. The volumes calculated for the months of November to April are higher than the volumes calculated for the months of May to October (Figure 4.10). The difference between the beach volumes for these two periods is approximately 50 m^3/m. The evaluation of the Beach volumes calculated using the dGPS data shows that there is some seasonality in the data.

The sub-aerial part of the Jarkus data is measured around April, which is the month for which the seasonal effect is small due to the transition from higher to lower values.

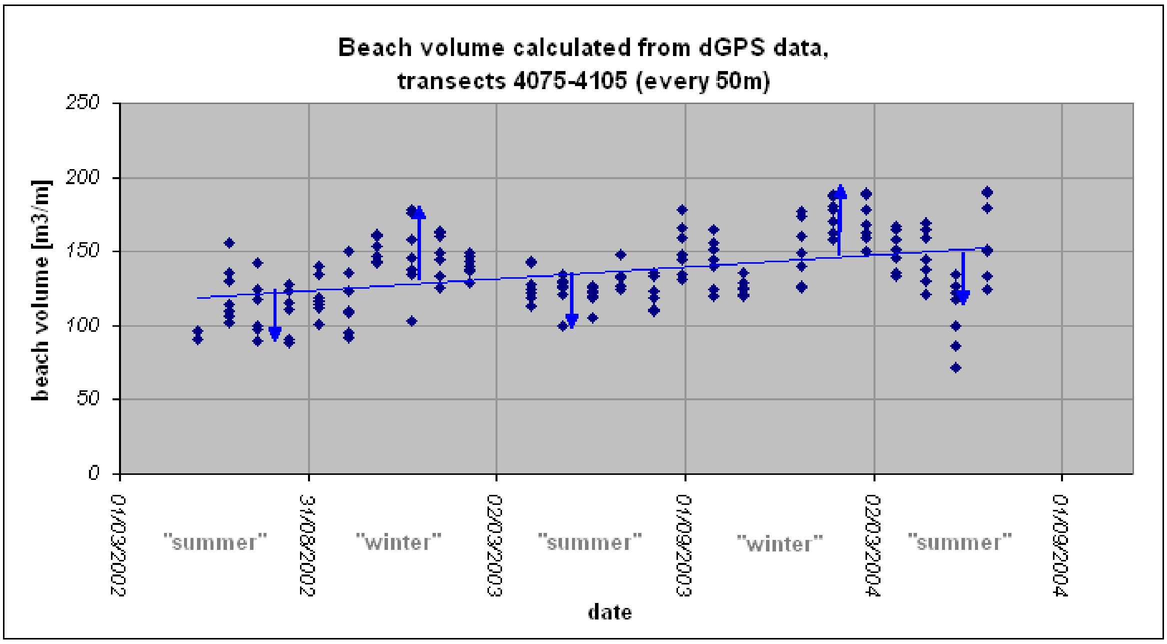

Figure 4.10 : Beach volumes [m3/m] calculated from dGPS data, transects 4075-4105 (every 50 m), years 2002 – 2004

Secondly, the Beach volumes calculated with the dGPS data are compared with those based on the Jarkus data. The Beach volumes calculated at transect 40.50 using the dGPS data exhibit a variation (Figure 4.11) similar to the one exhibited by the Beach volumes calculated using the Jarkus data. This analysis has been done for other transects and showed similar results (not shown here for the sake of brevity).

Despite their low frequency of acquisition, the Jarkus data are suitable descriptors for the yearly average development of the coast.

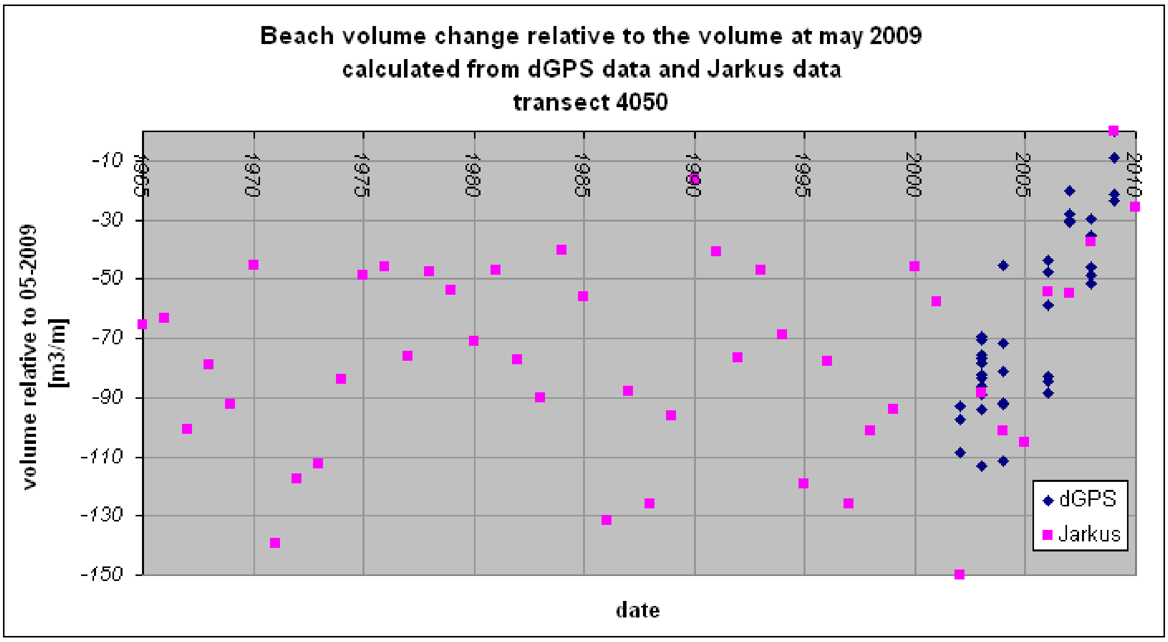

Figure 4.11 : Beach volume changes [m3/m] calculated from dGPS data and Jarkus data, for transect 4050, and for years 1965 – 2010, and relative to the volume at 05/2009

5 Morphological analysis

5.1 Introduction

The analysis in the previous chapter revealed that the observed developments of the upper parts of the profile (Beach and Dunes) in the Test and Reference areas show a comparable increase in Beach and Dune volume since 2007 (see Figure 4.8, Figure 4.9). The question now arises what is driving this continuous increase. Besides the installation of the PEM, the coast at Egmond is among the most frequently nourished areas along the Holland coast. Furthermore, the role of the cyclic bar behaviour at Egmond (with a cycle period of approximately 15 years) may have an influence. To establish the influence of the nourishments and of the cyclic bar behaviour, a detailed morphological analysis was carried out of which the main outcomes are summarised in this chapter. The complete analysis is presented in Appendix C.

The detailed morphological analysis (based on the Jarkus surveys from 2003 to 2010) is primarily aimed at identifying:

- The impact of the recent nourishments on the morphological (volume) development of the Test and Reference areas,
- The influence of the cyclic bar behaviour on the development of especially the beach and dune volumes.

5.2 Approach

In the analysis, a top-down approach is adopted starting at the largest considered spatial scales (viz. the 12 km alongshore area from Heemskerk to Egmond). The next step is to zoom in on smaller scales, especially to estimate sediment exchanges and eventually to assess the impact of the nourishments and bar behaviour on the beach and dune volumes.

The morphological analysis is based on an analysis of volume changes and the interpreted sediment exchanges between adjacent pre-defined areas. This requires the definition of areas that are vertically bounded in both the alongshore and the cross-shore directions. To ensure a consistent coupling with the analysis performed in Chapter 4, the cross-shore positions of the vertical boundaries are chosen to be the same as those used in the definitions of the Referenced Dune, Referenced Beach and Referenced MCL volumes by considering the same characteristic elevations. The vertical cubing volumes are indicated by an additional preceding “V-“ (viz. V-Dune, V-Beach, Lower V-MCL and Lower V-Shoreface, Figure 5.1). The Jarkus data was de-curved by setting the 2003 horizontal Dune foot position as the zero cross-shore coordinate.

Four areas with an alongshore length of 3 km each are defined directly adjacent to each other. The resulting de-curved Jarkus data, the areas for the vertical volumes and the location of the shoreface and beach nourishments carried out since 2004 are indicated in Figure 5.1.

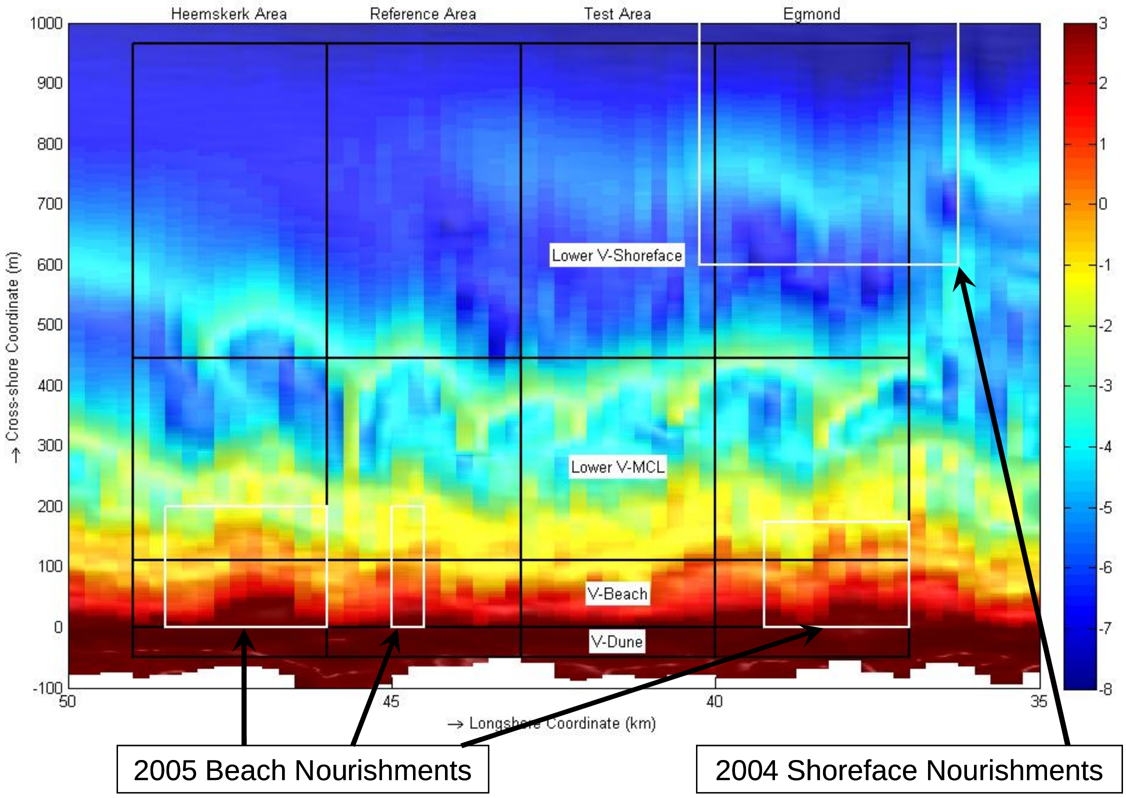

Figure 5.1 : De-curved 2006 bathymetry; the black boxes indicate the volume boxes; the white boxes indicate the nourishment locations.

5.3 Impact of the nourishments

- Q3: What is the impact of the recent nourishments on the morphological development of the Test and Reference areas?

From the cumulative bed changes from 2003 to 2010 (bottom plot in Figure 5.2) it is evident that the 2004 shoreface nourishment at Egmond is still present. The beach nourishments cannot be distinguished in the bathymetry plots, but the cumulative bed changes show a predominant sedimentation in the nourished beach areas.

The cumulative bed changes from 2003 to 2010 (bottom plot in Figure 5.2) clearly show the dominance of the offshore bar migration especially in the Lower V-MCL and Lower V-Shoreface regions. The distinct alongshore coherent erosion-sedimentation patterns indicate the bar migration over the considered period. For the Beach and Dune regions the longshore coherence is significantly lower, but alongshore coherent bed change patterns also seem to be present at some locations. For example in the Heemskerk area the cumulative bed changes in the upper beach and dune areas (bottom plot in Figure 5.2) show an alongshore coherence of about 1.5 to 2.5 km. Furthermore, the cumulative bed changes indicate that the beach nourishment at Heemskerk still seems to be noticeable in 2010. However, inspection of the annual results (Appendix D) reveals that only the lower part of the nourishment is still present, the upper part of the beach nourishment has eroded significantly in 2007-2008. In the following years, the upper beach recovers. For the Egmond area, a similar behaviour can be observed for the entire beach nourishment: it seems to have nearly completely disappeared in 2007-2008, but in the following years, the upper beach recovers.

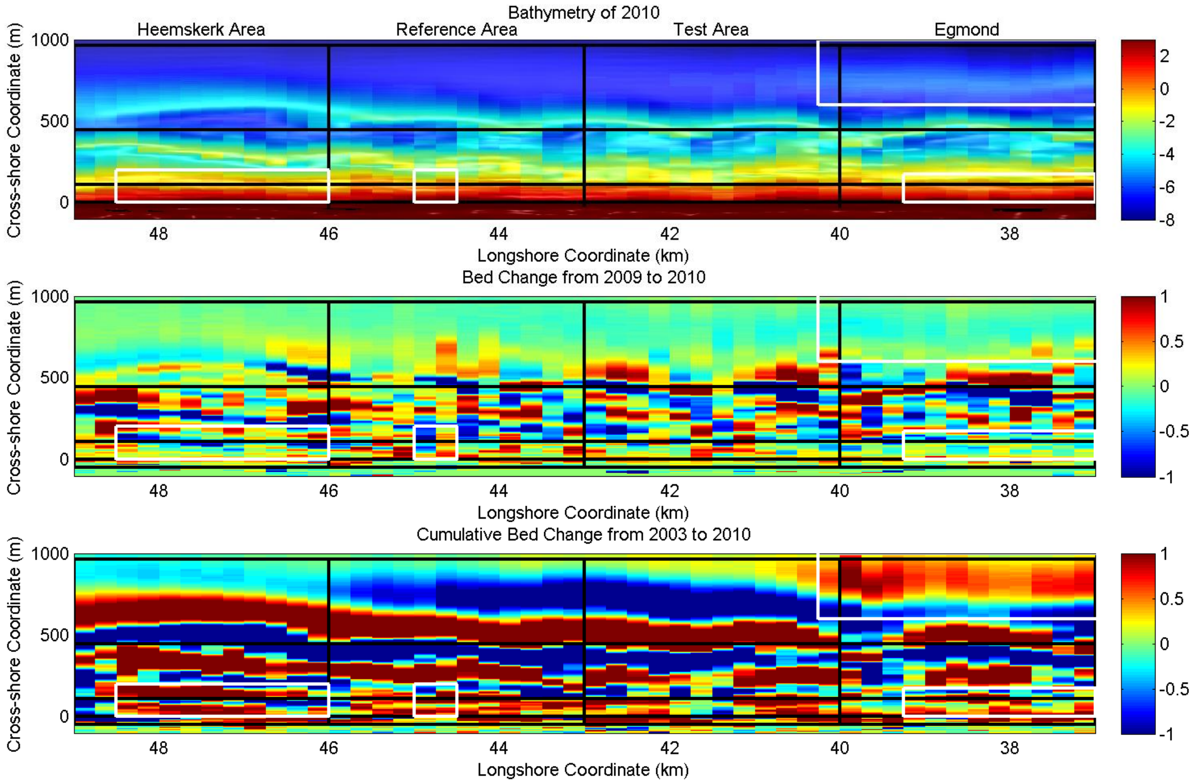

Figure 5.2: De-curved top view plots of the 2010 bathymetry (top), bed change from 2009 to 2010 (middle) and the cumulative bed change since 2003 (bottom). The black boxes indicate the areas considered for the analysis and the white boxes indicate the recent nourishment locations.

The volume development since 2003 for the entire boxes (i.e. the combined V-Dune, V-Beach, Lower V-MCL and V-Shoreface volumes for each area) is shown in Figure 5.3. In addition to the total volumes, the volumes of the combined Egmond - Heemskerk areas (nourished areas) and the combined Test - Reference areas are included as well.

The total volume (black line in Figure 5.3) shows a distinct increase in 2005 and 2006 which is associated with the implemented nourishments. The delay in the volume signal is caused by the fact that nourishments were carried out after the annual surveys in 2004 and 2005. The observed total volume increase (2.3 Mm^3) matches well with the total nourishment design volume (2.27 Mm^3, which excludes 800 m –approximately 0.36 Mm^3– of the 2004 Egmond shoreface nourishment that extended beyond –North of– the Egmond area). From 2006 to 2008, a relatively large total volume decrease (0.94 Mm^3) is observed. Since 2008, the total volume is showing relatively gradual and relatively small changes. According to Van Rijn (1997), sediment transports across the NAP – 8 m depth contour are zero on average, but have a range of 10 m^3/m/yr onshore or offshore. The total alongshore length is 12 km, which would result in offshore loss or gain of sand of 0.12 Mm^3/year. At most, this implies that the total volume loss observed between 2006 and 2008 must be primarily due to alongshore advection/diffusion of the nourishments out of the considered total area.

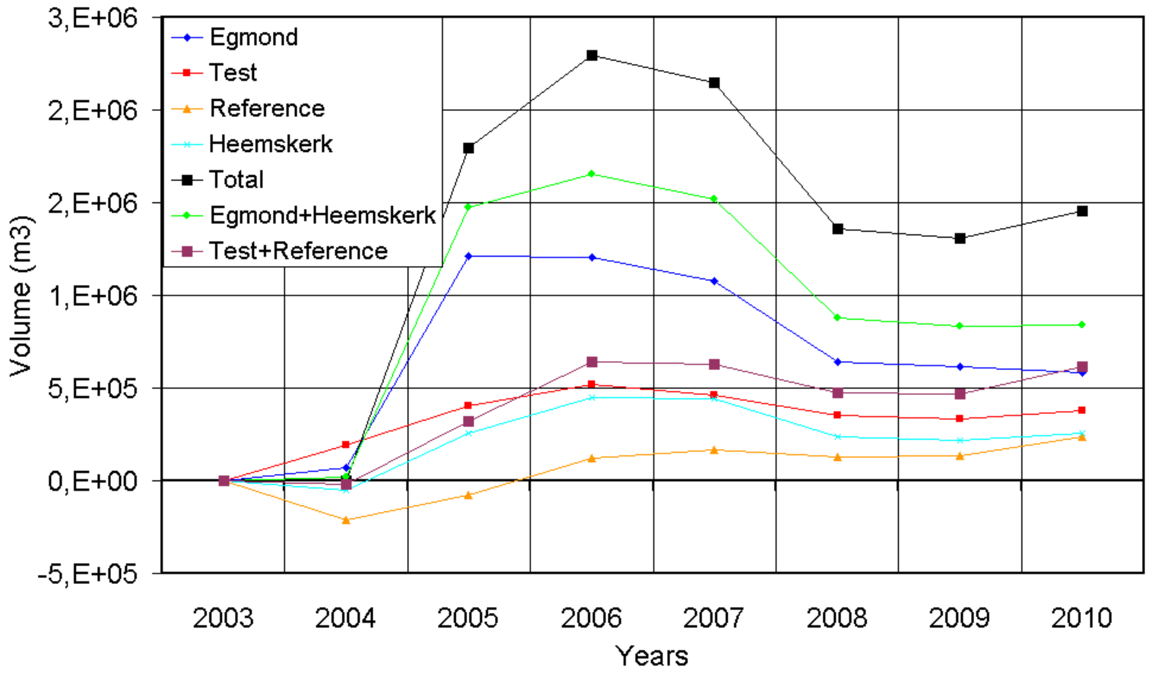

Figure 5.3: Temporal development of volumes of the entire areas relative to 2003; boxes are indicated in Figure 5.1.

For the Egmond area there is a clear nourishment signal that is primarily related to the shoreface nourishment. The other areas also show a volume increase from 2004 to 2006, but the changes are significantly smaller. For the Heemskerk area this could be related to the beach nourishment carried out in this area in 2005. For the Test and Reference areas the observed volume increases from 2004-2006 are probably partly caused by feeding from the adjacent nourishments. The 2004 Egmond shoreface nourishment extends about 200 m into the Test area (approximately 90,000 m^3), but this volume increase does not match the measured increase in the Test area which is about 50,000 m^3 (since 2003) or 35,000 m^3 (since 2004). The Heemskerk nourishment directly borders on the Reference area, making it likely that some of this nourishment was transported towards the Reference Area.

The development from 2007 to 2010 is more relevant as this is the period during which the PEM were present. It is especially of interest to establish whether the Test and/or Reference areas were affected by the nourishments in this period. The largest volume decrease of the areas that were nourished (Egmond and Heemskerk, green line in Figure 5.3) is about 650,000 m^3 from 2007 to 2008. However, the net change in the combined Test and Reference areas is also negative for the same period (purple line in Figure 5.3). The same result is found when considering the period from 2006 to 2008. Comparison of the annual volumes of the Test and Reference areas shows that the Reference area has its maximum one year later (2007) than the Test area. During 2006 to 2007, the Test area looses sand and the Reference area shows accretion, but the changes in absolute volumes are relatively small. The Reference area is approximately stable from 2006 to 2009. From 2009 to 2010, both the Test and Reference areas show the first volume increase since 2006. From 2006 to 2008, the bulk of the volume changes is occurring in the Egmond and Heemskerk areas. From 2008 onward, changes are gradual and quite small in all areas.

From Figure 5.4 (bottom-right plot) it can be seen that in 2010 there is still a substantial part of the 2005 shoreface nourishment present at the Lower V-Shoreface in the Egmond area. The execution of the beach nourishments in the Egmond and Heemskerk areas is clearly visible in the V-Beach volumes (top-right plot). The V-Beach volume time series for both areas show a remarkable agreement. Both Egmond and Heemskerk show a decrease in V-Beach volume in the two years after the nourishments (2006 to 2008) and an increase in the following year. The increase from 2008 to 2009 suggests that the impact of nourishments has decreased and has become smaller than the natural variability since 2008.

The impact of the nourishments on the volumes of the Test and Reference areas is clear in the two years after the nourishments were placed. However, the impact on especially the dune and beach regions in both areas is much harder to establish in the following years (2007-2010). The total volume development and the volume development of the cross-shore regions do not reveal a feeding signal: in the period after 2006 volume *decreases* in the Egmond and Heemskerk areas are not matched with *increases* in any of the considered cross-shore regions in the Test and Reference areas.

Based on this analysis it is concluded that since 2007 no noticeable influence of the nourishments on the development of the Test and Reference areas can be identified.

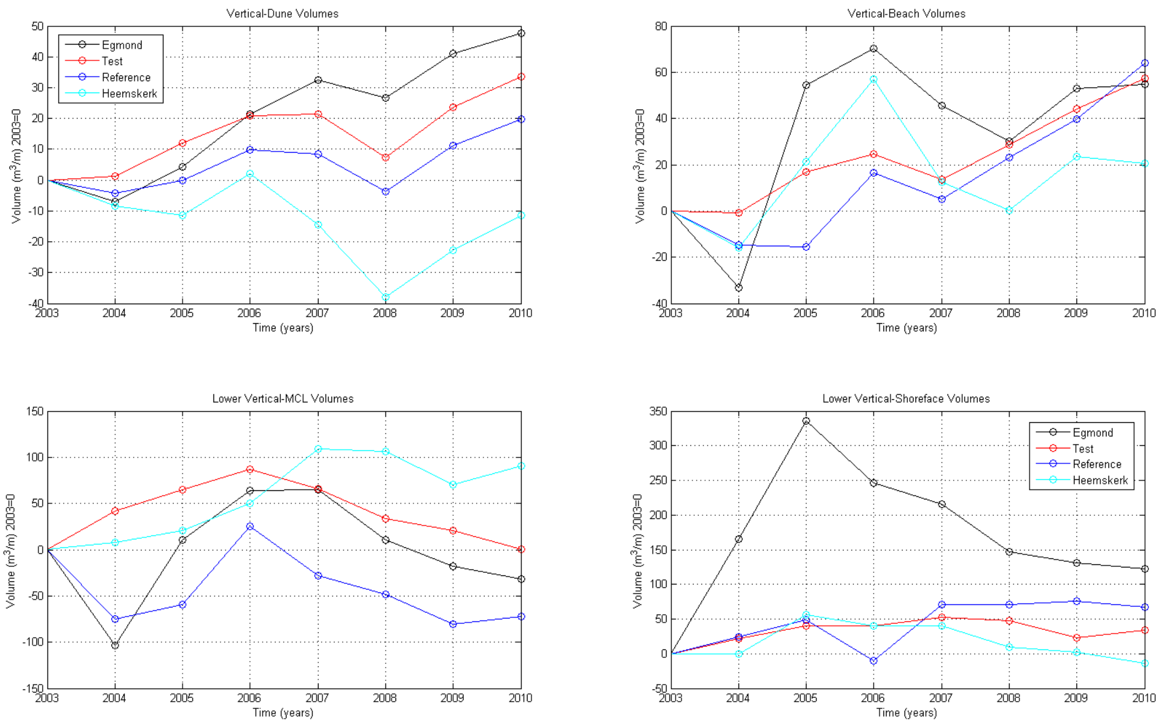

Figure 5.4: Comparison of the Dune, Beach, Lower MCL and Lower Shoreface volumes.

5.4 Influence of the cyclic bar behaviour

- Q4: What is the influence of the cyclic bar behaviour on the development of especially the beach and dune volumes?

Figure 5.5 displays the longshore averaged profiles for the four pre-defined areas. This figure shows that a large part of the observed (Lower V-MCL and Lower V-Shoreface) volume changes can be explained by the bar response. At Egmond the middle bar does not migrate or flatten during the period 2006-2010. This behaviour is the manifestation of the influence of the shoreface nourishment on the middle bar. The volume changes since 2007 in the Test and Reference areas for the lower parts of the profiles are also mainly caused by bar dynamics (i.e. migration, growth and decay). On the one hand, the figure shows that there is a coupling between the bar cycle and the V-Beach region. On the other hand, the influence of the bar dynamics on the upper parts of the profile is, similar to the impact of the nourishments, not visible in the figure.

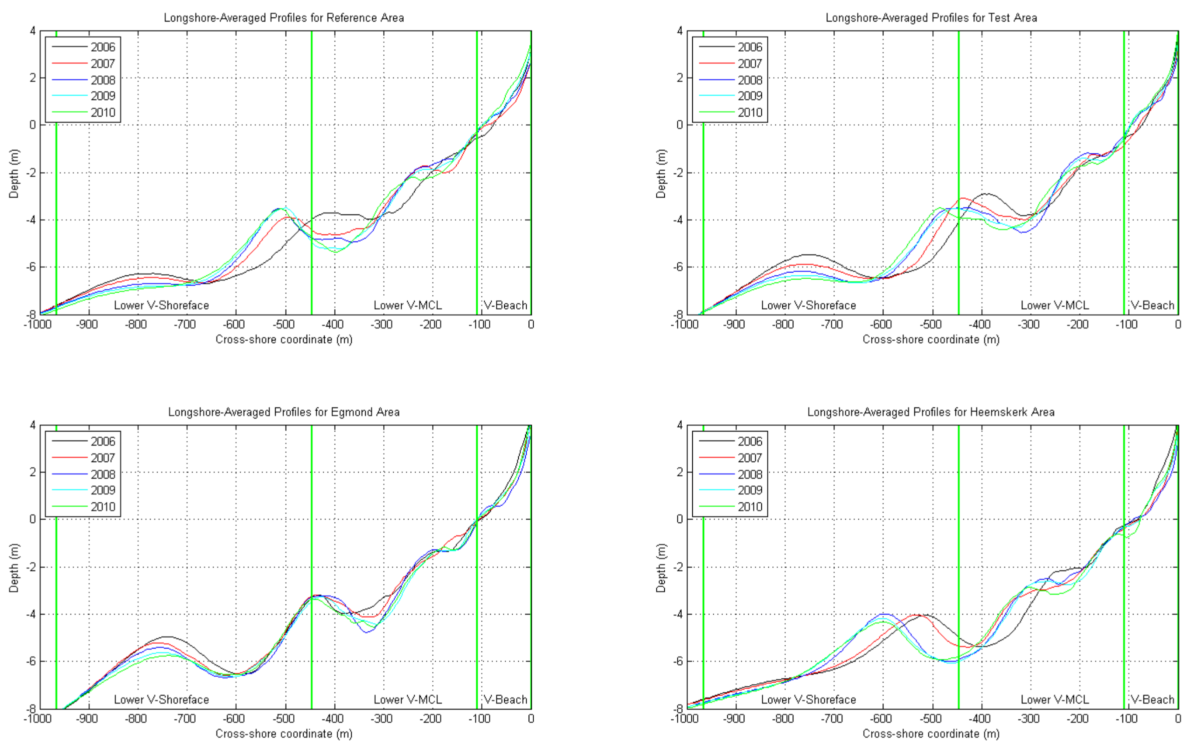

Figure 5.5: Longshore averaged profiles for the post-nourishment period from 2006 to 2010.

6 Quantification of changes in the CSI's behaviour

6.1 Introduction

A number of relevant aggregated parameters, so-called Coastal State Indicators (CSI) have been defined that describe the state of (parts of) the coastal system at Egmond. In the previous chapters, the behaviour of these CSI has been analysed, and temporal and spatial characteristics of the CSI's behaviour have been identified, in relation to the sensitivity to the data processing (e.g. aggregation), the (seasonal, temporal) variability of the data, as well as the impact of nourishment and other interventions on the coastal system, and the contribution of the surf zone bars to the observed variability. But the approach followed does not allow for a quantitative estimate of the influence of the Ecobeach system in the beach and dune regions.

In order to provide a quantitative insight into the impact that the Ecobeach system may have on the morphological development at Egmond in the area where the system has been installed, the changes in the behaviour of the coastal system (CSI) at Egmond are quantified in this chapter.

The quantification is performed based on the evaluation of CSI's changes compared to the natural trend. To that end, three fitting approaches are applied. The residuals (i.e. observations minus a model result) are evaluated for the periods before and after the installation of the Ecobeach experiment. Quantities that can indicate a change in the morphological behaviour of the coastal system are then computed.

6.2 Methodology

6.2.1 Formulation

For the evaluation and the forecasting of a time series of a CSI, linear parameterised regression fits have been defined. The CSI data obtained before the installation of the Ecobeach system are used for the estimation of the fit parameters for the natural situation.

The regression fits have to be embedded in a stochastic environment, which has the important advantage that apart from estimates of the parameters, uncertainties can also be derived for these fit parameters. Similarly, the uncertainty in the extrapolation of the fits of CSI (model results obtained after the installation of the Ecobeach system) can be estimated. Although this specificity has been used in the previous analyses, it is not the case for the final one that is reported here. For more details on the procedure for uncertainty assessment, the reader is referred to Brière and Van den Boogaard (2008, 2009).

The mathematical formulation of the model reads:

$$Z_t = \Phi\left(t \mid \vec{\Theta} \right) + V_t \tag{1}$$

Z_t represents the observed CSI at a time t. $\Phi\left(\cdot \mid \vec{\Theta}\right)$ is a parameterised function of time, representing the deterministic, long term systematic variations in the temporal evolution of a CSI. These systematic variations may consist of trends in the series, and/or seasonal or even longer term cyclic behaviour. V_t is a zero mean random noise, representing the uncertainties in the modelling of the CSI. The quantity V_t can be called as well a residual (i.e. observation minus model result).

The visual inspection of plots of the time series of the several (aggregated, Jarkus-based yearly samples) CSI over the period 1965 to 2006 suggests a temporal evolution that often contains a long term, gradually increasing (or decreasing) trend, and potentially a cyclic component. The proposed regression models are defined such that linear and cyclic representations are included.

As shown in Chapter 5, the influence of the bar dynamics on the upper parts of the profile is difficult to establish, but the results suggest that there is a coupling between the bar behaviour and the Dune and Beach systems. The bar generation close to the shore, the seaward migration and the degeneration at the outer margin of the nearshore bar zone have been observed by Ruessink and Kroon (1994) for a multiple bar system in the nearshore zone of the Dutch coast. The associated cross-shore sediment exchange might induce a harmonic modulation of the temporal signals of the CSI.

The cyclic component might therefore represent the cyclic coastal bar behaviour occurring in a LSCB-region defined as an area in which the coastal profiles exhibit similar large scale developments (Wijnberg and Terwindt, 1995). In their work, Wijnberg and Terwindt (1995) showed that the Egmond area belongs to the LSCB-region E (Petten to IJmuiden), that is characterized by a multiple bar system migrating at a return period of about 15 years.

More generally, more than one harmonic component may be present, or necessary to represent or approximate a periodic function. This is especially the case when the CSI's behaviour is described at a medium temporal scale, including seasonal variations. In our case, the fitting approach is applied to Jarkus-based yearly CSI. Trends are described using a linear (and potentially one harmonic) function of time t, leading to:

$$\Phi(t \mid \vec{\Theta}) = \alpha_0 + \alpha_1 \cdot t + A_l \cdot \cos\left(\frac{2\pi}{P_l} \cdot t\right) + B_l \cdot \sin\left(\frac{2\pi}{P_l} \cdot t\right) \quad (2)$$

In that case the vector of model parameters $\vec{\Theta}$ consists of:

$$\vec{\Theta} = (\alpha_0, \alpha_1, A_1, B_1, P_1) \quad (3)$$

in which α_0, α_1 represent the origin and the slope in the long-term linear trend, and A_1, B_1, P_1 represent the amplitudes and periods of the cyclic components.

6.2.2 Modelling procedure

In the present study, the calibration procedure follows closely the approach described by Van den Boogaard et al. (2006).

For a set of CSI $\left\{ t_k, \hat{Z}_{t_k} \right\}_{k=1}^{K}$, the model of Equation 1 reduces to a set of *K* stochastic equations:

$$\hat{Z}_{t_k} = \Phi\left(t_k \mid \vec{\Theta} \right) + V_{t_k} \tag{4a}$$

Fully equivalently, Equation 4a can be interpreted as a set of *K* observations for the noise V_t according to:

$$\hat{V}_{t_k} = \hat{Z}_{t_k} - \Phi\left(t_k \mid \vec{\Theta} \right) \tag{4b}$$

It is assumed that V_t is a zero-mean Gaussian white random process. Therefore the *K* observations $\hat{V}_{t_k}$ should satisfy a *K*-variant zero mean Gaussian probability density distribution $f_K(\cdot)$ with a $K \times K$ auto-covariance matrix Γ with entries $\Gamma_{k,k} = \sigma_V^2$ and $\Gamma_{k,\ell} = 0$ for $k \neq \ell$.

On this basis, a Maximum Likelihood criterion (Kendall and Stuart, 1961) can be applied to derive an estimate for the parameters $\vec{\Theta}$. In fact, this estimate $\hat{\Theta}$ is the value of $\vec{\Theta}$ that minimises the minus Log-Likelihood function $J(\Theta) := -\ell n\left(f_K\left(\hat{V}_{t_1}, \hat{V}_{t_2}, \cdots, \hat{V}_{t_K} \right) \right)$.

In the present case this function is:

$$J(\Theta) = \tfrac{1}{2} \cdot K \cdot \ell n\left(2 \cdot \pi \cdot \sigma_V^2 \right) + \tfrac{1}{2} \cdot \sum_{k=1}^{K} \left(\frac{\hat{Z}_{t_k} - \Phi\left(t_k \mid \vec{\Theta} \right)}{\sigma_V^2} \right)^2 \tag{5}$$

The modelling procedure acts therefore in such a way that the residuals (i.e. the observations minus the model results, for a defined period) are minimized.

Due to the non-linear dependence of $\Phi\left(\cdot \mid \vec{\Theta} \right)$ on $\vec{\Theta}$, the cost function of Equation 5 can not be minimised analytically. In the present applications, a Quasi-Newton gradient descent technique (see e.g. Press et al., 1986) is applied for the minimisation of the minus LogLikelihood function.

6.2.3 Model application

The evaluation is performed following the methodology detailed below:

1. The most representative CSI for quantification of the changes in the system behaviour of the area of the Ecobeach experiment are selected. These representative CSI consist of the Jarkus-derived Dune Foot position, Referenced Dune volume, Referenced Beach volume and Referenced MCL volume, as defined in section 3.3.
2. Two periods are selected: the 1990-2006 and the 1965-2006 periods. The first one corresponds to the period during which nourishment activities are performed in the project area (especially in Egmond, see Figure 2.4) and before the installation of the Ecobeach experiment. The second period corresponds to the overall period during which the data are available and before the installation of the Ecobeach experiment.
3. Three fitting approaches or models are defined, that consist of 1) a linear fitting through the 1990-2006 data, 2) a linear fitting through the 1965-2006 data, and 3) a linear and cyclic fitting through the 1965-2006 data.
4. The Costal State Indicators are aggregated by longshore averaging over 2.75 km. Four distinct areas are selected: the so-called Egmond area (aggregation from incl. RSP 37.25 to incl. RSP 39.75), the so-called Test area (aggregation from incl. RSP 40.25 to incl. RSP 42.75), the so-called Reference area (aggregation from incl. RSP 43.25 to incl. RSP 45.75), and the so-called Heemskerk area (aggregation from incl. RSP 46.25 to incl. RSP 48.75). These areas correspond to the ones defined in section 3.4 and displayed in Figure 2.3.
5. The three fitting approaches are applied to the four aggregated CSI's time series available for the four areas. In total, 48 applications (4 CSI * 3 fitting approaches * 4 areas) are performed.
6. The residuals (i.e. observations minus model results) are computed based on the results of the 48 applications, for each observation (i.e. each year), including the period before (hindcasting) and after (forecasting) installation of the Ecobeach system.
7. Parameters are derived from the computation of residuals, enabling the quantification of changes in the behaviour of the coastal system at Egmond. These parameters consist of the averages of the residuals obtained over the 4 years before and after the Ecobeach installation, and of the corresponding standard deviations.
8. The results are analyzed. The average of the residuals indicate to which extent the observations' averages differ from the model hindcasts (for the period 2003-2006) and from the model forecasts (for the period 2007-2010). The standard deviations support the analysis on the variability of the residuals, comparing results obtained for the periods before and after the installation of the Ecobeach experiment.

6.3 Analysis

6.3.1 Methodological example

This section provides a methodological example for the quantification of changes in the behaviour of the coastal system at Egmond. This example follows the step-by-step approach described in section 6.2.3 as applied to the transects 37.00 and 45.00 As an example, the Referenced Beach volumes at transects RSP 37.00 (Figure 6.1) and 45.00 (Figure 6.2) are selected here. In both figures, the blue dots correspond to observations obtained in the period 1965-2006, whereas the red dots correspond to observations obtained in the period 2007-2010. The dashed lines enable to distinguish the periods before and after the starting date of the intensive nourishment activities in the region.

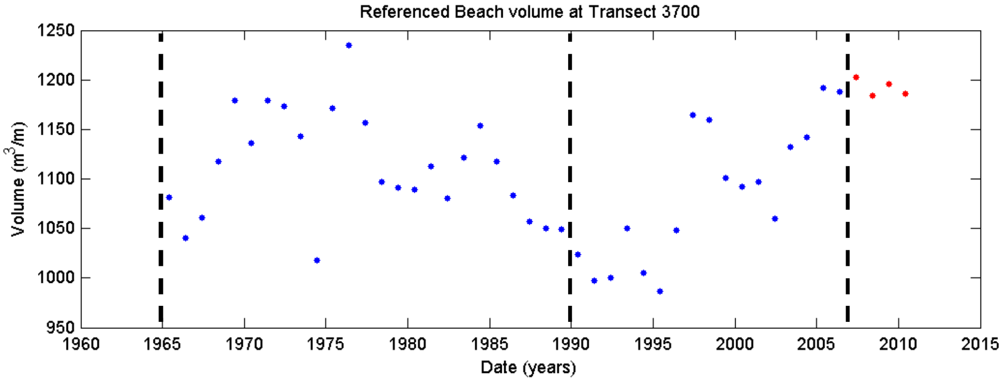

Figure 6.1 : Referenced beach volume at RSP 37.00

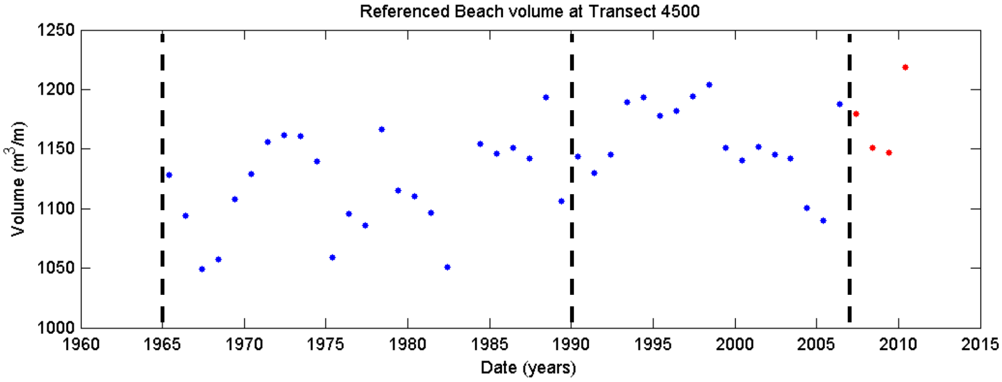

Figure 6.2 : Referenced beach volume at RSP 45.00

For transect RSP 37.00, examples of the model application are given in Figure 6.3 and Figure 6.4, when considering the linear fitting through the 1965-2006 data, and the 1990-2006 data, respectively.

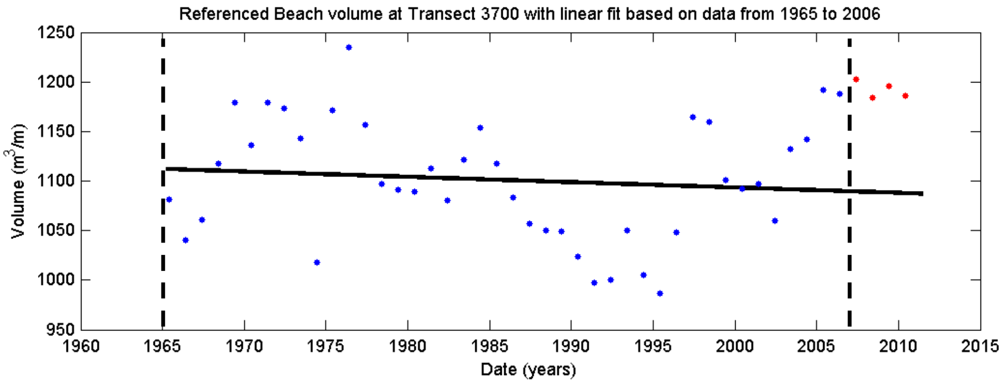

Figure 6.3 : Linear fitting through the 1965-2006 data of the Referenced beach volume at RSP 37.00

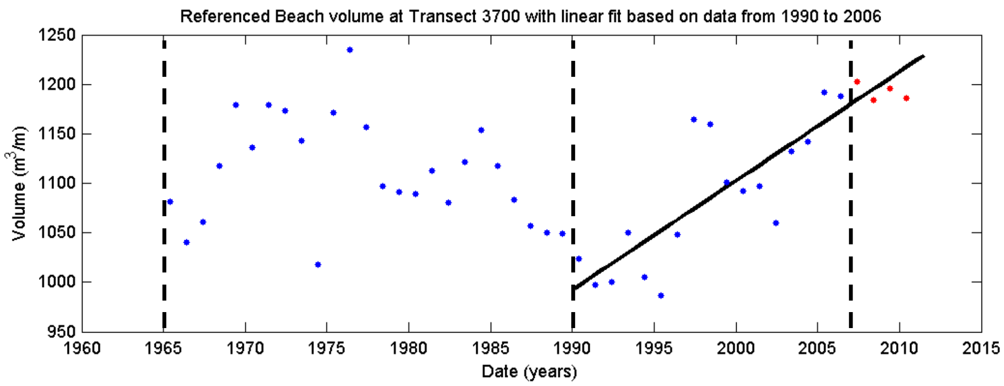

Figure 6.4 : Linear fitting through the 1990-2006 data of the Referenced beach volume at RSP 37.00

Figure 6.5 and Figure 6.6 show the results of the fitting through the 1965-2006 data at transect RSP 45.00. The results obtained when applying for the same transect the linear fit and the linear plus cyclic fit are displayed in the two figures, respectively.

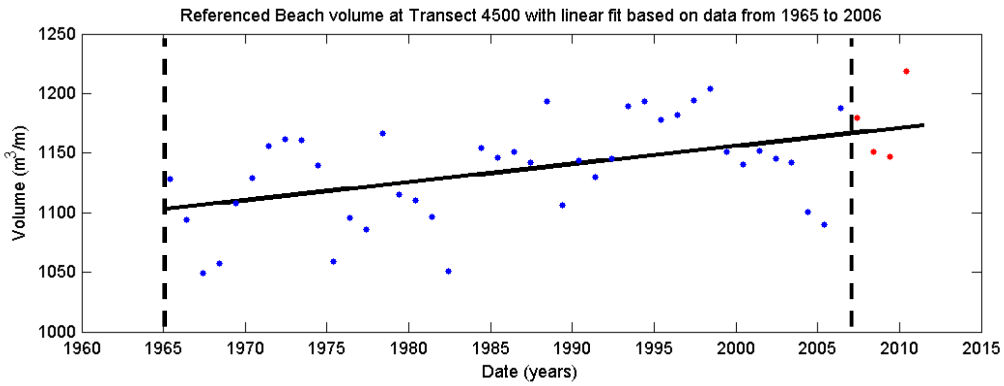

Figure 6.5 : Linear fitting through the1965-2006 data of the Referenced beach volume at RSP 45.00

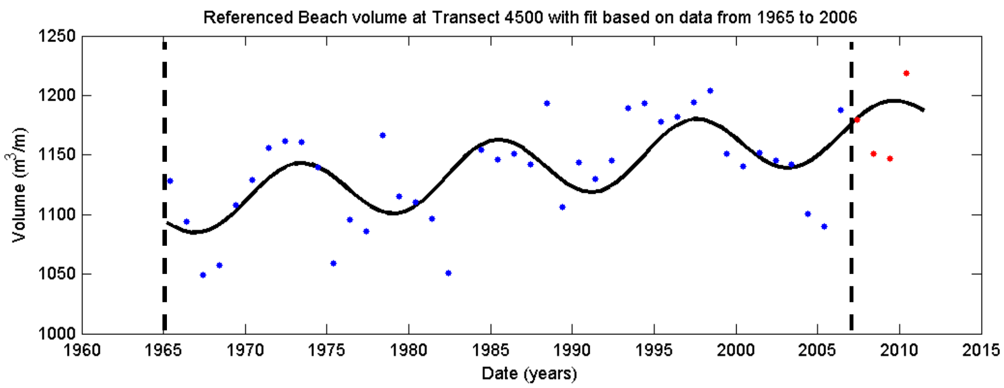

Figure 6.6 : Linear + cyclic fitting through the 1965-2006 data of the Referenced beach volume at RSP 45.00

The residuals (i.e. observations minus model results) for the Referenced Beach volume time series after fitting through the 1965-2006 data with a linear and cyclic function (Figure 6.6) is displayed in Figure 6.7.

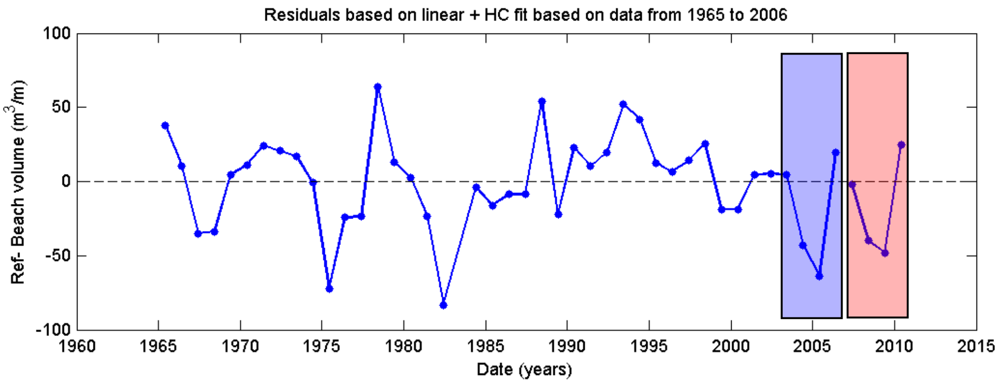

Figure 6.7 : Residuals derived after linear and cyclic fitting through the data available from 1965 to 2006 of the Referenced beach volume at transect RSP 45.00

6.3.2 Performance

For a specific dataset (e.g. the Referenced Beach Volume at transect RSP 37.00), three fitting approaches have been applied. The application of the regression models provides model results that can be used for judging the relative performance of each fitting approach. In this section, the performance is discussed with respect to the application of models for the description of the Referenced Beach volume behaviour. The analysis is not extended here to the three other selected CSI for the sake of brevity.

In the context of modelling the behaviour of the Referenced Beach volume, Figure 6.8 displays the longitudinal variation of the slope α_1 in equation 2 (upper panel) provided by the three regression models for the 13 transects covering the entire study area. The bottom panel displays the standard deviations of the residuals derived from the application of the fitting approaches. In both panels, the blue, red and black line refer to the linear fitting through the 1990-2006 data, to the linear fitting through the 1965-2006 data, and to the linear and cyclic fitting through the 1965-2006 data, respectively.

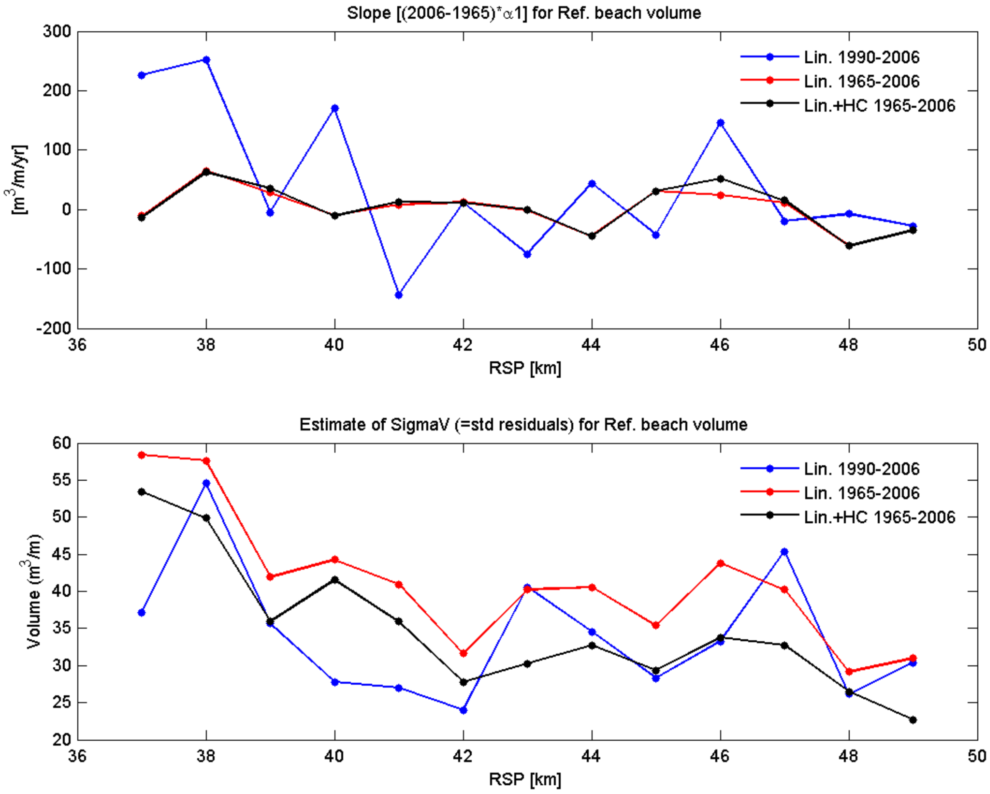

Figure 6.8 : Slope and standard deviations of residuals

The analysis of the slopes of the linear trends shows:

- The results obtained when fitting through the 1965-2006 data, or through the 1990-2006 data, are quite different
- A significant difference in the magnitude is especially obtained for transect RSP 37.00 to RSP 41.00, that can relate to a change in system behaviour between 1965-1990 and 1990-2006. It is anticipated that the change in system behaviour relates to the intensive nourishment activities that occured in Egmond since 1990. Figure 6.3 and Figure 6.4 support this analysis.
- The slopes of the linear trends when fitting through the 1965-2006 data (red line) and the 1990-2006 data (blue line) exhibit different behaviour from around RSP 41.00 northward. The area affected by the intensive nourishment activities at Egmond corresponds to this region (from around RSP 41.00 northward).
- From around RSP 41.00 southward, the red line exhibits less longitudinal variability than the blue line, for transects RSP 42.00 to 49.00. The fitting using the longest dataset seems to be therefore more reliable.
- Whatever the linear or the linear and cyclic fit that is applied, the slopes of the linear trends obtained when fitting through the 1965-2006 data hardly differ. It seems that adding a harmonic component corresponds only to a negligible adjustment of the linear (retreating or increasing) tendency.

A priori, a lower magnitude of the standard deviation relates to a better performance of the model. However, by definition, the standard deviations of residuals decrease when the number of parameters that have been quantified increase. Similarly, a smaller number of observations to be fitted through will in most cases provide a lower value for the standard deviation of the residuals, without necessarily meaning that the model is more reliable. The analysis of standard deviations of the residuals is therefore not used to judge the performance or the reliability of the chosen fitting approach, but gives only indication of the variability in the datasets. The lowest values are obtained for the profiles RSP 40.00 to 49.00, showing that the variability in the Egmond area (RSP 37.00 to 40.00) is higher. This relates to the intensive nourishment activities that have disturbed the system behaviour over the last two decades, especially in the northward region.

6.3.3 Longshore coherence

- Q5A: Can we quantify the alongshore coherence of the observed cross-shore sediment exchange?

Only one of the three selected fitting approaches involves the application of a harmonic component. This parameterisation provides information on the period P, and amplitudes A and B as defined in equation 2. From the values of A and B, the phase of the harmonic component can be obtained.

As discussed previously, the cyclic component might represent the cyclic coastal bar behaviour occurring in a LSCB-region defined as an area in which the coastal profiles exhibit similar large scale developments (Wijnberg and Terwindt, 1995). The period P and the phase of the harmonic component are therefore relevant indicators for the quantification of the alongshore coherence of the observed sediment exchange.

If choosing the Referenced Beach volume fitted with a linear trend and a harmonic component as an example, Figure 6.9 displays in the upper panel the longitudinal variation of the period P, whereas the bottom panel shows the phase of the harmonic component.

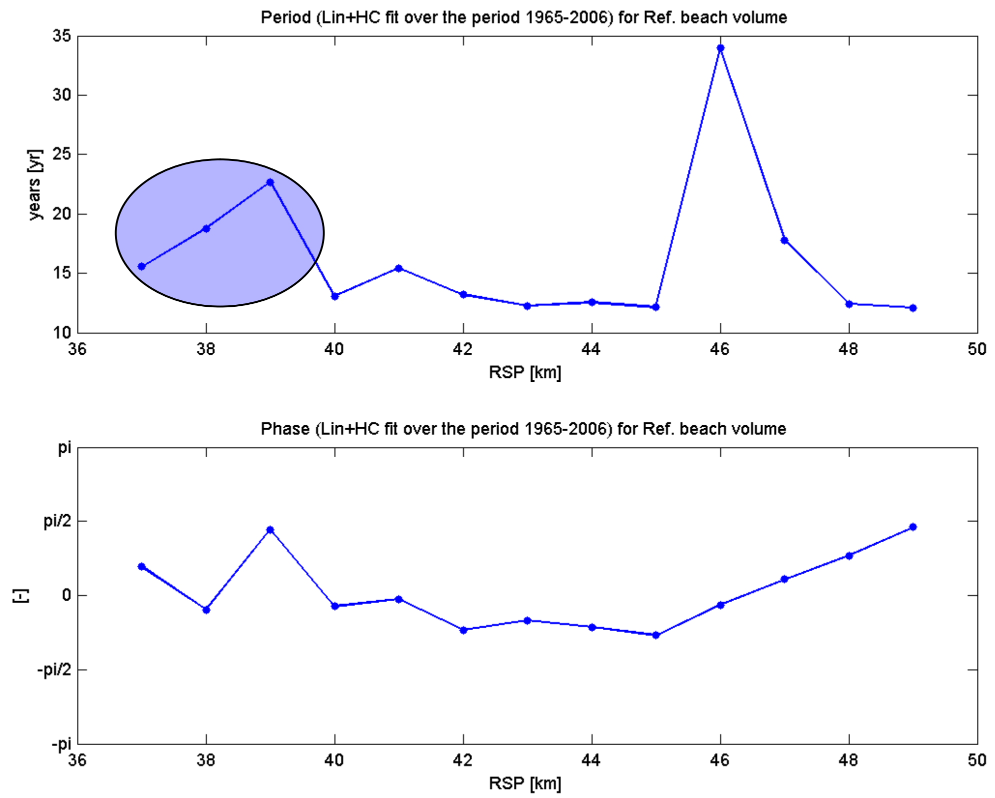

Figure 6.9 : Periods and phases derived from the linear + cyclic fitting applications

The results show that, from transects RSP 37.00 to 40.00, longshore varying periods and phases are obtained. The coastal section at Egmond is subject to nourishments that most likely disturb or froze the nearshore bar. As the cyclic component is aiming at representing the influence of the bar migration on the behaviour of CSI, it is therefore understandable that periods and phases of the cyclic component do not exhibit necessarily a longshore coherent behaviour.

From transect RSP 40.00 to transect RSP 45.00, a longshore uniform value is obtained for the period, ranging from 13 yrs to 15 yrs (Figure 6.9). Assuming that the cyclic component is describing the behaviour of the bar migration, such a result is in agreement with the literature (Wijnberg, 1995). The behaviour of the phase evolves from RSP 45.00 southward. Therefore, the nearshore bars over the Test area (RSP 40.00 to 43.00) seem to be more or less in phase with the nearshore bars present over the Reference area (RSP 43.00 to 46.00), whereas the nearshore bars present over the Heemskerk area (RSP 46.00 to 49.00) become out of phase.

6.3.4 Quantification of changes

- Q5B: Can we quantify the volume changes of the coastal system?

The residuals (i.e. observations minus model results) are used for computation of characteristic parameters. These parameters consist of the averages of the residuals obtained over the four years before and after the Ecobeach installation, and of the corresponding standard deviations, as described in section 6.2 (see Figure 6.7).

The results are provided such that the behaviour of the four selected CSI (Dune Foot position in Figure 6.10, Referenced Dune volume in Figure 6.11, Referenced Beach volume in Figure 6.12, and Referenced MCL volume in Figure 6.13) aggregated over the four pre-defined areas can be discussed.

In all figures, the upper, middle and bottom panels display the results obtained after linear fitting through the 1990-2006 data, after linear fitting through the 1965-2006 data, and after linear and cyclic fitting through the 1965-2006 data, respectively. In all panels, the 4-yr average of the residuals for the pre- and post- Ecobeach installation periods are represented by a blue and a red dot, respectively. The error bar ($= \mu \pm \sigma$) represents the standard deviation around the average.

On the one hand, the residuals average indicates to which extent the observations differ from the model hindcasts (for the period 2003-2006) and from the model forecasts (for the period 2007-2010). On the other hand, the standard deviations provide a quantification of the variability of the residuals.

Figure 6.10 presents the results obtained when fitting to the Dune foot position data. Whatever the fitting approaches used, the three regression models show their ability to hindcast (average close to 0, and blue error bar crossing the 0-line) correctly the behaviour of the dune foot position.

The results obtained for the period 2007-2010 in the Test and the Reference areas are in the same order as the ones obtained for the period 2003-2007. It is concluded that the Dune foot position after installation of the PEM does not exhibit behaviours different from the predicted ones (under natural conditions) in both the Test and the Reference areas.

Figure 6.11 displays the results obtained after application of the fitting approaches through the Referenced Dune volume data. The results obtained for Egmond area show that the linear fitting through the 1990-2006 data provides a reliable hindcast (top panel). In this case, the results obtained for the period 2007-2010 (red error bar, top panel) are well predicted.

In the Test area, the Reference area, and the Heemskerk area, the results, obtained when fitting through the 1965-2006 data (middle and bottom panels), seem to be more reliable, as the error bars (before installation of the Ecobeach system) are reduced.

In the Reference area, these regression models tend to underestimate the Referenced Dune volume (blue error bar, middle and bottom panels). In the three southward areas, the results obtained for the period 2007-2010 (red error bar, middle and bottom panels) show that the dune volume is exhibiting more or less similar behaviour as the one observed for the period 2003-2007 (blue error bar, middle and bottom panels).

Figure 6.12 presents the results obtained for the Referenced Beach volume. As for the Dune foot position and for the Referenced Dune volume, the linear fit through the 1965-2006 data seems to be more reliable when considering the Egmond area (better hindcast). However, the variability remains very high.

When considering the three other areas, and whatever the fitting approaches followed, the three regression models show their ability to hindcast (blue error bars) correctly the behaviour of the Referenced Beach volume. For this specific indicator, the results obtained for the period 2007-2010 (red error bars) confirm that the system experiences a change of behaviour in both the Test area, and the Reference area.

Based on the results obtained for the three fitting approaches, the volume changes in the 4-yr averages of the residuals are estimated to be + 33.2 $m^3.m^{-1}$ and + 34.5 $m^3.m^{-1}$ for the Test and the Reference areas, respectively. The residuals for the period 2007-2010 exhibit a higher variability in the Reference area.

Figure 6.13 displays the results obtained after application of the fitting approaches to the Referenced MCL volume data. For the Egmond area, the linear fit through the 1965-2006 data seems to be reliable (better hindcast), that is consistent with previous results. Similar to the Referenced Beach volume, the variability remains very high.

In the other three areas, and whatever the fitting approaches followed, the regression models show their ability to hindcast (blue error bars) correctly the behaviour of the Referenced MCL volume. However, and only in the Test area, the model results obtained by linear and cyclic fitting overestimate the observations (blue error bar, bottom panel). The results obtained for the period 2007-2010 (red error bars) confirm that the system experiences a change of behaviour in the Test area, the Reference area, and to a smaller extent in the Heemskerk area.

Based on the results obtained for the three fitting approaches, the volume changes in the 4-yr averages of the residuals are estimated to be + 74.2 $m^3.m^{-1}$ and + 103.3 $m^3.m^{-1}$ for the Test and the Reference areas, respectively. The residuals for the period 2007-2010 exhibit a higher variability in the Reference and the Heemskerk areas than in the Test area.

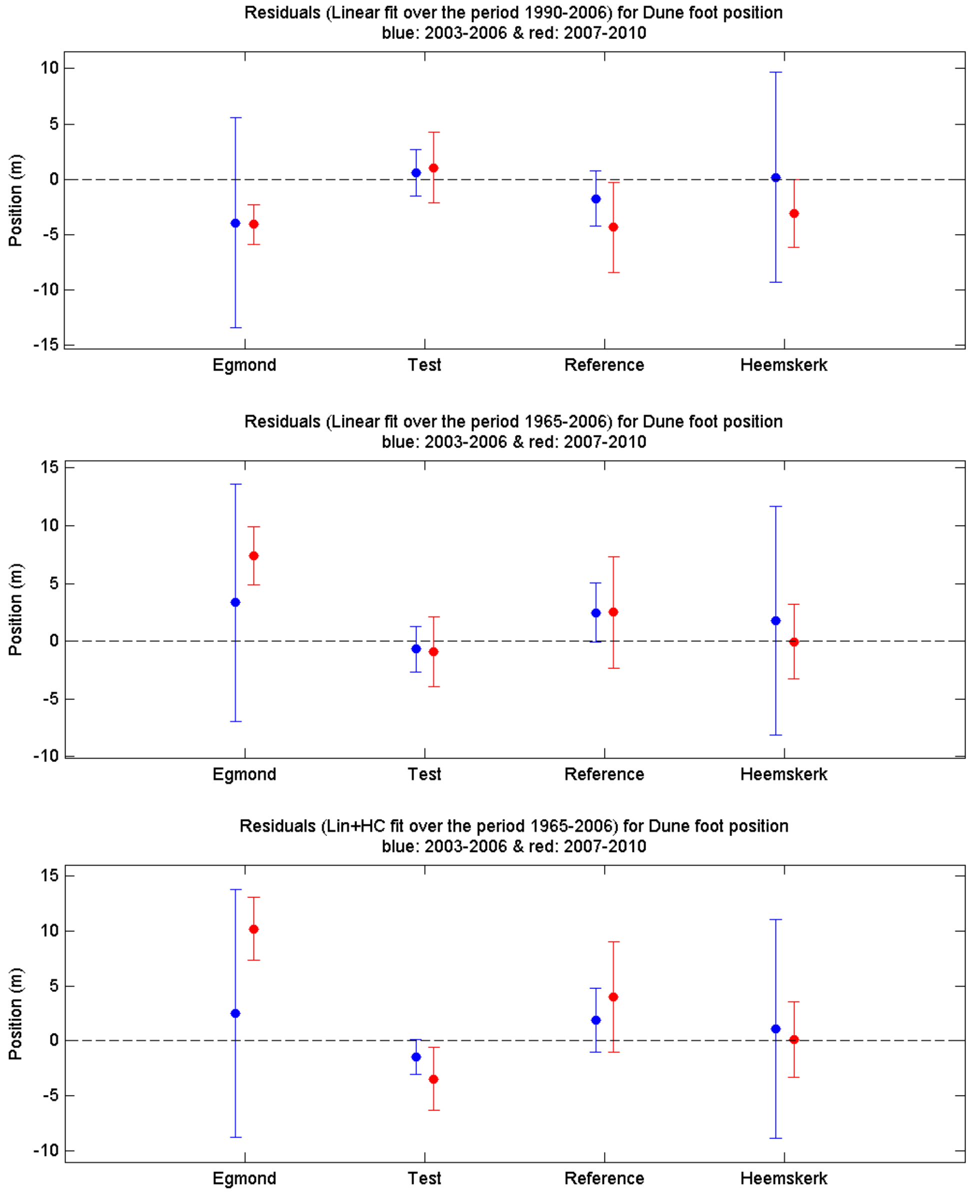

Figure 6.10 : Statistical parameters derived for the Dune foot position

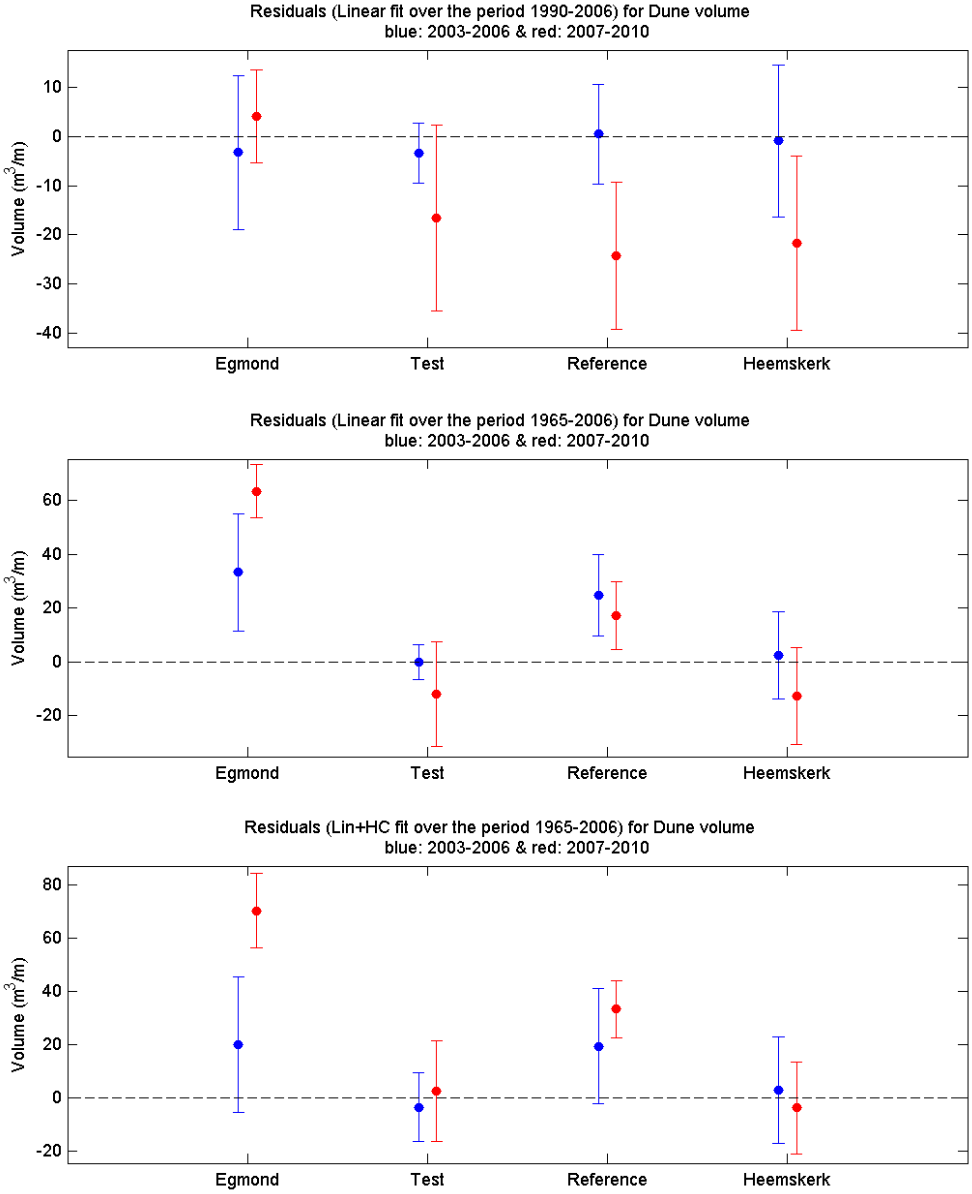

Figure 6.11 : Statistical parameters derived for the Dune volume

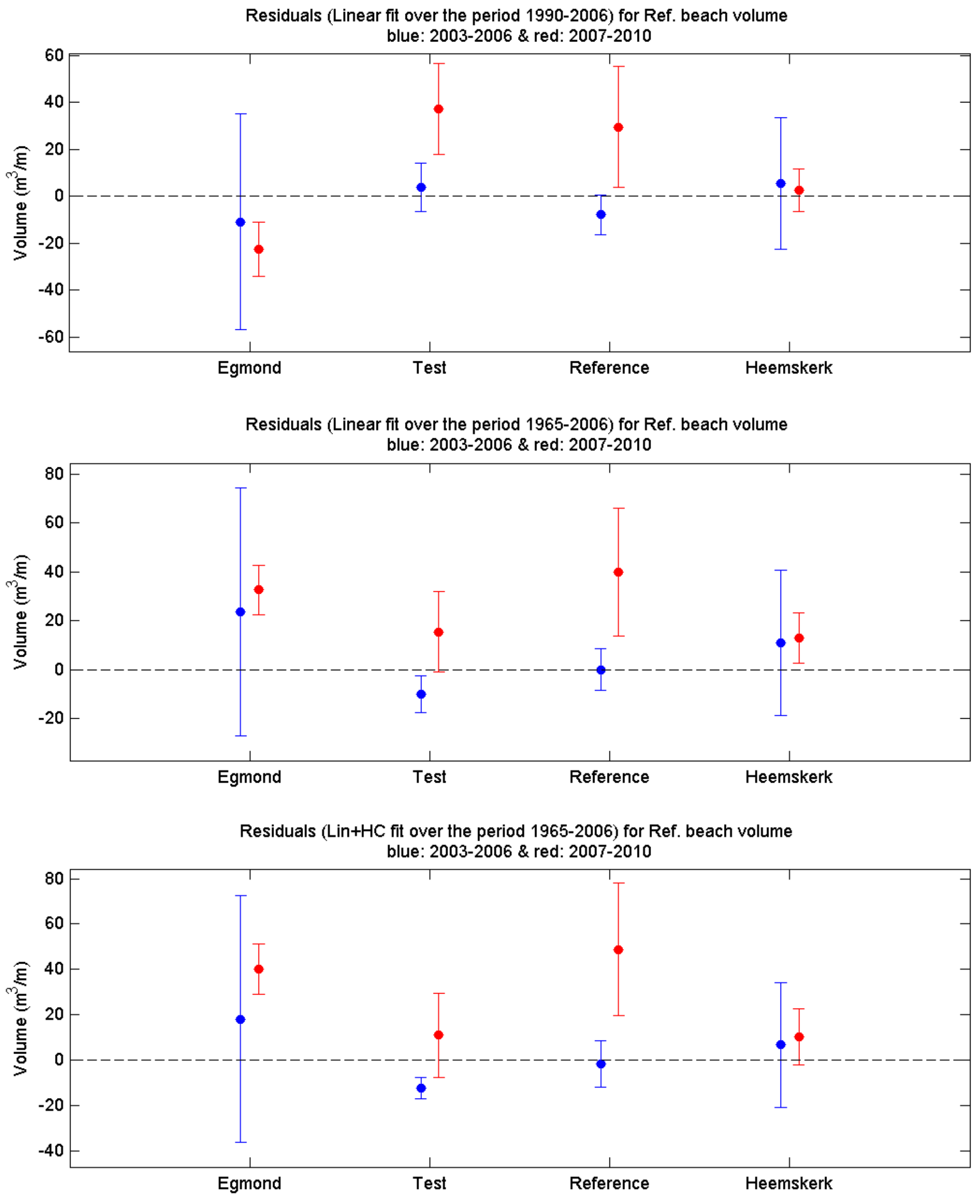

Figure 6.12 : Statistical parameters derived for the Referenced Beach volume

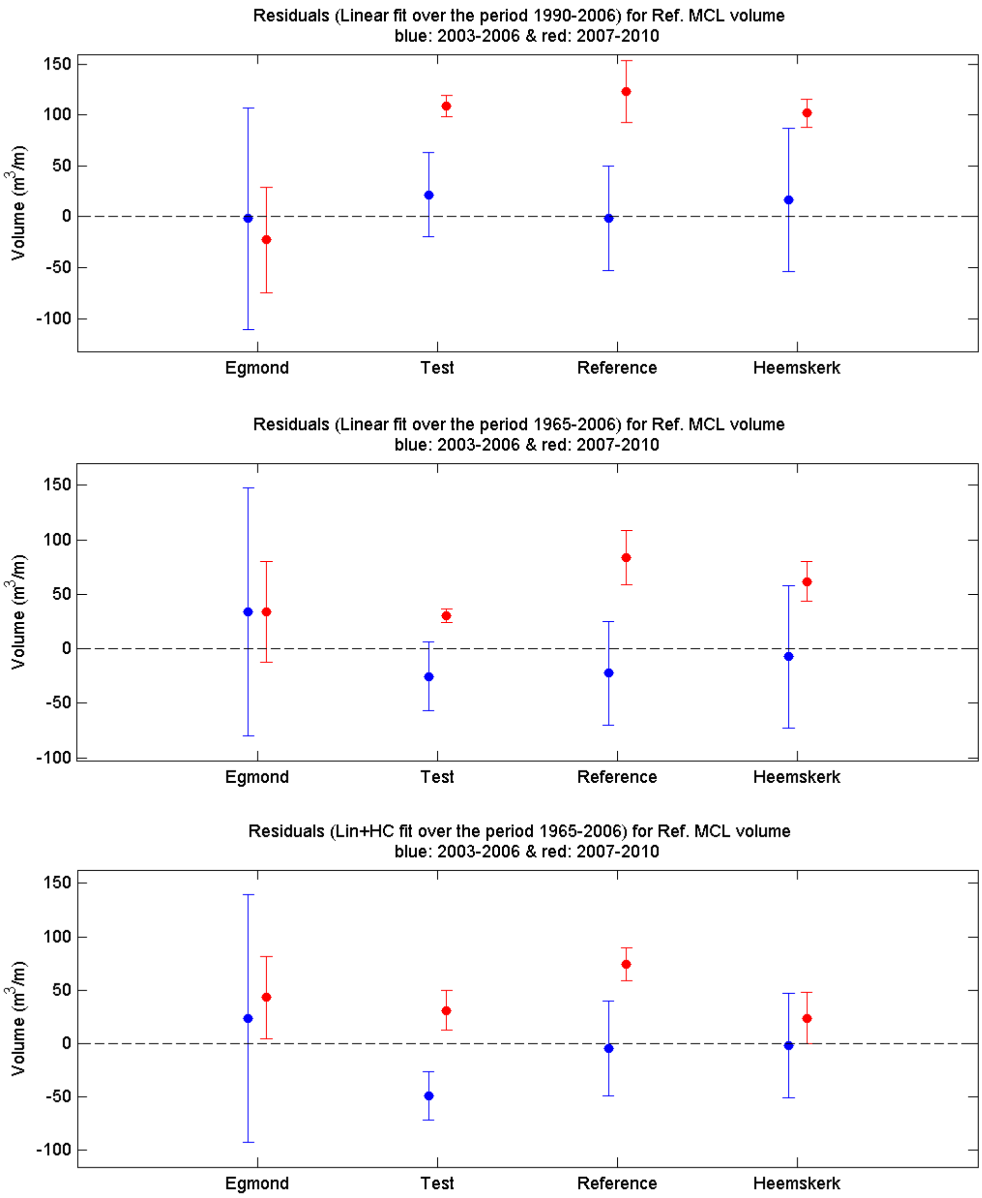

Figure 6.13 : Statistical parameters derived for the Referenced MCL volume

6.4 Summary

A number of relevant aggregated parameters, so-called Coastal State Indicators (CSI) have been defined that describe the state of (parts of) the coastal system at Egmond. The quantification of changes in the behaviour of the coastal system has been performed based on the evaluation of the CSI's changes compared to the natural trend. To that end, three fitting approaches have been applied. The residuals (i.e. observations minus a model result) were evaluated for the periods before and after the installation of the Ecobeach experiment.

The quantification of changes was aimed at evaluating the impact of the PEM on the coastal system, by comparing model predictions with the data obtained after the installation of the Ecobeach system. In case of inconsistency between the observations and the predictions, we can state that a significant trend break has occurred.

The changes in the behaviour of the coastal system at Egmond have been quantified by evaluating statistical parameters representative of the deviation of the model hincasts and forecasts from the observations (4 years- averages), and of the variability of the residuals (standard deviations). The obtained results are summarized in Table 6.1. In this table, each cell contains two values corresponding to the considered parameter computed for the periods before and after the installation of the Ecobeach system.

For the period 2007-2010, neither the Dune foot position, nor the Referenced Dune volume, exhibit behaviours different than the predicted ones (i.e. under natural conditions), in both the Test and the Reference areas. From the quantification of changes in the dune-related CSI, it can be concluded that the PEM have not induced morphological changes in the dune system beyond the observed coastal variability. Moreover, no significant trend breaks in the dune dynamics could be identified after the installation of the Ecobeach system.

The results obtained for the Referenced Beach volume and Referenced MCL volume and for the period 2007-2010 show that the system experiences a change of behaviour in both the Test area, and the Reference area. A significant trend break in the beach dynamics can be identified that coincides with the time of the installation of the Ecobeach system. As this trend break is present in the Test area, as well as in the Reference area, it is concluded that the PEM have not induced morphological changes in the beach system beyond the observed coastal variability.

Table 6.1 : Characteristic parameters (4 years- averages and standard deviations) of the residuals.

<table>
<tr><th colspan="3"></th><th>Egmond</th><th>Test</th><th>Reference</th><th>Heemskerk</th></tr>
<tr><td rowspan="6">Dune foot Position (m)</td><td rowspan="2">Linear 1990-2006</td><td>Average</td><td>-3.94
-4.09</td><td>0.58
1.04</td><td>-1.74
-4.34</td><td>0.17
-3.13</td></tr>
<tr><td>Std</td><td>9.47
1.82</td><td>2.12
3.19</td><td>2.50
4.07</td><td>9.50
3.06</td></tr>
<tr><td rowspan="2">Linear 1965-2006</td><td>Average</td><td>3.32
7.37</td><td>-0.66
-0.93</td><td>2.46
2.50</td><td>1.76
-0.03</td></tr>
<tr><td>Std</td><td>10.26
2.52</td><td>1.96
3.00</td><td>2.56
4.79</td><td>9.87
3.25</td></tr>
<tr><td rowspan="2">Linear + HC 1965-2006</td><td>Average</td><td>2.50
10.20</td><td>-1.48
-3.47</td><td>1.89
3.97</td><td>1.09
0.11</td></tr>
<tr><td>Std</td><td>11.26
2.84</td><td>1.60
2.86</td><td>2.89
5.04</td><td>9.95
3.43</td></tr>
</table>

Referenced Dune volume ($m^3.m^{-1}$)	Linear 1990-2006	Average	-3.24 4.15	-3.41 -16.57	0.47 -24.29	-0.92 -21.69
		Std	15.62 9.44	6.10 18.98	10.16 14.98	15.42 17.67
	Linear 1965-2006	Average	33.25 63.40	-0.16 -11.82	24.72 17.20	2.32 -12.69
		Std	21.66 9.91	6.43 19.40	15.02 12.50	16.20 17.92
	Linear + HC 1965-2006	Average	20.25 70.40	-3.41 2.67	19.47 33.45	3.07 -3.69
		Std	25.43 14.03	12.89 19.05	21.70 10.82	19.97 17.28
Referenced Beach Volume ($m^3.m^{-1}$)	Linear 1990-2006	Average	-10.89 -22.61	3.71 37.19	-7.96 29.37	5.50 2.50
		Std	46.00 11.51	10.46 19.36	8.49 25.79	27.98 9.24
	Linear 1965-2006	Average	23.60 13.00	-10.03 32.63	0.03 15.44	11.00 39.87
		Std	50.67 10.11	7.63 16.39	8.71 26.05	29.64 10.28
	Linear + HC 1965-2006	Average	18.10 40.13	-12.53 10.94	-1.71 48.87	6.75 10.25
		Std	54.32 11.23	4.68 18.45	10.08 29.15	27.53 12.37
Referenced MCL Volume ($m^3.m^{-1}$)	Linear 1990-2006	Average	-1.56 -22.69	21.80 108.63	-1.57 123.34	16.47 101.88
		Std	108.80 51.76	41.43 10.65	51.33 30.27	70.14 13.82
	Linear 1965-2006	Average	33.93 33.80	-25.19 30.38	-22.32 83.84	-7.27 61.83
		Std	113.68 45.94	31.27 5.94	47.65 25.09	65.32 18.26
	Linear + HC 1965-2006	Average	23.43 43.05	-49.19 30.88	-4.57 74.34	-2.02 23.83
		Std	116.02 38.41	23.02 18.62	44.76 15.29	48.82 23.87

7 Conclusions

The influence that the PEM may have on the morphological development of the beach and dune regions in the Test area has been investigated by analysing the temporal evolution of various CSI of the Test area and the adjacent coast.

A morphological analysis studied the volume changes of the adjacent areas to establish the influence the nourishments and the cyclic bar behaviour may have. The morphological analysis has resulted in a phenomenological interpretation of the observed developments.

A quantitative analysis was performed to: 1) identify trend breaks in the CSI of the Test area and 2) intercompare the CSI of the Test area and of the adjacent coast. The analysis was performed by applying three fitting approaches.

With the results of both analyses (presented in the Chapters 5 and 6), the final research question can be addressed.

- Q6: Can we identify and, if possible, quantify the effect of the PEM on the coastal system?

As the observed volume changes are in close agreement with the reported nourishment volumes, it is concluded that the entire study area (Rijks Strand Paal 37.00 to 49.00 km) is influenced by the nourishments carried out in 2004 and 2005. During the two post-nourishment years (2006 and 2007) a relatively large volume decrease is observed which is linked to the adjustment to the nourishments. This volume decrease is an order of magnitude larger than the maximum perceived offshore and onshore losses beyond the NAP – 8 m depth contour and the first dune. This implies that alongshore advection/diffusion of the nourishments of sediment out of the study area is the primary cause for the volume decrease. From 2008 to 2010 volume changes in the study area are gradual and an order of magnitude smaller than in the previous years.

Based on a detailed evaluation of the volume changes between separate areas, it is concluded that it is impossible to couple observed volume *decreases* from 2006 to 2008 in the Egmond and Heemskerk areas to volume *increases* in the Test and Reference areas. From the year 2008 onward, the changes are gradual and small, with largest changes occurring from 2009 to 2010. Based on the analysis of the volume development of the entire areas, it cannot be established that feeding of the Test and Reference areas occurs by the adjacent nourishments since 2007.

The temporal evolution of the sediment volumes and the longshore averaged profiles show a relatively large longshore coherence between the Reference and Test areas. This is consistent with the findings of the quantitative CSI analysis (Chapter 6). Particularly since 2006, the comparable Beach volume changes in both areas are probably a manifestation of alongshore coherence.

It is concluded that the comparable morphological development of the beach and dunes at both the Test and the Reference areas could be related to the cyclic bar behaviour. The approximate same phase of the bar cycle in both areas would be the main explanation.

The influence of the nourishments on the beach and dune regions since 2008 cannot be identified. The same holds for the influence of the PEM, for the entire installation period (captured in the 2007 to 2010 surveys).

The quantification of changes (Chapter 6) confirms that the temporal development of the CSI for the period 2007-2010 shows a change in behaviour in both the Test and the Reference areas. As the observed mean values for 2007-2010 of relevant CSI (e.g. MCL and Beach volumes) are outside the ranges predicted by all three employed fitting approaches, the change of behaviour is characterized as a significant trend break in both the Test and Reference areas.

For the period 2007-2010, the Referenced Beach volume increases with respect to the natural development which is estimated to be about 8 m^3/m/yr for both the Test area and the Reference area. For the same period, the Referenced MCL volume increases with respect to the natural development which is estimated to be about 19 m^3/m/yr and 25 m^3/m/yr for the Test and the Reference areas, respectively.

As both areas exhibit similar trend breaks, the evidence for identifying and quantifying a possible effect of the Ecobeach system is inconclusive.

The possible influence of the PEM on the local beach and dune morphology falls within the range of natural variability in the study area.

Discussion

At the end of 2010, the PEM system was removed. The morphological development in the coming years of the Test and Reference areas may provide additional information on the effect that the PEM may have (e.g. if a decoupled behaviour of the upper profile at both areas is observed).

In the study area and for the considered time period, the effect of the PEM is at best similar to the natural variability. It is therefore impossible to prove an effect solely based on the field experiment. An unambiguous proof that the PEM have an effect requires a description of the working mechanisms which should be confirmed experimentally.

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A Ecobeach system (United States Patent 6547486)

Patent information

Name: Method for Coastal Protection

Inventor: Poul Jakobsen

Assignee: SIC Skagen Innovationscenter

Patent no.: US 6,547,486 B1

Date of Patent: 15 April 2003

Abstract

In a method for coastal protection, where the coastal area has an underlying freshwater basin and below this a salt water tongue which extends obliquely down into the coastal area, the pressure is equalized in the groundwater basin at least along an area at the shore line completely or partly to the atmosphere through pressure equalization modules, preferably in the form of pipes with a filter at the bottom, which extend down into the groundwater basin. This causes sedimentation of material and thereby an increase in the width of the shore. The resulting sand drift may be utilized for additional building-up of the coastal area by further establishing fascines.

Claims

What is claimed is:

1. A method for protecting a coastal area which includes a beach area that meets salt water at a shoreline, and where a freshwater basin underlies the coastal area and a salt water tongue extends below the freshwater basin at an oblique angle, the method comprising extending at least one pipe downwardly in the beach area near the shoreline so as to reach the freshwater basin and communicate the freshwater basin with the atmosphere such that at least a partial equalization of a pressure in the freshwater basin with a pressure of the atmosphere is achieved in said beach area by means of said communication.

2. A method according to claim 1, wherein said at least one pipe includes a filter in a part thereof that extends into the freshwater basin.

3. A method according to claim 1, wherein a plurality of pipes are extended downwardly through the beach to the fresh water basin at a distance from the shoreline.

4. A method according to claim 3, wherein, said coastal area also defines a swash zone adjacent said shoreline, and including placing a plurality of additional said pipes in said swash zone to communicate with said freshwater basin.

5. A method according to claim 1 wherein fascines are provided on the coastal area.

6. A method according to claim 1, wherein said at least one pipe includes an anchoring element.

7. A method according to claim 6, wherein said at least one pipe has a pipe stub which protrudes upwardly from the coastal area and a downwardly bent extension attached to the stub which includes an aperture facing downwardly and which defines an upper free end of the pipe.

Description

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a method for coastal protection where the coastal area has an underlying freshwater basin and below this a salt water tongue which extends obliquely down into the coastal profile.

2. The Prior Art

For coastal protection, it is generally known to build breakwaters of huge stones or concrete blocks which extend from the beach to a distance into the water. Breakwaters are effective, but the costs of construction and maintenance are relatively great. Another coastal protection method is coastal feeding where large amounts of sand are transported to the stretch of coast which is to be protected. This method also involves great costs of construction and maintenance, since large amounts of sand have to be transported. These two methods are still the most widely used coastal protection methods.

In connection with the establishment of intakes for the pumping of sea water for use in salt water aquarias, it was discovered in the early 1980s that sedimentation took place around the intake, which became clogged because of the deposits on top of the intake. This was the incentive for experimenting with a new method for coastal protection, as described in DK 152 301 B. The idea of the method is to pump water from drains established along the shore line, resulting in sedimentation at the drains. However, this method never found extensive use, as it requires a great pumping capacity and consequently high costs of construction and high pump operating costs.

U.S. Pat. No. 5,294,213 discloses a similar system likewise based on drainage pipes established in parallel with the coastal both on the beach and in the water. The operation of the system, which is likewise based on pumping of water, is adapted to the weather, i.e., whether ordinary water level, low water, high water or storm conditions. The system includes a water reservoir into which the water may be pumped through the drainage pipes, and water may be pumped through these into the sea, e.g., to remove sand banks formed by a storm.

A corresponding method is known from U.S. Pat. No. 4,898,495 to keep an inlet, which debouches into the sea, open. This method is likewise based on pumps. The system comprises various diffuser arrangements to remove deposits from the mouth of the inlet by fluidizing these and transporting the material further downstream of the inlet mouth by generating a flow. Sedimentation is carried out downstream of the inlet mouth by pumping water from drains to the diffuser arrangements.

An object of the present invention is to provide a method for coastal protection which is not vitiated by the drawbacks of the known coastal protections.

SUMMARY OF THE INVENTION

This is achieved according to the invention by a method which is characterized in that the pressure of the groundwater basin at least along an area at the shore line is equalized completely or partly through pressure equalization modules, preferably in the form of pipes with a filter at the bottom, which extend down into the groundwater basin.

It has surprisingly been found by the invention that positioning of pressure equalization modules in the beach results in sedimentation of material at the area where the modules are placed.

A possible explanation as to why coastal accretion takes place is that the very fine sand which is fed to the profile partly by the sea and partly by the wind and which is packed with silt and other clay particles, reduces the hydraulic conductivity. Deeper layers in the coastal profile, which have exclusively been built by the waves of the sea, are primarily coarse in the form of gravel and pebbles which have a greater hydraulic conductivity. The difference in hydraulic conductivity will be seen clearly when digging into a coastal profile, it being possible to dig a hole in the profile, and the groundwater will then rise up into the profile once the water table is reached. The reason is the very different hydraulic conductivity and that the freshwater is under pressure from the hinterland. Thus, the coastal profile may be compared to a downwardly open tank where the tank is opened at the top with the pressure equalization modules which extend through the compact layers of the profile so that the water runs more easily and thereby more quickly out of the profile in the period from flood to ebb. This means that a pressure equalized profile is better emptied of freshwater and salt water in the fall period of the tide. When the tide then rises from ebb to flood, a greater fluctuation occurs in the foreshore, as the salt water in the swash zone is drained in the swash zone so that materials settle in the foreshore during this period of time. Conversely, coastal erosion takes place if the freshwater is under pressure in the foreshore, as the salt water will then run back into the sea on top of the freshwater and thereby erode the foreshore. In reality, the pressure equalization modules start a process which spreads from the pressure equalization modules, as the silt and clay particles are flushed out of the foreshore when the fluctuation is increased because of the draining action of the modules. Further, a clear connection has been found between the amount of sediment transport on the coast and the rate of the coastal accretion.

It has been found that the pressure equalization modules create a natural equilibrium profile with a system of about 1:20, so that the waves run up on the beach and leave material, as water in motion can carry large amounts of material which settle when the velocity of the water decreases. The profile must therefore have a given width with respect to the tide and a maximum water level in the area. Coastal profiles with pressure equalization modules naturally become very wide, which results in a very great sand drift on the foreshore. This great sand drift is utilized by establishing longitudinal fascines high up in the beach and transverse fascines with an increasing height toward the foot of the dune, the fascines forming the upper part of the beach profile.

The invention will be described more fully below with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a cross-section through a coastal profile,

FIG. 2 shows a pressure equalization module intended to be positioned on the beach,

FIG. 3 shows a pressure equalization module intended to be positioned in the swash zone,

FIG. 4 shows a stretch of coast seen from above with pressure equalization modules and fascines, and

FIG. 5 shows a coastal profile in the stretch of coast in FIG. 4.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

As shown in FIG. 1, a freshwater basin is present below a coastal profile 1, and this freshwater basin is defined at the bottom in a downwardly inclined plane by a tongue of salt water 3 which has a greater density than freshwater.

The reason for coastal erosion is thus that when the freshwater below the beach profile is under pressure, the salt water seeping down into the profile runs back into the sea on top of the freshwater 2, as shown in FIG. 1. When the pressure of the freshwater decreases, the salt water seeps down through the material in the coastal profile and is mixed with the freshwater and thus does not erode the coastal profile, but, instead, material settles on the beach.

As shown in FIG. 2, the pressure equalization modules may consist of a rigid filter pipe 6 which is connected to a pipe 7 having a sleeve 7a. The filter and the pipe may thus be pressed, flushed or dug into the freshwater basin 2. Preferably, the pipe 7 has a length such that it protrudes slightly above the surface of the coastal profile 1 when the filter is in position in the freshwater basin. The pipes with filters, as shown in FIG. 2, are arranged in a row in a line which is perpendicular or approximately perpendicular to the shore line. The pipe 7 is open at the top so as to create good hydraulic contact down to the freshwater basin.

When the pressure in the freshwater basin has been equalized by means of the pressure equalization modules 12, the sedimentation of material on the stretch of coast may be accelerated according to the invention by establishing further pressure equalization modules 13 in the swash zone 4. An expedient arrangement of a module to be positioned in this zone is shown in FIG. 3 and comprises a rigid pipe 7' connected with a horizontal filter pipe 6'.

In both cases, the modules are provided with an anchoring element 8 intended to be dug into the sand to prevent unauthorized removal of the modules. The anchoring element is in the form of two angled plate elements secured to the rigid pipe. Furthermore, the pipe end, which protrudes from the sand, is provided with a curved termination 9 to prevent unauthorized filling of the pipe with sand, stone, etc. Optionally, the pressure equalization modules may be connected with dug pipes which are run to the foot of the dune where free communication with the atmosphere is created, thereby avoiding protruding pipe stubs.

The use of such pressure equalization modules on a stretch of coast has resulted in a land reclamation of a width of 4-6 metres and an increase in the coastal profile of 60-70 cm in 40 days.

Coastal profiles with pressure equalization modules naturally become very wide, as mentioned, which results in a great sand drift on the foreshore. As will appear from FIGS. 4 and 5, this great sand drift is utilized by establishing longitudinal fascines 10 high up in the beach and transverse fascines 11 of an increasing height toward the foot of the dune. The upper part of the beach profile may be given the desired shape by adapting the length, orientation and height of the fascines. The fascines may, e.g., be formed by brushwood of pine and spruce or the like dug into the coastal profile or stacked between buried piles, which makes it easy to give the fascines the desired shape.

The invention is unique by low costs of construction and operation, the cost of operation involving merely ordinary inspection and maintenance of the systems.

New research in the field has documented that the groundwater pressure on a coastal profile is very decisive for its appearance. It has been demonstrated that coastal profiles having a high freshwater pressure become narrow and concave (also called winter profile), while coastal profiles without noticeable freshwater pressure become wide and convex (also called summer profile). Narrow, concave coastal profiles having a high freshwater pressure are seen in Denmark typically at Vejby Strand on the north coast of Zealand and south of Lønstrup at Mårup Kirke.

Narrow, concave coastal profiles are greatly exposed to erosion, while wide, convex coastal profiles have beach accretion. With the invention, as described, it is possible to convert a narrow, concave coastal profile into a wide, convex coastal profile and thereby to protect the coast.

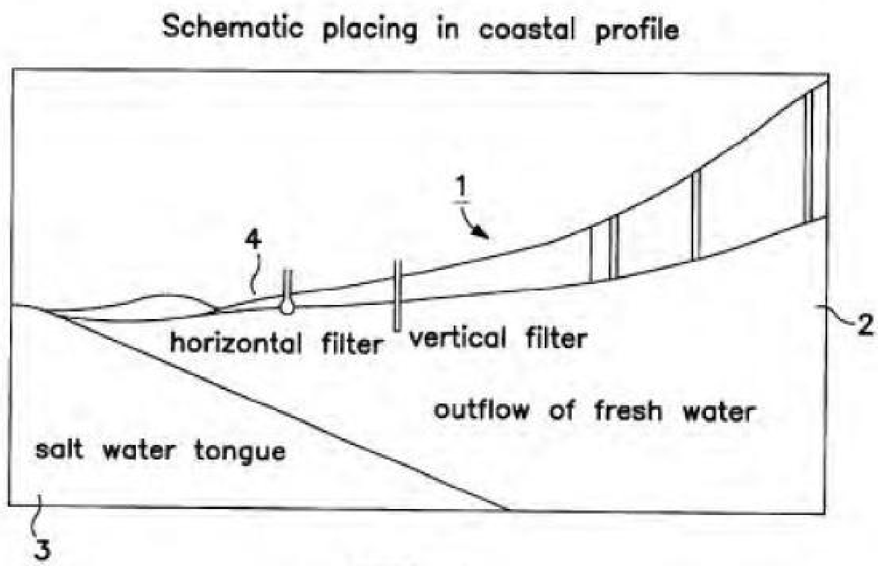


FIG. 1

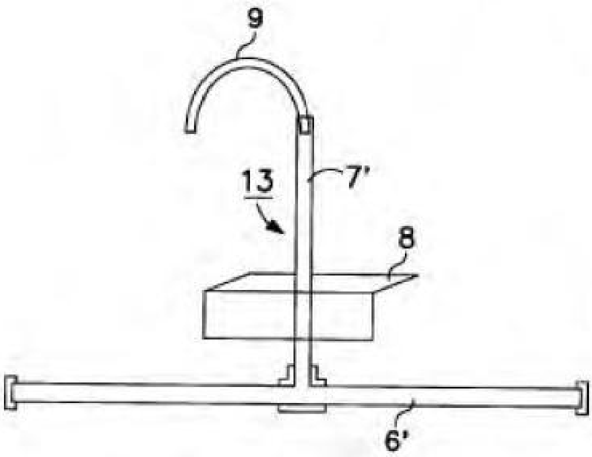


FIG. 3

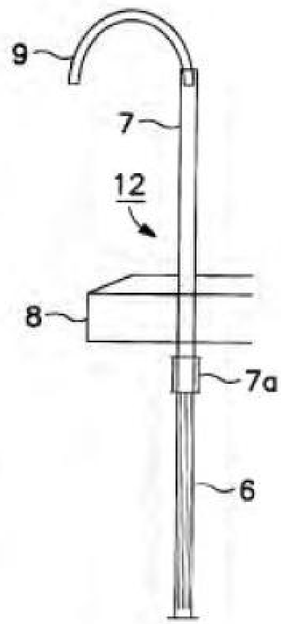
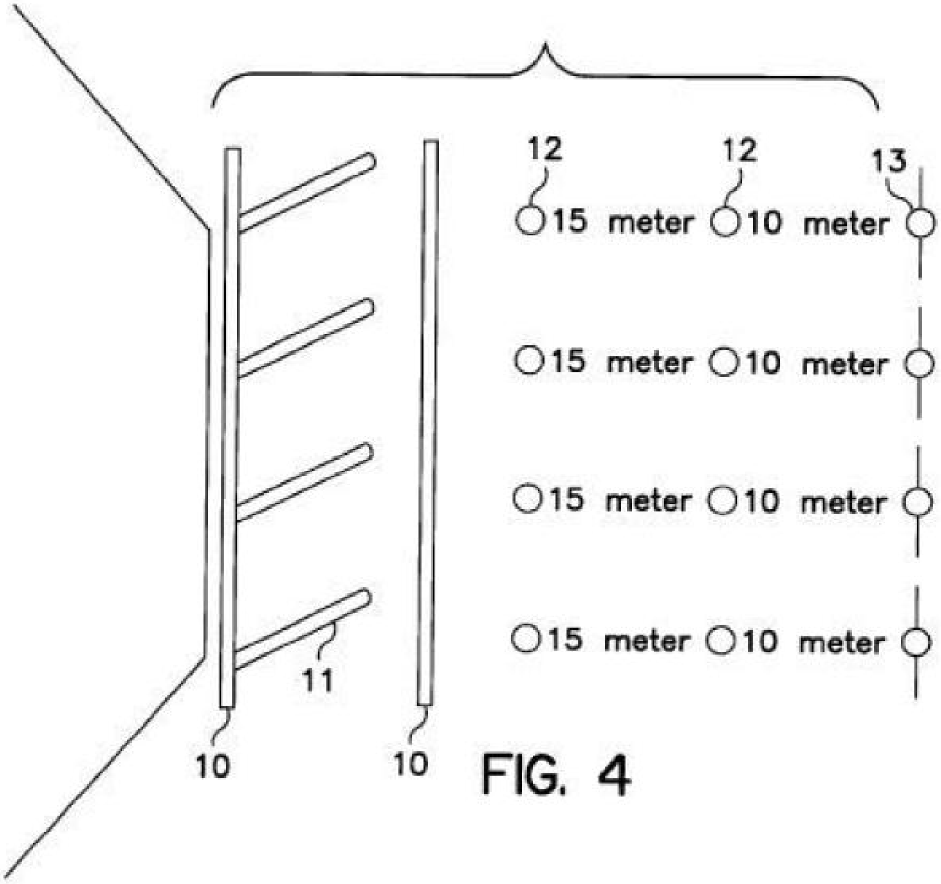


FIG. 2


12
12
13
15 meter
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15 meter
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11
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FIG. 4

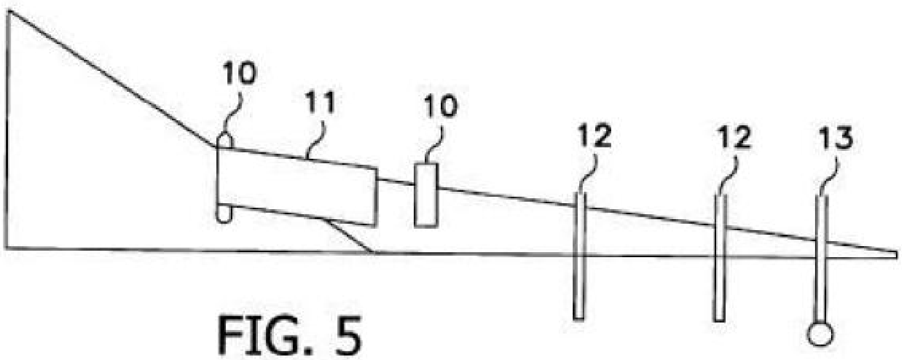
10
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FIG. 5

B Complete results from the analysis of profile-data

This appendix shows various plots of processed profile-data (CSI) that have supported the analysis performed in Chapter 4.

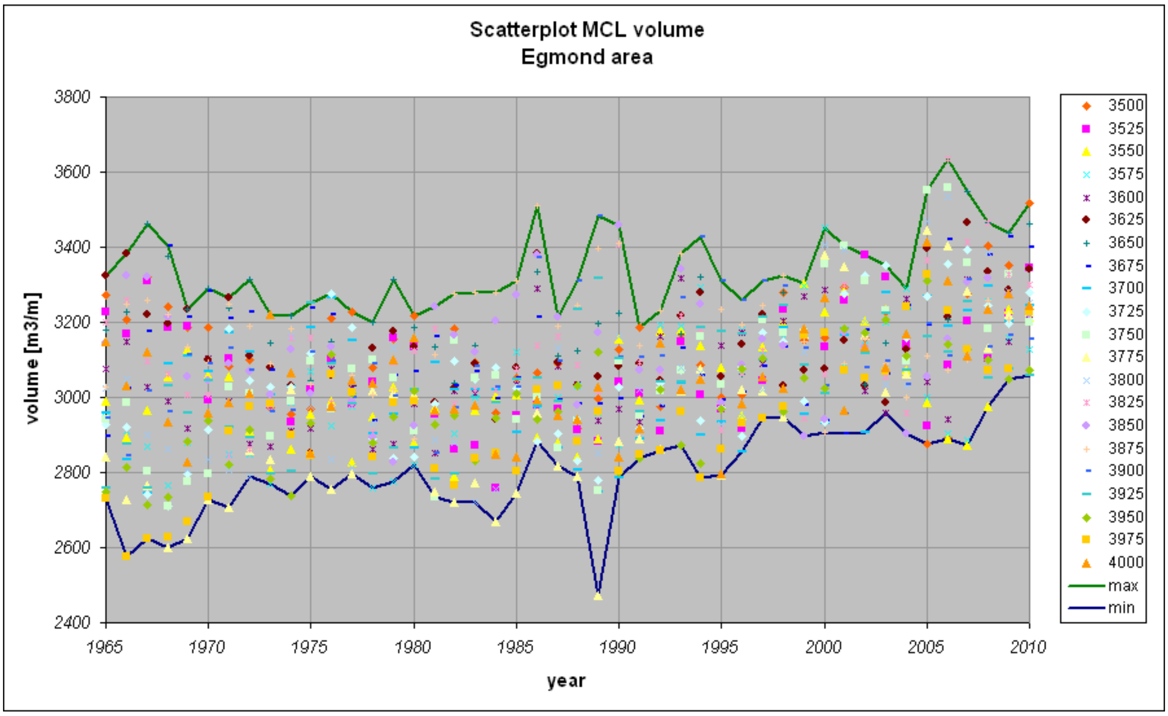

Figure B.1 Scatter plot of the Referenced MCL volume for the Egmond extended area(5 kms)

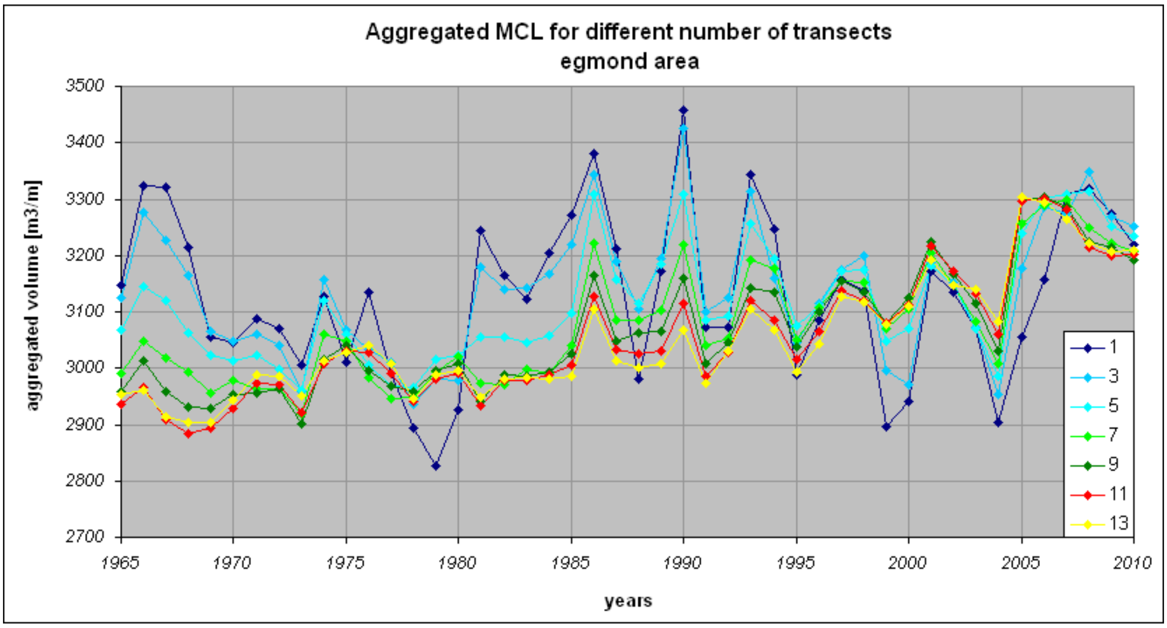

Figure B.2 Aggregated Referenced MCL volume over different numbers of transects for the Egmond area

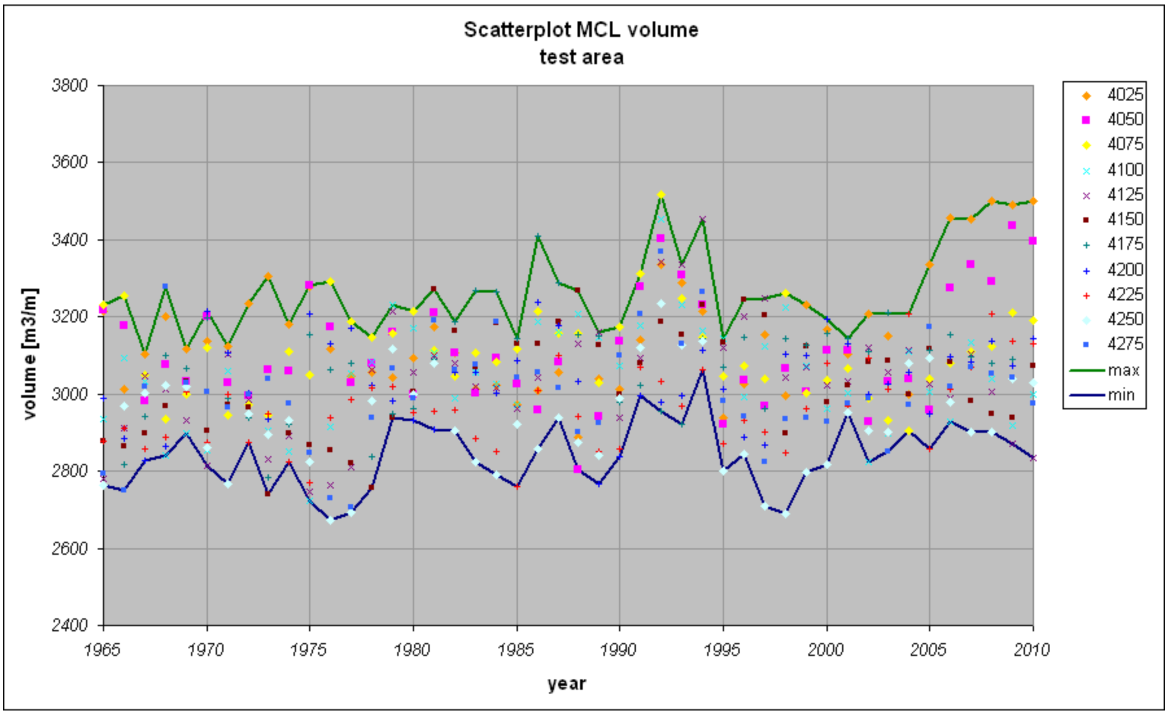

Figure B.3 Scatter plot of the Referenced MCL volume for the Test area

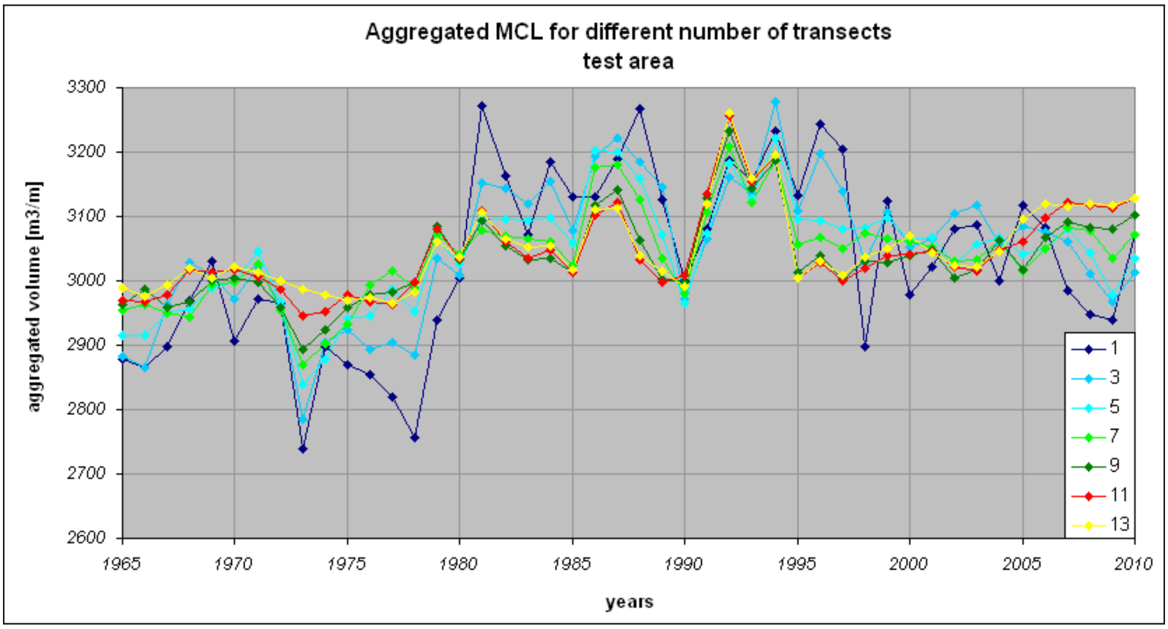

Figure B.4 Aggregated Referenced MCL volume over different numbers of transects for the Test area

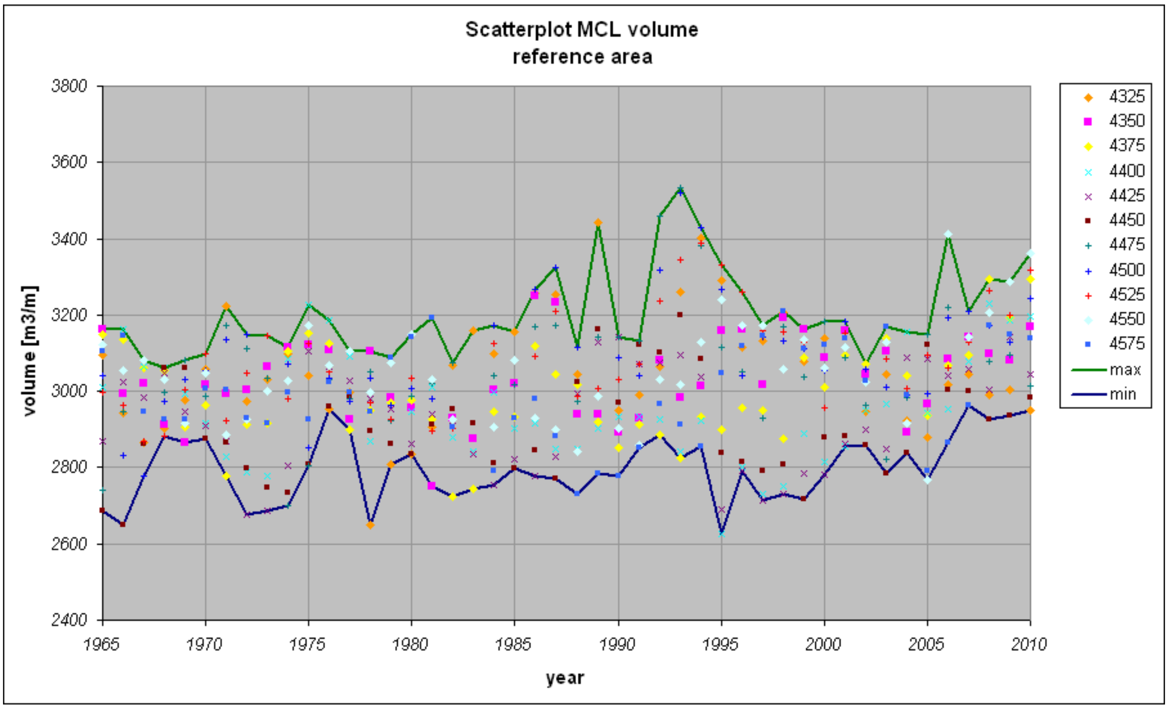

Figure B.5 Scatter plot of the Referenced MCL volume for the Reference area

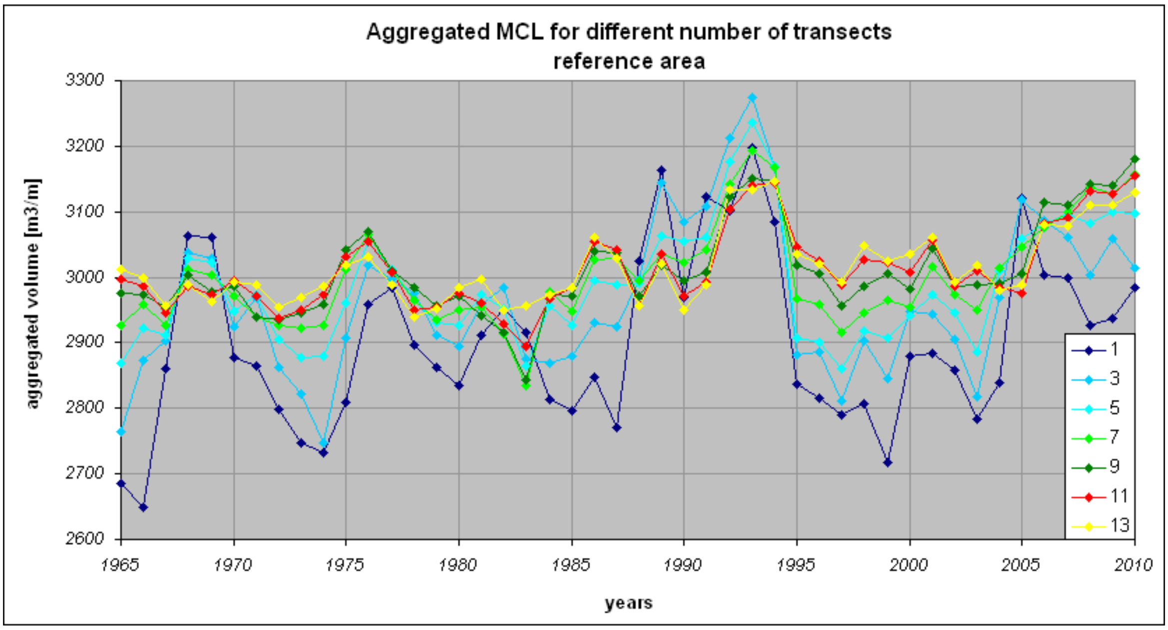

Figure B.6 Aggregated Referenced MCL volume over different numbers of transects for the Reference area

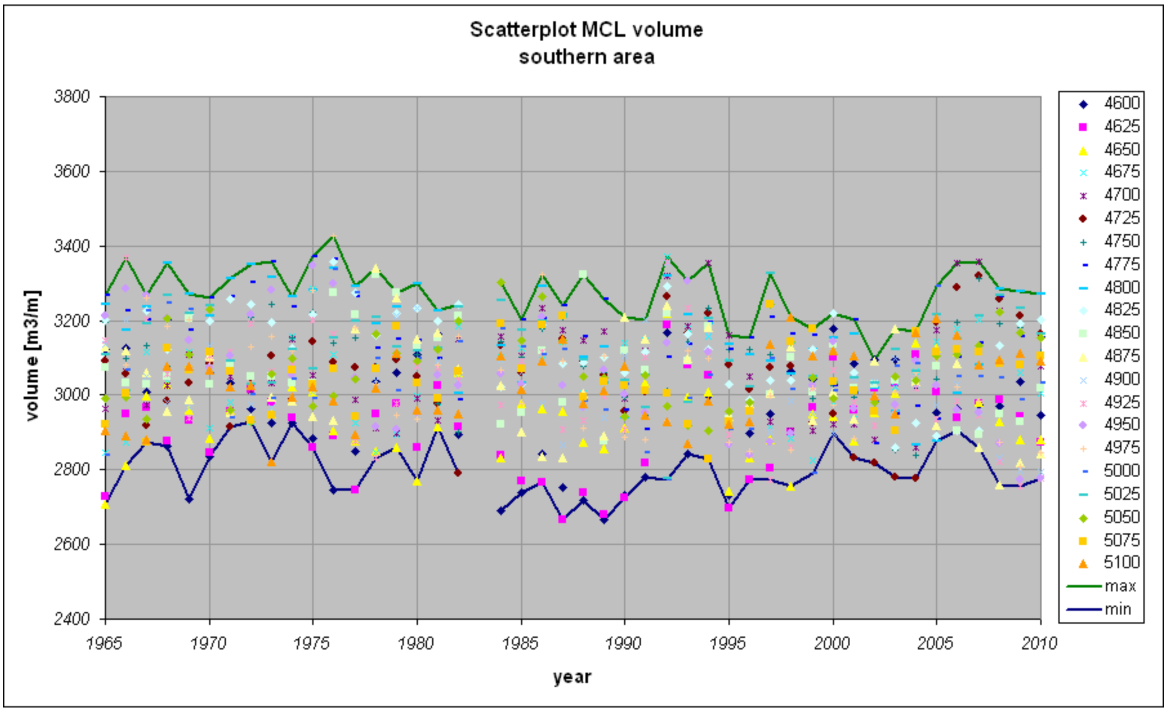

Figure B.7 Scatter plot of the Referenced MCL volume for the Heemskerk extended area (5 kms)

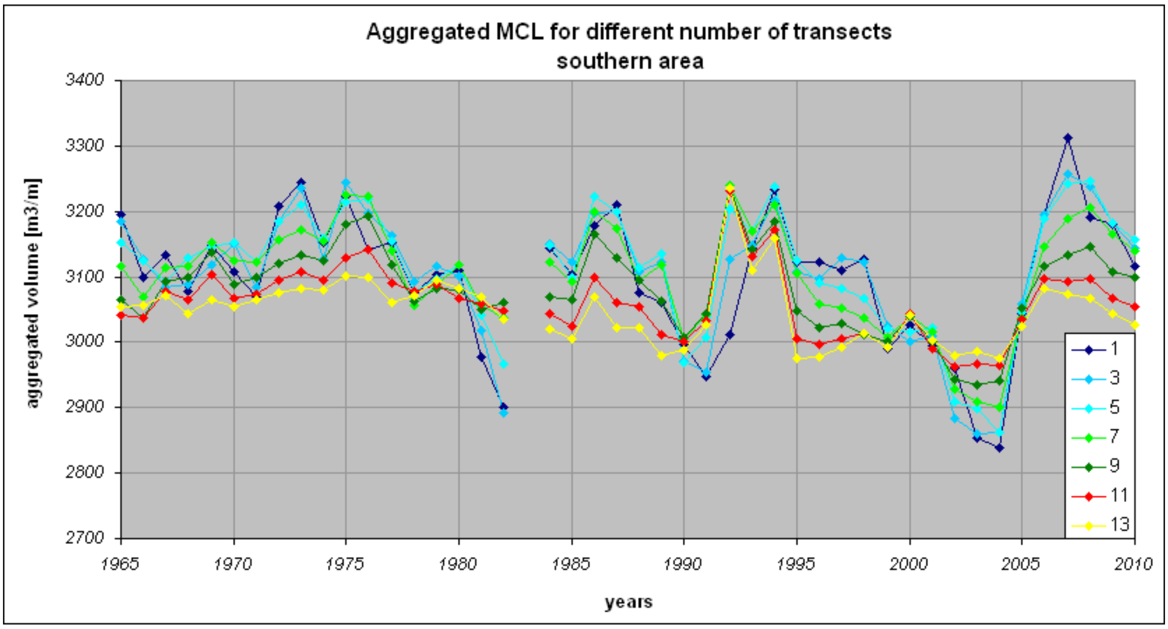

Figure B.8 Aggregated Referenced MCL volume over different numbers of transects for the Heemskerk area

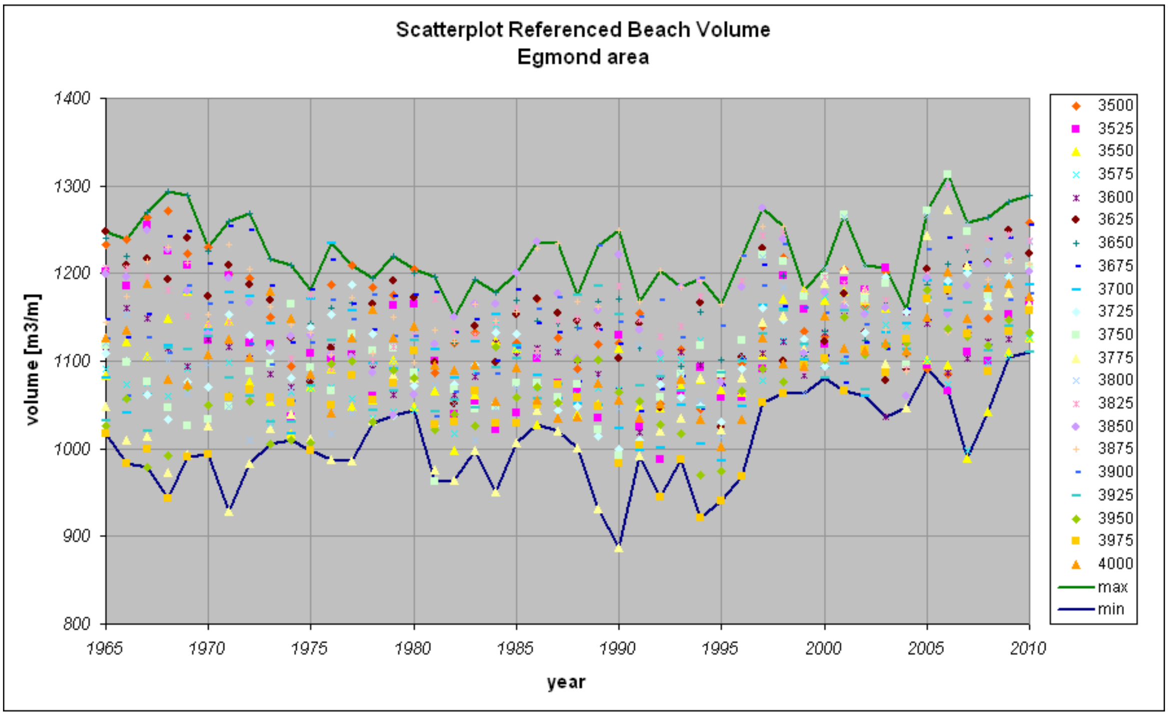

Figure B.9 Scatter plot of the Referenced Beach volume for the Egmond extended area (5 kms)

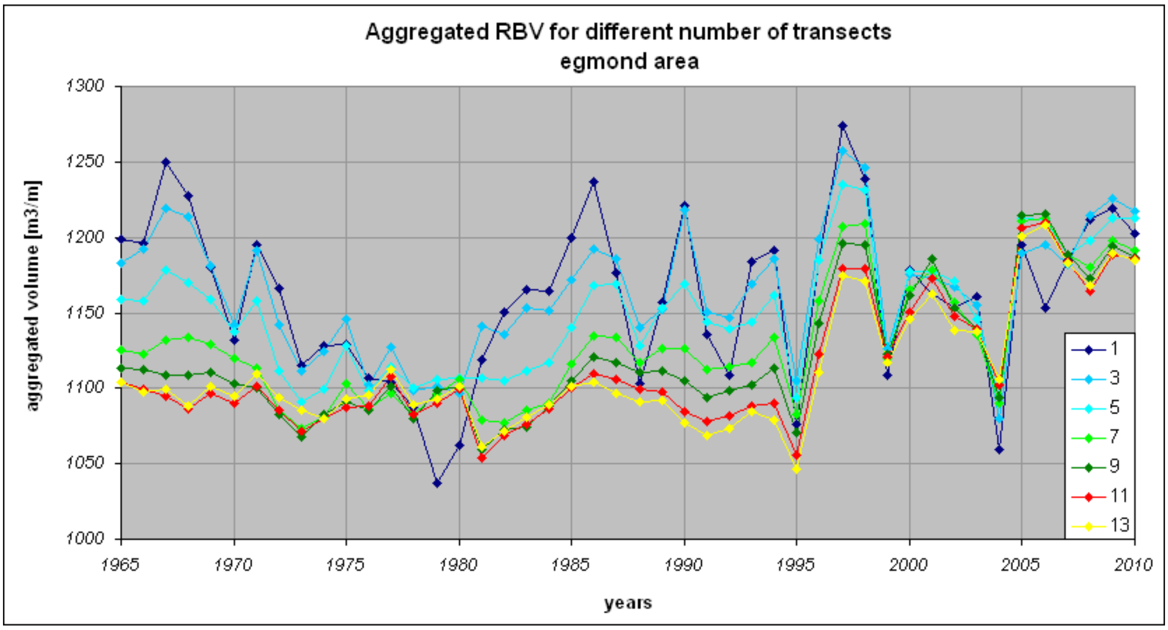

Figure B.10 Aggregated Referenced Beach volume over different numbers of transects for the Egmond area

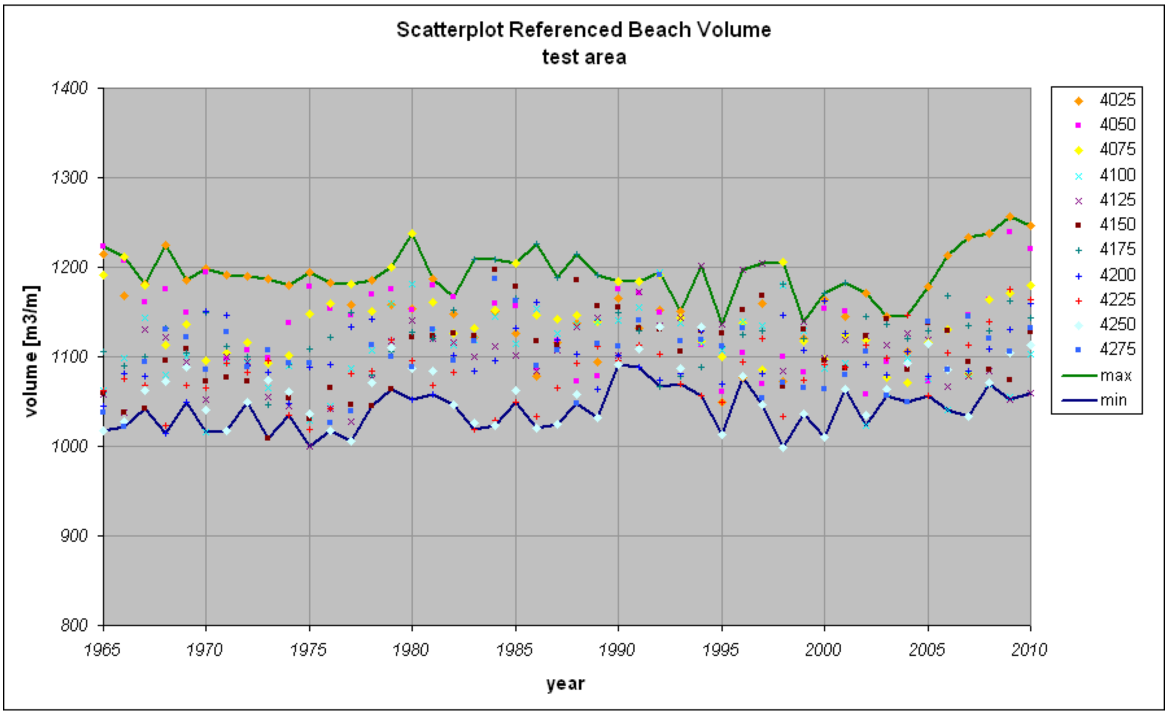

Figure B.11 Scatter plot of the Referenced Beach volume for the Test area

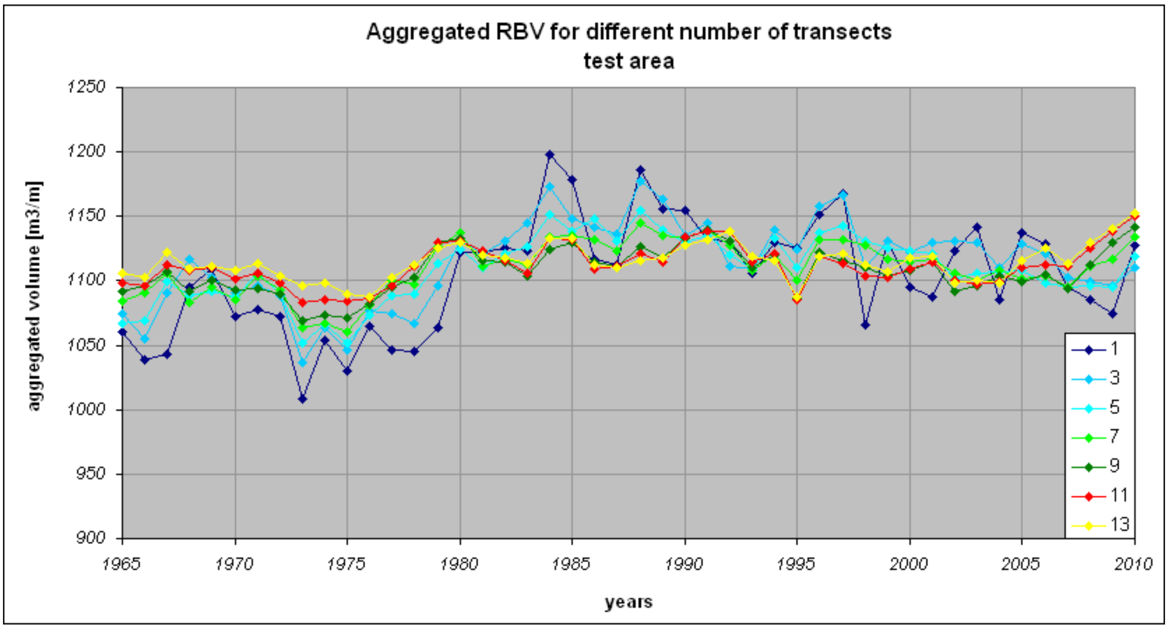

Figure B.12 Aggregated Referenced Beach volume over different numbers of transects for the Test area

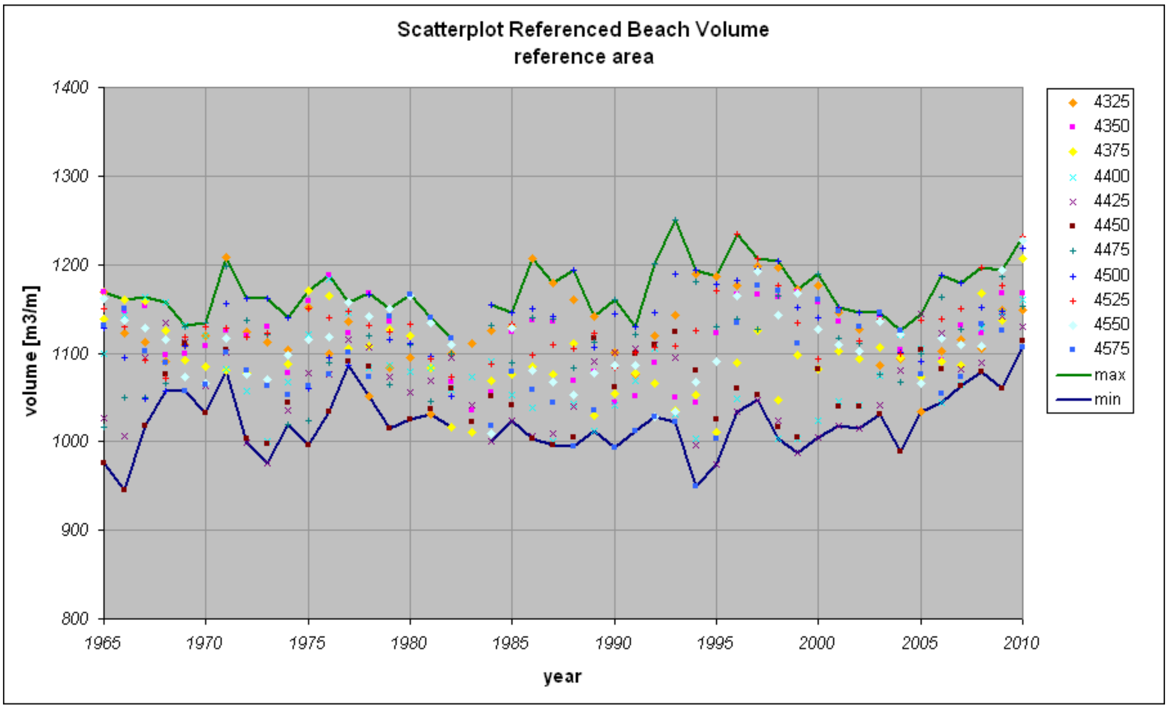

Figure B.13 Scatter plot of the Referenced Beach volume for the Reference area

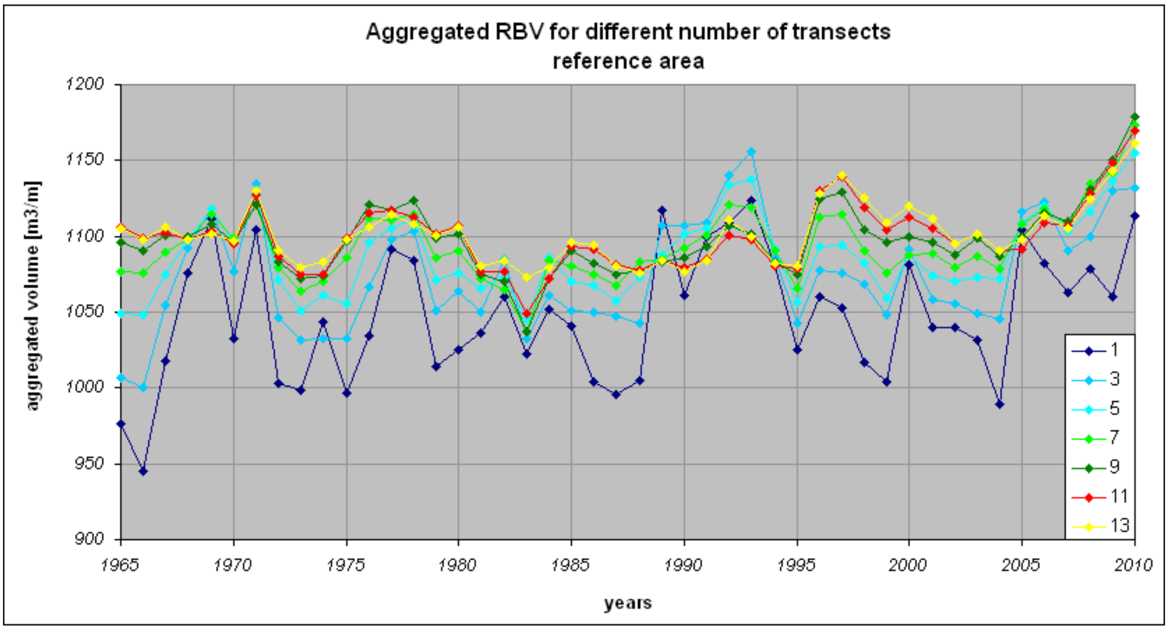

Figure B.14 Aggregated Referenced Beach volume over different numbers of transects for the Reference area

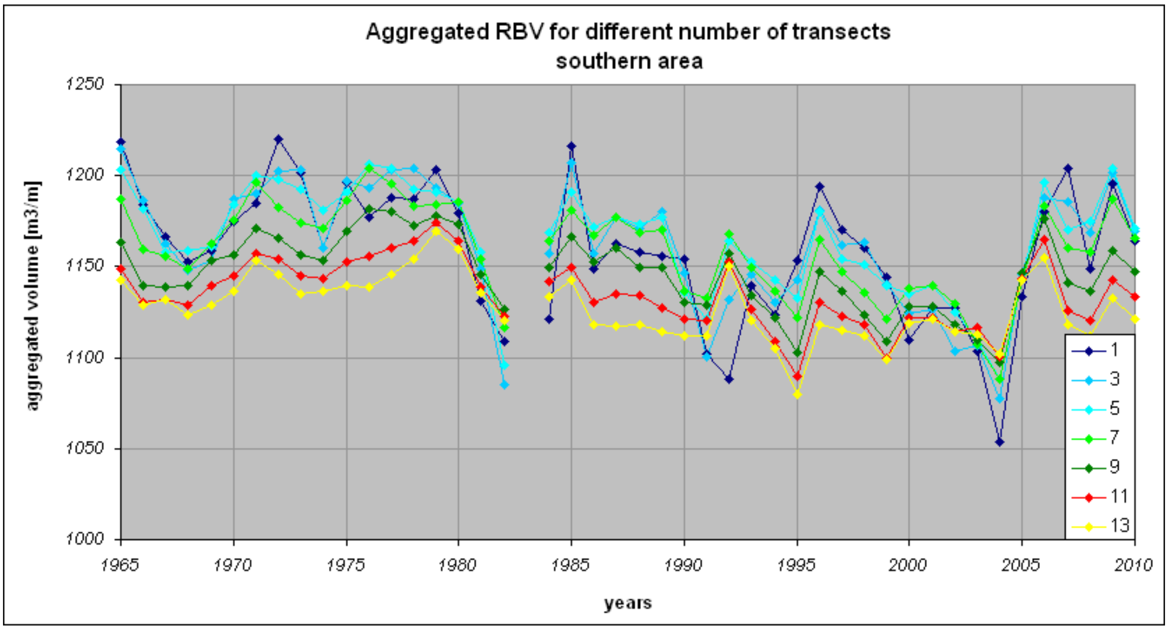

Figure B.15 Scatter plot of the Referenced Beach volume for the Heemskerk area

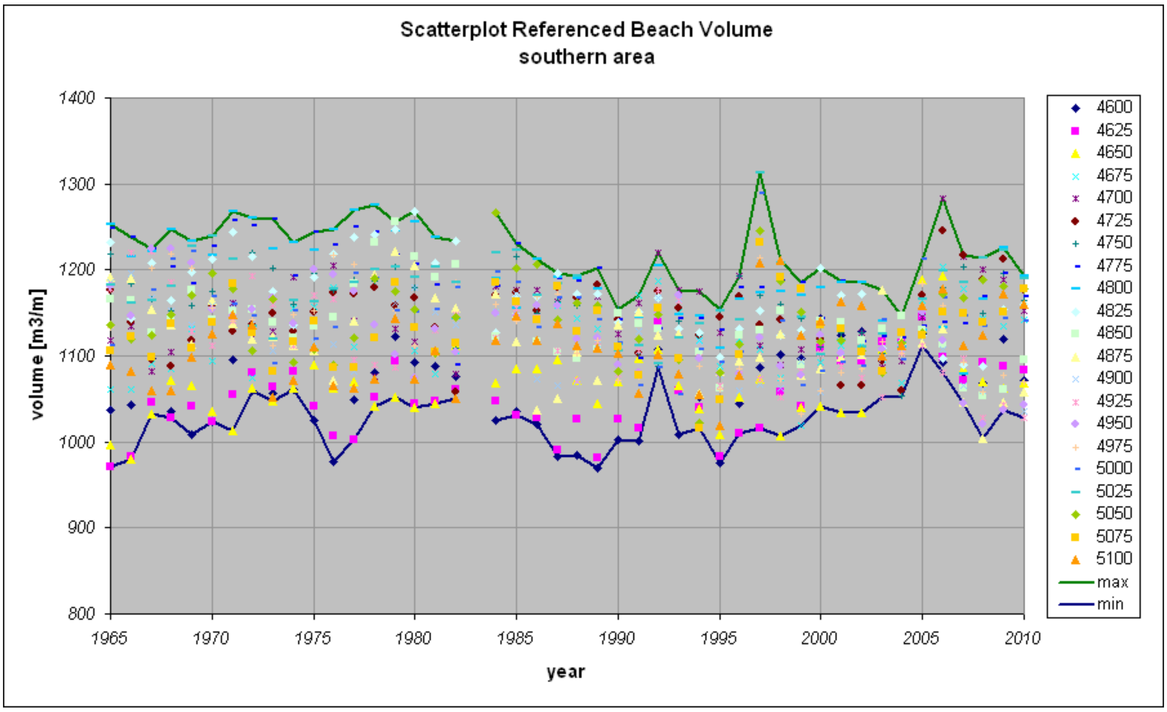

Figure B.16 Aggregated Referenced Beach volume over different numbers of transects for the Heemskerk extended area (5 kms)

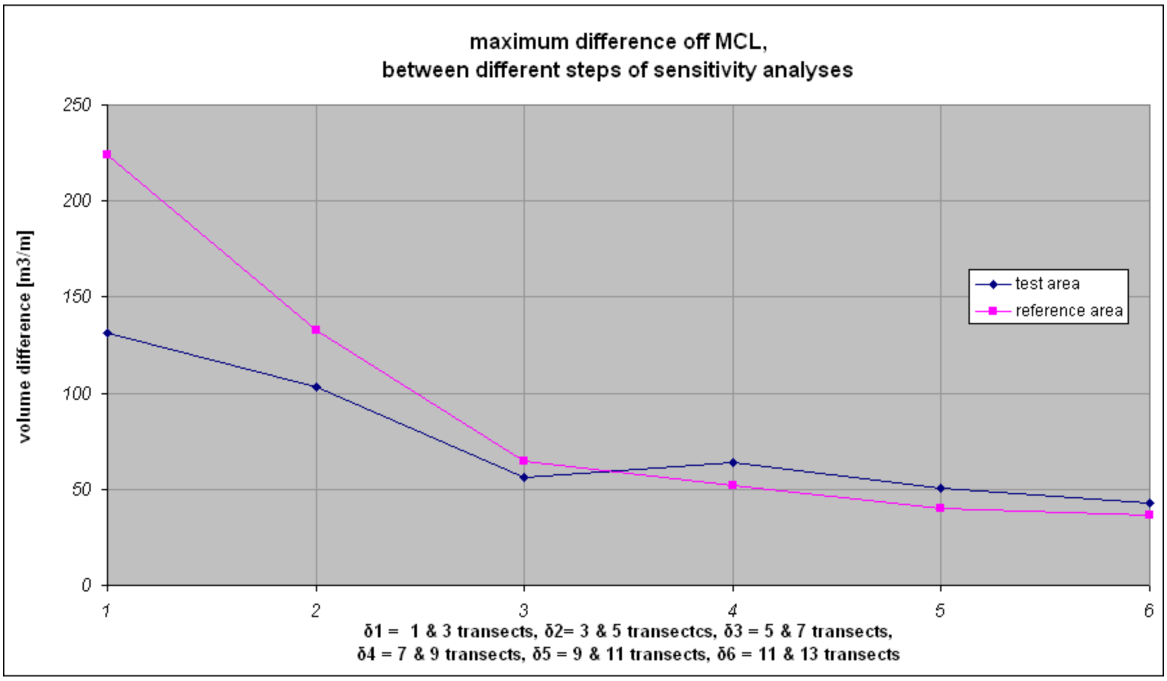

Figure B.17 Difference in Referenced MCL volume induced by data aggregation over different number of transects

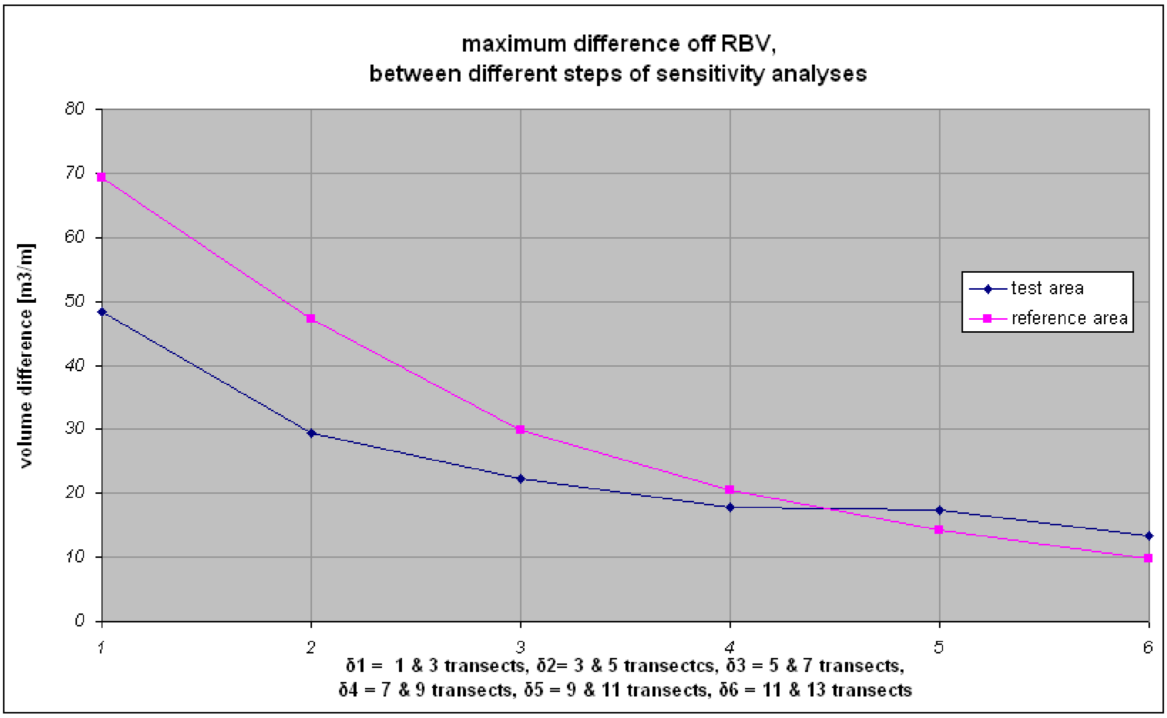

Figure B.18 Difference in Referenced Beach volume induced by data aggregation over different number of transects

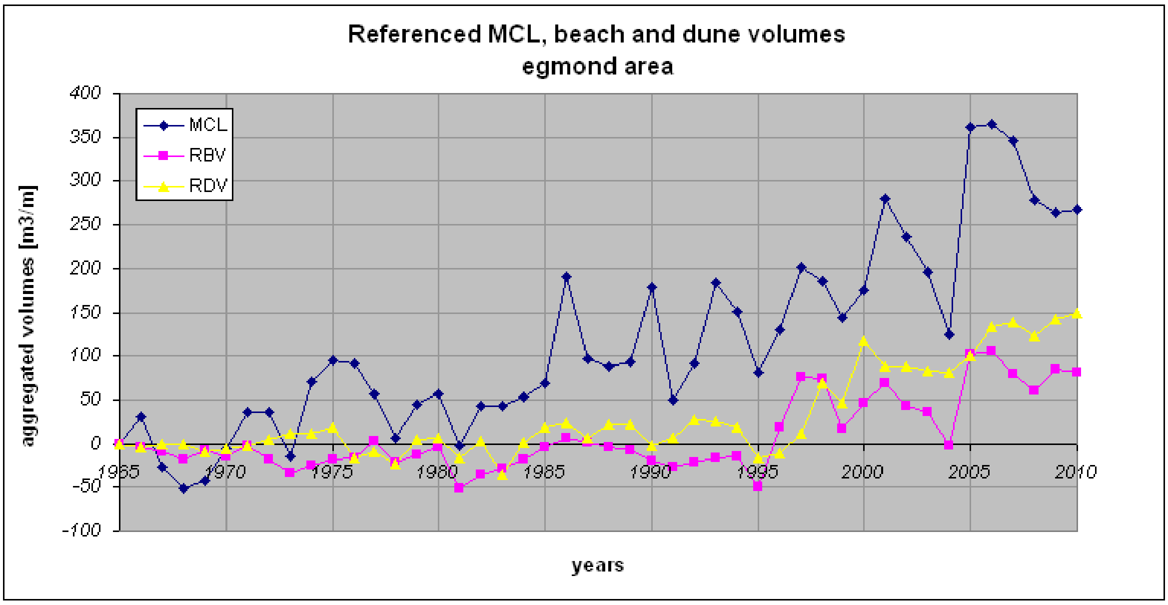

Figure B.19 Referenced MCL volume, Referenced Beach volume and Dune volume for the Egmond area

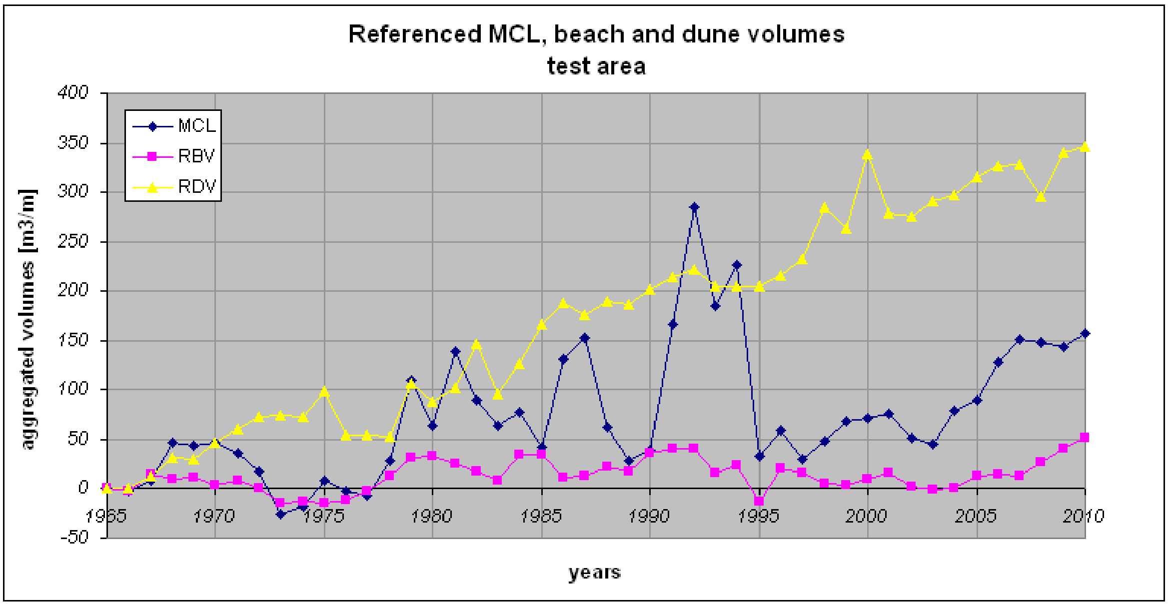

Figure B.20 Referenced MCL volume, Referenced Beach volume and Dune volume for the Test area

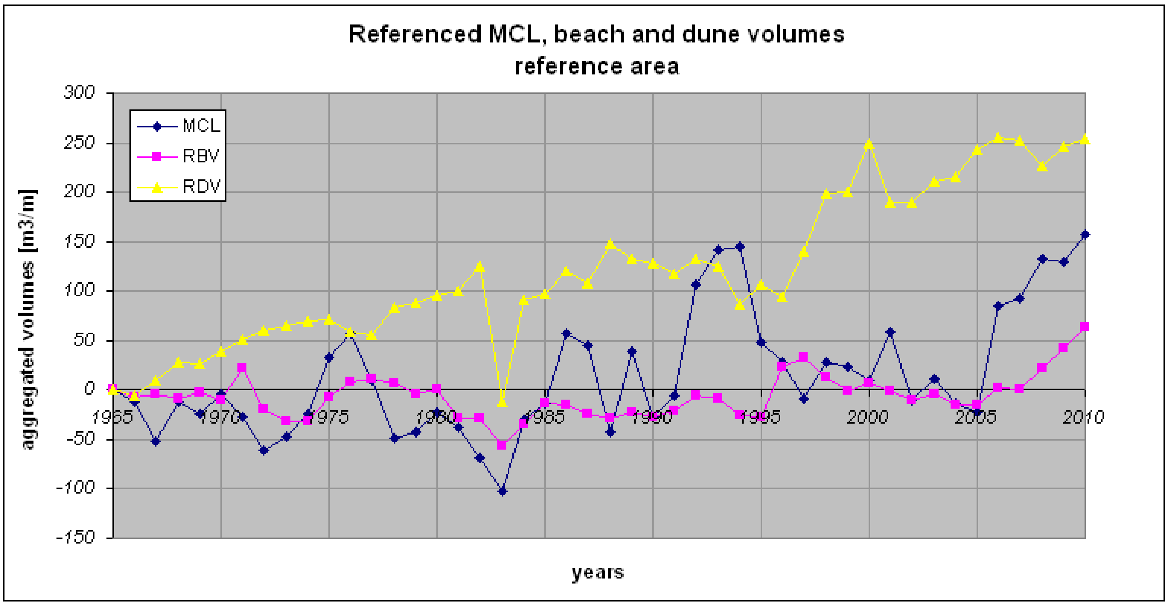

Figure B.21 Referenced MCL volume, Referenced Beach volume and Dune volume for the Reference area

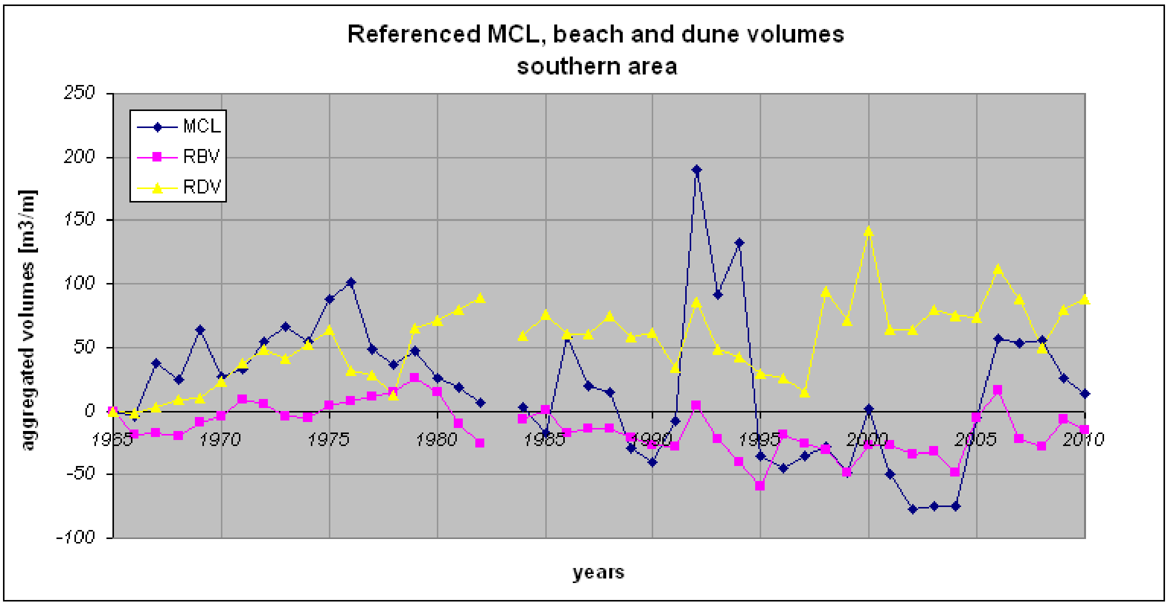

Figure B.22 Referenced MCL volume, Referenced Beach volume and Dune volume for the Heemskerk area

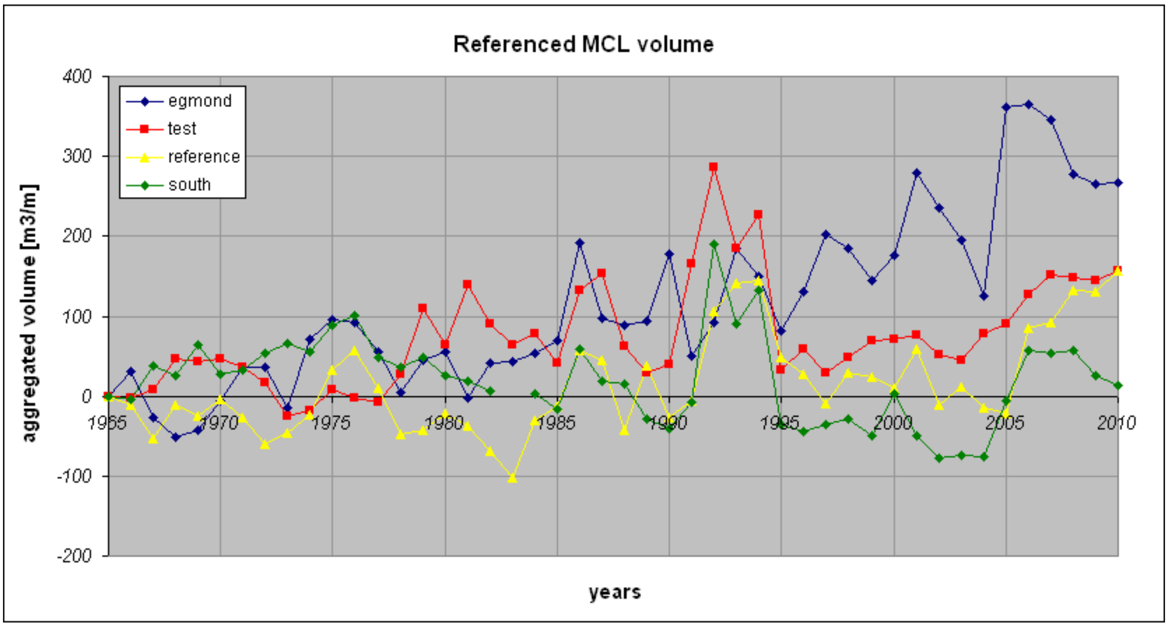

Figure B.23 Referenced MCL volume for the four areas

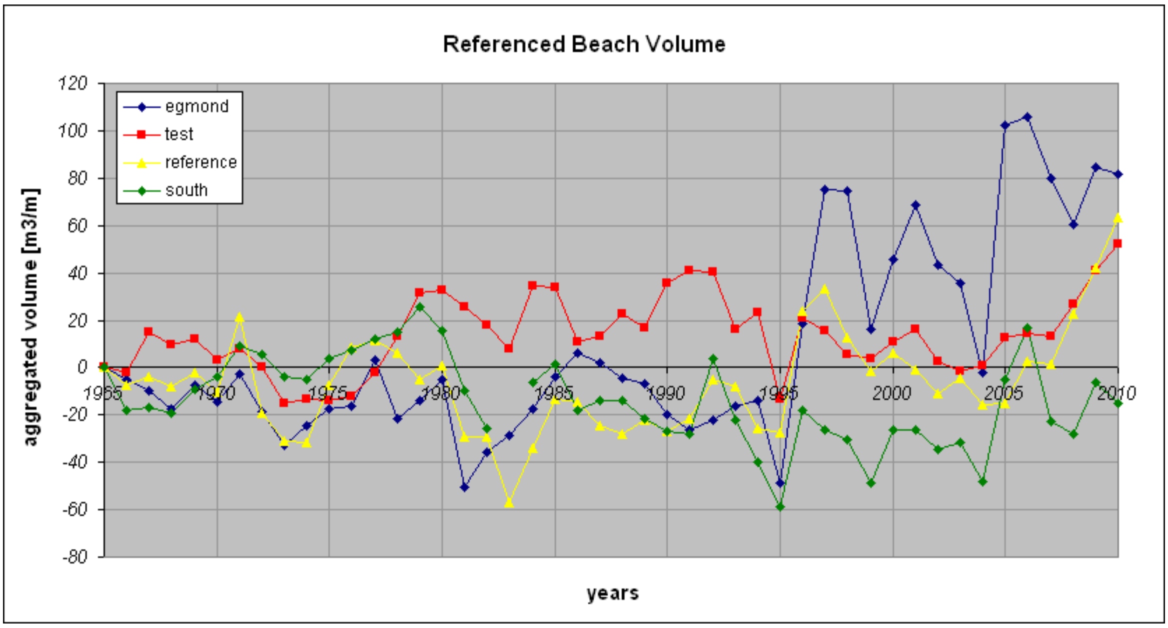

Figure B.24 Referenced Beach volume for the four areas

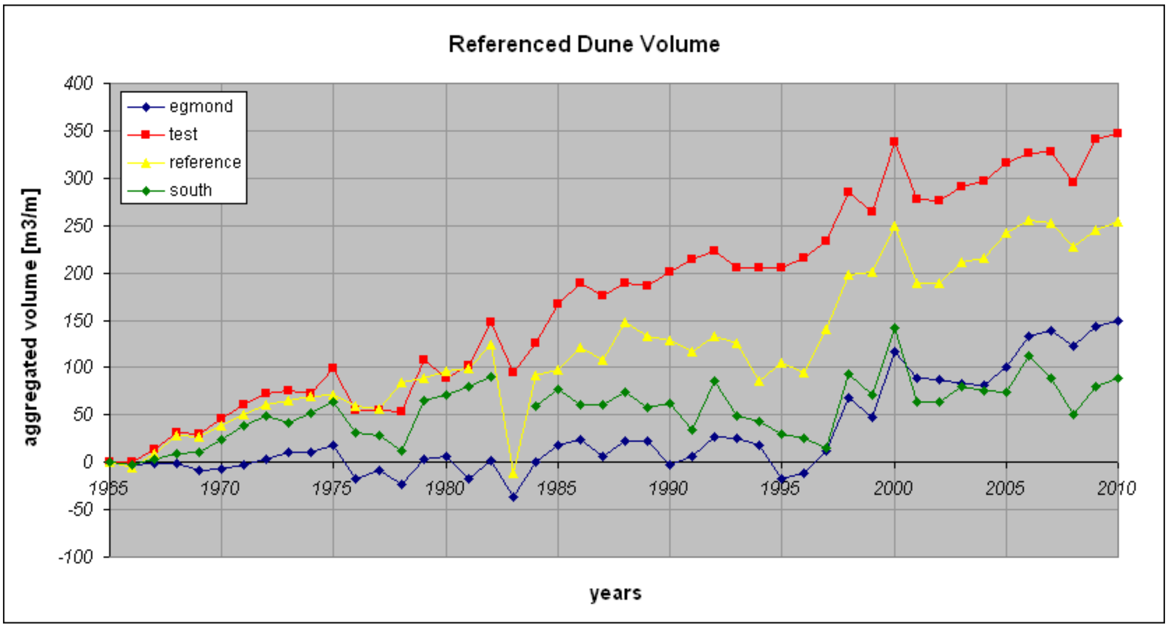

Figure B.25 Dune volume for the four areas

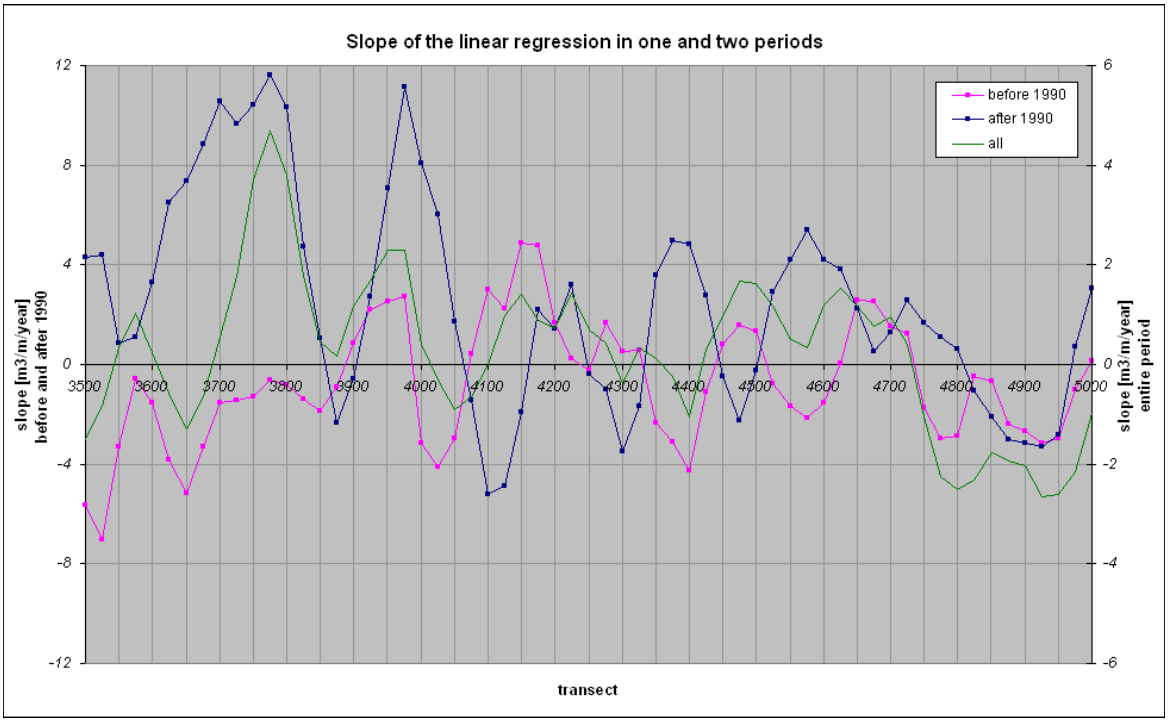

Figure B.26 Slope of the one and two period's linear regression analysis [m3/m/year] in the Referenced Beach volume signals

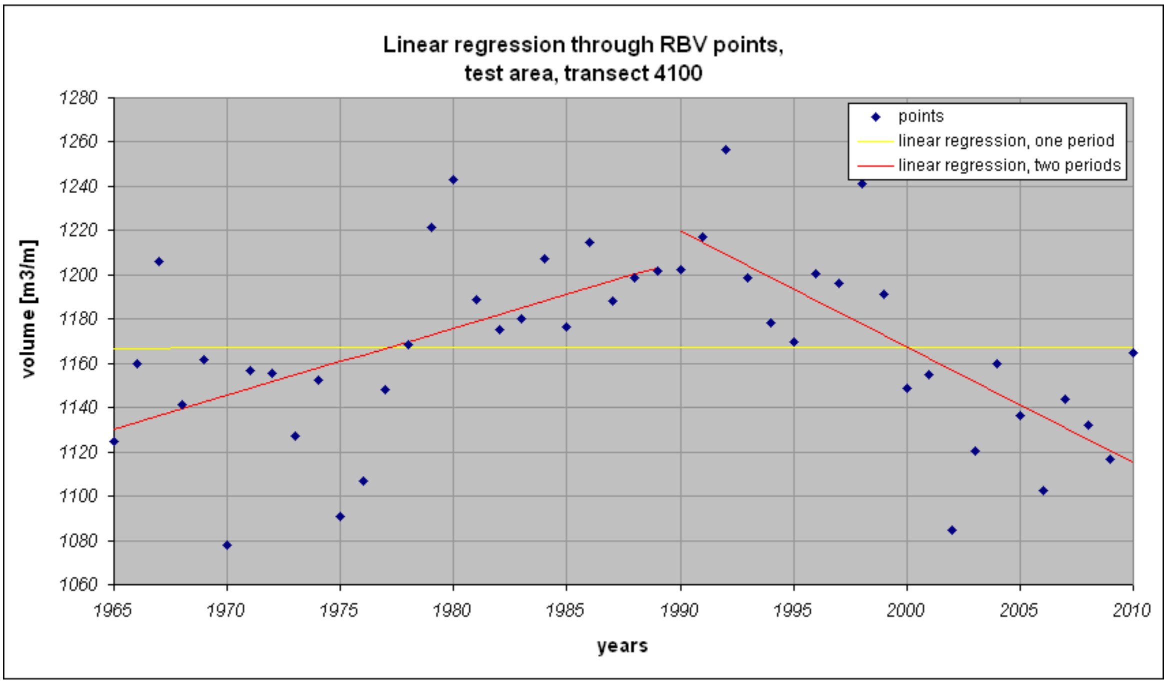

Figure B.27 Results of the linear regression through the Referenced Beach volumes data at transect RSP 41.00

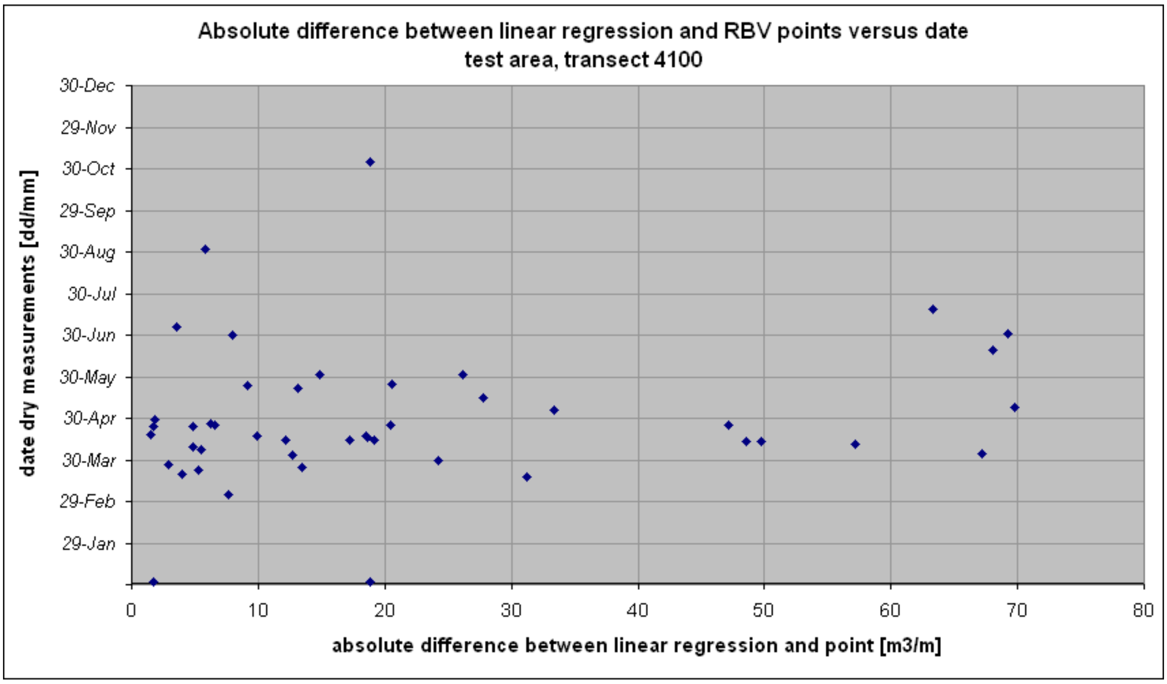

Figure B.28 Temporal variations of the absolute difference between the results of the linear regression and the Referenced Beach volumes data at transect RSP 41.00

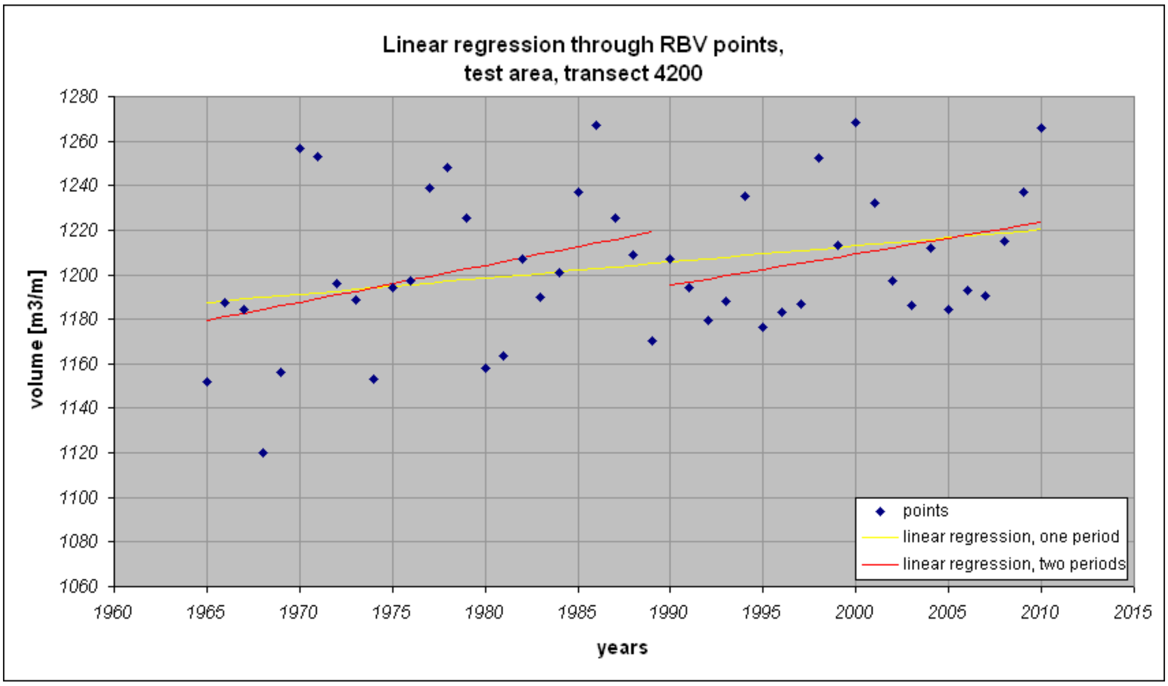

Figure B.29 Results of the linear regression through the Referenced Beach volumes data at transect RSP 42.00

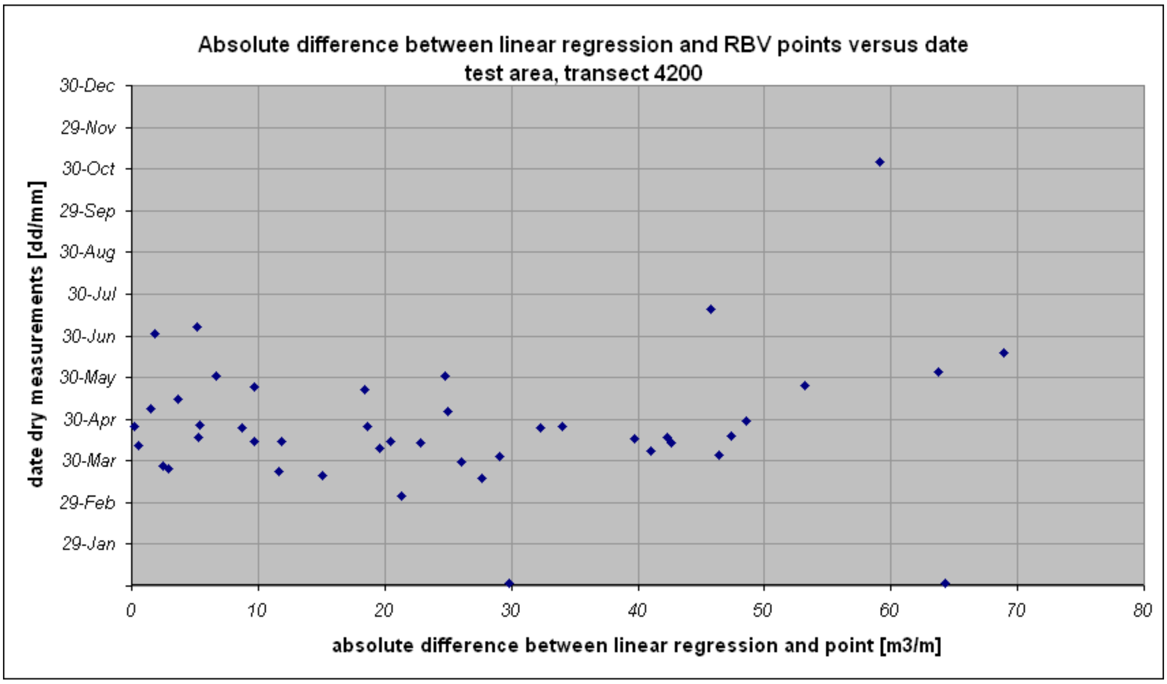

Figure B.30 Temporal variations of the absolute difference between the results of the linear regression and the Referenced Beach volumes data at transect RSP 42.00

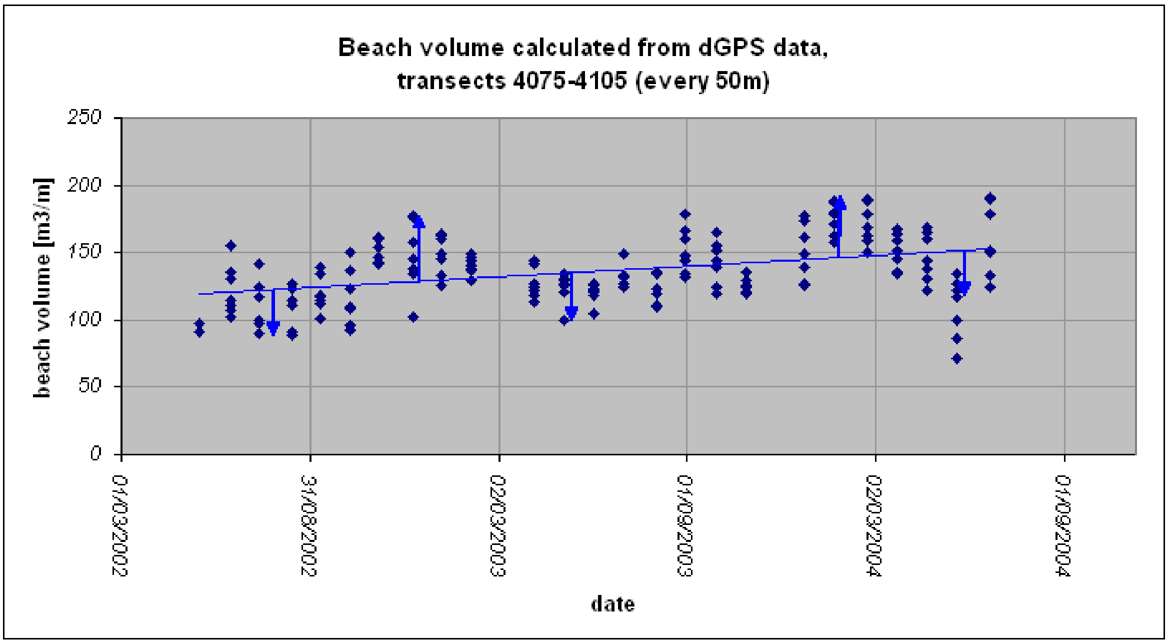

Figure B.31 Beach volumes calculated from dGPS data

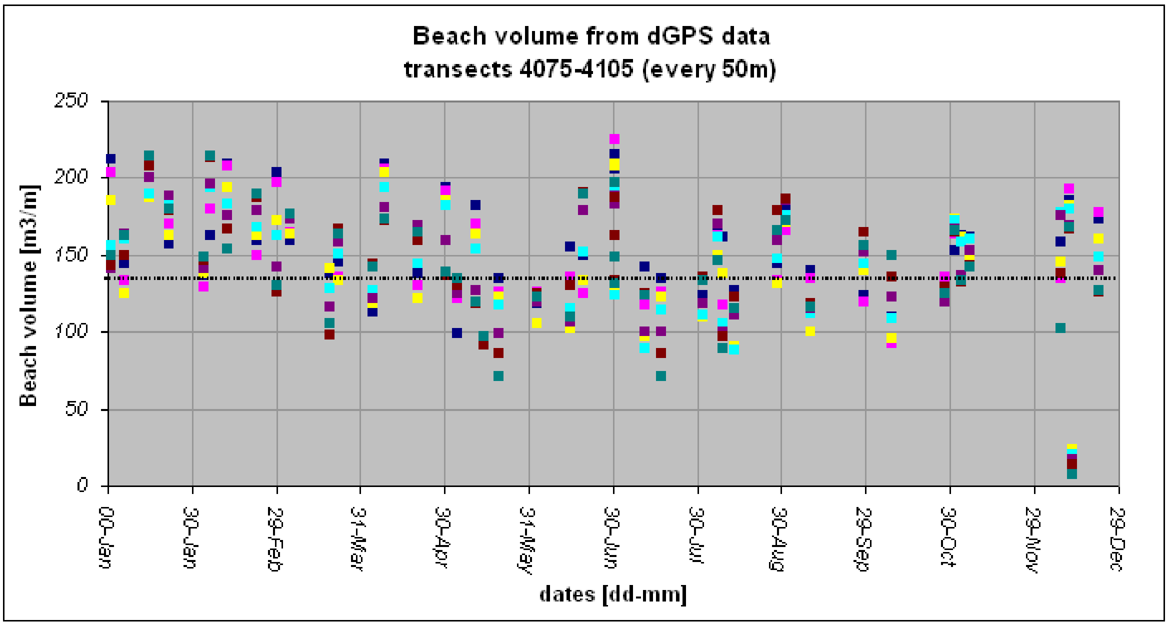

Figure B.32 Yearly temporal variations of the Beach volumes calculated from dGPS data

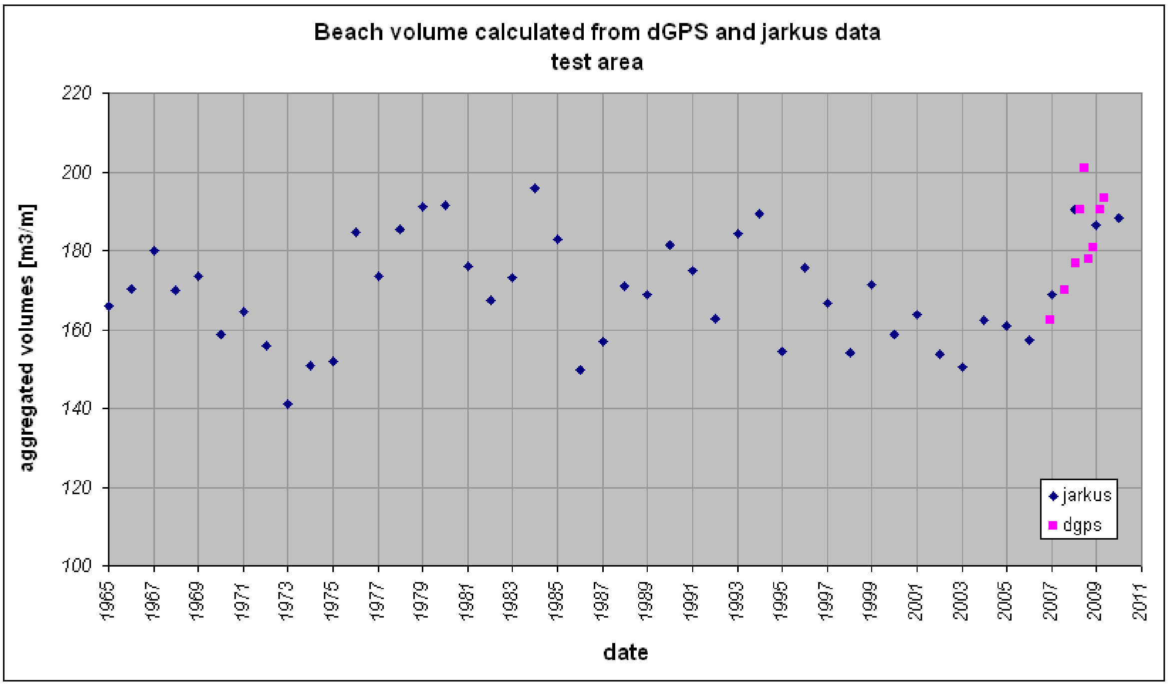

Figure B.33 Beach volumes calculated from dGPS and Jarkus data for the Test area

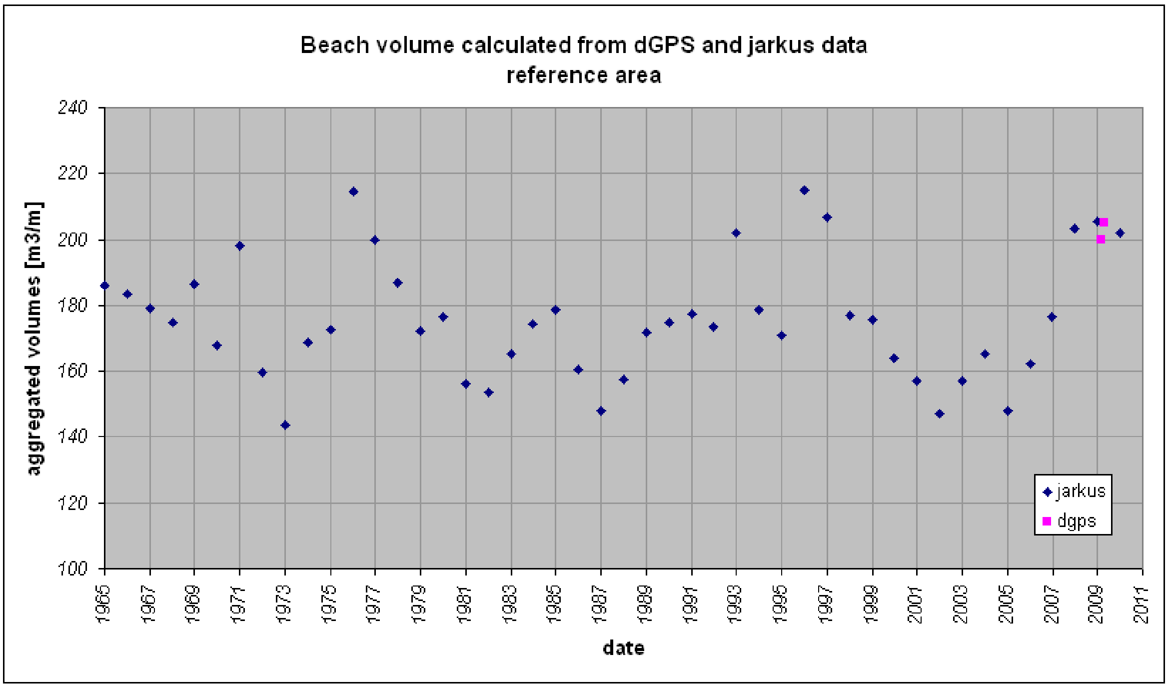

Figure B.34 Beach volumes calculated from dGPS and Jarkus data for the Reference area

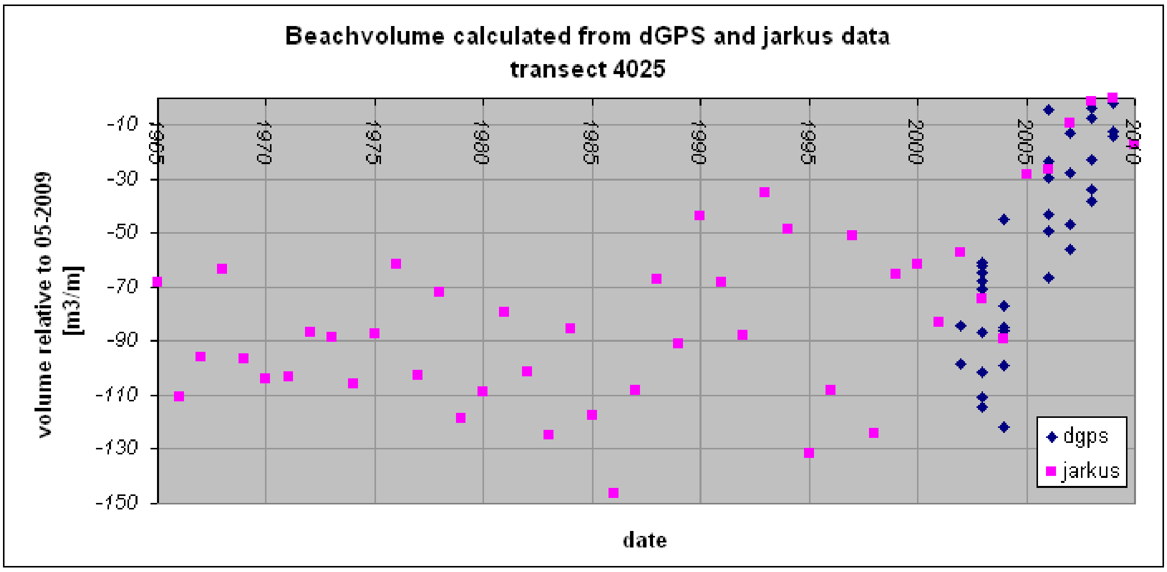

Figure B.35 Beach volumes calculated from dGPS and Jarkus data at transect RSP 40.25

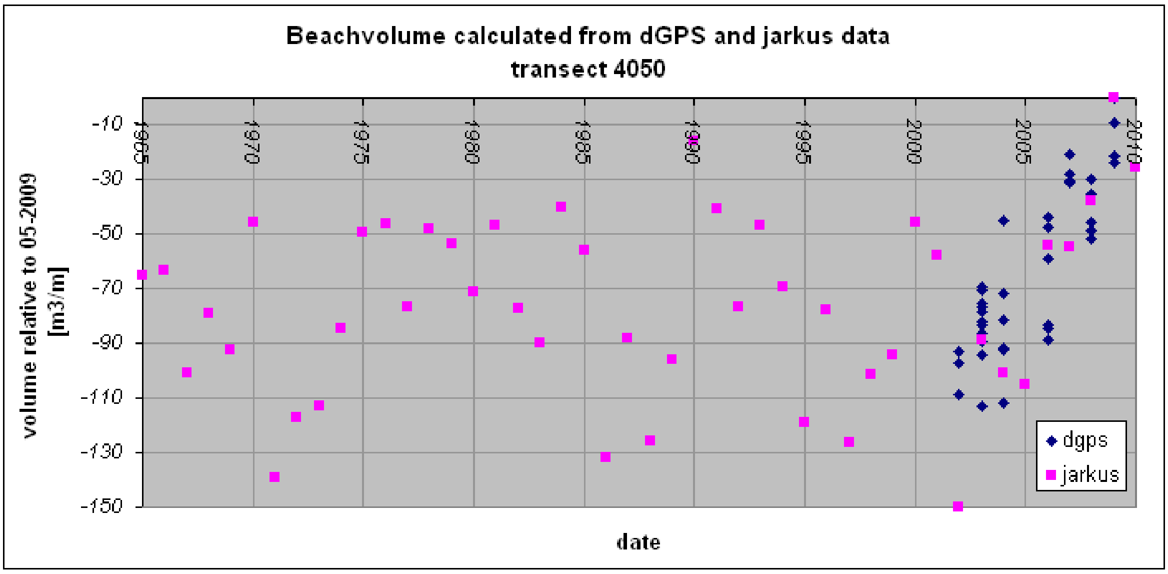

Figure B.36 Beach volumes calculated from dGPS and Jarkus data at transect RSP 40.50

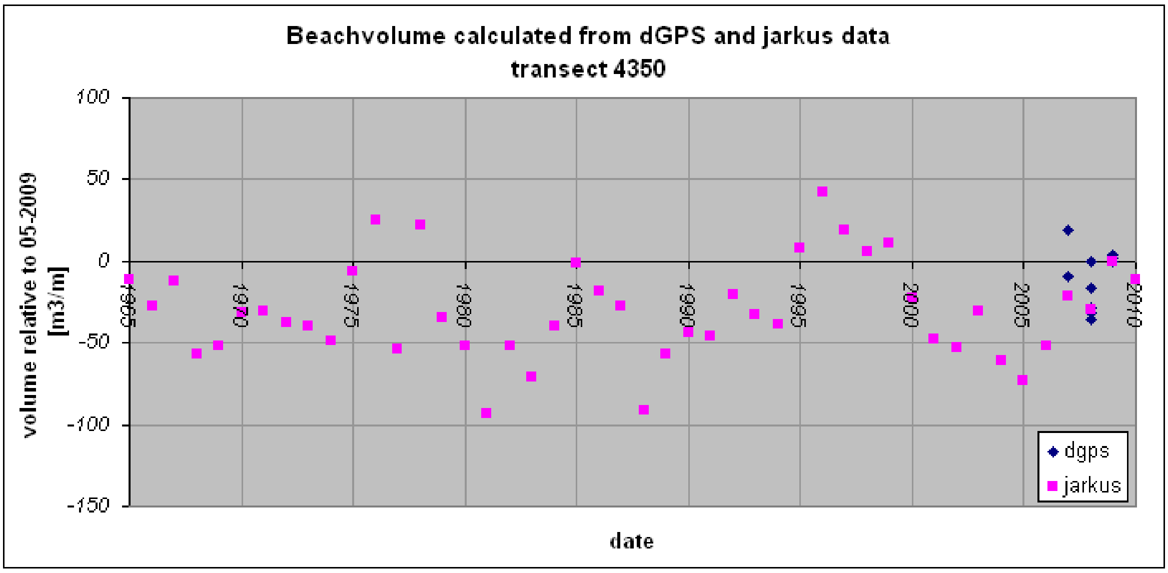

Figure B.37 Beach volumes calculated from dGPS and Jarkus data at transect RSP 43.50

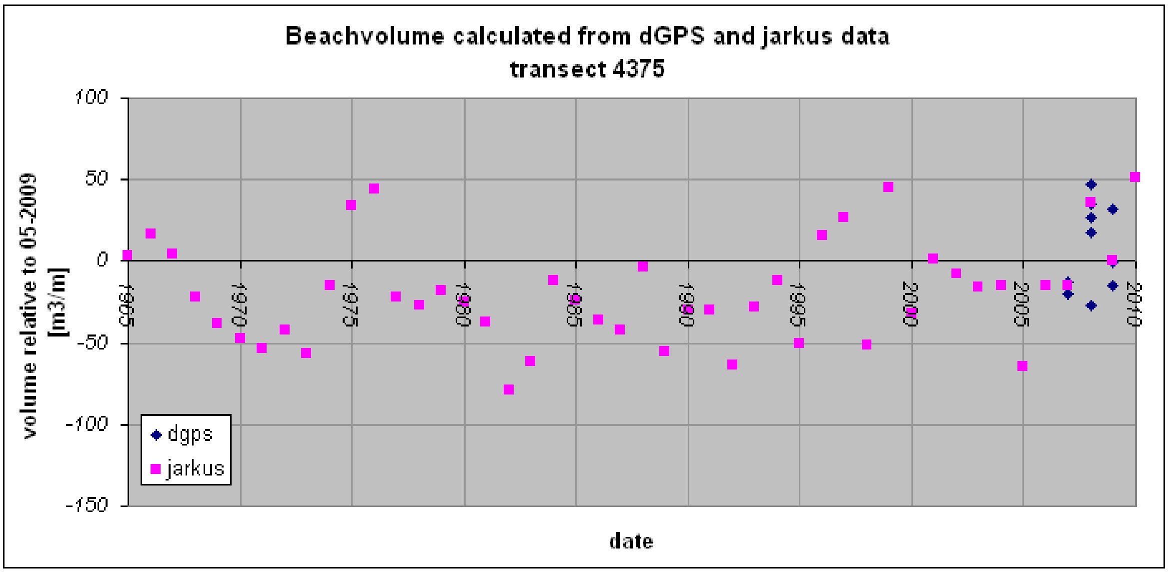

Figure B.38 Beach volumes calculated from dGPS and Jarkus data at transect RSP 43.75

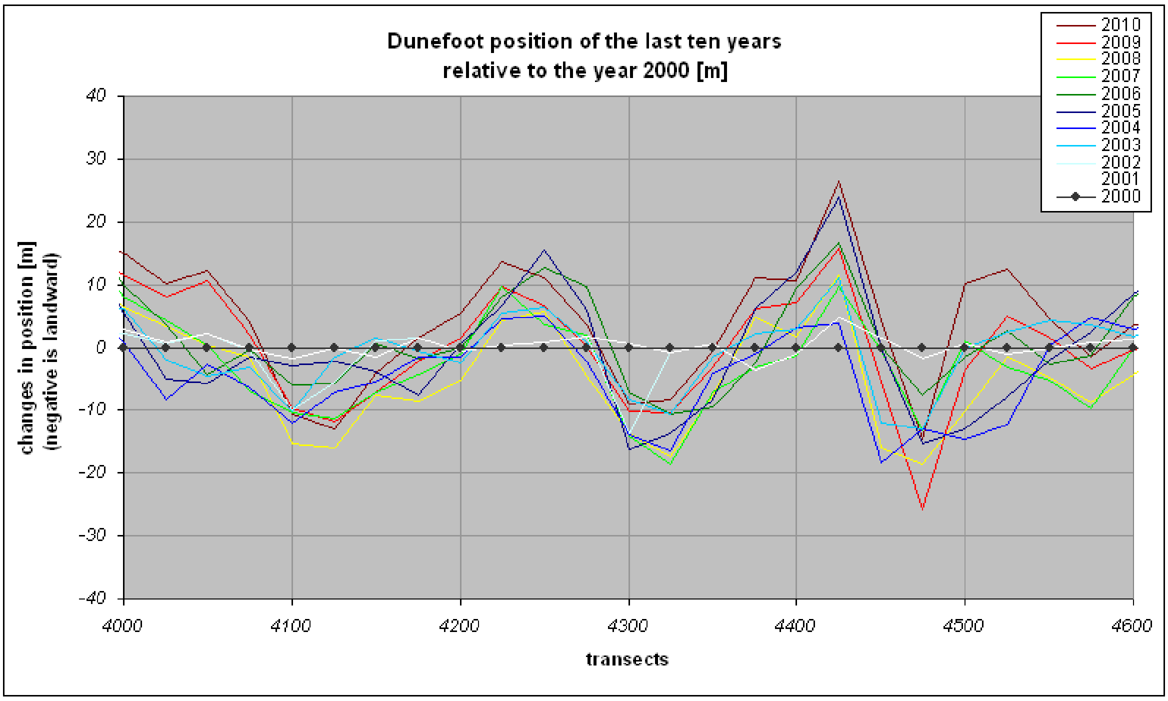

Figure B.39 Dune foot positions relative to year 2000 from transects RSP 40.00 to 46.00

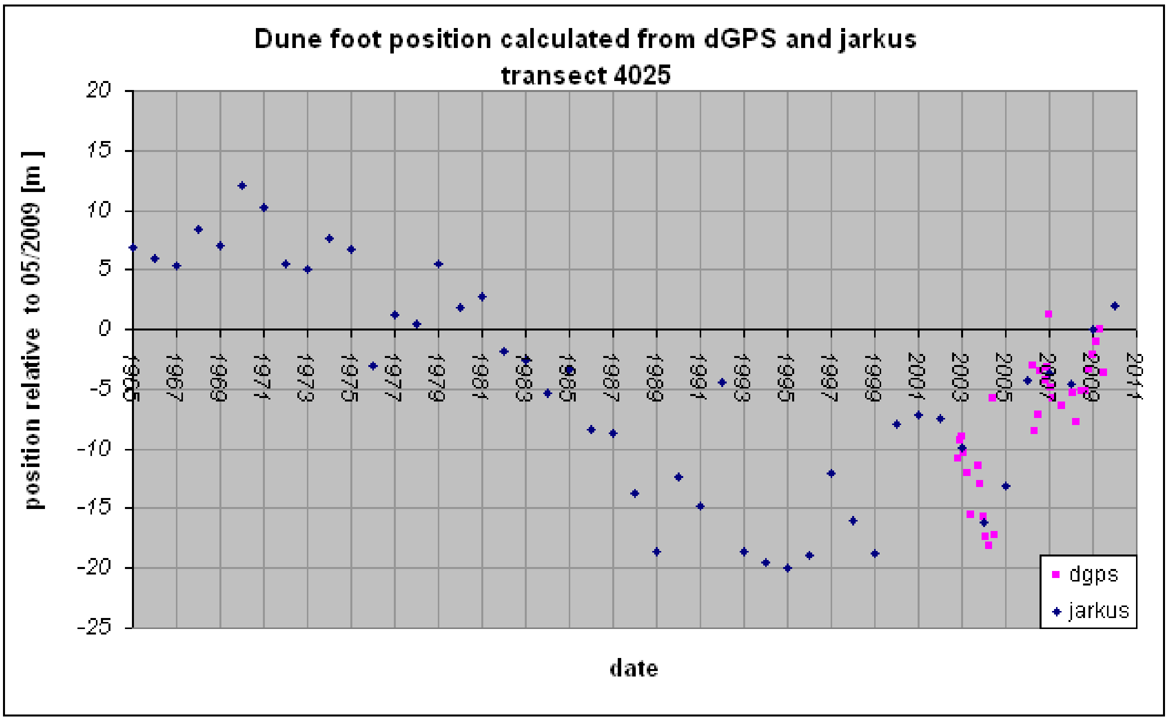

Figure B.40 Dune foot positions calculated from dGPS and Jarkus data at transect RSP 40.25

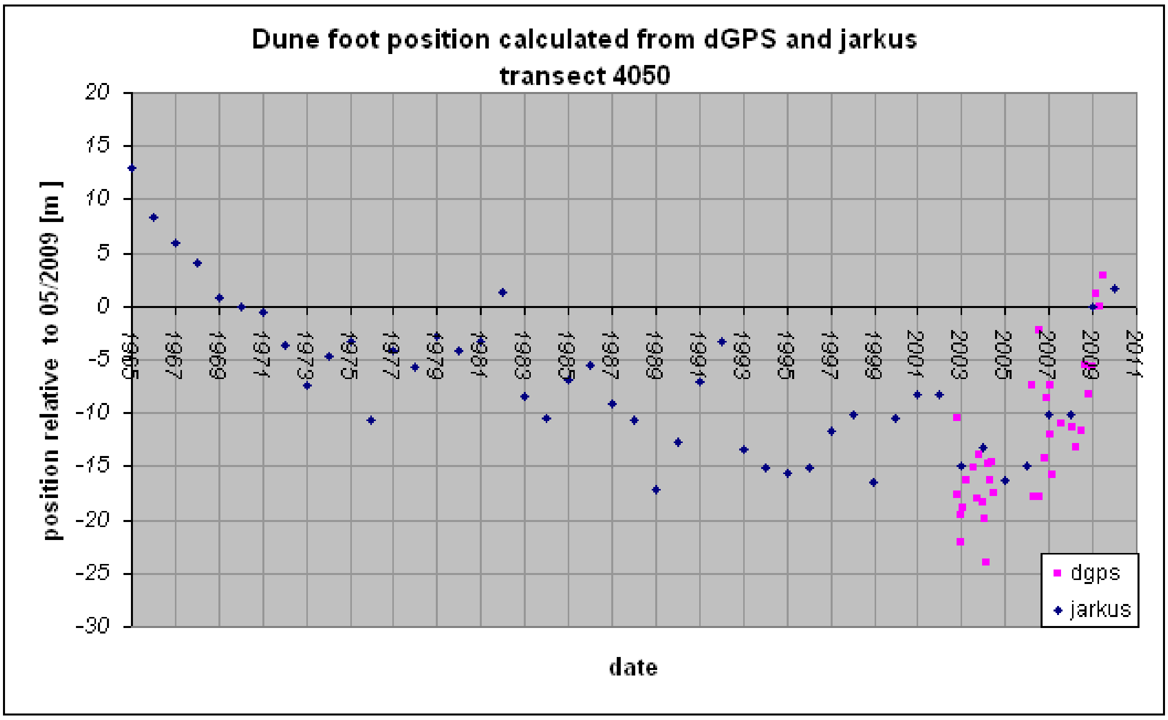

Figure B.41 Dune foot positions calculated from dGPS and Jarkus data at transect RSP 40.50

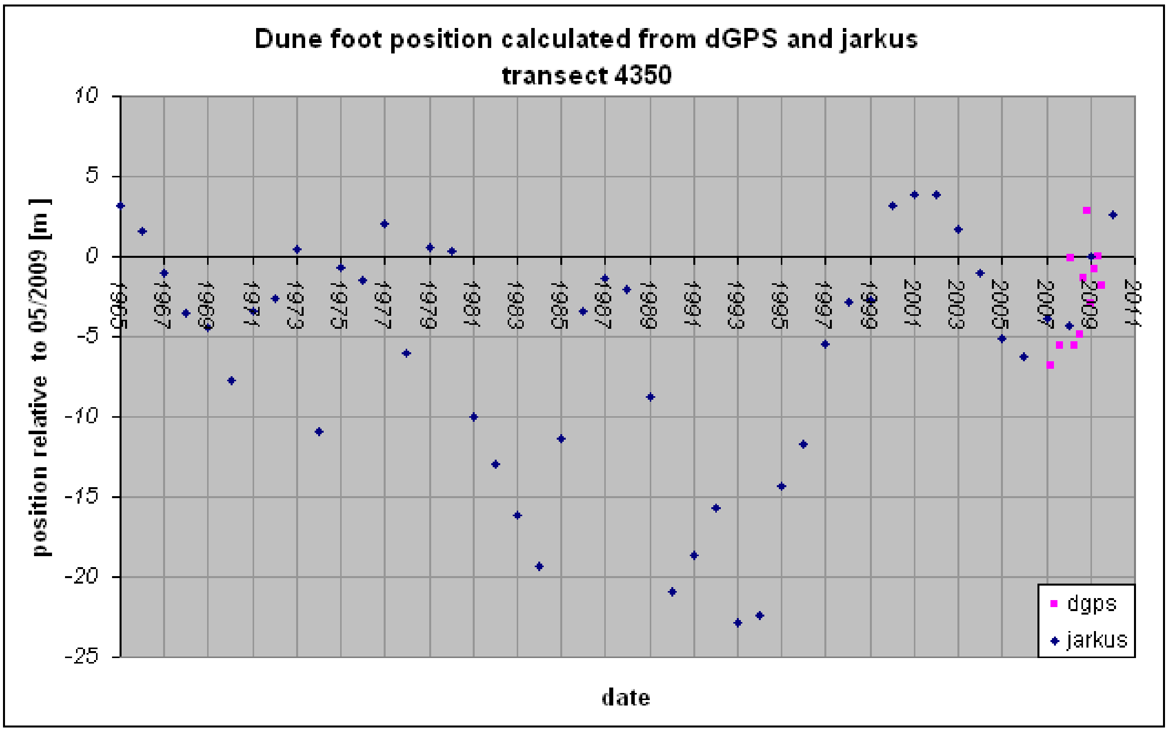

Figure B.42 Dune foot positions calculated from dGPS and Jarkus data at transect RSP 43.50

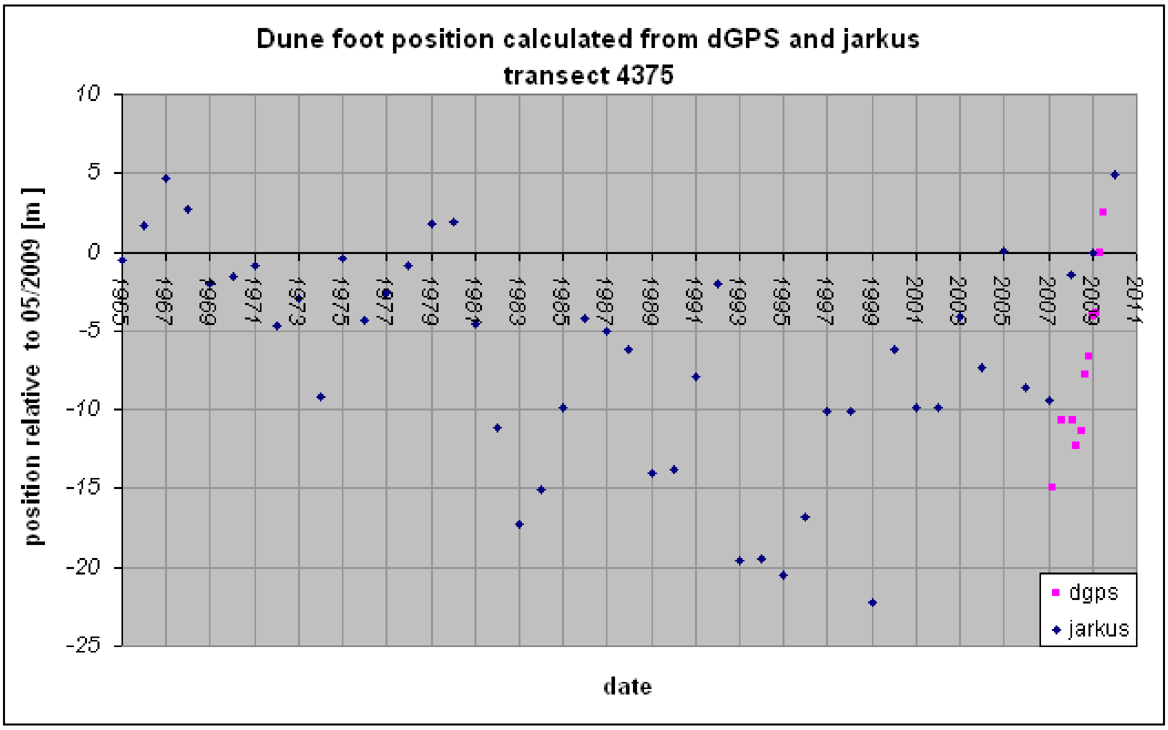

Figure B.43 Dune foot positions calculated from dGPS and Jarkus data at transect RSP 43.75

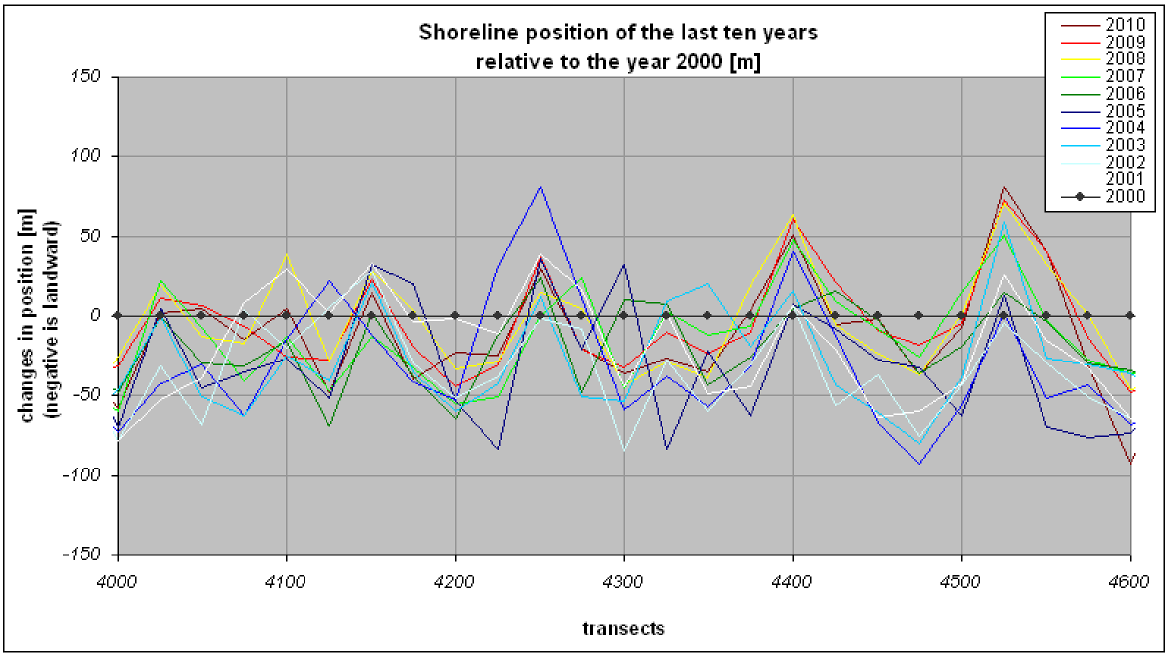

Figure B.44 Shoreline positions relative to year 2000 from transects RSP 40.00 to 46.00

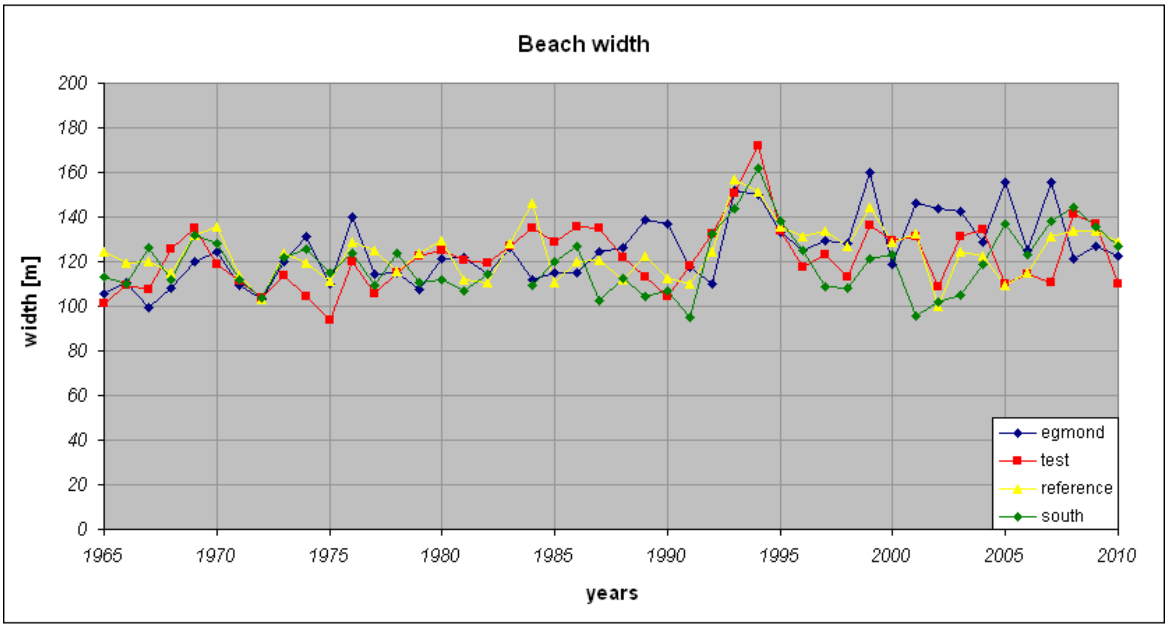

Figure B.45 Beach width for the four areas

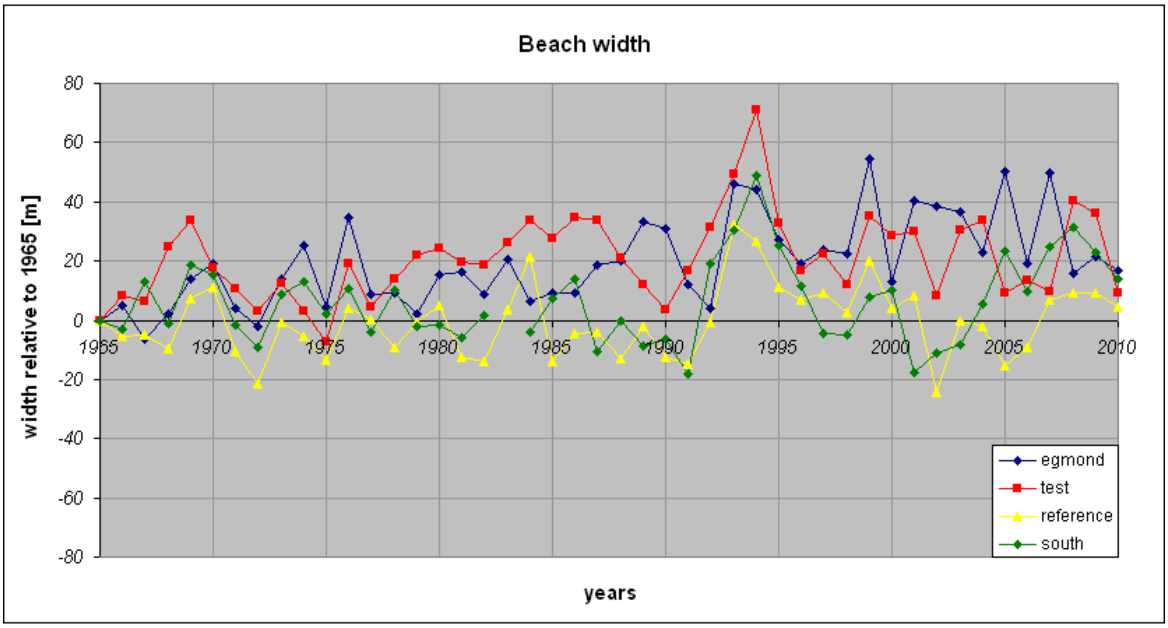

Figure B.46 Beach width relative to year 1965 for the four areas

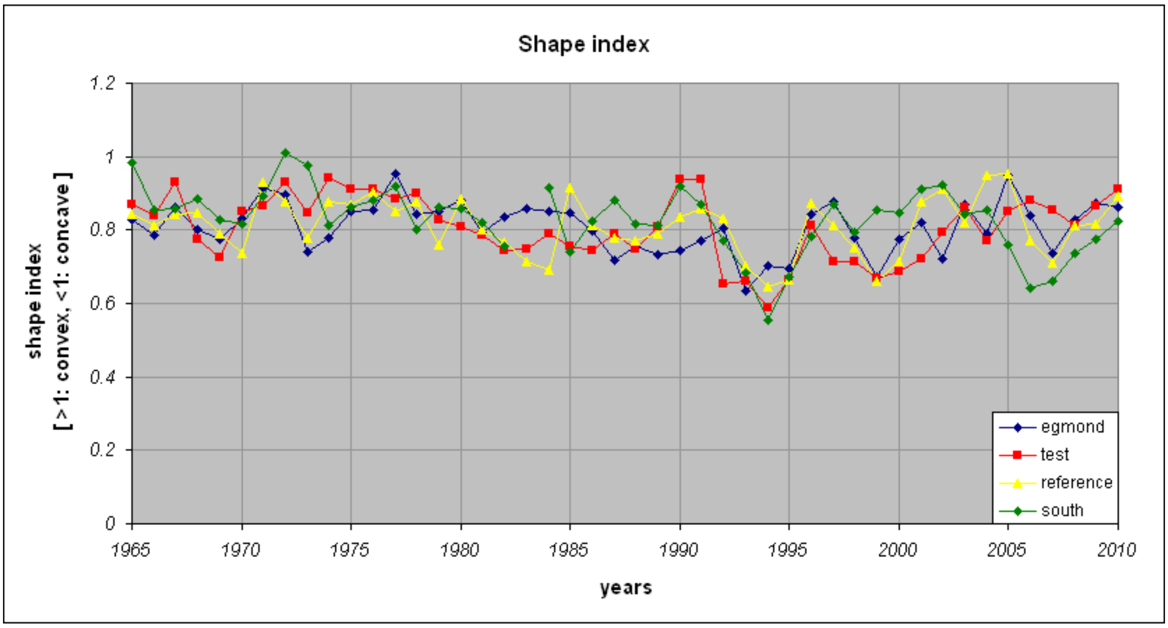

*Figure B.47 Shape index (defined as the ratio between the Beach volume and 0.5 * ($X_{Z=+3\,m} - X_{Z=MSL}$) * H with $X_{Z=+3\,m}$, $X_{Z=MSL}$ and H defined in Figure 3.4) for the four areas*

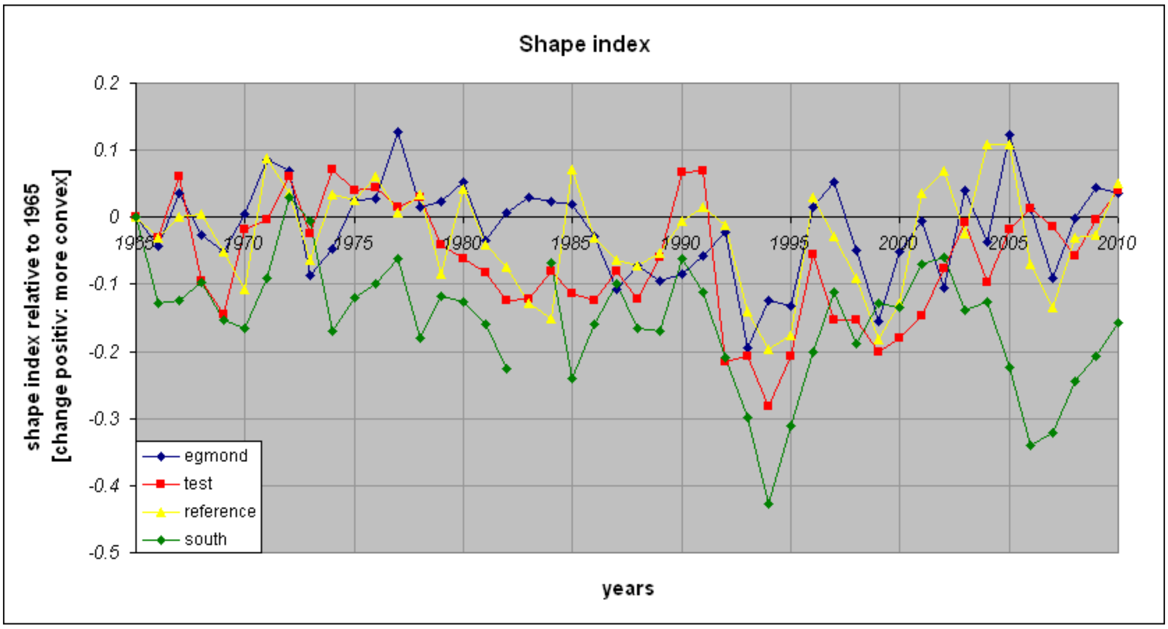

Figure B.48 Shape index relative to year 1965 for the four areas

C Details of the morphological analysis

C.1 Introduction

The observed developments of the upper parts of the profile (Beach and Dunes) in the Test and Reference areas show a comparable increase in Beach and Dune volume since 2007 (Figure 4.8, Figure 4.9, and Appendix B). The question now arises what is driving this continuous increase. Besides the installation of the PEM, the coast at Egmond is among the most frequently nourished areas along the Holland coast. Furthermore, the role of the cyclic bar behaviour at Egmond (with a cycle period of approximately 15 years) may have an influence.

This appendix discusses a morphological analysis which is aimed at identifying:

- the impact of the recent nourishments on the morphological (volume) development of the Test and Reference areas,
- the influence of the cyclic bar behaviour on the development of especially the beach and dune volumes.

The considered time period is 2003 to 2010. The year 2003 is selected because it is one year prior to the placement of the shoreface nourishment in Egmond.

The morphological analysis is based on the sediment exchange in the horizontal plane which requires a vertical cubing (instead of the horizontal cubing method used in the Chapter 4). This also requires the definition of areas sub-divided in both the alongshore and cross-shore directions. The adopted analysis method and the differences with the horizontal cubing method applied in the Chapter 4 are discussed in the next section.

In the analysis, a top-down approach is adopted starting at the largest considered spatial scales (viz. the 12 km alongshore area from Heemskerk to Egmond). The next step is to zoom in on smaller scales, especially to estimate sediment exchanges and eventually to assess the impact of the nourishments and bar behaviour on the beach and dune volumes. Both analysis steps follow the same approach: first, a number of research questions are identified, followed by a description of the observed morphological developments based on which the research questions are answered.

However, first an overview is given of the applied aggregation method based on vertical boundaries. This is followed by a comparison of the vertical and horizontal aggregation methods. Next, the observed morphological changes are discussed in combination with a summary of the shoreface and beach nourishments constructed since 2004. Subsequently the two analysis steps (largest scale and detailed scale) are discussed.

C.2 Approach

The morphological analysis is based on an analysis of volume changes and the derived or interpreted horizontal sediment exchanges between adjacent pre-defined areas. This requires the definition of areas that are vertically bounded in both the alongshore and the cross-shore direction. To ensure a consistent coupling with the analysis performed in the Chapter 4, the cross-shore positions of the vertical boundaries are in agreement with the definitions of the Dune, Beach and MCL volumes as much as possible. This requires the following steps:

1. The definition of the cross-shore boundaries based on the depth contours that were used to define the Dune, Beach and MCL volumes in Chapter 4.
2. The definition of longshore areas. Here we follow the definitions in Chapter 2 as much as possible by considering a Heemskerk, Reference, Test and Egmond area of each 3 km alongshore length. The main difference with the approach in the Chapter 3 and Chapter 4 is that the areas are directly adjacent to each other without considering a buffer area.
3. Referencing the cross-shore profiles to a fixed depth contour to remove the alongshore coastal curvature.

A volume calculation based on vertical boundaries implies that the horizontal position will vary if the profile changes (whereas in the Chapter 4 the elevations were prescribed allowing the horizontal positions to vary). Vertically and horizontally bounded volumes may results in different volume changes. This is illustrated in Figure C.1 in which the volume changes for both types of volume calculation are compared: the volume changes determined with the horizontal boundaries (yellow + green areas) which differ from the volume changes with the vertical boundaries (yellow + blue areas).

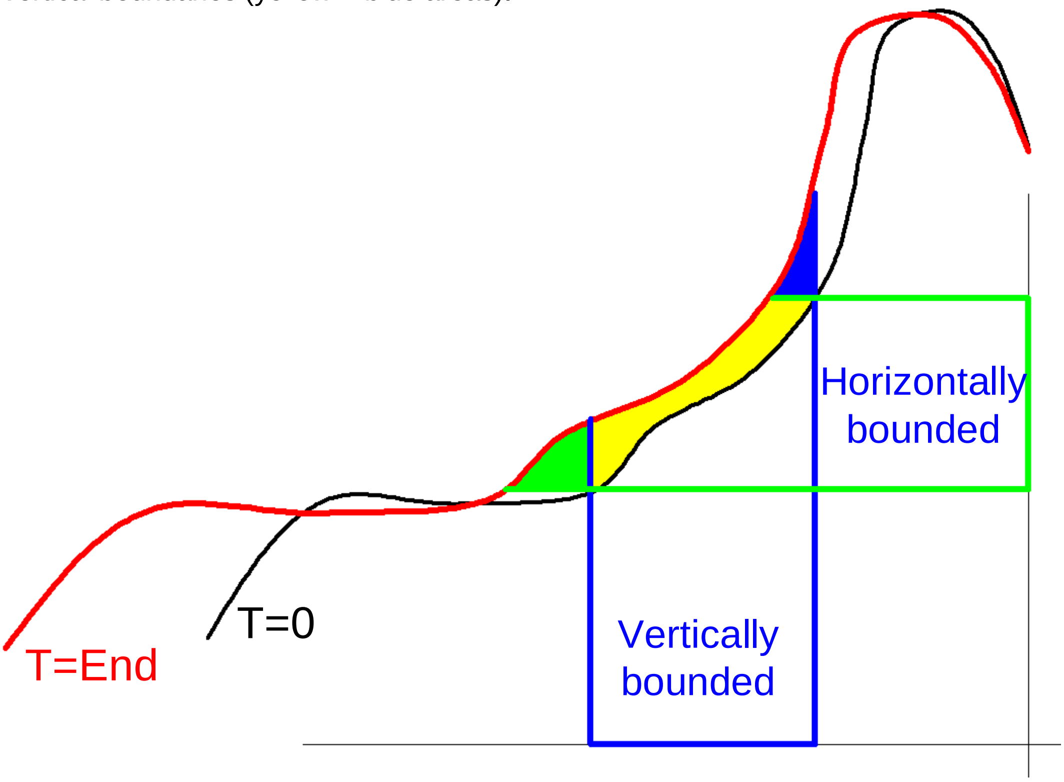

Figure C.1: Schematic example of vertical (blue) and horizontal (green) integration methods

The cross-shore positions of the vertical boundaries are specified by considering the 2003 survey. The seaward boundary of the Dune area is defined by the NAP + 3 m position (i.e. the Dune foot in 2003). The landward limit for the Dune area is limited to the data coverage for the considered 2003-2010 period which was found to be 50 m landward of the dune foot position in 2003. The dune foot position was also used to reference all the considered cross-shore profiles (i.e. horizontal dune foot position is set as x = 0 m for all profiles). These referenced profiles in the 12 km alongshore area were subsequently averaged to obtain an averaged profile. This alongshore averaged profile is used to couple the prescribed depth contours of Dune, Beach, Lower MCL to cross-shore positions (see also Figure C.2):

- Vertically bounded dune area (Vertical-Dune, NAP + 3 m and higher): x = -50 to 0 m,
- Vertically bounded beach area (Vertical -Beach, NAP + 3 m to NAP – 0.78 m): x = 0 m to x = 115 m,
- Vertically bounded Lower MCL area (Lower Vertical-MCL, NAP – 0.78 m to NAP – 4.56 m): x = 115 m to x = 435 m,
- Vertical bounded Lower Shoreface area (Lower Vertical-Shoreface, NAP – 4.56 m to NAP – 8 m): x = 435 to x = 980 m.

In the Figure C.2, the profiles are shown. The grey lines represent the individual referenced profiles in the considered area; the thick solid line is the longshore averaged profile on which the boundary definitions are based (shown in green).

Four areas with an alongshore length of 3 km each are defined directly adjacent to each other (see Figure C.3, in which black rectangles indicate the defined volume boxes). The location of the shoreface and beach nourishments carried out in since 2004 are included in the analysis and are indicated by the white rectangles in Figure C.3. The extent of the areas considered in the current morphological analysis is shown in Figure C.4.

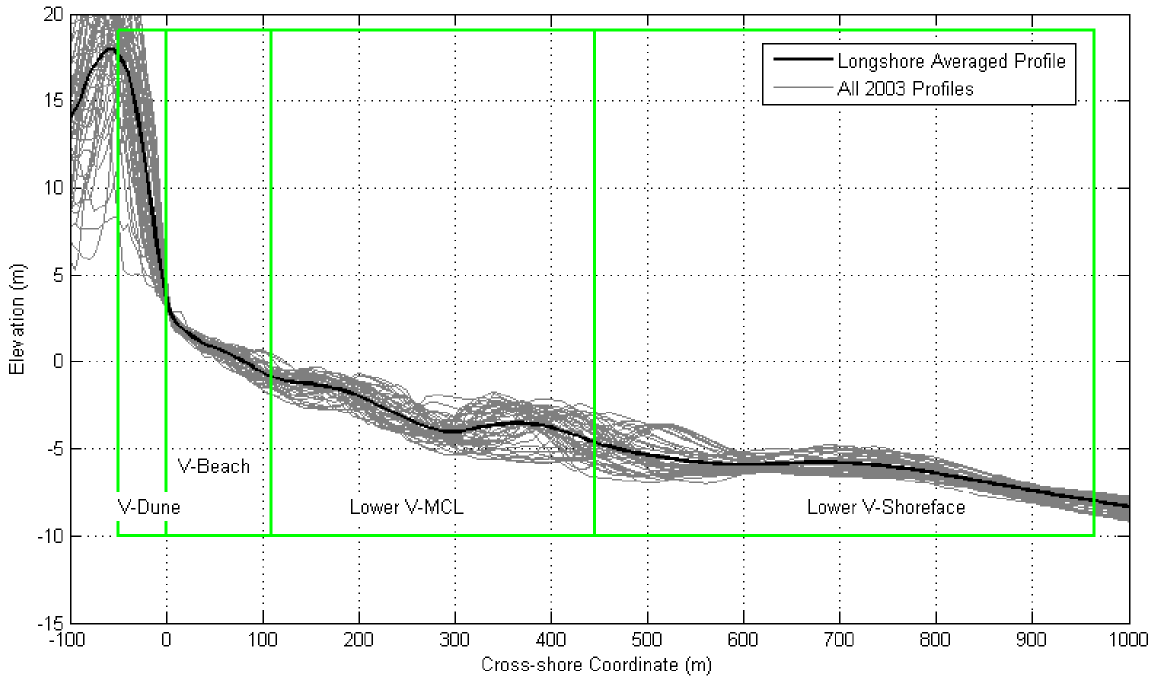

Figure C.2: Profiles (year 2003) referenced to the dune foot position (grey), longshore averaged profile (black) and the derived cross-shore boundaries used for the morphological analysis (green).

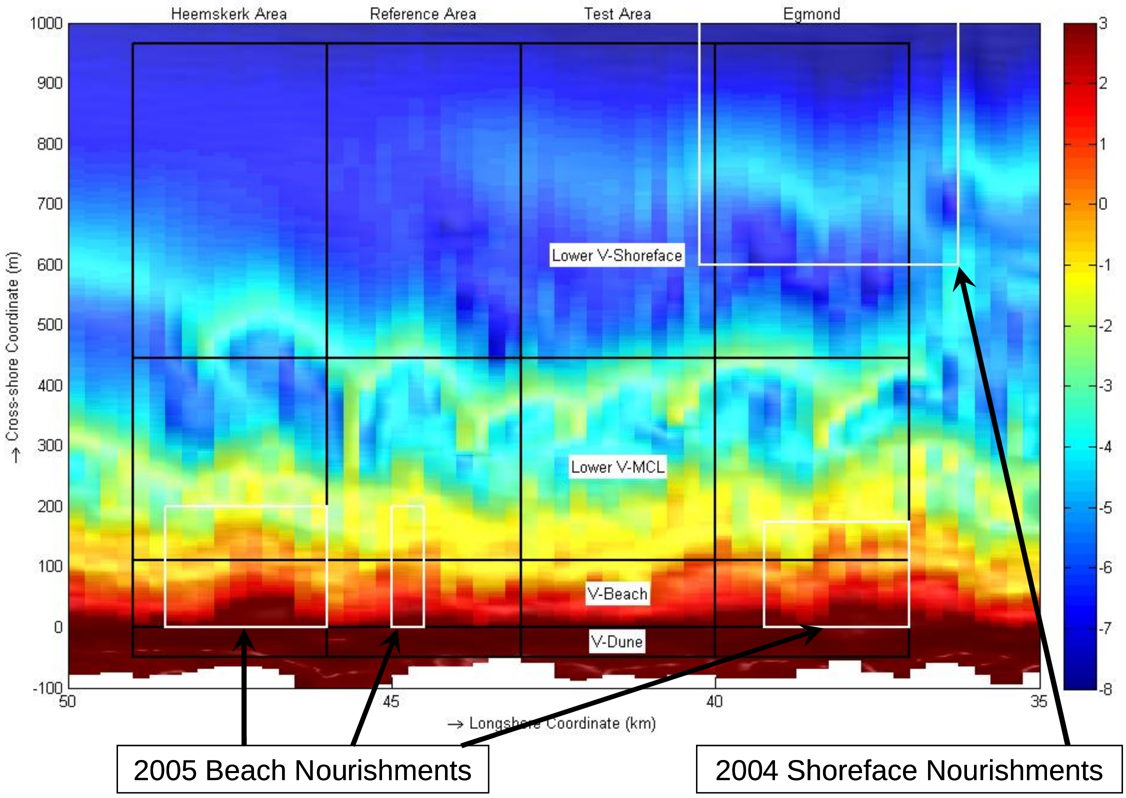

Figure C.3: De-curved 2006 bathymetry; the black boxes indicate the volume boxes; the white boxes indicate the nourishment locations.

Figure C.4: Map of the coastal stretch considered for the analysis. Extension of vertical boxes used in the analysis is displayed in the figure.

C.3 Comparison of integration methods

For plane parts of the profile the vertical and horizontal integration method as defined in the previous section will typically result in similar volume changes. This is illustrated in Figure C.5 where both integration methods are compared for the Test and Reference areas. It can be seen that for the Dune and Beach parts of the profile both methods agree very well. However, for the Lower MCL there is no agreement which is directly related to the presence of the bars in this region.

This is illustrated by comparing the vertical and horizontal integration volumes in Figure C.6. When bars migrate offshore beyond the seaward vertical boundary this will typically result in a vertical volume decrease. However, for the horizontal volume the influence of the offshore migrating bar is much less. Only when the bar moves further offshore or decays it affects the horizontal volume. The same applies to changes in the trough. Erosion of the trough will have no effect on the horizontal volume when it is below the horizontal volume box, whereas it will continue to affect the vertical volume.

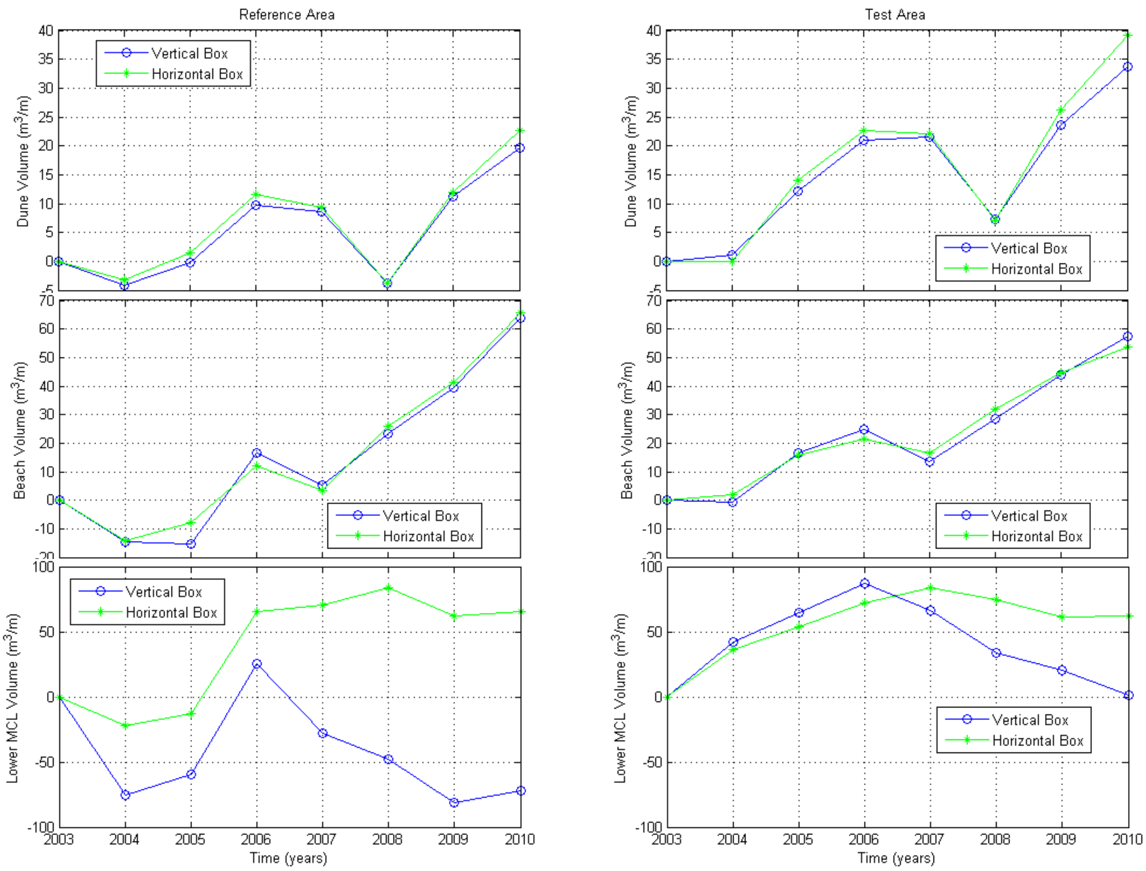

Figure C.5: Comparison of vertical and horizontal integration methods. Left column is reference area, right column is test area. Top row: Dune volume (2003=0), middle row: beach volume (2003=0) and bottom row: Lower MCL volumes (2003=0).

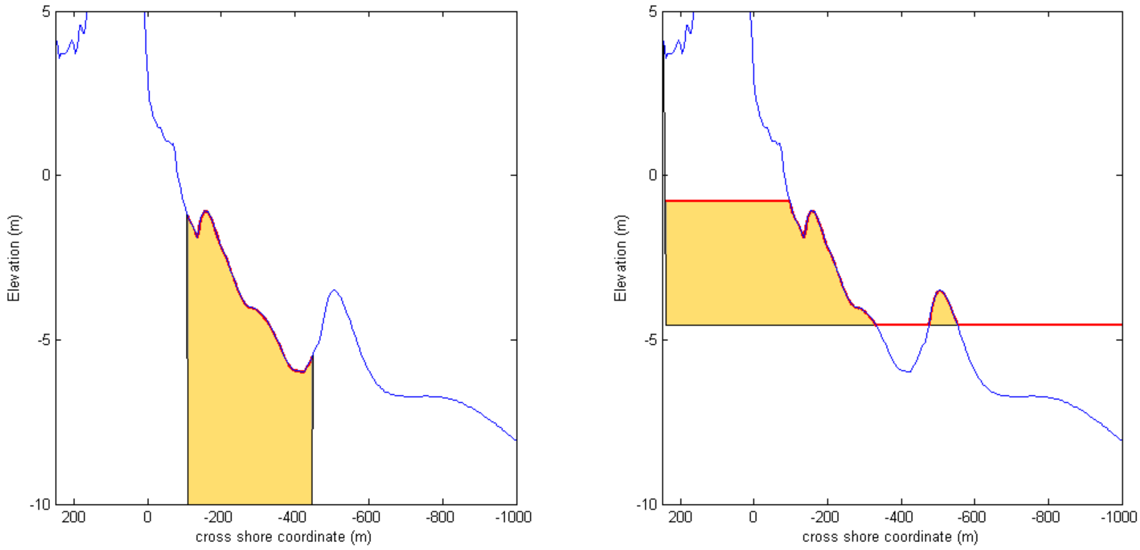

Figure C.6: Comparison of vertical and horizontal integration methods for an arbitrary profile. Left plot shows vertical integration volume (sand color); right plot shows the horizontal integration volume.

C.4 Morphological Development

In Figure C.7, the top plot shows the 2006 bathymetry. In this survey, the nourishments since 2004 are captured. The middle plot displays the change with the previous year (2005) and the bottom plot shows the cumulative changes since 2003 (pre-nourishment). In Figure C.8, the results for 2010 are shown. The black boxes indicate the study areas which are also sub-divided into four cross-shore regions (i.e. Vertical-Dune, Vertical-Beach, Lower Vertical-MCL, and Lower Vertical-Shoreface). For completeness sake the annual observations from 2003 to 2010 are included in Appendix D.

A shoreface nourishment (2004) and a beach nourishment (2005) have been executed near Egmond, as well as a beach nourishment (2005) in the Heemskerk area. The latter nourishment design is between transects RSP 46.50 and RSP 48.50. However, this nourishment was slightly over-sized and an extra 6 600 m^3 sand was positioned at the North of the nourishment design area. These extra volumes were transported by truck towards the North, near the beach entrance and beach restaurants in the Reference area. This additional sand was used to restore the beach as a trough was moving landward.

In the cross-shore Jarkus profiles these extra volumes were captured by the surveys in transects RSP 44.75 and RSP 45.00. The original beach nourishment was captured by the surveys in transects RSP 46.50 to RSP 47.50 and RSP 48.50.

If the bathymetries and the cumulative bed changes from 2006 and 2010 are compared (see Figure C.7 and Figure C.8) it is evident that the 2004 shoreface nourishment at Egmond is still present. The beach nourishments cannot be distinguished in the bathymetry plots, but the cumulative bed changes show a predominant sedimentation in the nourished beach areas in 2006. The beach nourishments were carried out before the 2005 bathymetry survey, but after the 2005 topography survey. This causes the sedimentation in the upper beach in the annual changes from 2005 to 2006 (middle plot in Figure C.7). Consequently, beach nourishments are only fully captured by the cumulative bed changes (bottom plot in Figure C.7).

Comparison of the cumulative bed changes between 2003 and 2010 (Figure C.8) reveals that the beach nourishments at Egmond and Heemskerk still seem to be noticeable in 2010. This is especially the case for the Heemskerk beach nourishment. However, inspection of the annual results (Appendix C) shows that only the lower part of the nourishment is still present, the upper part of the beach nourishment has eroded significantly in 2007-2008. In the following years, the upper beach recovers. For the Egmond area, a similar behaviour can be observed for the entire beach nourishment: it seems to have nearly completely disappeared in 2007-2008, but in the following years, the upper beach recovers. The cumulative bed changes from 2003 to 2010 (bottom plot in Figure C.8) clearly show the dominance of the offshore bar migration especially in the Lower Vertical-MCL and Lower Vertical-Shoreface regions. The distinct alongshore coherent erosion-sedimentation patterns indicate the bar migration over the considered period. For the Beach and Dune regions the longshore coherence is significantly lower, but alongshore coherent bed change patterns also seem to be present at some locations. For example in the Heemskerk area the cumulative bed changes in the upper beach and dune areas (bottom plot in Figure C.8) show an alongshore coherence of about 1.5 to 2.5 km.

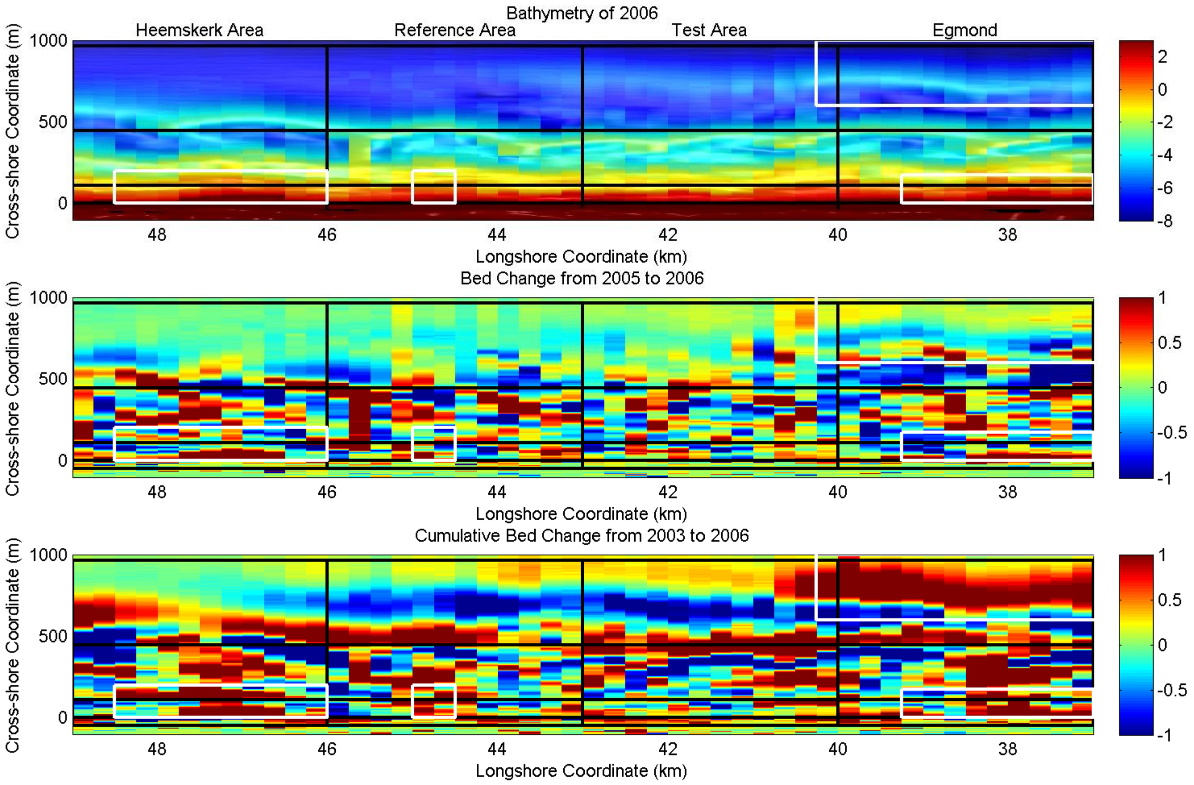

Figure C.7: De-curved top view plots of the 2006 bathymetry (top), bed change from 2005 to 2006 (middle) and the cumulative bed change since 2003 (bottom). The black boxes indicate the considered areas for the analysis and the white boxes indicate the recent nourishments.

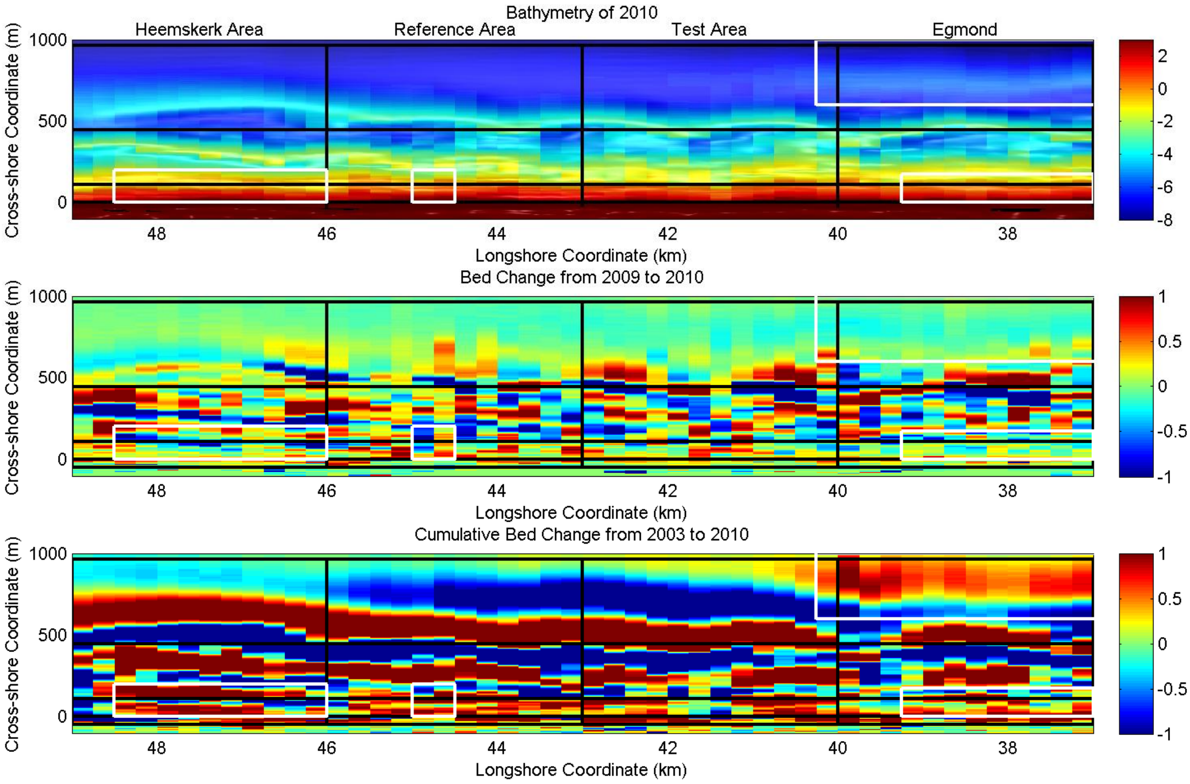

Figure C.8: De-curved top view plots of the 2010 bathymetry (top), annual bed change from 2009 to 2010 (middle) and the cumulative bed change since 2003 (bottom). The black boxes indicate the considered areas for the analysis and the white boxes indicate the recent nourishments.

C.5 Step 1: Alongshore Sediment Exchange

This analysis provides insight in the development of the active part of the coastal system based on the four 3 km alongshore integrated areas from the dune to the NAP – 8 m depth contour. This volume analysis, based on the entire areas, is used to answer the following research questions:

- Q3A: What is the impact of the nourishments on the total coastal volume over the period 2003 to 2010?
- Q3B: Do the nourishments influence the volume development of Test and Reference Areas?
- Q3C: What is the residual sand transport direction over the period 2003 to 2010?

<u>*Observations*</u>

The approach to answer the research questions above is to study the temporal development of the observed volumes of the complete areas. The volume development since 2003 for the entire boxes is shown in Figure C.9. In addition to the volumes of the four areas combined (total) also the volumes of the combined Egmond - Heemskerk areas (nourished areas) and the combined Test - Reference areas are included.

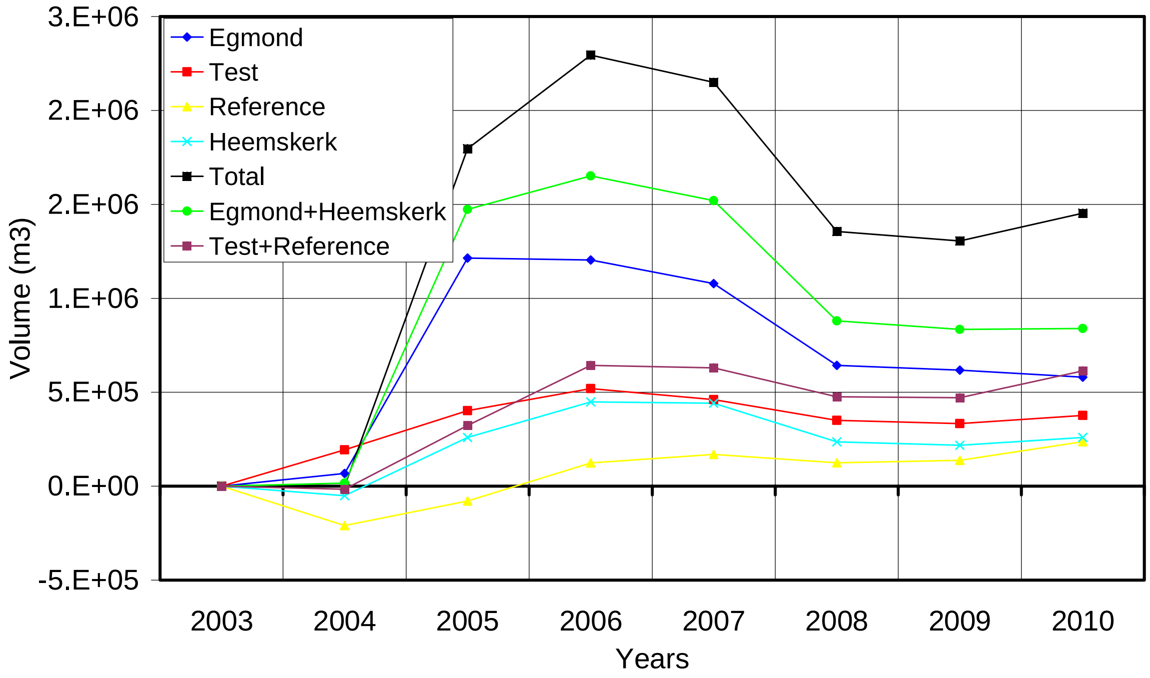

Figure C.9: Temporal development of volumes of the entire areas relative to 2003; boxes are indicated in Figure C.4

The total volume (black line in Figure C.9) shows a distinct increase in 2005 and 2006 which is associated with the implemented nourishments shown in Figure C.7. The delay in the volume signal is caused by the fact that nourishments were carried out after the annual surveys in 2005 and 2006. The total volume increase (2.3 Mm^3) matches well with the total nourishment volume (2.27 Mm^3, which excludes 800 m –approximately 0.36 Mm^3– of the 2004 Egmond shoreface nourishment that extended beyond (North of) the Egmond area). From 2006 to 2008, a relatively large total volume decrease (0.94 Mm^3) is observed. Since 2008, the total volume is showing relatively gradual and relatively small changes. According to Van Rijn (1997), transports across the NAP – 8 m depth contour are zero on average, but have a range of 10 m^3/m/yr onshore or offshore. The total alongshore length is 12 km, which would result in offshore loss or gain of sand of 0.12 Mm^3/year. This implies that the total volume loss observed between 2006 and 2008 must therefore be primarily due to alongshore advection/diffusion of the nourishments outside the considered total area.

To answer Q3B the volume development of the areas needs to be analysed. For the Egmond area there is a clear nourishment signal that is primarily related to the shoreface nourishment. The other areas also show volume increase from 2004 to 2006, but the changes are significantly smaller. For the Heemskerk area this could be related to the beach nourishment carried out in this area in 2005. For the Test and Reference areas the observed volume increases from 2004-2006 are probably partly caused by feeding from the adjacent nourishments. The 2004 Egmond shoreface nourishment extends about 200 m into the Test area (approximately 90,000 m^3), but this volume increase does not match the measured increase in the Test area which is about 50,000 m^3 (since 2003) or 35,000 m^3 (since 2004). The Heemskerk nourishment directly borders the Reference Area, making it likely that some of this nourishment is transported towards the Reference Area.

The development from 2007 to 2010 is more relevant as this is the period during which the PEM were present. It is especially of interest to establish whether the Test and/or Reference areas were affected by the nourishments in this period. The largest volume decrease of the areas that were nourished (Egmond and Heemskerk, green line in Figure C.9) during this period is from 2007 to 2008, about 650,000 m^3. However, the net change in the Test and Reference areas combined is also negative for the same period (purple line in Figure C.9). The same result is found when considering the period from 2006 to 2008. Comparison of the annual volumes of the Test and Reference areas shows that the Reference area has its maximum one year later (2007) than the Test area. From 2006 to 2007, the Test area looses sand and the Reference area shows accretion, but the changes in absolute volumes are relatively small. The Reference area is approximately stable from 2006 to 2009. From 2009 to 2010, both the Test and Reference areas show the first volume increase since 2006. From 2006 to 2008 the bulk of the volume changes are occurring in the Egmond and Heemskerk areas. From 2008 onward, changes are gradual and of similar magnitude for all areas.

In Figure C.10, the volume changes over the period 2003-2006, and the post-nourishment periods (2006-2008 and 2008-2010) are compared for the individual areas. From 2003 to 2008 (also for 2003-2007 and 2006-2008) the bulk of the volume changes occur in the Egmond area. The changes over the first two considered periods in Figure C.10 reveal that all areas shows the same type or response (sedimentation in 2003-2006 and erosion from 2006 to 2008), only in the last period (2008-2010) there is an opposite response between the Egmond area and the other areas.

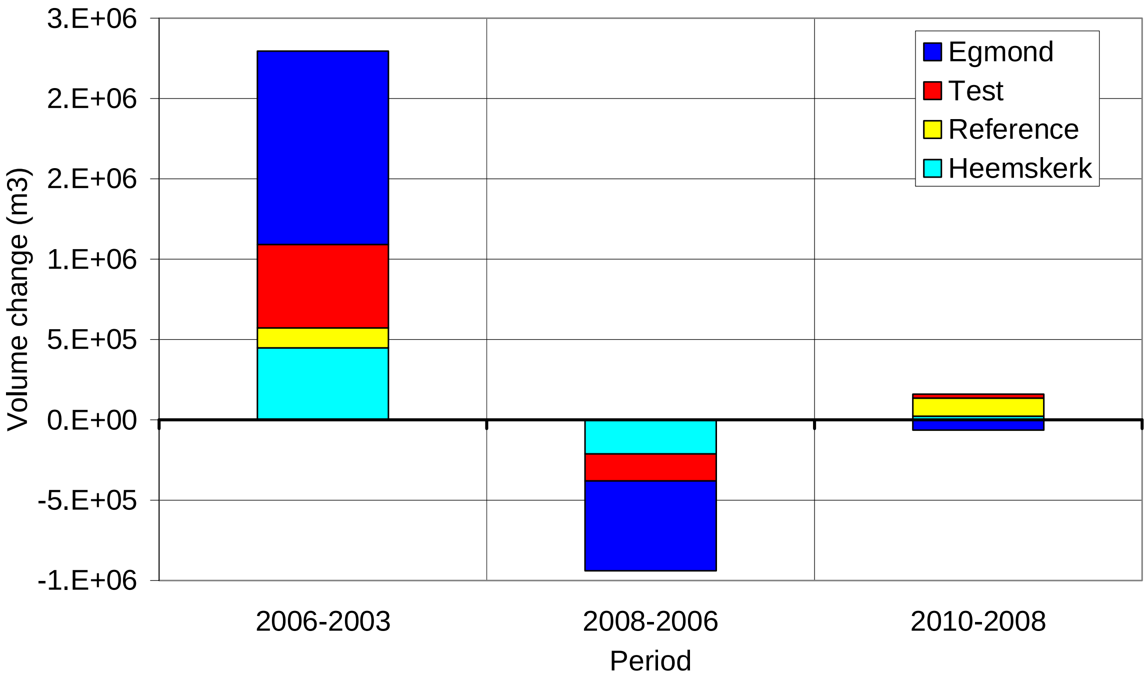

Figure C.10: Volume changes over pre- and post-nourishment periods, boxes are indicated in Figure C.4

The analysis on the area scale can also be used to estimate the longshore sediment transports. The total sand loss from 2006 to 2008 is 940,000 m^3. The volume decrease for the Egmond area and the Heemskerk area are 560,000 m^3 and 210,000 m^3, respectively. If it is assumed that there is no transport across the NAP – 8m depth contour, an alongshore transport distribution can be derived assuming a certain transport direction. Here we are considering two scenarios: 1) northward net transport and 2) southward net transport.

Conceptually, a net northward transport of a part of the 500,000 m^3 beach nourishment at Heemskerk should result in erosion in this area (assuming no trapping of sediment) which should be balanced by a depositional signal in: first the Reference area, and possibly subsequently in the Test area or even the Egmond area. A similar effect should be observed if net southward transport is assumed, where the depositional signal should originate from the eroding shoreface and beach nourishments at Egmond. However, the volume changes do not show such a coupled erosion – deposition signal from which the transport direction can be derived. This could be due to the fact that diffusive transports (induced by gross longshore transport components) are dominant over the net transports. Another explanation could be that the natural variability dominates the observed volume changes. Van der Rest (2004) compared a number of sediment budget studies focussing on the Holland coast (Figure C.11). In the study area (RSP 37 to 49), the net longshore transports are affected by the IJmuiden harbour moles. The various studies do not agree on the net transport direction. However, the net transport rates in the study area are relatively low in most studies compared to other parts of the Holland coast. This implies that gross transport may be relatively important in the study area.

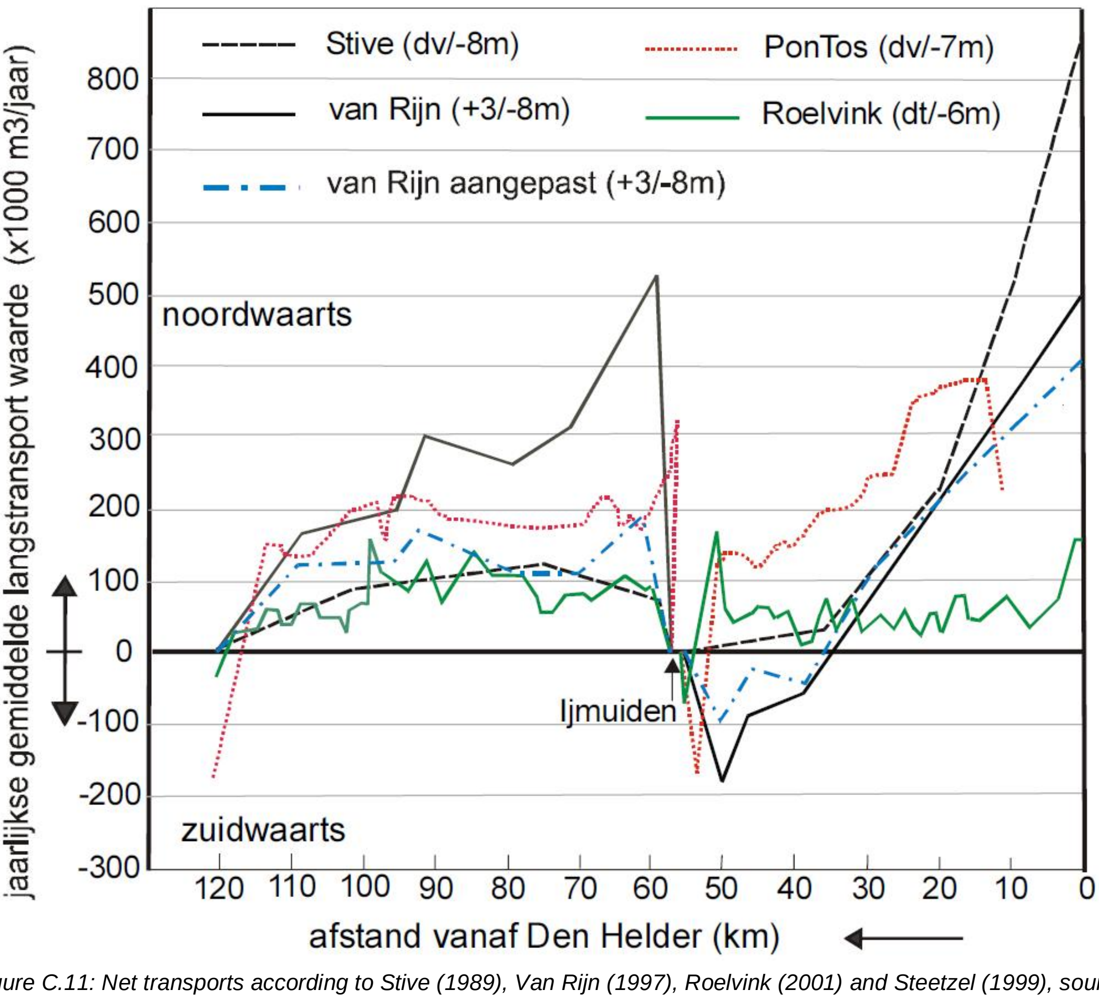

Figure C.11: Net transports according to Stive (1989), Van Rijn (1997), Roelvink (2001) and Steetzel (1999), source van der Rest (2004).

Answers to the research questions

Based on the preceding analysis of the volume development of the entire boxes, the research questions are answered below:

- Q3A: What is the impact of the nourishments on the total coastal volume over the period 2003 to 2010?

The total volume is clearly influenced by the nourishments. In the two post-nourishment years (2006 and 2007) a relative large decrease is observed, but from 2008 to 2010 changes are gradual and do not contain a clear signal that can be related to the nourishments. Assuming no cross-shore transport across the NAP – 8m depth contour, the volume losses are due to alongshore advection/diffusion of the nourishments.

- Q3B: Do the nourishments influence the volume development of the Test and Reference areas?

From 2003 to 2006 the observed volume increases are mainly caused by the nourishments. The observed volume *decrease* from 2006 to 2008 in the Egmond and Heemskerk areas are not matched by volume *increases* in the Test and Reference areas (the Test erodes and the Reference area is approximately stable during this period). Therefore, the volume developments of the Test and Reference areas do not show a feeding trend originating from the adjacent nourishments. From 2008 onward, the changes are gradual and small, with the first volume increase occurring from 2009 to 2010. Based on the analysis of the volume development of the entire areas it cannot be established that feeding of the Test and Reference areas occurs by the adjacent nourishments since 2006/2007.

- Q3C: What is the residual transport direction over the considered period 2003 to 2010?

Based on the observed temporal volume development it is not possible to identify the dominant transport direction. It seems most likely that the combined effect of gross transports (i.e. diffusion) and the natural variability are the main causes for this. Available studies do not agree on the net transport direction in the study area due to the presence of the IJmuiden harbour moles. But, the net transports are relatively low at the study area in all studies. This seems to indicate that that the gross transports are relatively important in this area (implying that diffusion of the nourishments in both northerly and southerly directions may be significant). However, the analysis of the observed morphological development is inconclusive with respect to the relative importance of the net and gross transports. This is probably due to the fact that the natural variability is dominant over the impact of the nourishments.

C.6 Step 2: Cross-shore Sediment Exchange

From Step 1, it is clear that there is no obvious longshore exchange of sediment between the considered areas. The nourishments surrounding the Test and Reference areas do not seem to feed these areas beyond 2007. In Step 2, the volume changes for Vertical-Dunes, Vertical-Beach, Lower Vertical-MCL and Lower Vertical-Shoreface volumes are analysed. This volume analysis is used to study the following research questions:

- Q4A: What is the contribution of the cross-shore regions to the total volume changes?
- Q4B: Is there an alongshore coherence of the observed cross-shore sediment exchange between the areas?

- Q4C: Can the effect of the 2004 and 2005 nourishments adjacent to the Test and Reference areas be identified in the individual cross-shore regions?
- Q4D: What is the development in the PEM placement area (i.e. Beach volume of the Test area)?
- Q4E: What is the contribution of the surf zone bars to the observed variability relative to the impact of the nourishments?

Observations

Figure C.12 shows the temporal evolution of the Vertical-Dune, Vertical-Beach, Lower Vertical-MCL and Lower Vertical-Shoreface as well as the Total volume change for the separate areas. The longshore averaged profiles for each of the four areas from 2003 to 2006 and from 2006 to 2010 are shown in Figure C.13 and Figure C.14, respectively. The volume changes for each of the areas are discussed in combination with the observed longshore averaged profiles for each of the four areas. After the discussion of the four areas, the Vertical-Dune, Vertical-Beach, Lower Vertical-MCL and Lower Vertical-Shoreface volumes will be intercompared to further investigate the possible influences of the nourishments.

- Egmond Area

The largest changes are observed for the Lower Vertical-Shoreface of the Egmond area (notice the different vertical axis scale for this area) which is primarily due to the 2004 shoreface nourishment (which was captured by the 2005 Jarkus survey). During the same year, a beach nourishment was also carried out at Egmond which largely explains the positive trend of the Vertical-Beach volume from 2004 to 2006 (the beach nourishment was captured in the 2005 bathymetric survey, but only in the topographic survey of 2006). This can also be observed in the profiles (Figure C.13). The total volume changes are dominated by changes in the Lower Vertical-Shoreface volume. This can also be seen in the longshore averaged profiles. From 2004 to 2005 the shoreface nourishment appears as an outer bar and trough system with a bar crest at x=-750 m. From 2005 onward this outer bar slowly decays, but does not migrate. The middle bar (crest at x=-450 m) migrates offshore from 2003 to 2004, is stable in 2005, but migrates onshore from 2005 to 2006. This onshore migration is probably caused by the shoreface nourishment and was also observed for the 1999 shoreface nourishment at Egmond (Van Duin et al., 2004). From 2006 onward the middle bar remains more or less stable with an approximately constant bar height. However, the trough gradually deepens from 2006 to 2008, but is stable since then. The middle bar dynamics is captured by the Lower Vertical-MCL volume, primarily causing the increase from 2004 to 2007. The decrease from 2007 onward is mainly due to the deepening of the trough. Compared to the Lower Vertical-Shoreface and Lower Vertical-MCL the changes in Vertical-Dune and Vertical-Beach volume are small. The Vertical-Beach volume has a similar trend, but shows an increase from 2008 onward. The Vertical-Dune volume shows an overall increasing trend over the entire period (except for 2007-2008). As the middle bar is affected by the shoreface nourishment, the positive trend in the Lower Vertical-MCL volume from 2004 to 2007 is considerably influenced by this nourishment. From 2007 onward the Lower Vertical-MCL is probably still affected by the shoreface nourishment, but the changes are smaller and could also be dominated by the natural variability. The Vertical-Beach volume increases from 2004 to 2006 are primarily caused by the nourishment. However, from 2006 to 2008 the Vertical-Beach volume decreases, which could be resulting from the erosion of the beach nourishment. For this period, there is no obvious feeding trend from the deeper parts of the profile (LVSHF and LVMCL) to the upper parts of the profile. However, from 2008 to 2010 the Vertical-Beach and Vertical-Dune volumes increase, whereas the Lower Vertical-Shoreface and Lower Vertical-MCL volumes decrease, which would suggest feeding from deeper parts of the profile. However, the inconsistency in the volume developments between the 2006-2008 and 2008-2010 periods is likely caused by the natural variability which is of similar or greater influence as the impact of the nourishments.

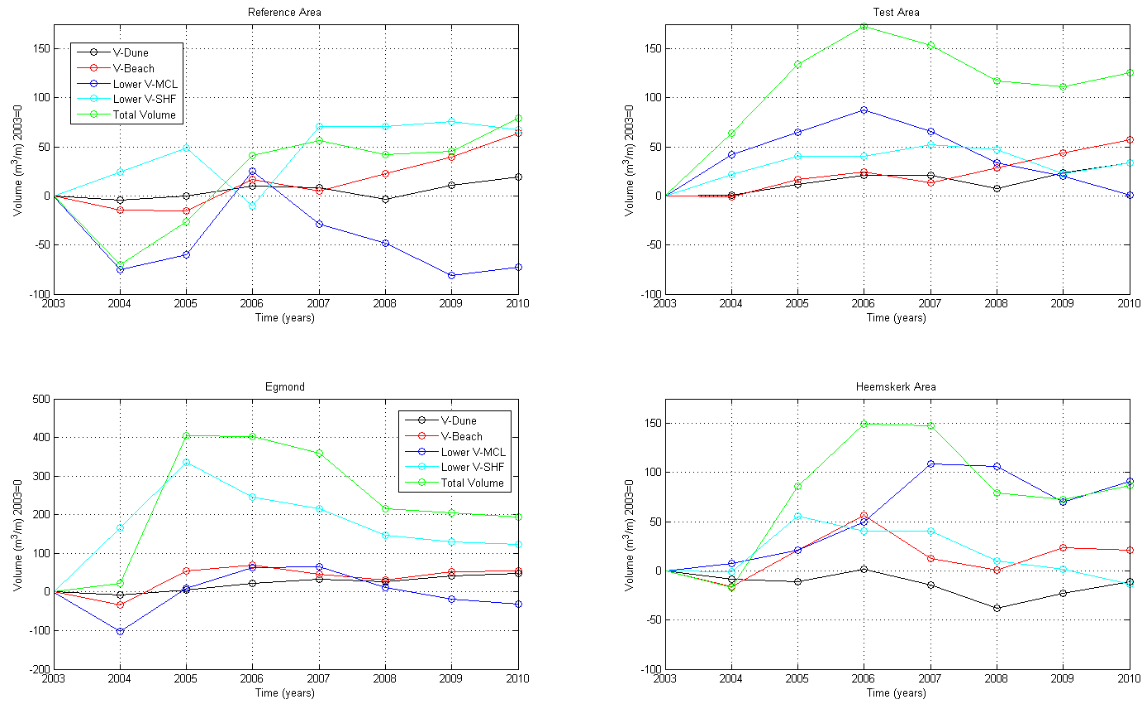

Figure C.12: Temporal development of volumes of the coastal zones relative to 2003 (boxes in Figure C.4)

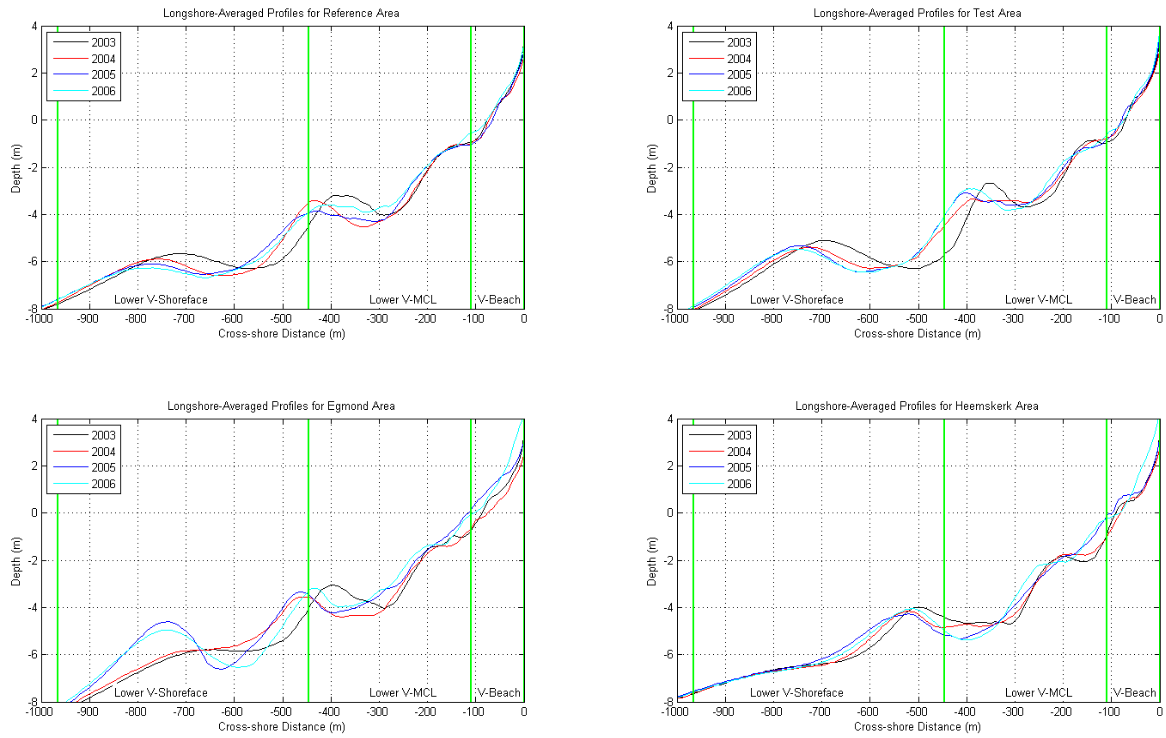

Figure C.13: Longshore averaged profiles for the pre-installation period from 2003 to 2006.

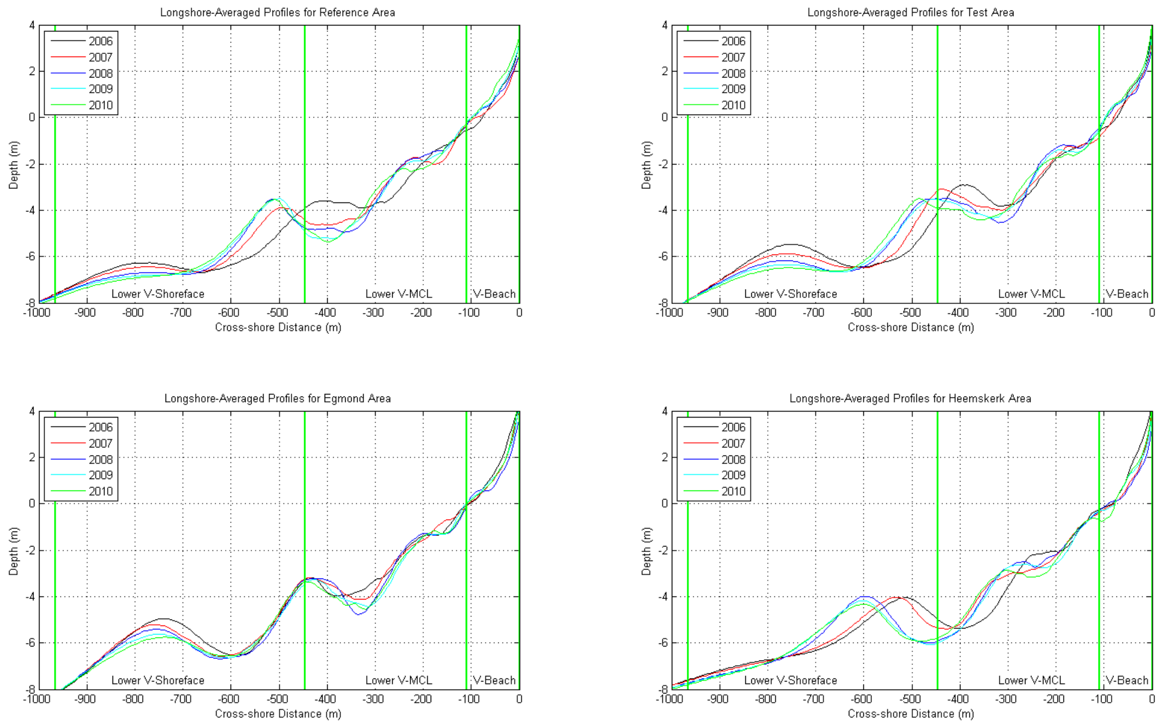

Figure C.14: Longshore averaged profiles for the post-installation period from 2006 to 2010.

- Heemskerk Area

The 2005 beach nourishment carried out in the Heemskerk area is clearly visible in the Vertical-Beach volumes (see Figure C.12). From 2006 to 2008, the Vertical-Beach volume decreases back to approximately its pre-nourishment volume. The beach nourishment contributes about 50% to the Total volume changes in 2005 and about 33% in 2006. The Vertical-Beach volume decrease from 2006-2007 is matched by an approximately similar volume increase of the Lower Vertical-MCL in the same period. In the longshore averaged profiles (Figure C.14) it can be seen that the entire beach profile is lowering during this period. The Lower Vertical-MCL part of the profile seems to be dominated by the offshore migration of the inner bar. From 2008 to 2009, the Vertical-Beach volume increases and slightly decreases in the next year. The increase of the Lower Vertical-Shoreface from 2004 to 2005 is primarily caused by the offshore migration of the outer bar into this region. The gradual decrease since 2005 is primarily associated with the outer bar dynamics: from 2006 to 2008 the bar (and trough) primarily migrates offshore, from 2008 onward the bar does not migrate, but gradually decays. The Vertical-Dune volume decreases from 2006 to 2007 implying no obvious feeding from the beach nourishment during this period. However, the November 2007 storm is likely to also have had a major impact on the dunes. From 2008 onward, the Vertical-Dune volume is steadily increasing.

The volume and profile analysis of the Heemskerk area clearly shows influences of the beach nourishment until 2007/2008. From the year 2008 onward, the beach and dune volumes have increased and also the total volume increased over this period, which implies that the natural variability has become dominant over the effect of the nourishment.

- Reference Area

The total volume increase from 2004 to 2006 is primarily resulting from increases of the Lower Vertical-MCL and Vertical-Beach volumes. As the beach nourishment at Heemskerk is just south of the Reference area (and there was also a small nourishment of 6 600 m^3 in the Reference area) it is likely that the observed increase is caused by these nourishments. From 2007 to 2009, the total volume remains more or less constant. However, especially the Vertical-Beach and Lower Vertical-MCL show relative large changes. The beach is accreting steadily whereas the Lower Vertical-MCL is losing sand. The longshore averaged profiles for this period (Figure C.14) show that mainly the lower part of the beach is accreting from 2006 to 2009. The Lower Vertical-MCL is initially (2006-2007) dominated by the offshore bar migration. From 2007 to 2009 the deepening of the trough (at x=-440 m) is causing the decrease of the Lower Vertical-MCL volume.

- Test Area

The Test area has a comparable total volume development as the Reference area. The main difference is the larger volume decrease from 2006 to 2008. The volume increase from 2003 to 2006 is mainly resulting from increases of the Lower Vertical-MCL and the Lower Vertical-Shoreface. As the 2004 Egmond shoreface nourishment was partly inside the Test area, this could partly explain the increase. However, the nourishment was located in the Lower Vertical-Shoreface region. This makes it unlikely that the increase in the Lower Vertical-MCL volume is caused by the shoreface nourishment. From 2006 onward the Lower Vertical-MCL volume is steadily decreasing, which is mainly caused by the offshore migration of the outer bar (see Figure C.14). The Vertical-Beach volume is showing an accreting trend for most of the considered period. Especially since 2007 there is significant beach accretion. This accretion of the beach is very similar to the observations in the Reference area.

Answers to the research questions

- Q4A: What is the contribution of the cross-shore regions to the total volume changes?

For the Egmond area, the volume changes are dominated by the Lower Vertical-Shoreface region. This is primarily caused by the shoreface nourishment in the area. In the other areas the Lower Vertical-MCL has the largest contribution to the total volume changes. For the Heemskerk area, the Vertical-Beach volume dominated the total volume change from 2004 to 2006, primarily caused by the beach nourishment in the area. For the Test and Reference areas the Lower Vertical-MCL has the largest changes most of the time. Only from 2008 to 2010 the combined changes of the Vertical-Dune and Vertical-Beach volumes are comparable to the Lower Vertical-MCL volume changes in both areas.

- Q4B: Is there an alongshore coherence of the observed cross-shore sediment exchange between the areas?

The temporal evolution of the sediment volumes and the longshore averaged profiles shows a relative large longshore coherence between the Reference and Test areas. This is consistent with the observed morphological development (section C.4).

This longshore coherence is studied in more detail by sub-dividing the Vertical-Beach and Lower Vertical-MCL regions into two equal parts. The volume development of the seaward half of the Lower Vertical-MCL volumes of the Test and Reference areas (plots at bottom row shown in Figure C.15) show an overall decreasing trend from 2006 to 2010, which dominates the Lower Vertical-MCL volumes most of the time. The landward half of the Lower Vertical-MCL region shows even more agreement for both areas: there is a gradual increase from 2003 to 2008 and a decrease from 2008 to 2010. Especially since 2006, the Vertical-Beach volume changes are comparable for both areas. For 2008 to 2010 (2007 to 2010), this is primarily caused by increases of the landward part of the Vertical-Beach volume for the Test area (Reference area). This alongshore coherence between both areas is likely caused by the offshore migration of the middle bar (x=~ – 450 m), which is influenced by the decay of the outer bar in both areas.

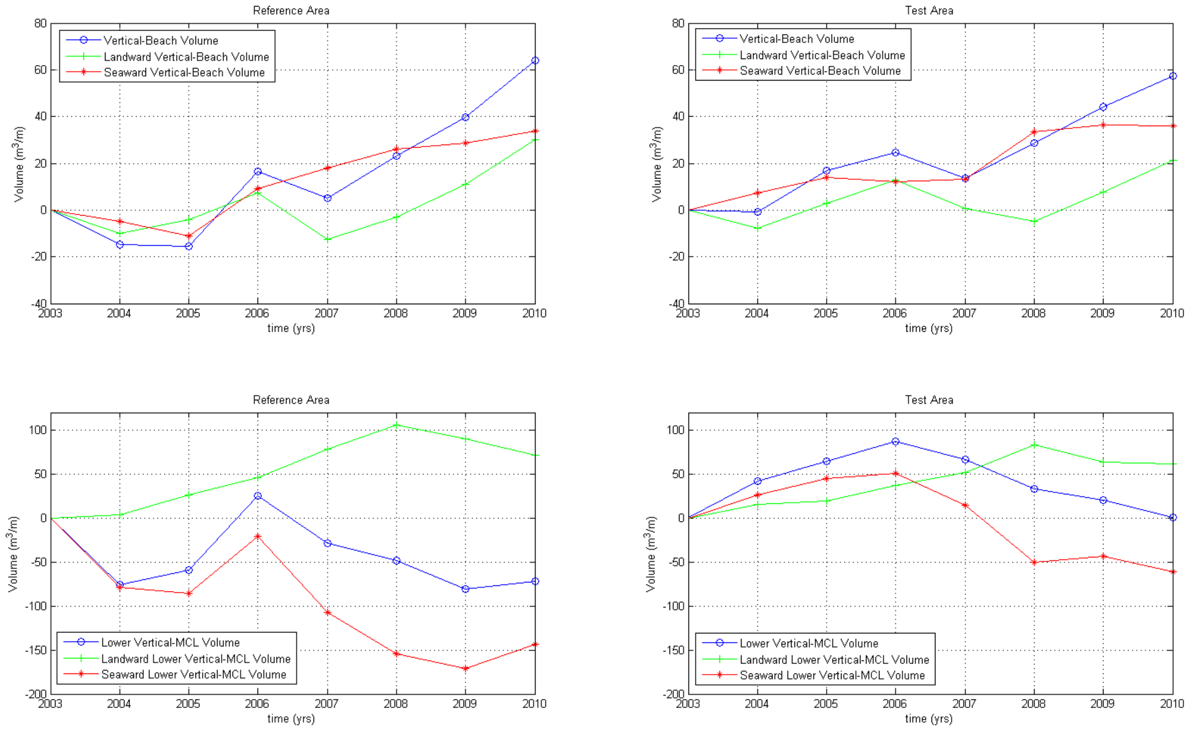

Figure C.15: Temporal volume development of the Beach and the Lower MCL regions (complete and sub-divided into two equal regions) for the Test and Reference areas.

The 2005 shoreface nourishment in the Egmond area is absorbed in the natural system as a new outer bar which hardly migrates and mainly decays. This is comparable to the behaviour of the outer bar in the Test and Reference areas. However, the middle bar in the Egmond area is responding to the presence of the shoreface nourishment by first migrating landward (2004-2006) and then remaining more or less at the same location. The Heemskerk area is in a different bar cycle phase: the outer bar has primarily migrated offshore and shows a limited amount of decay.

Although the shoreface and beach nourishments at Egmond and Heemskerk have resulted in a comparable Total volume development from 2004 to 2006 in all four areas (see Figure C.9), a longshore coherence between the Test and Reference area could only be identified for the Lower MCL and the Lower Shoreface regions since 2006. For the upper part of the profile, the longshore coherence is significantly less. However, it is likely that the beach and dune regions are also coupled to the bar cycle. The comparable temporal development of the Vertical-Beach and Vertical-Dune volumes in both areas indeed seems to suggest there is a link with the bar cycle, but this interpretation cannot be substantiated with the available observations.

- Q4C: Can the effect of the 2004 and 2005 nourishments adjacent to the Test and Reference areas be identified in the individual cross-shore regions?

In 2010 there is still a substantial part of the 2005 shoreface nourishment present at the Lower Vertical-Shoreface in the Egmond area. The response of the middle bar was to migrate shoreward and remain stable from 2006 to 2010. As the bars in the other areas are showing a gradual offshore migration during this period it seems likely that the middle bar at Egmond is still adjusting to the presence of the shoreface nourishment.

The execution of the beach nourishments in the Egmond and Heemskerk areas is clearly visible in the Vertical-Beach volumes. This is especially clear if those are plotted together (top-right plot in Figure C.16). The Vertical-Beach volume time series for both areas show a remarkable agreement. Both Egmond and Heemskerk show a decrease in Vertical-Beach volume in the two years after construction (2006 to 2008) and an increase in the following year. The increase from 2008 to 2009 seems to suggest that the impact of beach nourishments has decreased and the nourishments do not impact the beaches anymore since 2008.

The impact on the Test and Reference areas is clear in the two years after the nourishments were placed. However, the impact on especially the dune and beach regions in both areas is much harder to establish in the following years (2007-2010). As it was the case for the analysis in Step 1 for the Total volumes, also for the analysis in Step 2 no clear feeding signal could be identified: in the period after 2006 volume *decreases* in the Egmond and Heemskerk areas are not matched with *increases* in any of the considered cross-shore regions in the Test and Reference areas. Based on this analysis it is concluded that since 2007 no noticeable influence of the nourishments could be identified on the development of the Test and Reference areas.

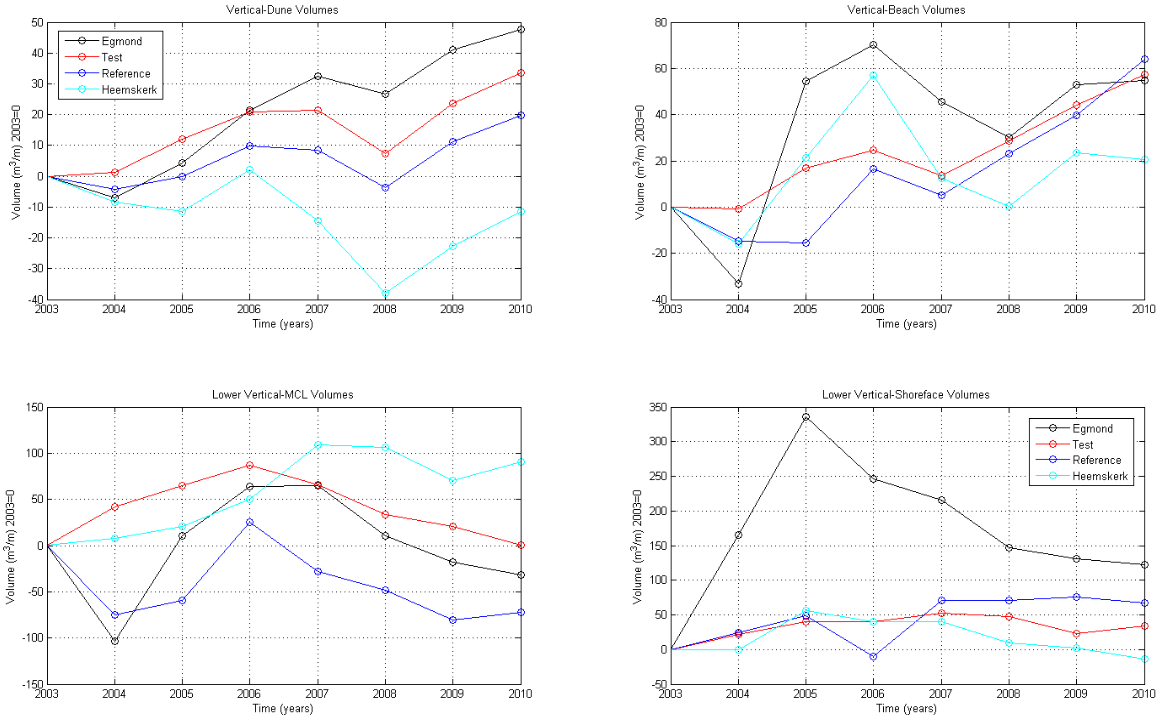

Figure C.16: Comparison of the Dune, Beach, Lower MCL and Lower Shoreface volumes.

- Q4D: What is the development in the PEM placement area (i.e. Vertical-Dune and Vertical-Beach volume of the Test area)?

The dune and beach regions of the Test area show a significant increase since 2008 and 2007, respectively (see Figure C.16). However, if the Vertical-Dune volumes for the four areas are compared it becomes clear that the there is a considerable coherence in the dune volume development. Although the magnitude may vary (e.g. due to varying sensitivity to storms), the annual trends are similar for all areas for most of the years since 2003 (only the Heemskerk area deviates in 2004-2005 and 2006-2007). The Vertical-Beach volumes of the Test and Reference areas show the same annual trend since 2005.

- Q4E: What is the contribution of the surf zone bars to the observed variability relative to the impact of the nourishments?

For the Lower Vertical-MCL and Lower Vertical-Shoreface a large part of the observed volume changes can be explained by the bar response. At Egmond the middle bar is still influenced by the presence of the shoreface nourishment. The impact of the nourishments is present until 2006/2007 in the Reference and Test areas, but from 2007/2008 onward no obvious feeding from the adjacent nourishments can be distinguished. The volume changes since 2007 in the Test and Reference areas for the lower parts of the profiles are mainly caused by bar dynamics (i.e. migration, growth and decay). The influence of the bar dynamics on the upper parts of the profile is similar to the impact of the nourishments difficult to establish. However, results suggest that there could be a coupling between the bar behaviour and the Vertical-Dune and Vertical-Beach regions (see also answer to question Q4B).

D Annually observed morphological development 2003-2010

This appendix shows de-curved top view plots of bathymetry (top), annual bed change (middle) and the cumulative bed change since 2003 (bottom) from 2003 to 2010.

The black boxes indicate the considered areas for the analysis and the white boxes indicated the recent nourishments (since 2004).

Figure D.1 2003 de-curved top view plots of bathymetry (top), annual bed change (middle) and the cumulative bed change since 2003 (bottom). The black boxes indicate the considered areas for the analysis and the white boxes indicated the recent nourishments (since 2004).

Figure D.2 2004 de-curved top view plots of bathymetry (top), annual bed change (middle) and the cumulative bed change since 2003 (bottom). The black boxes indicate the considered areas for the analysis and the white boxes indicated the recent nourishments (since 2004).

Figure D.3 2005 de-curved top view plots of bathymetry (top), annual bed change (middle) and the cumulative bed change since 2003 (bottom). The black boxes indicate the considered areas for the analysis and the white boxes indicated the recent nourishments (since 2004).

Figure D.4 2006 de-curved top view plots of bathymetry (top), annual bed change (middle) and the cumulative bed change since 2003 (bottom). The black boxes indicate the considered areas for the analysis and the white boxes indicated the recent nourishments (since 2004).

Figure D.5 2007 de-curved top view plots of bathymetry (top), annual bed change (middle) and the cumulative bed change since 2003 (bottom). The black boxes indicate the considered areas for the analysis and the white boxes indicated the recent nourishments (since 2004).

Figure D.6 2008 de-curved top view plots of bathymetry (top), annual bed change (middle) and the cumulative bed change since 2003 (bottom). The black boxes indicate the considered areas for the analysis and the white boxes indicated the recent nourishments (since 2004).

Figure D.7 2009 de-curved top view plots of bathymetry (top), annual bed change (middle) and the cumulative bed change since 2003 (bottom). The black boxes indicate the considered areas for the analysis and the white boxes indicated the recent nourishments (since 2004).

Figure D.8 2010 de-curved top view plots of bathymetry (top), annual bed change (middle) and the cumulative bed change since 2003 (bottom). The black boxes indicate the considered areas for the analysis and the white boxes indicated the recent nourishments (since 2004).

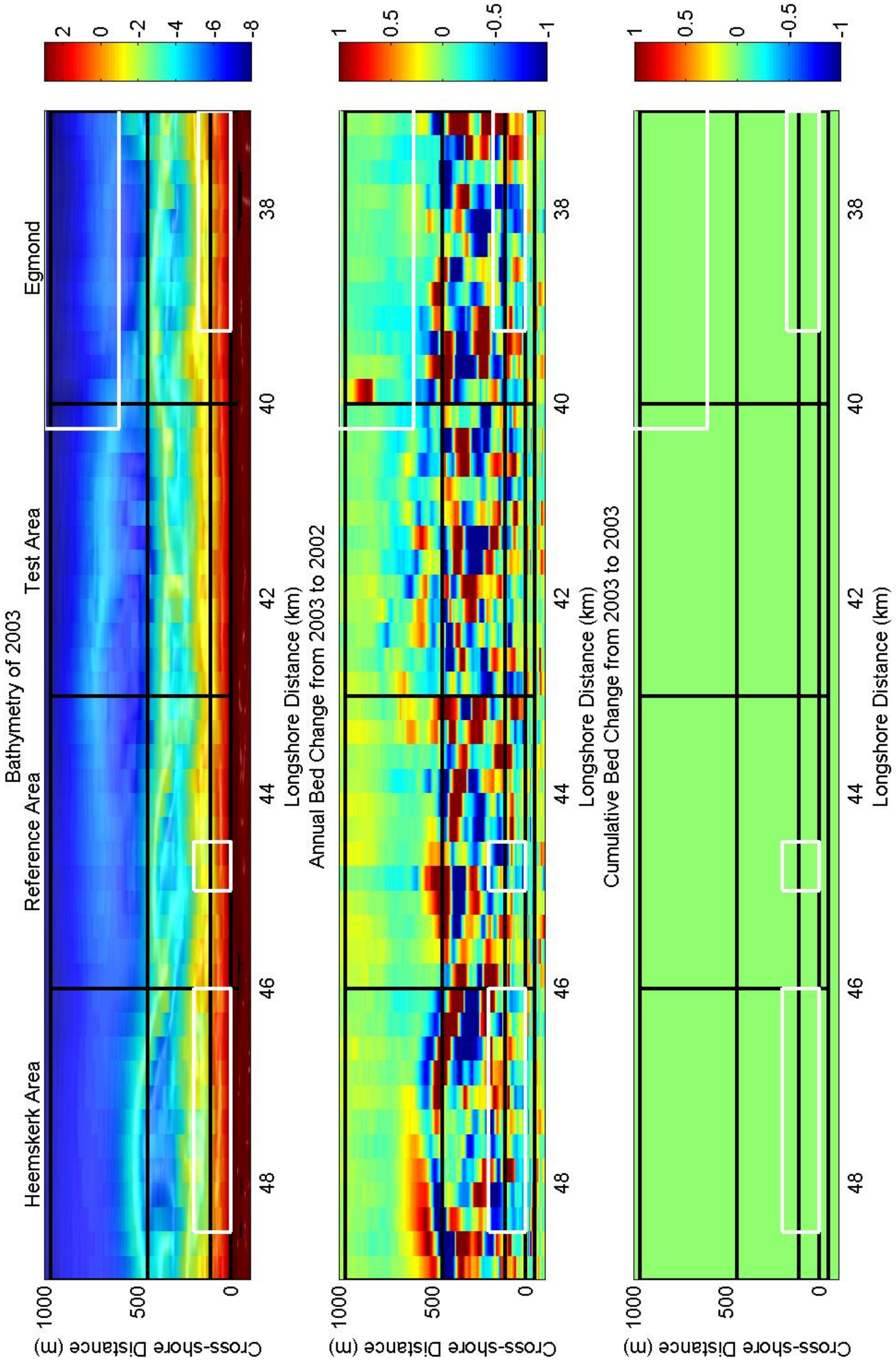

Figure D.1 2003 de-curved top view plots of bathymetry (top), annual bed change (middle) and the cumulative bed change since 2003 (bottom). The black boxes indicate the considered areas for the analysis and the white boxes indicated the recent nourishments (since 2004).

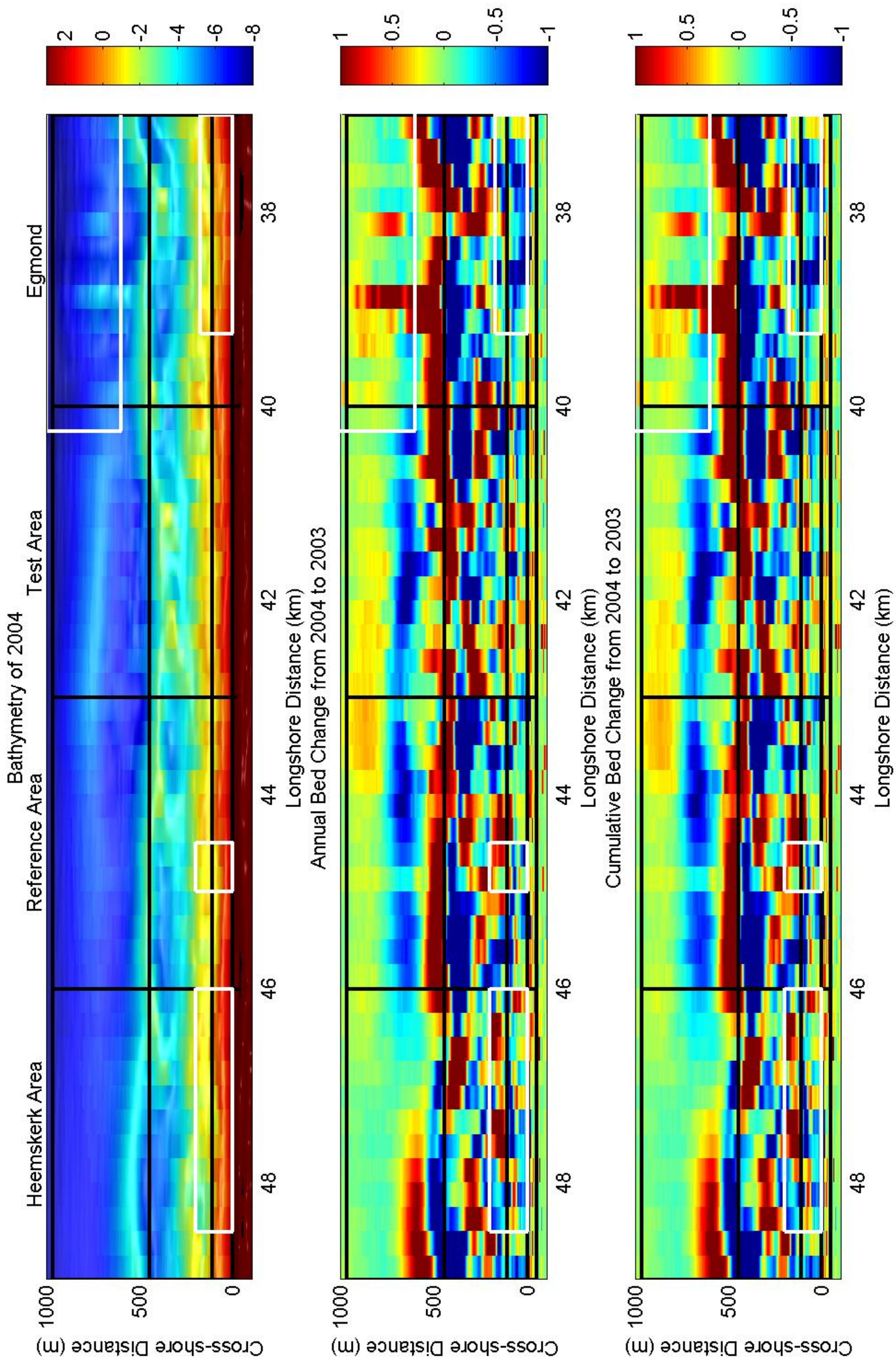

Figure D.2 2004 de-curved top view plots of bathymetry (top), annual bed change (middle) and the cumulative bed change since 2003 (bottom). The black boxes indicate the considered areas for the analysis and the white boxes indicated the recent nourishments (since 2004).

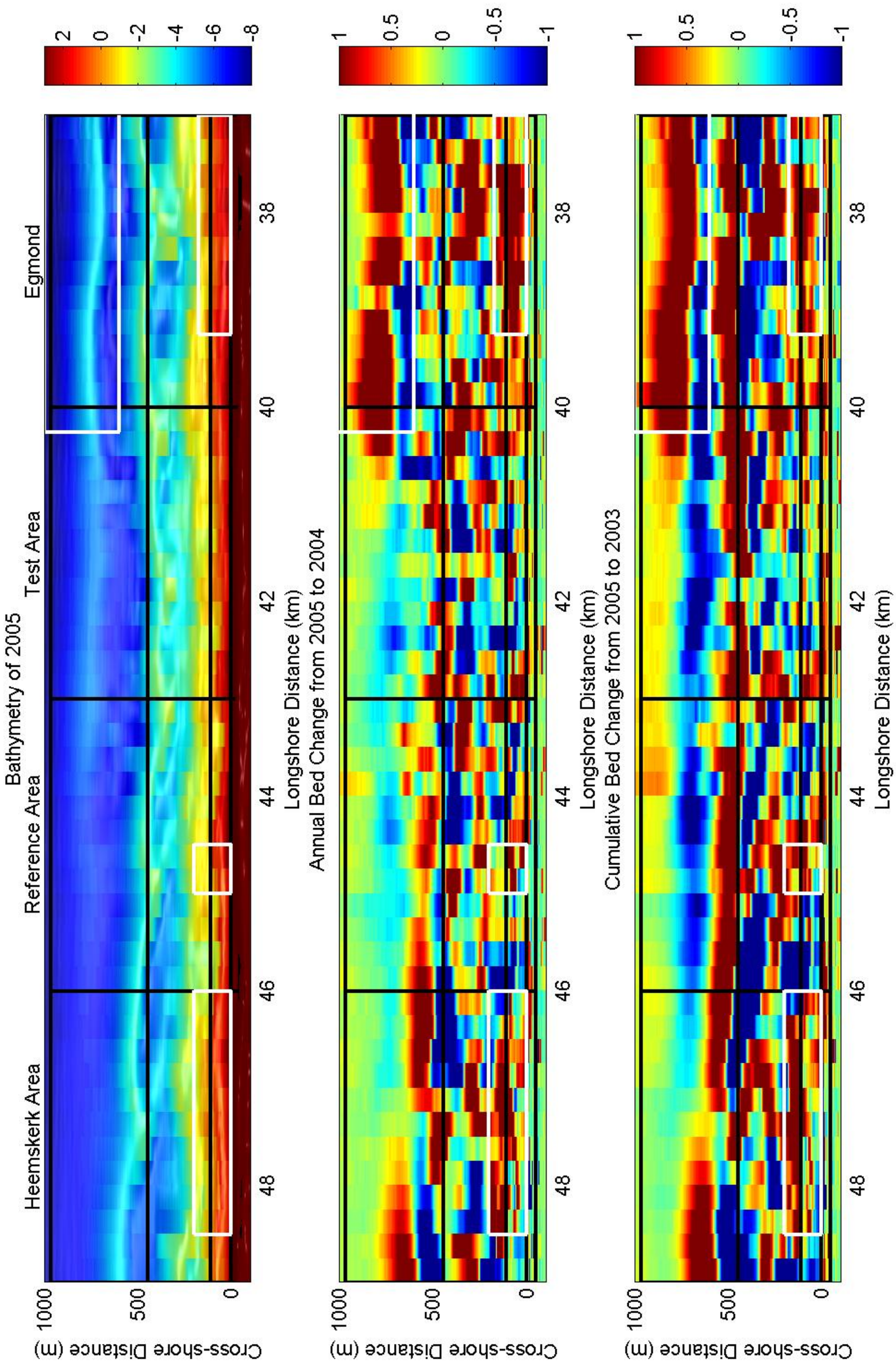

Figure D.3 2005 de-curved top view plots of bathymetry (top), annual bed change (middle) and the cumulative bed change since 2003 (bottom). The black boxes indicate the considered areas for the analysis and the white boxes indicated the recent nourishments (since 2004).

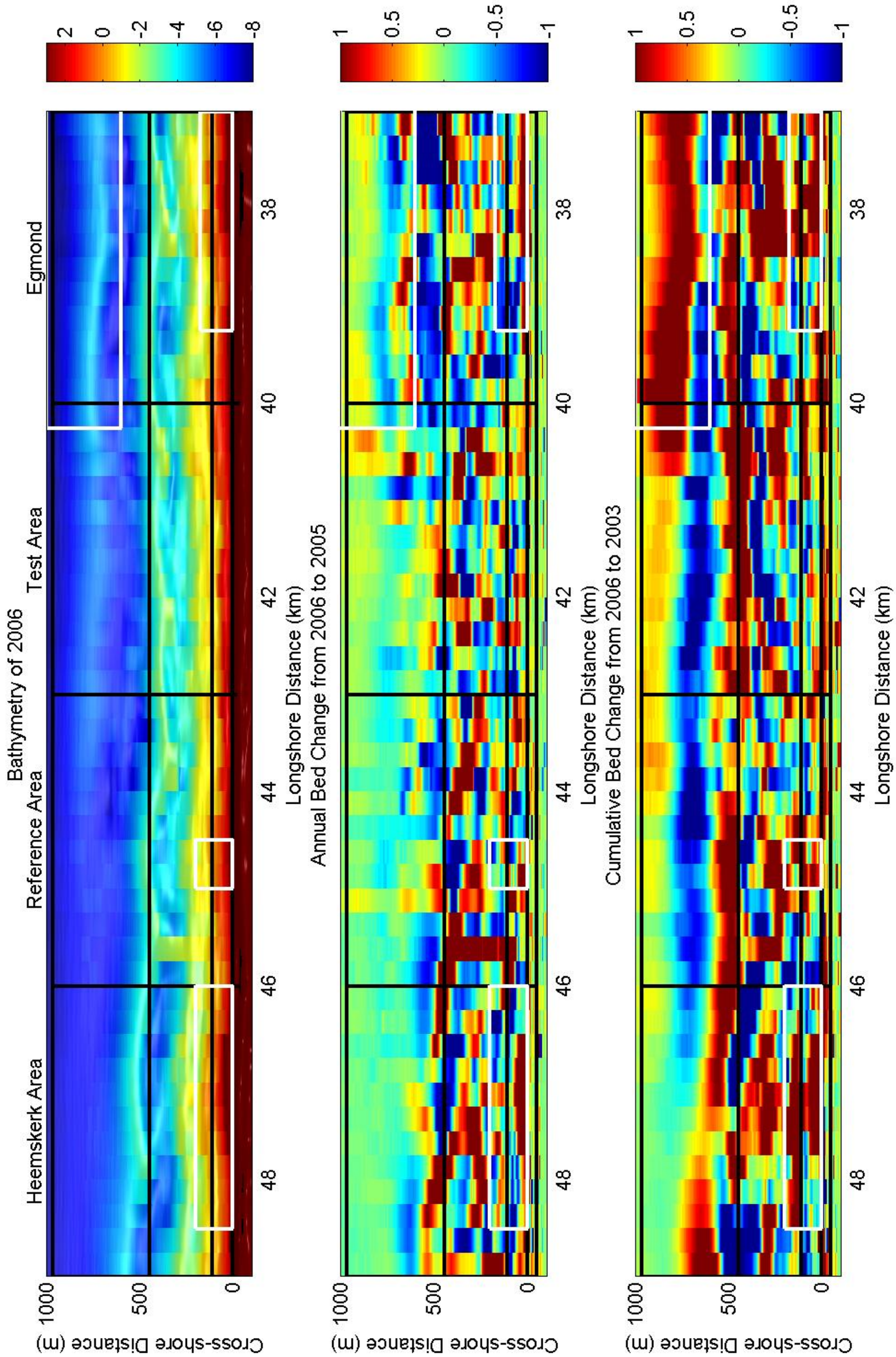

Figure D.4 2006 de-curved top view plots of bathymetry (top), annual bed change (middle) and the cumulative bed change since 2003 (bottom). The black boxes indicate the considered areas for the analysis and the white boxes indicated the recent nourishments (since 2004).

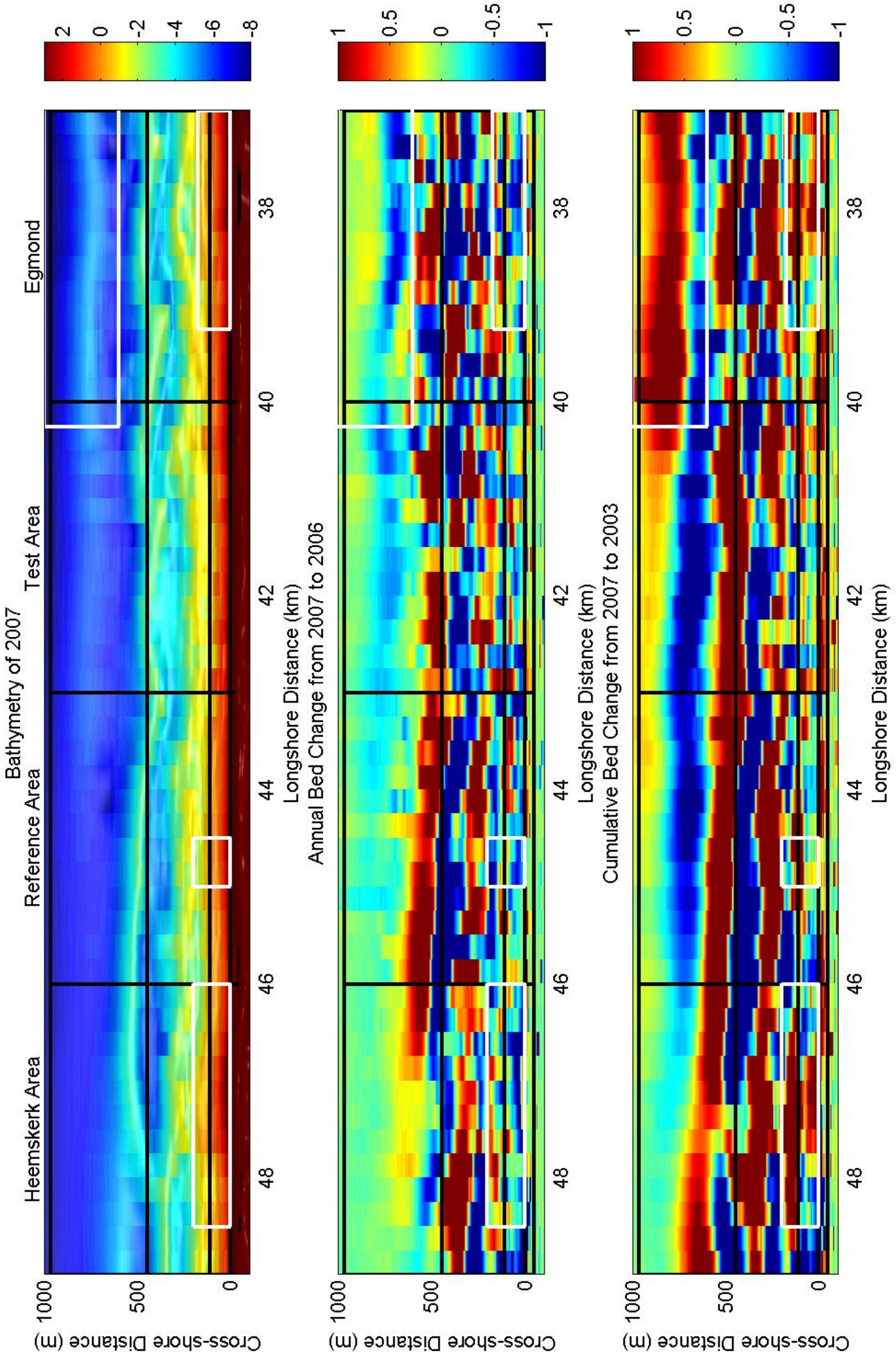

Figure D.5 2007 de-curved top view plots of bathymetry (top), annual bed change (middle) and the cumulative bed change since 2003 (bottom). The black boxes indicate the considered areas for the analysis and the white boxes indicated the recent nourishments (since 2004).

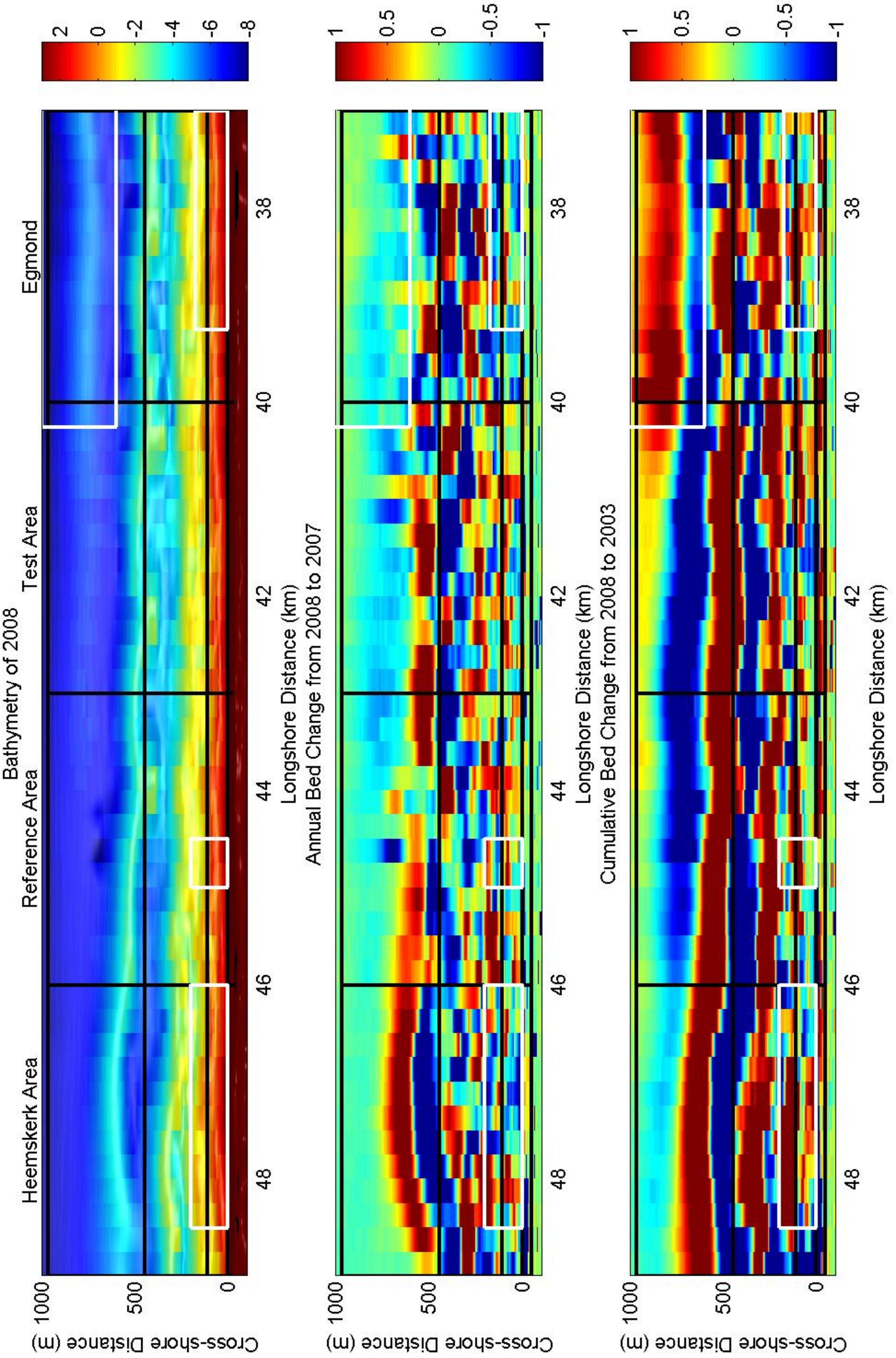

Figure D.6 2008 de-curved top view plots of bathymetry (top), annual bed change (middle) and the cumulative bed change since 2003 (bottom). The black boxes indicate the considered areas for the analysis and the white boxes indicated the recent nourishments (since 2004).

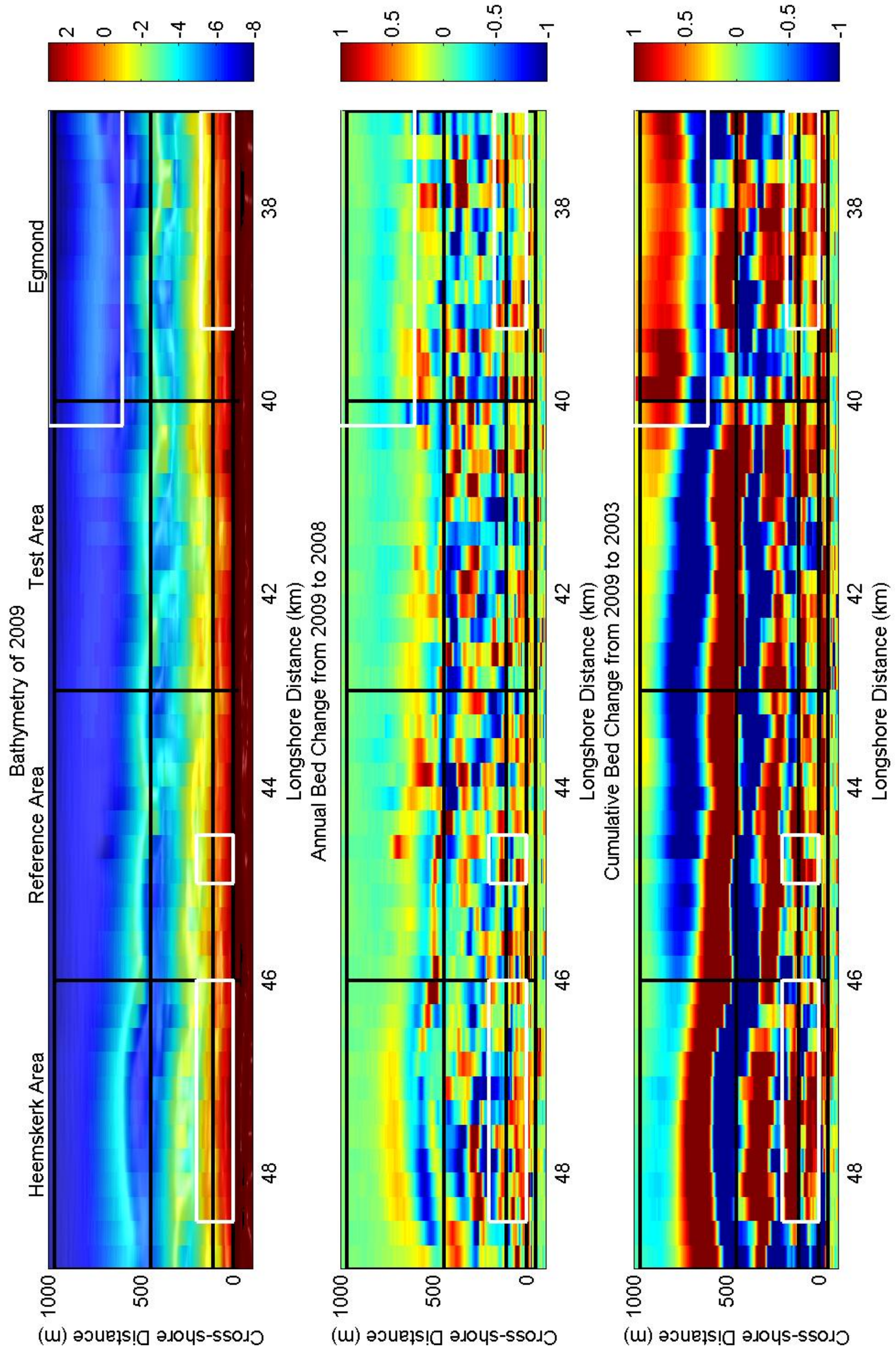

Figure D.7 2009 de-curved top view plots of bathymetry (top), annual bed change (middle) and the cumulative bed change since 2003 (bottom). The black boxes indicate the considered areas for the analysis and the white boxes indicated the recent nourishments (since 2004).

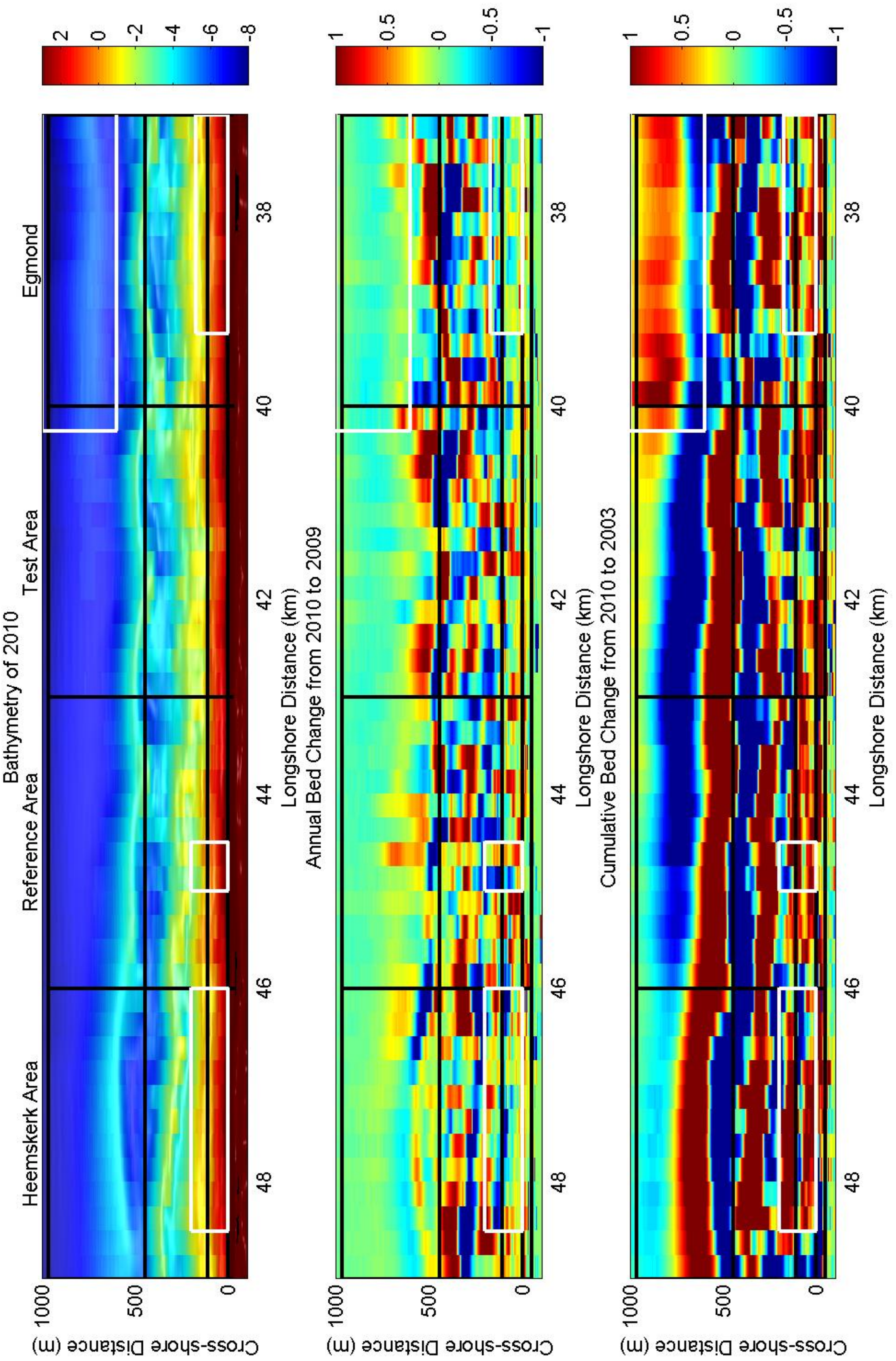

Figure D.8 2010 de-curved top view plots of bathymetry (top), annual bed change (middle) and the cumulative bed change since 2003 (bottom). The black boxes indicate the considered areas for the analysis and the white boxes indicated the recent nourishments (since 2004).