Preface

This report is the result of my master thesis project during my studies at Delft University of Technology (TUDelft), at the faculty of Civil Engineering, in the department of Hydraulics and Geotechnical Engineering, with specialization in Coastal Engineering. This research project has been carried out at the National Institute of Coastal and Marine Management (RIKZ) in The Hague.

I would like to thank the members of the graduation committee for their support and comment during the whole graduation process, prof. dr. ir. M. F. Stive, dr. ir. J. van de Graaff, dr. R. Spanhoff and ir. G. J. de Boer. I would especially like to thank dr. R. Spanhoff for the opportunity he gave me to carry out my graduation project at the RIKZ. Moreover, I would like to thank dr. ir. M. van Koningsveld, for his support using the marine and coastal analysis package toolbox (UCIT).

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Maria Bougdanou

The Hague, September 2007
Summary

General Introduction

Holland is a densely populated country with an important coastal zone that comprises most of the Dutch population. The dunes, the beach and the shoreface are a natural sandy protection for the Dutch coast. Natural processes, such as waves, winds and tides, coupled with human activity, may lead to shoreline erosion. Gradual recession of the coast can become a threat for the safety of the polders and consequently for the people that live behind the dikes and their properties.

In The Netherlands the most sufficient method to counteract is by adding sand in places where erosion has been observed (artificial nourishment). Beach nourishments are applied regularly since 1970’s. Nowadays, beach nourishment has been replaced by shoreface nourishment (first shoreface nourishment in 1993). During the application of a shoreface nourishment, the sand is not placed on the beach or the dunes, but under water on the shoreface. It is more effective and thus more attractive solution than beach nourishment.

Aim of the study

In this study the effects of three shoreface nourishments applied on the areas of Ter Heijde, Katwijk and Noordwijk are studied and analyzed. The natural systems of these three under investigation areas have been affected and the longshore and cross-shore processes have changed.

To increase the insight into the effects of a shoreface nourishment to the natural system a number of research questions are introduced. These research questions are presented below.

- How does the application of the shoreface nourishment influence the physical processes that occur in a coastal system? How is the autonomous behaviour of the cross-shore profiles volume changing? Has the behaviour of the cross-shore profile volume been significantly affected since completion of nourishment?
- How is the landward part of the profile affected? How do the higher parts of the profile react to the nourishment? Has the beach and dune volume been increased after application of nourishment?
- Does the shoreface nourishment result in beach widening?
- What is the behaviour of the longshore sediment transport, after completion of nourishment, in the lee side of the nourishment?
- Does the nourishment result in downdrift erosion and updrift sedimentation?
- How does the nourishment affect the onshore versus offshore sediment transport?

Aim of this study is to find answers to the above mentioned research questions. By this way it is possibly to obtain a more complete picture of the effects of a shoreface nourishment, in the coastal stretch that is applied.

Methodological approach

To find answers to the above mentioned research questions, the marine and coastal analysis package toolbox (UCIT), is used. UCIT consists of a dataset that contains coastal bathymetry data; acquired by the annual JARKUS profile measurements.
The coastal stretches of each area that are going to be studied and analyzed include the transects located in the nourishment area, a number of transects located south of the nourishment and a number of transects located north of nourishment.

A first analysis step is to study the volume evolution in each of the cross-shore profiles of the three study areas. The study is based on a transect by transect analysis. The total volume is divided in three horizontal subsections that represent the dune, the beach and the shoreface volume. To investigate the immediate effects that a shoreface nourishment has on the shoreface profiles, the shoreface profile volume is divided in sub sections. Each sub section represents a specific part of the cross-shore profile (e.g. Section 1 represents the higher parts of the profile and includes the dune and beach volume). Every section is determined by fixed boundaries. The effects of the nourishments in the autonomous behaviour of the cross-shore profile volume, the possibility of lee side effects downdrift of the nourishment, the salient effect and also the changes on the onshore and offshore sediment transport are being studied.

Two periods are introduced, the pre nourishment period and the post nourishment period. The volume changes during the pre nourishment and post nourishment period are compared. This comparison shows how the behaviour of the cross-shore profiles is influenced by the application of the shoreface nourishment.

Finally, to investigate whether or not the shoreface nourishment results in beach widening, the concept of the beach width indicator (BWI) is developed, which is based on volumes per unit length (quality is determined by the total volume of the beach).

**Conclusions**

The analysis of the shoreface nourishments applied in the areas of Ter Heijde, Katwijk and Noordwijk showed that there were differences concerning the results for the three areas. This can be attributed firstly to the fact that in Ter Heijde, the nourishment area is part of a dynamic system that can be classified as a one breaker bar system, while in Katwijk and Noordwijk the nourishment areas are parts of a dynamic system that can be classified as a two breaker bar system. Moreover, the nourishment in Ter Heijde was placed on a smooth profile, while in the other two cases; the coastal profiles have a milder slope. The shoreface nourishment in Ter Heijde was placed relatively close to the shore, while in Katwijk and Noordwijk the shoreface nourishment was placed relatively far offshore. Finally, the most important information for the present analysis is that the nourishment volume, in the cases of Katwijk and Noordwijk, was placed outside the yearly measuring range. Thus, the main research question of the present study; *how is the autonomous behaviour of the cross-shore profiles volume changing?* cannot be answered. Moreover, it cannot be studied the longshore sediment transport and how it was affected by the nourishment.

Below, the final conclusions are briefly mentioned.

- From the total volume analysis it can be concluded that in the area of Ter Heijde the shoreface nourishment did not affect the autonomous behaviour of the cross-shore profile of the transects located in the nourishment area. For Katwijk and Noordwijk it was observed a quick response of the nourishment.
- From the dune, beach and Section 1 (dune and beach volume) volume analysis, it can be concluded that the higher parts of the profile do not have a direct response of the nourishment. There is a delay of two to three years for all three areas. The nourishment did not resulted on the increment of the dune volume in the area of Ter Heijde. It resulted however on the dune volume increment in the areas of Katwijk and Noordwijk. The beach volume was slightly increased in the area of Noordwijk.
• From the beach width indicator approach concluded that the shoreface nourishment in general, did not result in beach widening.

• From the longshore sediment transport analysis it can be concluded that only for the case of Ter Heijde a clear answer can be formulated. The outgoing longshore sediment transport has been decreased. It is possible that the opposite effect of the salient effect occurred. For the cases of Katwijk and Noordwijk it is not possible to come up with conclusions. The longshore sediment transport is clearly affected by the cross-shore sediment transport.

• From the sub sections volume analysis it can be concluded that in all cases the nourishment volume is gradually shifting landward. Feeding processes of the higher parts of the profile are observed. The onshore sediment transport has been increased. In the cases of Katwijk and Noordwijk there was a quick response of the nourishment, for the ‘total volume’, and thus the nourishments can be considered to be successful. The extra volume was mainly preserved in the later years.
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1 Introduction

1.1 General introduction

Holland is a densely populated country with an important coastal zone (with a broad definition of the width of a coastal zone: approximately 50 km wide). The Holland coastal zone comprises most of the Dutch population since many people are living and working there. Moreover, from the economical point of view this area is of a great importance, since it is very developed and the economy is growing. In the Dutch coastal area human activities include fisheries, oil and gas extraction, sand extraction, shipping and companies that are related to that, shipbuilding, recreation and tourism. In the dry part the human activities apart from living also include drinking water extraction, recreation, agriculture and tourism.

Undoubtedly coastal zones are areas of a great importance due to the fact that they support a growing part of the world population. The Dutch coast consists mostly of sand, which serves as the foundation of the coast. The dunes, the beach and the shoreface are a natural sandy protection for the Dutch coast, which is continuously adapting itself to the sea level rise and to the loss of sand.

Erosion involves silt and other sediments, which is of crucial importance to the ecological function of the Wadden Sea. Gradual recession of the coast can become a threat for the safety of the polders and consequently for people that live behind the dikes and their properties.

About one third of the land of The Netherlands lies below mean sea level and approximately two thirds is at risk of flooding. This flooding might be due to the huge surges that might be created by storms or due to the river floods. Without the dikes and the dunes, which are a barrier to the sea, more than one third of the country would be flooded. A long range of sand dunes protects the western coast and covers three fourth of the total length of the North Sea coastline (350 km).

In The Netherlands the most sufficient method to counteract erosion and achieve the maintenance of beaches and shorefaces, is by adding sand in places where erosion has been observed (artificial nourishment). Nourishments are applied in The Netherlands since 1970’s. The North Sea bottom has become an important sand source for coastal nourishment. The seabed is a marine source, but the nourishing sand can also be taken from riverbeds or dry sand deposits which are concerned as land-based sources.

Some years ago a new way of nourishment was introduced, the shoreface nourishment which has become a standard way to protect the shoreline of the North Sea basin and more specific in The Netherlands and also in Denmark (Hamm et al., 2002).

1.2 Aim and set-up of the study

Shoreface nourishment is applied in order to counteract erosion. There are however aspects of a shoreface nourishment that cannot be still fully understood e.g. its effects cannot be still predicted. Shoreface nourishment should be placed in such a way that nature will try to incorporate a nourishment into the occurring coastal processes. The design and the implementation of shoreface nourishments are based on the assumption that the sand will eventually be carried to the shore. The procedure however is more complex and this complexity is been enhanced by the presence of bars in the system. Spanhoff and van de Graaff, (2006) stated that in designing a shoreface project, the status of the bar system must
be taken into account. In this way it is possible to avoid adverse effects with neighbouring bars.

The analysis is focused on three shoreface nourishments that have been applied along the southern part of the Dutch coast. These are the shoreface nourishment at Ter Heijde in 1997, the shoreface nourishment at Katwijk in 1998-1999 and the shoreface nourishment of Noordwijk in 1998. The evaluation of these three shoreface nourishments showed that they affected the natural system. It was observed that in every case the response of the coastal system to this new disturbance was different and also the shoreface nourishments showed a different morphological behaviour [Hanson et al., 2002].

The general question is if and how the natural processes of a coastal system are changing due to application of a shoreface nourishment and consequently how the autonomous behaviour (behaviour of the system before application of nourishment) of coastal cross-shore profiles is being affected.

The main objective of this study is to increase the insight into the effects that a shoreface nourishment has on the natural system and how it influences the physical processes. Thus, a number of research questions are being introduced. These are:

- How does the application of the shoreface nourishment influence the physical processes that occur in a coastal system? How is the autonomous behaviour of the cross-shore profiles volume changing? Has the behaviour of the cross-shore profile volume been significantly affected since completion of nourishment (gain or loss of sand volume out of a cross-shore profile)?

- How is the landward part of the profile affected? How do the higher parts of the profile react to the nourishment? Has the beach and dune volume been increased after application of nourishment?

- Does the shoreface nourishment result in beach widening?

- What is the behaviour of the longshore sediment transport, after completion of nourishment, in the lee side of the nourishment?

- Does the nourishment result in downdrift erosion and updrift sedimentation (salient effect)?

- How does the nourishment affect the onshore versus offshore sediment transport?

To investigate and analyze the effects of a shoreface nourishment on the natural processes that occur on a coastal system a transect by transect analysis is applied. The volume evolution in each of the profiles of the three areas under investigation is determined using the coastal analysis package UCIT (Van Koningsveld, 2004). UCIT consists of a database that contains bathymetric data sets that have been collected during various surveys. These surveys are the JARKUS surveys (JARKUS is an annual monitoring program that measures the coastal depth profiles) and the nourishment soundings surveys (additional monitoring surveys that were performed only after the completion of the nourishments). Moreover to define the beach quality a beach width indicator (BWI) is introduced.
1.3 Structure of the report

Chapter 2 includes an introduction to the shoreface nourishment. The analysis is focusing to the application of nourishment projects in The Netherlands together with a short description of the relevant Dutch policy. Finally, the types of nourishment are reported as well.

Chapter 3 contains the definition of the problem regarding the effects of the shoreface nourishment on the natural coastal system and summarizes the main objective of the present study.

Chapter 4 describes the methodological approach that is followed in order to answer the research questions. In regard to this, the marine and coastal analysis package toolbox (UCIT), its main applications and its dataset that contains coastal bathymetry data; acquired by the annual JARKUS profile measurements and the additional nourishment monitoring soundings, are introduced.

Chapters 5, 6 and 7 include the analysis of the effects of the shoreface nourishments that have been applied in the areas of Ter Heijde, Katwijk and Noordwijk respectively.

Chapter 8 presents the final conclusions gathered from the analysis of the three areas together with proposals for further research.
2 Introduction to the shoreface nourishment in The Netherlands

2.1 The Netherlands

The Netherlands can be divided in three natural topographical parts: the dunes, the river floodplanes with lowlands or "polders" and the higher eastern section of the country. A considerable part of the coastal area consists of protected natural areas, which have high international value (part of the Northwest European dune biotope). About 75% consists of dune areas, 10% consists of beach width, another 10% consists of beach flats along the tips of the northern Wadden islands and 15% consists of sea dikes and other hydraulic structures that are used as a sea barrier.

Dunes are formed all the time, but still many mechanisms of these processes are unknown. The "polders" are areas that are enclosed by dikes. The water level in these areas is lower than the water level in the surrounding area. The number of "polders" is increased drastically over the years.

Since the 13th century, the water boards are responsible for the dike system and the water levels (also in the "polders"). Nowadays some 85 water boards exist in The Netherlands. Water boards are responsible for the management of defences and the quality and quantity of the local and regional water supplies. The Provinces are supervisors of the water boards and the national authorities have final control.

In 1798, the institution Rijkswaterstaat was founded. Some aspects concerning the water management could be addressed better at a local level. Rijkswaterstaat, which is an executive body of the National Ministry of Transport, Public Works and Water Management, is responsible to give a national guidance. The National Ministry of Transport, Public Works and Water Management is responsible to Parliament for all aspects of flood defence and water management.

After the flood-disaster in 1953, it was decided by the national government that the dunes and the dikes must be able to resist a storm surge occurring once in the 10,000 years, for the central part of The Netherlands. By this it was meant that the chance that this area will flood is less than 1/10,000 per year. However, for different areas the standards differ. For areas with lower economic value the safety standards were lower (1/2000 per year-1/4000 per year). The safety measures had as a main objective to bring all sea defenses to a predefined safety level: the Delta strength. Therefore the Delta project was born that took more than 25 years to be completed.

2.2 Coast and Erosion

Natural processes, such as waves, winds and tides, coupled with human activity, may lead to shoreline erosion. There is a removal and deposition of sand that permanently changes beach shape and beach structure. All over the world large parts of sandy coasts are prone to structural erosion, which has become a problem of growing intensity. Beaches are powerful economic engines and a big part of the population of every country has been gathered near the coastal zone areas. Coastal erosion causes many problems to coastal communities concerning the housing and the land values on the waterfront. Thus, their preservation constitutes a main concern for the global wealth.
The careful selection of the protective measures against erosion has become of primary interest for the coastal managements. There are two ways to counteract erosion. The ‘hard’ solution, which is the construction of seawalls or revetments, series of groynes, offshore and/or submerged breakwaters and the ‘soft’ solution which is the sand nourishment. The basic idea of the latter one is the artificial addition of sediment in areas where the loss of sand becomes crucial.

There has been a gradual change from ‘hard’ to ‘soft’ methods over the last decades, since the ‘hard’ methods failed to protect sandy beaches (lee side erosion takes place). These ‘hard’ coastal defence techniques are permanent constructions. In case of malfunctioning it is not easy to modify. Moreover, their maintenance is often too costly. ‘Soft’ solutions like beach nourishment became effective solutions due to their incorporation with nature, which had as a result the slow down of the coastal retreat. Furthermore, ‘soft’ countermeasures are widely regarded as an environmentally accepted method of beach and dune protection and restoration. Finally, they are considered to be more cost-effective methods comparatively to the hard alternatives. Sand suppletion must be repeated from time to time.

In The Netherlands beach nourishments are applied regularly since 1970’s and on systematic national scale since 1990’s. Nowadays, beach nourishment has been replaced by shoreface nourishment. Shoreface nourishment is more flexible in execution, since no pipelines or shovels are used. It is considered to be a more effective and thus a more attractive solution, than beach nourishment.

During the application of a shoreface nourishment, the sand is not placed on the beach or the dunes, but under water on the shoreface. The first shoreface nourishment in the Netherlands took place at Terschelling in 1993 and since 1997 more than 10 new shoreface nourishment projects have been performed (Spanhoff et al., 2003). The price per $m^3$ of a shoreface nourishment is half of that of a beach nourishment. The sand volume that is used for a shoreface nourishment is often two times the volume of the sand that would have been used for beach nourishment, subsequently the total cost of both options are of the same order.

2.3 The Dutch policy

A national coastal policy was introduced by the Dutch government in 1990, which was called ‘Dynamic Preservation of the coast line’. The strategic objective was to guarantee a sustainable preservation of values and functions in the dune area. The operational objective of this policy was to keep the coastline at least at the position that it had in the year 1990, so no further retreat of eroding stretches of coast was allowed.

To determine the coastline position the concept of momentary coastline (MCL) has been developed. The methodology that can objectively determine the MCL in any given cross-shore profile has been developed based on the area of sand between two horizontal planes. The lower and upper boundaries are each located at a distance ‘H’ from the mean low water level (MLWL) and determine the MCL area. This area is divided by the difference in height of the upper and lower boundaries. ‘H’ is a vertical distance that denotes the vertical difference between the dune foot and the mean low water level (Figure 2-1).
Figure 2-1 Definition of the MCL zone

\[ H = \text{Height between dune foot and M.L.W.}[m] \]
\[ A = \text{Momentary Coastline Zone}[m^2] \]
\[ B = A/2H = \text{Momentary Coastline position}[m] \text{ with respect to position of DuneFoot} \]
\[ C = \text{Distance dune foot to reference}[m] \]

The calculation of the MCL was based on the data set from the Dutch yearly coastal monitoring program JARKUS, which is operational since 1963. The bathymetric dataset that is being collected during the JARKUS surveys guides the annual coastal nourishment planning. This bathymetric dataset contains echo-sounding data. Also aerial photography of the dry beach and dunes had been used in the past, but since 1998 it was been replaced by laser altimetry from an aircraft (Figure 2-2).

Figure 2-2 JARKUS surveys

The annual JARKUS monitoring program is measuring the coastal depths profiles, since 1964. The surveys are being performed along the coastline. A fixed reference frame is used, (since 1850’s) which is known as the R.S.P beach poles. Two or three poles are positioned to indicate the location of the cross-shore profiles (surveys lines perpendicular to a longshore reference line). These cross-shore profiles are extended from the first dunes up to 1 km in the seaward direction. Along the shore the spacing between successive transects is approximately 200 m to 250 m.
2.4 Description of the types of nourishment

When the strategic and operational objectives are not fulfilled, sand is suppleted at various locations in the coastal system. There are three different locations where nourishment can be placed on. These are:

**The beach zone**: Sand is placed between the M.L.W. and the dune foot (M.S.L. +3 m). In the long run this sand is distributed over the total height of the foreshore slope. The effects of this type of nourishment, volume increment and beach widening, can be observed after its completion. The sand is dumped as high as possible on the beach with two ways. Either by onshore transport (rainbow) or by stock piles (Figures 2-3 and 2-4).

![Figure 2-3 Beach nourishment](image)

![Figure 2-4 Rainbow and stockpiles](image)

**The shoreface zone**: The longshore position of a shoreface nourishment is similar to the position that a beach nourishment would have. Sand is placed under water on the shoreface zone. A dredge that carries the sand (after approaching the coast and reaching a certain depth) releases it within a short time lapse (Figure 2-5). The sand is placed inside the active part of the profile, as high as possible in the cross-shore profile.

The nourishment acts either as a feeder berm or as a breaker bar [Spanhoff and Van de Graaff 2006]. In the feeder berm view, part of the suppled sand is expected to end up landward (only cross-shore transports are considered). In the breaker bar picture the shoreface nourishment acts at least temporarily, as a submerged breakwater that dissipates some of the wave energy. In this case the littoral drift closer to the shore is being reduced and effects like the salient effect (some sand is trapped) or lee side effects in the downdrift direction might occur.
Figure 2-5 Application of a shoreface nourishment, placement of shoreface nourishment

The dune zone: in the dune zone the sand can be placed either on the outer slope of the dune or on the inner slope and/or on the top of the dune. The objective of this type of nourishment is to reinforce and to protect the dune against breaching during storms.

The quality of the borrowed sand material should be similar to the existing one. Nourishment sediment characteristics should not differ from those of the native, pre-existing shoreline (erosion might be the result of a nourishment project when the additional sediment that is added to the cross-shore profile differs much from the naturally present sediment). When coarser material is used, a profile with steeper slopes is expected. On the other hand, when finer material is used a flatter profile is expected. In that case much of the sand material is transported to deep water. Fine grain increases the longshore sediment transport and there will be loss of material. Desalination of the sand material is also important, when nourishments of the dunes (especially on the inner slope of the dune) is applied.
3 Problem definition

3.1 Introduction

Coastal erosion is caused by a combination of various factors both natural and human induced. One of the main factors that are responsible for coastal erosion is the breaking wave. According to CERC formula the longshore sediment transport is generated by the waves that approach the coast under an angle. The main idea is that the longshore sediment transport does not change due to the placement of nourishment. Thus, the volume losses before and after nourishment are the same. This formula however does not take into account parameters like the slope of the beach profile or the properties of the sediments. Moreover, CERC formula does not give any information concerning the transport distribution, which is something important when bars are present.

Figure 3-1 presents the volume evolution in time. Before application of nourishment a trend line that is based on the calculated cross-shore profile volumes can be seen. A nourishment is applied and afterwards a new trend line has been drawn. The two trend lines have the same slope. The slope indicates the sand losses in $m^3/m/year$. When a small amount of sand is placed on the system (beach nourishment), the autonomous behaviour is not expected to change. In the cross-shore direction the hydrodynamics do not change and also in the longshore direction the longshore gradients are not affected. When a shoreface nourishment is applied however the extra volume that is placed on the system is rather big. How the coastal system is been influenced by this disturbance?

![Figure 3-1 The volume evolution in time before and after application of nourishment](image)

3.2 Problem definition

To increase the insight into the effects that the three shoreface nourishments have on the natural systems of the three areas under investigation (Ter Heijde, Katwijk and Noordwijk), an artificial distinction between longshore and cross-shore processes is made (in practice they are always mixed).

In the longshore direction the question is whether or not a shoreface nourishment affects the longshore sediment transport. Shoreface nourishment acts as an artificial reef berm that dissipates the wave energy. This results in the reduction of the wave-driven longshore
currents in the area landward of the nourishment, as well as an increase at the nourishment itself. The net effect is unclear. Sand is trapped in the lee side of the nourishment area (salient effect) and also updrift. In the downdrift direction it is possible that erosion occurs, since there is not sufficient material supply (transport capacity is been reduced).

In most of the areas where nourishment is applied bars are present in the coastal system. Spanhoff and Van de Graaff (2006), state that nature tries to incorporate the shoreface nourishments as a new bar into the natural system. The already existing bars and the ones that are developed due to the nourishment affect the longshore sediment transport (non-linearities in the seabed).

In the cross-shore direction the question is how the sand is redistributed into the natural system after application of nourishment since the hydrodynamics all over the profile are being disturbed. When the extra sand volume is placed in shallow water the waves break at the seaward side of the nourishment. This results in the reduction of the cross-shore currents at the landward part of the cross-shore profile. The landward and seaward cross-shore transports are changing (the onshore sediment transport increases and the offshore sediment transport reduces. Moreover the shoreface nourishment acts as a feeder bar. It is expected that the seaward losses are minor and most of the nourishment sand will gradually end up landward. In this way the higher parts of the profile (beach and dunes) benefit.

To study and analyze the changes that occur in a coastal system when a shoreface nourishment is applied, it is important firstly to determine the study area and secondly to apply a transect by transect analysis. Focusing is the nourishment area, lee-side effects through longshore gradients like the salient effect, can be observed. By extending the study area in the north and south direction by including to the analysis more transects (transects that are located outside the nourishment area) it is possible to define whether the nourishment influences the adjacent areas. Changes that might occur in the updrift and/or in the downdrift direction can be also seen.

Thus, each of the three study areas (area of Ter Heijde, area of Katwijk and area of Noordwijk) is divided into three sub areas; the area north of the nourishment area, the area where the nourishment is applied (nourishment area) and finally the area south of the nourishment area. By this division it is possible to detect various aspects that will help to understand various changes that occur in the natural system after application of nourishment.

It is worth mentioning however, that it is rather difficult to determine the exact boundaries of the area that is influenced by the shoreface nourishment, since a coastal stretch is not only influenced by the placement of extra sand volume but also changes occur due to human interference. The later one should be always taken into account otherwise it is possible to come up with misleading conclusions.

3.3 Main objective of the study

A number of research questions were introduced in the previous section. The aim of this study is to increase the insight into the effects of a shoreface nourishment to the natural system. This is accomplished by trying to find answers to the research questions, which are presented below.

- How does the application of the shoreface nourishment influence the physical processes that occur in a coastal system? How is the autonomous behaviour of the cross-shore profiles volume changing? Has the behaviour of the cross-shore profile...
volume been significantly affected since completion of nourishment (gain or loss of sand volume out of a cross-shore profile)?

- How is the landward part of the profile affected? How do the higher parts of the profile react to the nourishment? Do the beach and dune volume increase after application of nourishment?

- Does the shoreface nourishment result in beach widening?

- What is the behaviour of the longshore sediment transport, after completion of nourishment, in the lee side of the nourishment? Figure 3-2

- Does the nourishment result in downdrift erosion and updrift sedimentation (salient effect)? Figure 3-2

- How does the nourishment affect the onshore versus offshore sediment transport? Figure 3-3

For the Dutch coast, most of the times, the waves come from two dominant directions (oblique waves, Figure 3-4). The shoreface nourishment seems to act, at least temporarily, as a submerged breakwater. The waves break at the nourishment and some of the wave energy is being dissipated. Landward of the nourishment a slightly reduced wave action is present. The waves increase the bed shear stress. The sediment particles, that have been stirred up and been brought into suspension are transported by longshore currents. These currents have been generated due to the oblique incident waves. The littoral drift is decreasing. Volume of sand is being trapped behind the nourishment and an effect such as the salient effect occurs. Accretion in the lee side of the nourishment and erosion in the updrift and downdrift direction occurs.

In the following chapter the methodological approach that aims to find answers to the above mentioned research questions, is been described.
4 Methodological approach

4.1 Data gathering

To find answers to the research questions mentioned in Section 3.3, the marine and coastal analysis package toolbox (UCIT) and its main applications for volume estimation and plotting, are used. The Universal Coastal Intelligence Toolbox (UCIT) has been implemented in the WL|Delft Hydraulics research environment (in Matlab environment). In Matlab routines are created, that process the data extracted from the database to come to basic information that can be used in the analysis process (Van Koningsveld and Lescinski, 2006).

The UCIT program is an information system that uses the available data on coasts, models and coastal state indicators by integrating them into one user platform. Its purpose is to combine quickly this information for coastal zone managers and to focus coast-related research. UCIT consists of a dataset that contains coastal bathymetry data; acquired by the annual JARKUS profile measurements and the additional nourishment monitoring soundings.

The available survey data from the annual JARKUS surveys are from the year 1966 till the year 2006. The additional nourishment monitoring soundings were performed for evaluation of the nourishment projects and also to ensure that the projects were completed according to the design. The later ones are more extended to the seaward direction and in the landward direction they stop at the dune foot position (NAP+3 m). The specific dates of the additional nourishment monitoring soundings are mentioned in Table 4-1.

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Table 4-1 Overview of the nourishment monitoring soundings

The first survey in Ter Heijde was performed in 1998 (Table 4-1), right after the completion of the shoreface nourishment project in 1997. In Katwijk the first survey was performed 13 months (in 2000) after completion of the shoreface nourishment project in 1998-1999. Finally in Noordwijk, the nourishment was completed in 1998 and the first survey was performed almost 25 months later, in 2000.
4.2 Research set-up

The placement of extra volume in the coastal system results in changes in the physical processes. Consequently the behaviour of the cross-shore profiles is changing. These changes might be major or minor, depending most of the times on the magnitude of the extra volume that is placed. When beach nourishments are applied the behaviour of the cross shore profiles does not significantly change (since the volume of the suppled sand is relatively small). On the other hand, after application of a shoreface nourishment, due to the big amounts of sand volume that are used, extra erosion or accretion might be observed. If the analysis is limited only to the nourishment area, changes that might occur outside of this area e.g at the downdrift direction are not detected. Consequently important information, concerning the effects on the behaviour of the cross shore profiles that a shoreface nourishment may have at the far field, are not taken into consideration. In this case the analysis can be considered as insufficient.

Thus in this study the coastal stretches of each area that are going to be studied and analyzed include the transects that are located in the nourishment area, a number of transects that are located south of the nourishment and a number of transects that are located north of the nourishment. The coast is directed from south to north.

A first analysis step is to study the volume evolution in each of the cross-shore profiles of the three study areas. Apart from the total volume evolution, also the dune, beach and shoreface volume evolution is investigated. The study is based on a transect by transect analysis. By this way the changes that occur on the coastal system are better detected and analyzed.

4.2.1 Definition of the total, dune and beach volumes

The total volume is divided in two horizontal subsections that represent the dune and the beach volume. The analysis of the dune volume evolution aims to answer the question whether or not the shoreface nourishment results in an increase of the dune volume. The same holds for the beach zone volume. Figure 4-1 shows four definition sketches for the total, dune and beach cross-shore profile volumes.
A UCIT application that facilitates an automated profile volume analysis is used. The landward, seaward and lower boundaries are determined with respect to the available data. For the total and shoreface profile an arbitrary fixed lower boundary is set at -11 m with respect to NAP (Normaal Amsterdams Peil, local ordnance level).

For the total profile volume the most landward point present in all profiles is chosen as landward boundary. Landward of this point no serious changes occur. The most seaward point present in all transects is chosen as fixed seaward boundary. It is also assumed that seaward of this point no serious changes occur. Moreover, it is preferable for the seaward boundary that a possible position of shoreface nourishment is been incorporated.

For the dune profile volume the landward boundary is the same as above. The seaward boundary is a vertical line that crosses the profile at the point where the dune foot position is (NAP+3 m). The seaward boundary is not fixed for all profiles. The lower plane is at NAP+3 m, which is the dune foot position.

Finally, for the beach profile volume the upper plane is defined at NAP+3 m (dune foot position). The lower plane is the horizontal line that defines the MLW level. Finally the seaward boundary is determined by the point, where the MLW line crosses for the last time the cross-shore (from seaward to landward direction). For each transect this point is different every year since it depends on the MLW level position. The user does not determine the landward boundary since the program by taking the upper, lower and seaward boundary can determine automatically the area of interest.

4.2.2 Definition of the sub sections of beach/dune and of the shoreface

The application of a shoreface nourishment has immediate effects on the shoreface profiles. In order to investigate these effects suitable sub sections are selected. Every section is determined by fixed boundaries that were selected with respect to the developments that were observed in the period 1996-2000 (5 years of observations) for all the three coastal stretches under investigation.

With this approach the sand distribution in the cross-shore profile and in the alongshore direction is investigated. The possibility of lee side effects downdrift of the nourishment, the salient effect and also the effect on onshore and offshore sediment transport are studied.

The beach and dune profile volume is studied as a total; Section 1. The landward boundary for this section is the one that is chosen for the total profile volume. As mentioned before the MLW position is changing from year to year. For reasons of simplification, for every profile...
the most landward and the most seaward x value of the MLW line were chosen from all years. The most landward value is referred as $X_{\text{min MLW}}$ value and the most seaward value is referred as $X_{\text{max MLW}}$ value. The seaward boundary of Section 1 is defined by the $X_{\text{min MLW}}$ value. Section 1 includes the higher parts of the profile, which are the beach and the dune zone volume. Figure 4-2, shows the cross-shore profiles for 4 different years. The boundaries of the Sections for each area (Ter Heijde, Katwijk and Noordwijk) are fixed.

![Different Cross-Shore Profiles for Four Years](image)

**Figure 4-2** Cross-shore profiles (of an arbitrarily transect) for 4 different years

The shoreface profile volume is divided in 5 (sometimes 6) sub sections (Section 2 through to Section 6 sometimes 7). Figure 4-3 gives the definition sketches for all Sections.

![Volume of Section 1 and Volume of Section 2](image)

**a) Volume of Section 1**  
**b) Volume of Section 2**
The landward boundary for Section 2 is the seaward boundary of Section 1. As seaward boundary the $X_{\text{max}}$, $MLW$ value is chosen. Section 2 is a small section. The landward boundary in Section 3 is the seaward boundary of Section 2. The seaward boundary is selected according to the morphologic changes that occur in each of the three areas. The seaward boundary is the lower part of a trough (approximately). The landward boundary for Section 4 is the seaward boundary of Section 3. After a number of observations the seaward boundary is determined (approximately) as the lower part of a bar and/or the starting point of the nourishment. Section 5 determines the area where the nourishment is placed. Thus as landward boundary the starting point of nourishment is chosen and the ending point depicts the seaward boundary. Section 6 includes the seaward part of the nourishment. The end of the nourishment is the landward boundary and the seaward boundary is the seaward boundary that is chosen for the total profile volume.

JARKUS measurements however are not extended enough to cover the entire study area. In the case of Ter Heijde, the seaward part of the nourishment is not included in the measured profile. In the cases of Noordwijk and Katwijk the nourishment area is only partly situated in the measured profiles. Since no complete picture could be drawn from these profiles also the data acquired from the nourishment soundings program are utilized. In these two cases (Noordwijk and Katwijk) the shoreface profile is divided in more sub sections.

4.2.3 Volume changes analysis

The total, dune and beach profile volume changes and the volume changes that occur in each of the sub sections, are studied separately. Two periods are introduced, the pre nourishment
period (the years before application of nourishment) and the post nourishment period (the years after application of nourishment). For each of the three areas the periods differ since the shoreface nourishments were applied on different years. The volume changes during the pre nourishment and post nourishment period are compared. This comparison shows how the autonomous behaviour of the cross-shore profiles is influenced by the application of the shoreface nourishment.

A brief analysis showed that the available dataset from the years 1965-1979, for the three coastal stretches, did not fulfill the requirements of the present study. The yearly measuring range till 1979 covers a rather limited area. In the seaward direction a possible position of shoreface nourishment is mainly outside of the measured cross-shore profile and in the landward direction the dunes are only partly included in the profiles; see Figure 4-4. Therefore the available data from the last 27 years of JARKUS surveys are analyzed (1980-2006) and also the dataset acquired by the nourishment soundings program (for the post nourishment period only), as it has been already mentioned in Section 4.1.

The absolute volumes were scaled with the 2005 volume since in this study the volume changes are investigated. The year 2005 is chosen because is the last year of measurements that JARKUS monitoring program and nourishment soundings program have in common.

To better estimate the volume changes, which occur to the coastal system due to the extra volume of sand that is placed during the application of a shoreface nourishment project, a correction on the total volumes was applied. The corrected volumes were generated by cumulatively subtracting the average nourished volumes from the beach nourishments, per transect, under the assumption that the nourished sand was 100% effective in adding volume to a particular transect. The nourishment volumes are estimated by dividing the total volume of suppled sand with the length of the nourishment. Moreover, it is assumed that the erosion rate was not affected by the beach nourishments (remained unchanged) and if no shoreface nourishment was applied the rate would remain the same (Figure 4-5).

In Figure 4-5, the volume changes for an arbitrarily chosen transect (transect 113.38, Ter Heijde, Figure A.1-5, Appendix A.1) can be seen. The dashed line depicts the corrected values, the vertical green line shows the starting date of the nourishments and the vertical red line corresponds to the ending date of the nourishments (beach and shoreface nourishments).
In 1998 a big jump in the volume is observed. This jump is due to the application of a shoreface nourishment. Moreover, three linear trend lines can be seen. In general the trend lines are based upon the uncorrected volume changes estimations when there is no application of a nourishment, and when there is application of a nourishment they are based upon the corrected volume estimations. In this case for the period 1980-1987, since there was no application of nourishment the trend is based upon the uncorrected values. The same holds for the period 1998-2006. Finally for the period 1988-1997 the trends are based upon the corrected values. The absolute slopes of the linear trend lines indicate the gain or loss of sand volume in $m^3/m/year$ for each of transects of the three study coastal stretches.

![Figure 4-5 Total volume evolution, transect 113.38](image)

### 4.2.4 Definition of the beach width

Beaches are dynamic fast changing systems, which are vitally important to the tourism-oriented economy of The Netherlands. The formation or restoration of recreational beaches is considered one of the objectives of artificial sand nourishments. Coastline retreat and the possible narrowing of the beach are issues of a great importance. To estimate the quality and beach health the concept of the beach width indicator (BWI) is developed, which is based on volumes per unit length. Figure 4-6 gives the definition sketch for the absolute distance and the beach width indicator position.
The beach profile volume is the area determined by a lower, an upper and a seaward boundary. The lower boundary is determined by the MLW level line, the upper boundary is determined by the dune foot level (NAP+3 m) and the seaward boundary is determined by the point where the MLW line crosses for the last time the cross-shore profile (from seaward to landward direction). The vertical distance between the dune foot and the mean low water level divides the volume of sand that is included in this area. ‘H’ denotes this vertical distance; ‘A’ denotes the beach zone volume in $m^3/m$; ‘B’ is a typical distance that represents the beach width indicator (BWI).

\[ H = \text{Height between dune foot and M.L.W.}[m] \]
\[ A = \text{Beach zone (volume)}[m^3/m] \]
\[ B = A / H = \text{magnitude of the BWI}[m] \]

The beach width indicator (BWI) is an indicator that is determined by the total volume of the beach. It is less sensitive to small events such as bank migration, storms, swash etc. Thus it is more stable in time and can give a more accurate indication of the beach health and quality.

The horizontal distance between the seaward (SWB) and the landward boundary (LWB) determines the absolute distance (AD). The absolute distance is not a good measure of the beach quality, since its calculation is based on the MLW line (MLW determines the seaward boundary), which varies from time to time since the area between LWL and HWL is a dynamic area that many changes occur. It is possible that even if a small amount of sand shifts landward or seaward, large changes in the shape of the profile concerning the measured absolute distance will occur even though the volume of the beach profile did not change at all.

The fluctuations on the beach width indicator (BWI) and the fluctuations on the absolute distance (AD) are compared. The BWI is being multiplied by a scaling factor 2 in order to be comparable with the absolute distance ($2 \times B \approx \text{the beach width}$). The result of this comparison indicates whether or not is better to determine the beach width by applying the beach width indicator (if the scattering of the BWI is less than the scattering observed for the definition of the beach width BWI is the most appropriate indicator). In Figures 4-7 a, b and c, typical examples of the comparison between the measured absolute distance (distance between the seaward boundary which is the MLW level and the landward boundary which is the dune foot position), and the beach width indicator (BWI) are presented.
It can be seen from Figure 4-7 the fluctuations of the BWI are not as big as the fluctuations of the AD. Thus, the definition of the beach width in this study, will be based on the BWI.

The concept of the beach width indicator (BWI) differs from the MCL (Momentary Coastline) concept. The differences are that the measured area in the BWI concept is above MLW level while in the MCL concept the measured area includes also a part under the water, and the horizontal distance $B$, contrary to the MCL concept, is not with respect to R.S.P.. The main interest in the BWI concept is to define the beach area (above MLW level) that can be used for tourism and recreation.

In this chapter, the methodological approach was introduced. A transect by transect analysis is applied and the study area is determined. To study the behaviour of the cross-shore profile volume (total, dune, beach and sub sections’ volumes), the volume evolution in time for two periods, the pre and post nourishment period, is analyzed. Finally, the beach health and quality is determined by the beach width indicator. In the following chapters (Chapters 5, 6 and 7) the areas of Ter Heijde, Katwijk and Noordwijk are studied and analyzed.
5 Analysis of the shoreface nourishment in the area of Delfland

5.1 Introduction

In Chapter 5 the effect of the shoreface nourishment that was implemented in Ter Heijde (in Delfland) is analyzed and evaluated. First the overall behaviour of the total, dune and beach profile volume is analyzed in terms of volume changes per year. The shoreface profile volume is divided in sub sections and the profile volume of each sub section is also analyzed in terms of volume changes per year. The pre nourishment and post nourishment volume evolution is studied. Hereafter with the use of linear trend lines that follow the volume changes in years, the gain or loss of sand in \( m^3/m/year \) is calculated. Finally the quality of the beach is defined by applying a beach width indicator (BWI).

5.2 Area under investigation

Ter Heijde is a village in the area of Delfland that is located along the southern part of Holland coast where groynes (reinforcement of the coast) exist, and it is close to the access channel to the port of Rotterdam. The coast orientation is from southwest (SW) to northeast (NE). The characteristics of the coast are a sandy, inlet-free, micro-tidal, wave dominated coast. The waves are mainly approaching the coast from south-westerly (mostly during fair-weather conditions) and north-north-westerly directions. Due to the geometry of the North Sea basin, swell will always approach the Holland coast from northerly directions. The average tidal range is of the order of magnitude of 1.8 m. Moreover, tides along this coast are semidiurnal. Finally the winds along the Holland coast come mainly from the North Sea.

The shoreface nourishment in this area was applied in the year 1997 (between August and November). The suppletion sand was placed between R.S.P. 113.15 and R.S.P. 114.85, between the depth contours N.A.P -5 m and N.A.P. -7 m. The shoreface nourishment was placed in a smooth profile by means of trailer suction hopper dredgers. In alongshore direction the shoreface nourishment was almost homogeneous. The sediment was dumped as high as possible on the shoreface. The total volume of the nourishment sand that was used was approximately 1.000.000 \( m^3 \), which is 600 \( m^3/m \) (\( m^3 \) per longshore metre of coast). The borrow sand was coarser in comparison with the naturally present sediment.

The coastal stretch that is studied and analyzed in this chapter includes 4 transects, located in the part south of the nourishment area, 9 transects, located in the nourishment area, and 3 transects, located in the part north of nourishment. Transects 111.96, 112.21 and 112.44 that also are included in the area of Ter Heijde are not going to be studied since these transects were nourished with a shoreface nourishment in the year 2001. The period after nourishment for these transects is not considered sufficient (only 4 years) for a good estimation of the profile volume behaviour.

The post nourishment period is from the year 1998 (just after the completion of nourishment) until the year 2006 (the last JARKUS survey). For the volume analysis the pre nourishment period in the case of Ter Heijde is determined from the year 1988 until the year 1997 (just before the application of the shoreface nourishment). The year 1988 is chosen as the starting year of the pre nourishment period because of a complication that was observed in the years 1986, 1987.
In 1986 nourishment was applied on the dune zone for dune reinforcement from R.S.P. 107.73 to R.S.P. 115.60. According to the available data the volume of sand that was used for dune reinforcement was of the order of 3,200,000 $m^3$, which is approximately 400 $m^3/m$. This volume was placed in 1986 on the outer slope of the dunes and it was taken off a year later. With trucks the sand was placed on the inner slope of the dunes. The borrow sand, since it was taken from the bottom of the sea, had big portions of salt. Therefore its quality was low (too salty). By initially placing the sand on the outer slope, a big portion of the sand diffused into the sea due to the seaward transport of the sediments. The sand that remained was desalinated. In this way its quality was increased. Nevertheless, the volume of sand that was removed from the outer slope of a dune of a specific transect was not essentially placed on the inner slope of the same transect. Thus it was not possible to determine the exact volume that was finally placed on the dunes.

Moreover, JARKUS surveys were performed during the implementation of this nourishment. In Figure 5-1 a big jump in the volume after 1986 and a different behaviour in the total volume can be seen after 1987. From Figures A.1-1 until A.1-16 in Appendix A.1 it can be seen that this big jump in the volume in some transects occurred after 1986. Thus it was decided the autonomous behaviour to be studied from 1988 until 1997.

In 1970’s an artificial triangle was constructed south of the study area (at R.S.P. 118.50). This artificial triangle, is the Van Dixhoorn triangle and is been yearly nourished (beach nourishments) ever since, in order to retain its (artificial) shape. From R.S.P. 118.50 to R.S.P. 117.15, the total nourishment sand is about 200,000 $m^3$ per year. The longshore sediment transport from southwest to northeast was blocked after the construction of the harbor mole. Consequently the hydrodynamics of the area were affected and the behaviour of the coastal system changed.

In section 5.3 a detailed analysis of the total volume evolution is presented.
5.3 Analysis of the total volume changes

For the analysis of the total volume evolution the methodological approach that is described in Chapter 4 is used. A volume correction was applied where beach nourishments were implemented. In Appendix A.1 the figures that present the volume changes and the trend lines for every period can be seen. Every period is analyzed separately. Figure 5-3 presents the volume evolution for transect 113.94, which is located in the middle of the nourishment area. The dashed line depicts the corrected values, the vertical green line shows the starting date of the nourishments and the vertical red line corresponds to the ending date of the nourishments (beach and shoreface nourishments).
The pre nourishment period is from 1988 to 1997. The post nourishment period is from 1998 to 2006. A big jump in the volume is observed after 1997 (after application of nourishment). Moreover a jump in the volume is observed after 1987 when the dune reinforcement project was implemented in the area.

### 5.3.1 Transect by transect analysis

The coastal stretch is divided in transects located south of the nourishment area, transects located in the nourishment area and transects located north of the nourishment (three sub areas). The orientation of the coast is from south to north. In Figure 5-4 a definition sketch of the total volume is given.

![Figure 5- 4 Definition sketch of the total profile volume](image)

The transect by transect analysis starts with a brief analysis of the transects located at the edges of each sub area. The transects 115.60 and 114.88 for the area south of the nourishment area, the transects 114.69 and 113.19 for the nourishment area, the transects 113.01 and 112.63 for the area north of the nourishment area and also of the transect located at the middle of the nourishment area, transect 113.94, are analyzed.

Figure 5-5 summarizes the slopes of the trend lines for the periods before and after application of nourishment for all the transects that are being studied. The bar plots illustrate the gain (structural accretion) or sand losses (structural erosion) in $m^3 / m / year$. 

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Comparison before and after nourishment for the total volume

Figure 5- 5 Overview of total volume change trends per transect for the pre and post nourishment periods.

**Transect 115.60** (Figure A.1-16, Appendix A.1) is located in the part south southern part of the study area. For the period 1988-1997 there is gain of sand. In the years after nourishment, as it can be clearly seen, the trend remains positive the sand gain in $m^3/m/\text{year}$ has roughly been doubled compared to the 1988-1997 period.

**Transect 114.88** (Figure A.1-13, Appendix A.1) is located in the part south of the study area. For the period 1988-1997, there is gain of sand. In the years after nourishment (1998-2006), the trend remains slightly positive. The magnitude of gain of sand is almost $45 m^3/m/\text{year}$. 

**Transect 114.69** (Figure A.1-12, Appendix A.1) is located at the southern edge of the nourishment area. During the pre nourishment period the trend is negative. After nourishment application (1998-2006), the volume losses in $m^3/m/\text{year}$ have been decreased and the lower rate of erosion is calculated.

**Transect 113.94** (Figure A.1-8, Appendix A.1) is located in the middle of the nourishment area. Before application of nourishment there are sand losses. After application of nourishment (1998-2006), there is an increment of the losses in $m^3/m/\text{year}$ and compared to the period 1988-1997 these losses have been roughly doubled.

**Transect 113.19** (Figure A.1-4, Appendix A.1) is located at the northern edge of the nourishment area. For the period 1988-1997 it can be seen from Figure 5-5, there is loss of sand that also continuous after application of nourishment (period 1998-2006). The losses of sand out of the cross-shore profile (in $m^3/m/\text{year}$) for the post nourishment period have been more than doubled.

**Transect 113.01** (Figure A.1-3, Appendix A.1) is located 180 m north from transect 113.19. During the period 1988-1997 the trend is negative. After the placement of the shoreface nourishment (post nourishment period from 1998 until 2003) the trend is positive and the gain of sand is of the order of $20 m^3/m/\text{year}$ as well.

**Transect 112.63** (Figure A.1-1, Appendix A.1) is located at the northern edge of the study area. The behaviour of the total profile volume of this transect for all periods is almost similar to transect 113.01.

For the pre nourishment period (1988-1997) in the southern part of Ter Heijde from transect 115.60 until transect 114.88, the trend is positive and the gain of sand is approximately of the order of $28 m^3/m/\text{year}$. The rate of accretion is maximum at transect 115.60 and it is decreasing to the north. The trend is negative from transect 114.69 until transect 113.19 that
are located at the southern and northern edges of the nourishment area respectively. The volume losses are continuously increasing to the north transects 114.31 and 114.12, where the rates of erosion reach their maximum value. The trends are negative for the transects 113.01, 112.82 and 112.63 that are located in the part north of the study area.

For the post nourishment period (1998-2006), there is a sand gain in the area south of the nourishment for all transects until transect 114.88 (the last transect just before the nourishment area). From transect 114.69 till transect 113.19 the trend similarly to the period 1988-1997, is negative.

The rates of erosion for transects 114.69, 114.50, 114.31 and 114.12, that are located in the southern half of the nourishment area, have been decreased after the placement of nourishment. For transects 113.94, 113.75, 113.56, 113.38 and 113.19 (located in the northern half of the nourishment area) the sand losses during the post nourishment period, have been increased. The higher sand losses can be seen for transect 113.94 that is located in the middle of the nourishment area. For transects 113.01, 112.82 and 112.63, that are located outside of the nourishment area at its northern part, the trend is positive.

For transect 113.19 the trend line for the period after nourishment is based on the uncorrected values (Figure A.1-4). According to the dataset of the nourishments in the coastal stretch of Ter Heijde two beach nourishments were applied in 2003 and 2004. The total volume was of the order of $440 \, m^3/m$. In general, to make a good estimation of the supplanted sand volume per longshore metre of coast, the length of the shoreface nourishment divides the total volume of sand that is used for nourishment. The same procedure also was followed in this case. These two nourishments however, were applied locally in some transects between R.S.P. 111.96 and R.S.P. 113.19. Thus, the $440 \, m^3/m$ volume of sand is not a representative estimation for the supplanted sand. Moreover, for transect 113.19, which is located at the edge of the nourishment area the volume in the year 2005 was hardly increased, as it can be seen from Figure A.1-4. The corrected values are not representative for the behaviour of the total profile volume after nourishment.

Furthermore, for transects 113.01, 112.82 and 112.63 the post nourishment period is determined by the years 1998 until 2003. After 2003 a number of beach nourishments (some of them locally) were applied in the area. From the available data it is not possible to determine the exact volume of sand that was placed on these specific transects. The volume changes (uncorrected values) after the year 2003 considered to be artifacts (Figures A.1-1 until A.1-3, Appendix A.1). Therefore for these transects, the trend lines used for the post nourishment period, are based upon the volume changes (uncorrected values) occurred between the years 1998 and 2003. It is assumed that if no nourishments were applied after 2003 the slope of the trend would remain the same until 2006.

After application of nourishment the total volume in the study area has been increased. During the transect by transect analysis of the area located south of the nourishment area (transects 115.60, 115.35, 115.10 and 114.88), a significant increment of the magnitude of the sand gain after nourishment, is observed.

In the area of Maasvlakte a harbour mole was constructed in 1970’s. This harbour mole, blocked the sand supply from south to north (the natural sediment transport was blocked). An artificial triangle, the Van Dixhoorn triangle, was constructed northeast of the access channel of the port of Rotterdam and it is being yearly nourished ever since (beach nourishment projects since 1970), in order to reach a new equilibrium in the area. Consequently the area that is located north of the Dixhourn triangle is being implicitly nourished. The effect of the construction of the triangle is gradually shifting to the north.
To determine whether or not the observed increment is due to the construction of the triangle or due to the application of the nourishment, the study area is extended to the south until R.S.P. 118.50. The total area is almost 6 km (from R.S.P. 112.63 to R.S.P. 118.50. Moreover, the pre-nourishment period starts from 1966 and is divided in three sub periods (1966-1969, just before the construction, 1970-1987 and 1988-1997). The post-nourishment period is from 1998 (just after the completion of nourishment) until 2006 (the last JARKUS survey).

For the period from 1966 until 1980 the measured profiles cover a limited area in the landward direction. The analysis of the transects available in the database showed that the differences between the total volume changes, when the landward boundary is defined as in Chapter 4 (Methodological approach) and when the landward boundary is set at -100 m, are minor (almost zero). In the seaward direction the seaward boundary for the profiles measured from 1966 until 1979 is approximately at 700 m from R.S.P.. After 1980 the seaward boundary is approximately at 800 m. A brief analysis showed that the volume changes occurred before 1980, in the section between 700 m and 800 m did not affect the total volume changes.

There were some difficulties in the analysis of transects 115.86 until 118.50. For the year 1970 there are no data available for all transects. For transects 117.00 until 118.50 the first measurement was performed in 1973. For all transects from R.S.P. 115.86 until R.S.P. 118.50, for the years 1983 until 1986, the dunes are only partly included in the measured profile (landward boundary < -100 m). Therefore, the calculated volumes of these years are not included in the analysis. Finally a brief analysis of transects 116.56, 116.62 116.87, 117.75, 118.00, 118.25 and 118.50 showed that the available data were insufficient. The cross-shore profiles of these transects coming up of this analysis were quite misleading. Thus these transects are excluded from the present research. In Appendix A.1, Figures A-17 to A.21 present the volume evolution for transects 115.86, 116.11, 117.00, 117.25 and 117.50

The analysis however showed that the construction of the Van Dixhoorn triangle combined with the annually beach nourishment projects in the area, might have yielded an increment of the total profile volume in a wide area from the triangle north, but the effect was gradually diminishing towards the north (the highest value is observed for transect 115.60 and afterwards the trend is decreasing to the north where at R.S.P. 114.69 becomes negative) and probably ceases to exist near the nourishment area.

If the observed increment in the volume for the transects located south of the nourishment area (transects 115.60, 115.35, 115.10 and 114.88) was due to the construction of the triangle, the figures that present the volume evolution in time should have a more exponential shape, Figure 5-6 a. This hypothetical figure indicates that the above mentioned transects have been gradually affected by the construction of the triangle and the annually nourishment of the area. The sediments of sand placed in the area are gradually transported to the north and increased the volume of the cross-sections of transects. This is not the case however and this can be verified by Figures A.1-13 to A.1-16 in Appendix A.1. Figure 5-6 b, presents the calculated volume evolution for transect 115.60, which is one of transects that appeared to have a major gain of sand during both periods and especially during the post nourishment period.
5.3.2 Longshore sediment transport

For the study area it is assumed that it is a closed system where import of sediments does not occur in the cross-shore direction and thus there are no sand losses seaward and landward of the cross-shore profiles. Moreover it is assumed that in the longshore direction the incoming longshore sediment transport rate $S_{in}$ before and after nourishment is the same (the wave conditions in the years before and after the nourishment, it was also assumed that are approximately the same). The equation that defines the relation between $S_{in}$ and $S_{out}$ is

$$M_{out} = S_{in} - S_{out}$$

where, $M$ = the total erosion or accretion [$m^3/\text{year}$]

$$M = a \cdot d$$

where, $a$ = the observed amount of sand loss or gain [$m^3/m$/year] in a measured transect and $d$ = the distance between two successive transects

The actual values of the incoming and outgoing longshore sediment transport (before and after nourishment) cannot be defined since there are not enough data. It is possible however to estimate the changes in the outgoing sediment transport after nourishment. For reasons of simplification $S_{in}$ assumed to be zero for both periods, so $S_{out} = -M$. The ‘longshore transport’ (with $S_{in}$=0), is defined for each transect. For transect 115.60 that ‘transport’ is $M_{115.60}$, for transect 115.35 is $M_{115.35} + M_{115.60}$, for transect 115.10 is $M_{115.10} + M_{115.35} + M_{115.60}$ and so on. The same procedure is performed for both periods. Figure 5-7 presents the ‘longshore transport’ for both periods. Before nourishment application there was sedimentation in the area south of the nourishment. Moving to the north the ‘longshore transport’ is steadily increasing and this indicates erosion to the area. It can be seen however that the ‘longshore transport’ after application of nourishment has been significantly decreased and sedimentation occurred in the total study area. It is quite possible
that the nourishment acted as a breaker bar that dissipated some of the wave energy and thus the ‘longshore sediment transport’ is being reduced.

![Comparison of the longshore sediment transport before and after nourishment](image)

**Figure 5-7** Comparison of the ‘outgoing longshore sediment transport’ before and after nourishment.

### 5.3.3 Absolute volume analysis

The analysis of the trend lines does not give any indications concerning the increment of the absolute volumes after application of nourishment. Thus a separate analysis of the absolute volumes is following. This analysis is based on the uncorrected volumes in order to estimate the exact amount of volume that remained in the system after placement (the beach nourishment volumes are included).

Figure 5-8 presents the differences of the absolute volume in 1997 and 1999 in comparison with the average nourishment volume ($605 \text{ m}^3/\text{m}$). After placement, the volume in the nourishment area has been increased. The jump in the volume after nourishment is expected to be almost equal to the volume added during the nourishment. The total volume for the southern half of the nourishment area appears an increment of the order of $400 \text{ m}^3/\text{m}$. In the northern half of the nourishment area this increment is amounted over $600 \text{ m}^3/\text{m}$. An increment in the total volume can be seen also in the cross-shore profiles of the transects that are located outside the nourishment area (north and south of it).
Comparison between the nourishment volume and the volume differences of 1997 and 1999 for the total volume

Figure 5-8 Differences of the absolute volume in Ter Heijde between 1997 and 1999 in comparison with the average nourishment volume as indicated.

The absolute volumes were added in order to acquire the global picture of the nourishment site and of the areas north and south of it. From Figure 5-9 it can be seen that before placement for the years 1988 to 1997 there is a small increment in the volume. The jump in the volume that can be seen is amounted approximately 960.000 m³ and the volume of sand that was placed is 1.000.000 m³.

After application of nourishment the total volume of sand was more or less conserved for two years and in the later years (after 2000) as it can be seen also from Figures A.1-4 to A.1-12, Appendix A.1, the total volume at the nourishment area is decreasing almost linearly.

For the transects that are located at the part south of the nourishment it can be seen that the volume since 1988 is increasing almost linearly. For the transects north of the nourishment area the volume remains fairly stable and starts to increasing after 1999.

Figure 5-9 Volume of nourishment area and the areas north and of south of it as a function of time. All volumes are scaled in the 2005 volume.

The volume in the nourishment area, after placement has been increased. The increment in the volume (the jump in the volume is amounted approximately 960.000 m³ which is 96% of the volume of sand that was placed) is observed since nourishment completion. The volume of the jump has largely been conserved in the later years. Nourishment affected the area where it
was placed and probably the part south of the study area, since during the pre nourishment period (1988-1997) the increment in the volume in this part had been less, compared to that in the post nourishment period. A total quantity of about 65% of the initial nourishment volume is still present in the nourishment area (the magnitude of the volume that has been eroded in the nourishment area since 1998 (until 2006) is approximately 350,000 m$^3$ of the 1,000,000 m$^3$ added in the system).

The volume in the part north of the nourishment remains fairly stable with some fluctuations; a more positive trend is observed after 2003, when a number of beach nourishment projects were applied in the area.

5.4 Analysis of the dune volume changes

In this section the dune volume evolution for the coastal stretch that is being investigated, is studied and analyzed. The procedure that is chosen for this analysis is demonstrated in Chapter 4 (Methodological approach). The study period includes two periods. The pre nourishment period, that is from 1988 until 1997 and the post nourishment period from 1998 until 2006 (see Appendix B.1 Dune volume evolution). For the calculation of the linear dune volume change trends the absolute volumes were not corrected. In Figure 5-10 a definition sketch of the dune volume is given (the seaward boundary is determined by the vertical line above dune foot position, NAP+3 m).

![Figure 5-10 Definition sketch for the dune volume](image)

**Transect by transect analysis**

For the two periods (pre nourishment period and post nourishment period) the slopes, of the linear trend lines, that determine the gain or loss of sand in m$^3$/m/year are calculated. Figure 5-11 summarizes the slopes of the trend lines for the two periods before and after application of nourishment all the transects that are being studied. The bar plots illustrate the gain (structural accretion) or sand losses (structural erosion) in m$^3$/m/year. In Appendix B.1, the figures that present the volume changes and the trend lines for every period can be seen.
Figure 5-11 Overview of dune volume change trends per transect for the two periods.

From the Figure 5-11, it can be seen that in the southern half of the nourishment area, before the application of nourishment, the growth rate is decreasing to the north. The sand gain for transect 113.94 (that is located in the middle of nourishment area) is almost one-sixth compared to the sand gain for transect 114.69 that is located in the southern edge of the nourishment area.

For the northern half of the nourishment area, transect 113.75, the rate of accretion is almost equal for the two periods. For transects 113.56, 113.38 and 113.19 the dune zone volume before placement of nourishment, yields a small gain of sediment of the order of 1.2 $m^3/m/year$ can be seen. For the post nourishment period this gain of sediment has been significantly increased. An increasing trend can be observed that growths to the north. The magnitude of the sand that it has been gained is approximately 15 to 20 $m^3/m/year$. The same is observed for transects 113.01, 112.82 and 112.63, that are located outside of the nourishment area, at its northern part. The rate of accretion has been increased.

One might easily be tempted to conclude that the dune volume has been significantly increased due to the application of the shoreface nourishment, as it has been already done in previous studies. However, by observing the Figures B.1-1 to B.1-16 in Appendix B.1 it can be seen that for transects 113.94 (that is located in the middle of the nourishment area) to transect 112.63 (that is located in the northern edge of the domain of our interest) the autonomous behaviour had been already changed before application of nourishment (3 to 4 years before), right after the year 1993 (Figures B.1-1 to B.1-8).

Moreover, for transect 115.60 (that is located in the southern edge of the coastal stretch that is been studied) until transect 114.12 (transect in the southern part of the nourishment area), the dune volume is increasing since 1988 with a constant speed. The autonomous behaviour has not been affected by the placement of the extra volume in 1997. Figure 5-12 presents the trend lines a) for transect 113.19, located at the northern edge of the nourishment area, for the period 1994-2006 and b) for transect 114.69, that is located at the southern edge of the nourishment area, for the period 1988-2006. Both pictures show that the autonomous behaviour of the cross-shore profiles, for the dune zone volume has not been affected by the placement of the shoreface nourishment.
The dune foot position has been also calculated. From Figure 5-13 it can be seen that the progress speed after application of nourishment for most of the transects, has either remained constant or it has been increased. For transects 114.12, 113.75 and 113.56 the progress speed has been decreased after application of nourishment. The dune volume however for these transects has been significantly increased and this is possible due to the increment of the dune height since completion of nourishment.

Figure 5-13 Dune foot trend for the pre and post nourishment period.

For the area south of nourishment, the nourishment area and the area north of nourishment the average growth rate is calculated for both periods.

Table 5-1 presents the average growth rate of the dune foot position (seaward migration) for both periods and the difference between them. For the transects located outside the nourishment area the increment in the growth rate is significant.
Average growth rate in m/year for both periods

<table>
<thead>
<tr>
<th>Areas</th>
<th>Average growth rate in m/year</th>
<th>Increment/Decrement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area south of nourishment</td>
<td>3</td>
<td>4.6</td>
</tr>
<tr>
<td>Nourishment area</td>
<td>2.5</td>
<td>2.8</td>
</tr>
<tr>
<td>Area north of nourishment</td>
<td>2.6</td>
<td>4.3</td>
</tr>
</tbody>
</table>

The dune foot position is presented for four different dates (Figure 5-14). For the year 1988 the most landward position of the dune foot can be seen. For the years 1997 (just before nourishment) and 1998 (just after nourishment) the dune foot position remains almost stable. Finally for the year 2006 it can be seen that the dune foot has shifted almost 40m seaward, compared to its 1988 position.

![Dune foot position](image)

**Figure 5-14 Comparison of the dune foot position for four different years.**

For the dune zone volume, a major increment of the volume is observed, especially in the northern half of the coastal stretch. The dunes are growing already before the shoreface nourishment and the growth rate of the dune foot position has been remained fairly stable for the nourishment area. North and south however of the nourishment area, the growth rate has been significantly increased.

### 5.5 Analysis of the beach volume changes

In this section the beach volume evolution is analyzed. The procedure that is chosen for this analysis is demonstrated in Chapter 4 (Methodological approach). The study period includes two periods: the pre nourishment period which is from 1988 until 1997 and the post nourishment period from 1998 until 2006 (see Appendix C.1 Beach volume evolution). In Figure 5-15 a definition sketch of the beach volume is given (above MLW level and below dune foot position, NAP+3).
Figure 5-15 Definition sketch of the beach volume

Figure 5-16 summarizes the slopes of the trend lines for the two periods before and after application of nourishment. The bar plots illustrate the gain (structural accretion) or sand losses (structural erosion) in $m^3/m^2/year$ in the beach zone volume. The beach volume calculations are based on the uncorrected volumes.

![Comparison before and after nourishment for the beach volume](image)

Figure 5-16 Overview of beach volume change trends per transect for the two periods.

As it can be seen from Figure 5-16, for transects located south of the nourishment, there are differences before and after application of nourishment. For transect 115.60 a negative trend can be observed before nourishment, but after nourishment a sediment gain has been observed. For transects 115.35 and 115.10 high sediment losses during the pre nourishment period can be seen. For the post nourishment period the trend for transect 115.35 remains negative, but the sediment losses have been noticeably decreased. For transect 115.10 the losses have also been decreased and are almost zero. A small increment of the losses, for the period after nourishment, can be observed for transect 114.88, the losses however for the two periods are minor.

For transects 114.69 and 114.12 a negative trend can be seen for the two periods. The sediment losses after application of nourishment are decreased. For transects 114.50, 114.31 and 113.94 the same behaviour is observed. The rate of erosion is increased for the three transects, after nourishment. For transect 113.75 the volume losses for both periods remained rather constant. For transects 113.56 and 113.19 the volume was increasing before nourishment and after nourishment it is decreasing. For transect 113.38 the opposite behaviour can be seen.
Finally for transects 113.01, 112.82 and 112.63, that are located outside the nourishment area at its northern part; the beach volume zone has increased during the post nourishment period. The trends are positive and for transect 112.63 the trend was positive also before nourishment.

The beach zone volume in general, continues to loose the same amount of sand after the application of nourishment and inside the nourishment area for some transects the losses are increased. At the south and north part of the nourishment area however, there was a small gain of sand.

5.6 Analysis of the volume evolution of the Sections 1 to 6

In this section a detailed analysis of the volume changes of the beach/dune volume is applied. Furthermore, the shoreface profile volume is divided in five sub sections. The volume changes of each sub section will be also studied and analyzed. Similarly to the total, dune and beach volume analysis, a transect by transect analysis is applied. The trend lines are based on the uncorrected volumes. In Appendix D.1 the figures that present the volume changes for all Sections and the trend lines for every period can be seen. In Figure 5-17 a definition sketch of the profile volume of Section 1 is given. The boundaries are fixed for all cross-shore profiles of the same transect.

![Figure 5-17 Definition sketch of the profile volume of Section 1](image)

For the total study area, erosion was calculated before application for Section 1. Section 1 (Figure 5-18 summarizes the slopes of the trend lines for the periods before and after application of nourishment) includes the beach zone and the dune zone volume. During the years that followed the nourishment application, until the last measurement in 2006 accretion was observed in Section 1. There is a significant net gain in this Section. From Section 5.5 it is concluded that the magnitude of erosion, in the beach zone volume has been decreased.

Before application of nourishment, positive trends mainly observed for the southern part of the study area. After placement all trends are positive. The sand gain for the northern part of the coastal stretch is major.
An absolute volume analysis based on the uncorrected volumes is also applied for Section 1. Figure 5-19 presents a comparison between the absolute volume (in $m^3/m$), that was gained from 1997 until 1999 and the suppleted sand volume ($605 \, m^3/m$) for the study area. The increment in the volume, at the southern half of the study area, amounts almost $100 \, m^3/m$. For the northern half, the increment in the zone volume of Section 1 is minor and the volume seems to remain fairly stable.

The absolute volumes of Section 1, were added for the nourishment area, for the area south of the nourishment and for the area north of the nourishment area. Figure 5-20 gives the Volume of nourishment area and the areas north and of south of it as a function of time for Section 1.
The volume in Section 1 for the nourishment area before application of nourishment is increasing. After application of nourishment the positive trend remains and the growth speed has been increased. From the Figure it can be seen that three years after nourishment (in 2000), a jump in the volume occurred (from 2000 to 2001) of the order of 80,000 $m^3$. There is a response of the nourishment with a delay of three years. After this jump and in the later years, an increasing positive trend is seen.

For the area south of the nourishment a positive trend that did not change much after nourishment can be seen. For the area north of the nourishment, a slightly positive trend is observed that changes after 2001. In this area a number of beach nourishment projects implemented, thus this change can be mainly attributed to the beach nourishment projects.

Section 1 represents the higher parts of the profile that includes the dune and beach zone volume. In the nourishment area, the response of this Section to the nourishment comes with a three years delay. The nourishment is gradually shifting landward and feeds the higher parts of the profile. In the southern part of the study area the volume in Section 1 was already linearly increasing before nourishment. No changes occurred after nourishment in the zone volume of Section 1 of this area. The volume increment observed after 2001 in the part north of the study area is mainly attributed to the beach nourishment projects that have been applied. It is possible however that this jump in the volume is an effect of the nourishment, since the jump in volume in this area occurred a year after the jump in volume in the nourishment area.

For Section 2 (Figure 5-21, a definition sketch of the profile volume of Section 2) accretion was calculated during the pre nourishment period and after application of nourishment the net gain was increased.
Figure 5- 21 Definition sketch of the profile volume of Section 2

Figure 5-22 summarizes the slopes of the trend lines for the periods before and after application of nourishment.

From Figure 5-22 it can be seen that the highest gain of sand after nourishment, has been calculated for the transects located north of the nourishment area. Sand losses after application are mostly observed for the transects located inside the nourishment area at its northern half (only for transect 114.31, located at the southern half of the nourishment area, the volume losses have been increased after nourishment). This sub section however, is rather small and the changes that occur are minor.

For Section 3 (Figure 5-23, a definition sketch of the profile volume of Section 3) the analysis showed that before application of nourishment the volume was eroding.

Figure 5- 23 Definition sketch of the profile volume of Section 3
Figure 5-24 summarizes the slopes of the trend lines for the periods before and after application of nourishment.

![Comparison before and after nourishment for Section 3](image)

**Figure 5-24 Overview of Section 3 volume change trends per transect for the two periods.**

After application of nourishment the magnitude of erosion has been decreased. For the pre-nourishment period, from transect 114.69, that is located in the southern edge of the nourishment, and moving north a sediment loss can be observed. The greatest losses are observed for transects 113.01, 112.82 and 112.63. Since completion of the nourishment these three transects showed a (great) net gain. The erosion has been significantly decreased and hence the sediment transport.

In Section 4 (Figure 5-25, a definition sketch of the profile volume of Section 4) considerably changes can be observed. Before application of nourishment the southern half of the total coastal stretch was continuously loosing volume of sand. The erosion that was calculated for this part was of the order of 8,000 $m^3/year$. The northern half is gaining sand (10,000 $m^3/year$). For the total coastal stretch, accretion was observed.

Transect 114.88, that is located south of the nourishment area, shows a significant net gain of the order of almost 20 $m^3/m/year$ since completion of nourishment. There is accretion in the southern half of the study while in the northern half erosion is observed. Before application the opposite situation is observed.

![Figure 5-25 Definition sketch of the profile volume of Section 4](image)

Figure 5-26 summarizes the slopes of the trend lines for the periods before and after application of nourishment.
**Figure 5-26** Overview of Section 4 volume change trends per transect for the two periods.

*In Section 5* (Figure 5-27, a definition sketch of the profile volume of Section 5) before application of nourishment a net loss can be observed from R.S.P. 113.19 to R.S.P. 114.88. Gain of sand is only observed in the northern and the southern part of the coastal stretch, on the transects that are not included in the area where nourishment was applied. Since completion of nourishment a similar behaviour can be seen. Before the placement of the extra volume of sand, accretion has been calculated for the total coastal stretch (from transect 115.60 to 112.63). Since nourishment was completed erosion is calculated.

**Figure 5-27** Definition sketch of the profile volume of Section 5 (the area where the nourishment placed in the profile)

Figure 5-28 summarizes the slopes of the trend lines for the periods before and after application of nourishment.
In Section 5 the losses have been considerably increased. To estimate whether or not, the total volume of nourishment has shifted north during the post nourishment period a further analysis is developed. A number of transects, that are adjacent to the coastal stretch at its northern edge, are also analyzed. These transects are transects 111.96, 112.21 and 112.44 that were nourished with a shoreface nourishment in the year 2001. For these transects the post nourishment period is defined by the years 1998 until 2003. After 2003 a number of nourishment projects applied in these transects and the physical processes were changed. Some of these nourishments were placed locally and the exact amount of the suppleted sand can not be defined. The volume changes that occurred after 2003 are artifacts. Thus it is assumed that the trend lines based on the years 1998 until 2003 can indicate more precisely how the shoreface nourishment affected the natural processes of the system. After a brief analysis it was concluded that if no nourishment were applied after 2003 the trends will continue to have the same slope. From Figure 5-28 it can be seen that the nourishment did not shifted in the longshore direction.

For Section 6 (Figure 5-29, a definition sketch of the profile volume of Section 6) it is not possible to come to any conclusions by only analyzing the JARKUS data that are available. The JARKUS survey data that were collected do not cover the part seaward of the nourishment. After completion of nourishment in 1998, extra monitoring soundings were performed. The data acquired from the monitoring campaign were also analyzed in the same way as the JARKUS survey data. It was concluded that the two shoreface nourishment survey data were comparable (gave almost the same results). Thus for the analysis of Section 6 the data from the monitoring sounding program were used.
There are however no available data for the pre nourishment period. Thus it is not possible to compare the two periods and come up with conclusions concerning the autonomous behaviour and how the shoreface nourishment affected it. It is possible however, as it has been already seen in Section 5, that the trend was also negative at the pre nourishment period and that the losses were increased after application of nourishment.

Figure 5-30 summarizes the slopes of the trend lines for the period after application of nourishment.

From Figure 5-30 it can be clearly seen that in this Section, for the post nourishment period, all transects have negative trends. The part seaward of the nourishment is eroding after application of nourishment. The negative trend reaches its higher value (transect 113.38) and then it starts decreasing to the north. The sand losses are significant, of the order of $13 \text{ m}^3 \text{ /m /year}$.

Table 5-2 summarizes the calculated accretion or erosion (in $\text{ m}^3 \text{ /year}$) for each section for both periods. It can be clearly seen that there was a significant accretion for Section 1 after placement, while at Section 5 where the nourishment is located there is major erosion which is normal. The volume of the nourishment on the shoreface can be considered as a disturbance of the equilibrium profile, thus coastal processes (longshore and cross-shore) try to flatten out this disturbance. Therefore the system diffuses the extra sand and erosion occurs.
The shoreface profile volume was divided in sub sections in order to obtain a clearer picture of how the distribution of sand occurs and how the shoreface nourishment affects the longshore and cross-shore sediment transport.

A plan view of the total study area is given in Figures 5-31 and 5-32. Figure 5-31 presents the sediment gain or losses in $m^3/m/\text{year}$ in every Section after nourishment. There is no any information about the behaviour of the system concerning the pre nourishment period for Section 6. It is believed however that also erosion occurred in the area before application of nourishment. Figure 5-32 presents the sediment gain or losses in $m^3/m/\text{year}$ in every Section as an effect of nourishment.

In Section 5, where the nourishment was placed, the losses have been significantly increased. A big amount of sand volume was placed on the system and the nature reacted to this intrusion by diffusing the extra volume of sand relatively fast. The magnitude of the volume of sand that was lost out of this section (for the nourishment area) from 1998 until 2006, is almost the 44% of the volume that has been added during the placement. This volume was distributed on the other Sections landward of the nourishment. The volume of sand however, that was gained in the landward part of the nourishment site is almost the 51% of the nourishment volume added in the system. This shows that the 7% of this extra volume that was gained is probably due to the decrement of the longshore sediment transport, or due to the Aeolian sediment transport from the north, that probably resulted in the dune volume increment.

In the case of Ter Heijde, sedimentation already occurred before 1997, south of the nourishment area. This sedimentation however has been increased since application of nourishment and the longshore sediment transport has been decreased. Thus, it is possible that the decrement of the longshore sediment transport is the result of the nourishment.

Sedimentation also occurred in the northern part of the study area (transects 113.01, 112.82 and 112.63) downdrift of the nourishment, mostly in the higher parts of the profile. Since the eroding nourishment volume distributed landward of the nourishment site, the accretion in the northern part of the study area cannot be clearly attributed to the nourishment. This accretion is also possible the effect of the beach and shoreface nourishment projects applied in the later years, in the area and to the north.

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Table 5-2 The calculated Accretion/Erosion for each section
### Gain or loss of sediment in m³/m/year after application of the shoreface nourishment

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<th>Seaward Boundary</th>
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<th>Section 5</th>
<th>Section 4</th>
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**Figure 5-31** Sediment gain or losses in $m^3/m/year$ for each Section after application of nourishment.

### Gain or loss of sediment in m³/m/year - effect of the shoreface nourishment

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**Figure 5-32** Sediment gain or losses in $m^3/m/year$. The effect of nourishment in each Section (For Section 6 there is not any information for the pre-nourishment period, thus it is not possible to determine the effect of the shoreface nourishment).
5.7 Definition of the beach quality

In Section 5.7, the health and quality of the beach after application of nourishment is investigated. The main interest is if and how the volume of the area between the dune foot position and the MLW level line is affected by the shoreface nourishment. A beach width indicator is applied (BWI) and is determined with respect to the landward boundary (LWB, which is the dune foot position and it is different for each cross-shore profile) and not with respect to R.S.P. which is a fixed boundary.

The growth or decrement rate of the BWI for the pre and post nourishment periods is calculated, Figure 5-33. Figures E.1-1 to E.1-16 in Appendix E.1 present the changes of the beach width indicator per year for each transect.

![Beach Width Indicator](image)

**Figure 5-33 Beach Width Indicator trend for the pre and post nourishment period.**

For the period before application of nourishment the surveys indicate for most of the transects a negative trend. BWI is a length that is decreasing. Only for transects 113.38, 113.01, 112.82 and 112.63, that are located in the part north of the coastal stretch, the BWI zone volume is increasing. The growth rate is approximately of the order of 1 to 1.5 m/year. After application of nourishment for the transects that are located in the most southern part of the coastal stretch, the decrement rate has been reduced. For the transects that are located inside the nourishment area the BWI is remained constant or decreased. Finally, for the transects located at the northern part of the study area the BWI has been increased.

Comparing now the BWI length for four different periods (Figure 5-34) 1988, 1997, 1998 and 2006, a decrement can be seen. In 1988 the BWI for most of the transects appear to have its highest value. That is due to the beach nourishment applied a year earlier (no correction is applied for the beach volume). At the southern part of the coastal stretch the BWI from 1988 to 1997 (just the year before application of nourishment), has significantly changed. In 1997 the value of the BWI is higher compared to the value in 1988. Comparing now the 1997 with the 1998 BWI it can be seen that there are no significant changes. In 2006 however there is an decrement of the BWI. From R.S.P. 115.60 to R.S.P. 113.56 the BWI, compared to the year 1988, has been decreased almost 20m.
Figure 5-34 Comparison of the BWI position for four different years.

It is observed that the nourishment did not affect the beach width. The fluctuations occurring in BWI in the nourishment area, since application of nourishment, are almost of the same magnitude as the ones seen for the same transects, before application. The dunes benefited faster and more than the beach from the nourishment and are growing while the beach is not becoming wider and in some cases it also became narrower.

5.8 Conclusions

In Ter Heijde, a shoreface nourishment was applied in the year 1997 (between August and November). The total volume of the nourishment sand that was used was approximately 1,000,000 m$^3$, which is 600 m$^3/m$. The evolution in time of the total volume, has been studied. The erosion rate in the nourishment area remained the same after placement. The nourishment did not affect the autonomous behaviour of the area, while at the updrift and downdrift directions there was a significant increase of the volume. The longshore sediment transport processes have been affected and they have been reduced. In the cross-shore direction, there is an increase in the onshore transport of the sediments. The dune volume is increasing before nourishment application and this increase continuous after application of nourishment. It is possible however, that south of the nourishment, the increase rate of the dunes was affected by the application of nourishment. The beach volume did not change and also the beach width was not affected by the nourishment.

In Chapter 3 Section 3.3, a number of basic questions have been formulated. In this Section the answers to these research questions are presented.

**How does the application of the shoreface nourishment influence the physical processes that occur in a coastal system?** How is the autonomous behaviour of the cross-shore profiles volume changing? Has the behaviour of the cross-shore profile volume significantly affected since completion of nourishment (gain or loss of sand volume out of a cross-shore profile)?

- For the nourishment area, the losses during the pre nourishment period are almost of the same magnitude as the losses calculated during the post nourishment period. The rate of erosion did not change after placement. This indicates that the behaviour of the cross-shore profile volume inside the nourishment area was not actually affected by the nourishment. The cross-shore profiles of each of the transects, located inside the nourishment area, appear to have changes in their sediment content (volume increment/decrement).
• The shoreface nourishment seems that it has affected the southern part of the coastal stretch (transects 115.60, 115.35, 115.10 and 114.88). It is not clear where the nourishment effect stops. It is possible that the effect of nourishment in the southward direction do not stop in R.S.P. 115.60 (the southern edge of the study area of the present research) but is extended until transect 116.11. That is almost 1.4km south from the southern edge of the nourishment area. Further analysis that includes more transects might lead to more concrete results.
• The area south of the nourishment area was probably not been affected by the changes that occurred in the natural coastal system due to the construction of the Van Dixhoorn triangle. It is important however to mention, that during the pre nourishment period the behaviour of the cross-shore profile volume of the area south of the nourishment was different of the behaviour of the cross-shore profile volume of the nourishment area. Why the area south of the nourishment was accreting before application while the area that the nourishment was placed was eroding is a question that has not be handled in the present research.
• In the northern part it is not clear whether or not, the natural processes were mostly affected by the shoreface nourishment that applied between transects 114.69 and 113.19 in 1997 or by the beach and shoreface nourishments applied between transects 107.40 and 112.50 (2002, 2003). This area was eroding before application. After nourishment there is a significant accretion. This accretion was mainly observed on the higher parts of the profile.
• The dune reinforcement in 1986-1987 probably affected the natural coastal stretch, since a big volume of sand was placed on the system. From Figures A.1-1 to A.1-16, Appendix A.1, it can be seen that the trend line after 1988 has changed. How this dune reinforcement project affected the study area needs more research.

How has the landward part of the profile been affected? How do the higher parts of the profile react to the nourishment? Has the beach and dune volume been increased after application of nourishment?

Does the shoreface nourishment result in beach widening?

• The higher parts of the profile do not have a direct response of the nourishment. There is a delay of three years.
• The nourishment did not result in the increment of the dune volume in the nourishment area. It is possible however that the nourishment resulted in the increment of the speed of the growth rate in the areas north and south of the nourishment. The volume of the dunes, north of the nourishment have been significantly increased. This increment can also be attributed to the Aeolian (wind-induced) sediment transport, since is the basic mechanism for the formation of the dunes.
• The beach volume in total was slightly increased since the application of nourishment.
• Shoreface nourishment did not result in beach widening.

What is the behaviour of the longshore sediment transport, after completion of nourishment, in the lee side of the nourishment?
How the nourishment affects the onshore versus offshore sediment transport?
Does the nourishment result in downdrift erosion and updrift sedimentation (salient effect)?
• The outgoing longshore sediment transport has been decreased due to the volume of sand trapped landward of the nourishment. In the downdrift direction a significant sedimentation is observed. Moreover in the updrift direction sedimentation also occurred.

![Oblique waves](image)

**Figure 5-35 Accretion/Erosion due to the longshore and cross-shore sediment transport processes**

Figure 5-35 shows the calculated accretion/erosion as an effect of the nourishment, due to the longshore and cross-shore sediment processes. What it would have been expected, is sedimentation landward of the nourishment, while in the updrift and downdrift direction, erosion would occur (salient effect, Figure 3-4, Section 3.3). This however is not what actually occurred, since there is accretion updrift and downdrift of the nourishment (Figure 5-35). The effect that occurred is symmetrical and probably due to the same mechanism.

A possible explanation is that due to the nourishment a trough was created landward of it (Section 4, Figure 5-32, from R.SP.114.32 to R.S.P 112.63). The sediments from this trough moved to the south and increase the volume of the area south of the nourishment. Thus we observe increment in the updrift direction. In the downdrift direction also sedimentation occurred. It is possible that part of the nourishment volume shifted to the north and landward.

Moreover, it is quite possible that what is observed in Figure 5-35 is the opposite effect of the salient effect. The oblique waves from SW break at the nourishment. That might give a surplus of the water (extra water) in the nourishment area with respect to the neighbouring areas (set-up). Due to that, there are longshore currents in the north direction and in the south direction. Thus there is sedimentation in the updrift direction. The same mechanism is considered to be responsible for the accretion in the downdrift direction (NE waves). Since the observed accretion in the downdrift direction is more (compared to the sedimentation in the downdrift direction) it is possible that the part northof the study area has been influenced by the beach and shoreface nourishments applied to the neighbouring area (to the north).

• The nourishment volume is a disturbance of the equilibrium profile. Sand is being moved up or down the profile without leaving the profile. The onshore sediment transport seems to have been increased and the nourishment sand is gradually shifting landward. Feeding processes of the higher parts of the profile are observed.
6 Analysis of the shoreface nourishment in the area of Katwijk

6.1 Introduction

In Chapter 6 the effect of the shoreface nourishment that was implemented in the area of Katwijk is analyzed and evaluated. The available data collected during the JARKUS surveys do not cover the entire area of interest. The nourishment was placed outside the yearly measuring range. The first complete picture of the entire nourishment area can be drawn only by using the monitoring survey data collected almost a year after completion of nourishment. From the analysis of this data it is not possible to obtain information relating to the autonomous behaviour of the cross-shore profiles. Moreover, for the post nourishment period, two years of information that concern the effects of the nourishment on the natural coastal stretch are missing. Thus, in the present research, for the study and analysis of the Katwijk nourishment the JARKUS survey data is utilized.

The fact that the amount of data is insufficient adds complexity to the process of analyzing the area of Katwijk, in contrast to the analysis that was performed for the area of Ter Heijde. In the latter area the nourishment volume was included in the study area. The basic research question of this study, which concerns the behaviour of the cross-shore profile volume before and after nourishment, cannot be handled. On the other hand, useful and interesting conclusions can be derived and also used for further research and study, such as the response of the nourishment and how the nourishment volume approximately affects the study area (i.e. the nourishment volume is shifting landward, cross-shore sediment transport etc.). Therefore, the Katwijk nourishment is studied and analyzed similarly to the Ter Heijde nourishment.

The overall behaviour of the total, dune and beach profile volume is analyzed in terms of volume changes per year. The shoreface profile volume is divided in sub sections and the profile volume of each sub section is also analyzed in terms of volume changes per year. For the analysis of these sub sections, the survey data collected by the monitoring program is also used. The pre nourishment and post nourishment volume evolution is studied. Hence, with the use of linear trend lines that follow the volume changes in years, the gain or loss of sand in $m^3/m/year$ is calculated. Finally the quality of the beach is defined by applying a beach width indicator (BWI).

6.2 Area under investigation

Katwijk, which is in the area of Rijnland, is a popular coastal resort and former fishing village in the western part of the Dutch coast. It has a 2 km long boulevard with various facilities. The length of the beach is 4.5 km. The coast orientation is from southwest (SW) to northeast (NE). The characteristics of the coast are a sandy, outlet-free, micro-tidal, wave dominated coast. The waves are mainly approaching the coast from southwesterly (mostly during fair-weather conditions) and north-north-westerly directions.

The shoreface nourishment in this area was applied in the year 1998-1999 (between September 1998 and February 1999). It was placed between RSP 87.50 and RSP 89.50, between the depth contours N.A.P -5 m and N.A.P. -7 m, by means of trailer suction hopper dredgers that dumped the sediment as high as possible on the shoreface. The total volume of the nourishment sand that was utilized was 760.000 $m^3$ (which is about 400 $m^3$ per longshore
metre of coast). The borrowed sand was relatively coarser in comparison with the native sediment. The median grain size of the borrowed sediment was almost two times the median grain size of the native sediment.

In this chapter, the coastal stretch includes the transects from R.S.P. 92.00 to R.S.P. 89.75 south of the nourishment area, the transects from R.S.P. 89.50 to R.S.P. 87.50, located in the nourishment area, and the transects from R.S.P. 87.25 to R.S.P 85.00, located north of the nourishment (Figure 6-1) is been studied.

In 2002 (from February 2002 until December 2002) a second shoreface nourishment applied in the southern part from RSP 97.00 to RS.P 91.00. The total volume of the suppletion sand that was used was 3.000.000 m$^3$, which is 500 m$^3/m$. The study and analysis of the effects of this shoreface nourishment is beyond the scope of the current research.

The period before nourishment application is chosen as the years from 1980 until 1999. The post nourishment period includes the years from 1999 until 2006 (the nourishment was completed on February 1999 and JARKUS surveys performed five months later, thus the starting year for the post nourishment period is the year 1999).

![Figure 6-1 Overview of JARKUS transects in the area of Katwijk](image)

### 6.3 Analysis of the ‘total volume’ changes

Analogously to the nourishment in the area of Ter Heijde, the volume evolution in each of the transects has been studied according to the methodological approach that is described in Chapter 4.

In the Katwijk nourishment area no nourishment projects have been applied before the shoreface nourishment of 1998-1999. In the area south of the nourishment (transect 92.00 to transect 91.00) however, a beach nourishment in 1996 (from R.S.P. 93.50 to R.S.P 91.00, 400.000 m$^3$ of sand were placed) and a shoreface nourishment in 2002 have been applied. The
nourishment area is part of a dynamic system that can be classified as a two breaker bar system. There is an offshore migration of these bars that have a 4 year (pattern) repeat cycle. Volume correction is not applied since the nourishment volume is not included in the study area. In Appendix A.3 Figures A.3-1 to A.3-29 present the ‘total volume’ changes per year and the trend lines for the pre nourishment and post nourishment period. Every period is analyzed separately. The trend lines for both periods are based on the uncorrected values.

Figure 6-2 presents the volume evolution for transect 88.50 which is located in the middle of the nourishment area. The dashed line depicts the corrected values, the vertical green line shows the starting date of the nourishments and the vertical red line corresponds to the ending date of the nourishments.

![Figure 6-2 ‘Total volume’ evolution](image)

The pre nourishment period from 1980 to 1997 can be seen. The post nourishment period is from 1998 to 2006. A jump in the volume is observed after 1997 (after application of nourishment) though the nourishment volume is not included in these measurements (JARKUS measurements do not cover the entire nourishment area).

### 6.3.1 Transect by transect analysis

The coastal stretch that is being analyzed, is divided in transects located south of the nourishment area, transects located in the nourishment area, and transects located north of the nourishment area (three sub areas). Though the nourishment sand volume was placed outside in the seaward boundary of the so called nourishment area, for simplification in this study, this area will continue to be referred as the nourishment area. In Figure 6-3 a definition sketch of the total profile volume is given.
The transect by transect analysis starts with a brief analysis of the transects located at the edges of each sub area. The transects 92.00 and 89.75 for the area south of the nourishment area, the transects 89.50 and 87.50 for the nourishment area, the transects 87.25 and 85.00 for the area north of the nourishment area and also of the transect located at the middle of the nourishment area, transect 88.50, are analyzed.

Figure 6-4 summarizes the slopes of the trend lines for the periods before and after application of nourishment for all the transects that are being studied. The bar plots illustrate the gain (structural accretion) or sand losses (structural erosion) in $m^3/m/year$ from R.S.P. 92.00 to R.S.P. 85.00.

Transect 92.00 (Figure A.3-29, Appendix A.3), is located in the southern part of the study area. During the pre nourishment period a gain of sand can be seen from Figure 6-4. Since completion of nourishment the trend remains positive. The magnitude of the gain of sand has been increased.

Transect 89.75 (Figure A.3-20, Appendix A.3), is located in the southern part of the study area. There is a small gain of sand during the pre nourishment period. After application of nourishment a significant increment is observed.

Transect 89.50 (Figure A.3-19, Appendix A.3), is located in the southern edge of the nourishment area. Before application of nourishment a small gain of sand is observed for this transect. After application of nourishment the trend line is still positive and the total zone volume has been significantly increased. The gain of sand is of the order of $25 \ m^3/m/year$. 

Figure 6-4 ‘Total volume’ trend for the pre and post nourishment period.
Transect 88.50 (Figure A.3-15, Appendix A.3), is located in the middle on the nourishment area. Before application of nourishment a small gain of sand can be seen. The trend line however, after application of nourishment is negative. The sand losses are of the order of 17 m$^3$/m/year.

Transect 87.50 (Figure A.3-11, Appendix A.3), is located in the northern edge of the nourishment area. For both periods a positive trend is observed. During the post nourishment period the magnitude of the sand that has been gained, has increased.

Transect 87.25 (Figure A.3-10, Appendix A.3), is located 250 m north from transect 87.50. During the pre nourishment period a sand gain has been calculated. After application of nourishment the magnitude of the sand gain has been decreased.

Transect 85.00 (Figure A.3-1, Appendix A.3), is located in the northern edge of the study area. The trend for both periods is positive. After application of nourishment however the magnitude of the sand that is gained has been decreased (this decrement is almost 20 m$^3$/m/year).

Before application of nourishment, for transect 86.00, (Figure A.3-5 Appendix A.3) the trend is negative. This transect is located in the area where an outlet with a sluice exists. The horizontal longshore position has shifted due to a reconstruction of the outlet. This possible explains the behaviour that is observed. In general the ‘total volume’ is accreting. On the part southof the study area (from transect 92.00 to transect 89.75) the volume of the sand that is gained during the pre nourishment period is fluctuating from transect to transect. The highest value is observed for transect 91.75 (26 m$^3$/m/year). Concerning the nourishment area (from transect 89.50 to transect 87.50), the transects that are located in the middle of the nourishment area, transects 88.50 and 88.25, appear to have a gain of sand of the order of 2-3 m$^3$/m/year, while for transect 88.00 the trend is negative (losses of the order of 3 m$^3$/m/year). For the transects that are located in the northern part of the study area, the magnitude of the sand that is gained during the pre nourishment period is between 10 and 30 m$^3$/m/year.

After application of nourishment, at the southern edge of the study area, the trend is positive. Moving to the north however, the trend becomes negative. Inside the nourishment area, for transects 88.50, 88.25 and 88.00 the trends are negative. The trends are positive for the rest of the transects that are located inside the nourishment area. Moving northward from transect 87.75 the positive trend is decreasing until transect 86.75 where it becomes negative. From transect 86.75 the sand losses are increasing. For transects 85.25 and 85.00 that are located in the northern edge of the study area the trend remains positive as it was before application of nourishment, but the gain of sand has been decreased.

The ‘total volume’ in the area of Katwijk has been decreased since completion of the shoreface nourishment (before application, accretion of the order of 70,000 m$^3$/year have been calculated, while after there was erosion of the order of 10,000 m$^3$/year). For the transects located at the southern edge of the study area, the changes in the behaviour of the total profile volume have started before the application of the shoreface nourishment. These transects seem to be part of a different coastal system than the one of the nourishment area. This coastal stretch (from transects 92.00 to 91.00), has probably been affected by the 1996 beach nourishment and later by the 2002 shoreface nourishment. From Figures A.3-25 to A.3-29 in Appendix A.3, it can be clearly seen that the behaviour of the total profile volume for these transects, had changed right after the 1996 beach nourishment and then after the 2002
shoreface nourishment. Thus the observed changes cannot attributed to the shoreface nourishment of 1998-1999.

For the transects located closer to the southern edge of the nourishment (transect 91.75 to transect 89.75) it can be said that they have been probably affected by the nourishment. There is a significant decrement of the volume after placement. The losses have been increased and the behaviour of the total profile volume has changed.

### 6.3.2 Longshore sediment transport

In the case of Ter Heijde the study area was treated as a closed system where no seaward sediment losses occurred and also there was not any sediment import in the cross-shore direction. In the Katwijk case however, due to the fact that the nourishment volume is located outside the study area, it must be taken into account that there is a significant cross-shore sediment transport. The nourishment sand is shifting landward and feeds the study area. The cross-shore and longshore sediment transport cannot be studied separately in this case. The same analysis as in Ter Heijde is also applied in Katwijk. It is not expected however to come up with accurate conclusions that concern the outgoing sediment transport.

![Comparison of the longshore sediment transport before and after nourishment](image)

**Figure 6-5 Comparison of the ‘outgoing longshore sediment transport’ before and after nourishment.**

Figure 6-5, shows a decrement from south to north for the ‘outgoing longshore sediment transport’, during the pre nourishment period. For the post nourishment period it can be seen a fluctuation in the (hypothetical) ‘longshore transport’. Southern of the nourishment area (from transect 90.75 to transect 89.75), there is a significant increment. The same is observed for the area north of the nourishment. This indicates erosion in the downdrift and updrift direction. If there was no cross-shore sediment transport (the sand of the nourishment is shifting landward), the observed erosion could be attributed to the presence of the shoreface nourishment. Figure 6-5 shows that after nourishment the outgoing sediment transport has been increased.

### 6.3.3 Absolute volume analysis

The analysis of the trend lines does not give any indications concerning the increment of the absolute volumes after application of nourishment. Thus a separate analysis of the absolute volumes is following. Figure 6-6 presents a comparison between the absolute volume (in
that was gained from 1997 until 2000 and the supplanted sand volume (400 m$^3$/m$^3$) for the study area.

From Appendix A.3, Figures A.3-11 to A.3-17, shows that for transect 87.50 to transect 89.00 (located inside the nourishment area), after application of nourishment a jump in the volume occurred of the order of 150 to 400 m$^3$/m (for each transect the value is different).

After application of nourishment the ‘total volume’ for most of the transects inside the nourishment area, has been significantly increased. At the northern half of the nourishment area the total gain of sand, right after nourishment application, amounted over 200 m$^3$/m and for some transects this gain is over 300 m$^3$/m. Moreover, for transect 87.00 to transect 86.25 a volume decrement is observed a year after completion of nourishment. The amount of the decrement is approximately 100 to 200 m$^3$/m. The ‘total volume’ in the southern part of the study area has been mainly decreased.

![Comparison between the nourishment volume and the volume differences of 1997 and 2000 for the total volume](image)

**Figure 6-6 Differences of the absolute volume in Katwijk between 1997 and 2000 in comparison with the average nourishment volume as indicated.**

Dissimilarly to the case of Ter Heijde, the nourishment sand volume, in the Katwijk case, was placed completely outside the yearly measuring range. Figure 6-7 however provides a clear picture regarding the response of the nourishment. It can be seen that the effect of the shoreface nourishment is quickly visible in the survey that was performed a year after completion of nourishment (in 2000). The ‘total volume’ has been increased in the area where the nourishment applied. This implies a quick response of the nourishment.

The absolute total volumes were added for the nourishment area, for the area south of the nourishment area and for the area north of the nourishment area. Figure 6-8 gives the volume of nourishment area and the areas north and of south of it as a function of time.
It can be seen from Figure 6-7 that in the nourishment site, a jump in the volume occurred after application of nourishment. This jump is of the order of $440,000 \text{ m}^3$ (approximately). The volume in the nourishment area after placement has been increased. The volume of sand that placed in the system during the nourishment project was $760,000 \text{ m}^3$. Almost 58% of the nourishment sand shifted landward. Since the nourishment sand volume was placed completely outside the yearly measuring range, this jump might indicate that there was a quick response of the nourishment. Moreover, after placement the fluctuations of the total profile volume have been significantly decreased and the volume shows a more stable behaviour. The nourishment volume has partly shifted landwards and increased the ‘total volume’. Since 2000, (after the jump in the volume) the ‘total volume’ in the nourishment area has increased by another $90,000 \text{ m}^3$. The volume of the jump has largely been conserved in the later years, though the erosion rate for transects 88.50, 88.25 and 88.00 has been significantly increased.

For the area south of the nourishment a jump in the volume can also observed. This jump occurred after 1996, when a beach nourishment project implemented from 93.50 to 91.00. The nourishment sand was of the order of $400,000 \text{ m}^3$. The volume that placed between R.S.P. 92.00 and R.S.P. 91.00 is approximately $200,000 \text{ m}^3$. The jump is approximately $300,000 \text{ m}^3$ which is more than the extra sand. This possible indicates that there was sediment transport from the south. For the northern part it can be seen that after nourishment the volume is decreasing almost linearly but still it is higher compared to the pre nourishment period. For the area north of the nourishment the changes in the behaviour of the total profile volume after placement are big. The volume is eroding after application for most of the transects.

### 6.4 Analysis of the dune volume changes

In this section the dune volume evolution is studied and analyzed. The analysis of the dune volume changes is according to the Methodological approach that is analyzed in Chapter 4. The study period includes, similarly to the ‘total volume’ analysis, two periods. The pre nourishment period, that is from 1980 to 1998 and the post nourishment period from 1999 until 2006 (see Appendix B.3 Dune volume evolution). The calculation of the linear dune
volume change trends is based on the uncorrected volumes. In Figure 6-8, a definition sketch of the dune volume is given (above dune foot position, NAP+3 m).

![Figure 6-8 Definition sketch of the dune volume](image)

**Transect by transect analysis**

In Figure 6-9 the slopes of the trend lines for both periods can be seen. By observing the following figure it can be clearly seen that for the two periods the dune zone volume is increasing. Starting the analysis from the nourishment area it can be observed that for the southern part of the nourishment area the gain of sand for the two periods is similar. Moving north however, the magnitude of the sand gained during the post nourishment period is much higher (between 15 and 25 m$^3$/m/year) compared to the magnitude of the sand gained during the pre nourishment period (between 2 and 5 m$^3$/m/year). The dunes in the northern half of the nourishment area are accreting.

![Figure 6-9 Dune volume trend for the pre and post nourishment period.](image)

For the southern part of the study area, from R.S.P. 92.00 to R.S.P. 89.75, before application of nourishment the gain of sand is of the order of 7 to 15 m$^3$/m/year. After application of nourishment the trend remains positive.

For the northern part of the study area, from R.S.P. 87.25 to R.S.P. 85.00, before application of nourishment the positive trend is decreasing as moving north. It becomes negative for transects 86.25 and 86.00 and then becomes positive again and it is increasing until it reaches its highest value for transect 85.00, which is located at the northern edge of the study area.
After application of nourishment, from R.S.P. 87.25 to R.S.P. 85.00, the positive trend is decreasing to the north direction. It becomes zero for transect 86.25 and then it starts increasing again.

The highest increment in the volume can be seen for the transects that are located at the northern half of the nourishment area. Moreover by observing the Figures B.3-11 until B.3-19 (all transects that are included in the nourishment area) it can be clearly seen that the trend is changing right after the application of nourishment.

The dune foot position has been also determined. Figure 6-10 presents the trend for the dune foot position for the pre and post nourishment periods.

In the part south of the study coastal stretch the progress speed for both periods is almost constant. For the transects that are located in the nourishment area the progress speed during the post nourishment period has been significantly increased. The seaward migration that is observed is from 1 to 3 m/year. Before application of nourishment the growth trend was of the order of 0.5 to 1 m/year. For transects 86.75, 86.50 and 86.25 (located at the part north of the study area), a landward retreat is observed of the order of 1 m/year during the post nourishment period.

For the area south of nourishment, the nourishment area and the area north of nourishment the average growth rate is calculated for both periods.

Table 6-1 presents the average growth rate of the dune foot position (seaward migration) for both periods and the difference between them. Increment in the growth rate is only observed in the nourishment site. The position of the dune foot is shifting seaward with an increase of the growth rate of 2 m/year. For the two areas north and south of nourishment, the retreat rate has been slightly decreased.
<table>
<thead>
<tr>
<th>Areas</th>
<th>Average growth rate in m/year</th>
<th>Increment/Decrement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area south of nourishment</td>
<td>1.4</td>
<td>1.2</td>
</tr>
<tr>
<td>Nourishment area</td>
<td>0.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Area north of nourishment</td>
<td>0.6</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 6-1 Average growth rate in m/year for both periods

The dune foot position is presented for four different years (Figure 6-11). The year 1980 is the starting year of the pre-nourishment period. The position of the dune foot in 1980, compared to the next years is the most landward one.

![Dune foot position](image)

Figure 6-11 Comparison of the dune foot position for four different years.

The year 1998 represents the year just before the application of nourishment. Compared to 1980 the horizontal position of the dune foot has migrated in seaward direction almost 20 m. In 1999, just a year after application of nourishment the dune foot position remained at the same position as in 1980. In 2006 a seaward migration of the horizontal dune foot position can be seen, for the transects that are located inside the nourishment area. For the southern and northern part of the study area, the dune foot position is almost the same with the positions in the years 1998 and 1999.

For the dune zone volume, there was a significant increment in the dune volume in the nourishment area after application. The dunes became wider since completion and the growth rate has been increased from 0.5 m/year to 2.5 m/year.

### 6.5 Analysis of the beach volume changes

In this section the beach volume evolution is analyzed. The study area is divided in transects located south of the nourishment area, transects located in the nourishment area, and transects located north of nourishment.

The procedure that is chosen for this analysis is demonstrated in Chapter 4 (Methodological approach). The study period includes the pre-nourishment period (from 1980 until 1998) and
the post nourishment period (from 1999 till 2006, see Appendix C.3 Beach volume evolution). In Figure 6-12 a definition sketch of the beach volume is given (above MLW level and below dune foot position, NAP+3 m).

![Definition sketch of the beach volume](image)

**Figure 6-12 Definition sketch of the beach volume**

In Figure 6-13 the slopes of the trend lines for both periods for the beach volume can be seen.

![Beach volume trend](image)

**Figure 6-13 Beach volume trend for the pre and post nourishment period.**

From Figure 6-13 it can be seen that for the part south of the study area the trend was positive before application of nourishment and since the nourishment was completed the trend became negative. The sand losses are of the order of $5 \text{ m}^3/\text{m/ year}$. For the transects 88.50, 88.25 and 88.00, located in the nourishment area (in the middle and more to the north), the trend is negative after application and the sand losses are of the order of 6 to $9 \text{ m}^3/\text{m/ year}$. For the northern part of the study area the beach zone volume is in general accreting after application of nourishment (for transects 85.25, 85.50 and 85.75 there are volume losses).

The beach volume after nourishment has been in general decreased. More losses out of the beach profile observed after placement for the nourishment area. There is accretion only for the northern part of the study area.

### 6.6 Analysis of the volume evolution of the Sections 1 to 7

The beach/dune volume changes are analyzed in this section. Moreover, a detailed analysis of the volume changes of the sub sections of the shoreface profile volume is also applied. The shoreface volume in the case of Katwijk, is divided in six sub sections (including Section 1,
dune/beach volume, there are in total 7 Sections). JARKUS measurements do not cover the entire nourishment area. Only the landward part of the nourishment is included in the available JARKUS data. The first overview of the nourishment was constructed from survey data collected by the monitoring soundings program (almost) two years after the nourishment was completed.

The nourishment soundings data include a total number of 11 measurements between the years 2000 and 2005 for transect 92.00 until 86.25 and 19 measurements between the years 2000 and 2005 for transect 86.00 until 85.00. In the seaward direction the cross-shore profiles are extended approximately until 1600 m. These measurements cover the entire nourishment area and its seaward part. Section 6 determines the area where the shoreface nourishment was applied in 1999 and it is the 800-1000 m zone and Section 7, the 1000-Seaward boundary (SWB) zone, is the seaward part of the nourishment area. From the analysis of the nourishment soundings survey data, a better estimation is made concerning the volume evolution and the behaviour of the cross-shore profiles.

The beach and dune zone volume are studied as a total (Section 1). Similarly to the total, dune and beach volume analysis, a transect by transect analysis is applied. The trend lines are based on the uncorrected volumes. For Sections 6 and 7 (the 800-1000 m zone and the 1000-SWB zone respectively) for transects 92.00, 91.75, 91.50, 91.25 and 91.00 a volume correction is applied, since in 2002 a shoreface nourishment project was implemented and extra volume was placed (this extra volume is only included in the survey data acquired by the nourishment monitoring soundings). In Appendix D.3 the plots that show the volume evolution and the trend lines in each section can be seen. In Figure 6-14 a definition sketch of the profile volume of Section 1 is given.

![Figure 6-14 Definition sketch of the profile volume of Section 1. Nourishment area, from transect 89.50 to transect 87.50](image)

For the total study area, for Section 1 (Figure 6-15 summarizes the slopes of the trend lines for the periods before and after application of nourishment.) accretion was calculated after application of shoreface nourishment. The higher differences in the volume changes can be seen at the northern half of the nourishment area where the amount of sand volume that is gained during the post nourishment period is of the order of $20 m^3/m/year$. The highest losses can be seen for transect 86.00 for the pre nourishment period. The transects located at southern half of the nourishment area have also a positive trend during the post nourishment period. For transect 87.50 the trend during the post nourishment changed in the year 2002 (see Figure A.3-11, Appendix A.3), thus the trend that is presented in Figure 6-15 is not representative.
Figure 6-15 Overview of Section 1 volume change trends per transect for the two periods.

For Section 1 an absolute volume analysis is applied. Figure 6-16 presents a comparison between the absolute volume (in m$^3$/m), that was gained from 1997 until 1999 and the suppled sand volume (400 m$^3$/m) for the study area.

Figure 6-16 Differences of the absolute volume in Katwijk between 1997 and 2000 in comparison with the average nourishment volume as indicated, for Section 1.

For Section 1 it can be seen that the higher part in the profile (dune and beach zone volume) is not benefited right after the completion of the nourishment. The suppled sand is of the order of 400 m$^3$/m and for most of the transects in the nourishment area the amount of sand that is gained is almost 40 m$^3$/m. That means that only the 10% of the suppled sand was carried out in Section 1. In general there is not a significant loss of sand. Section 1 did not react massively to the shoreface nourishment.

The absolute volumes of Section 1, were added for the nourishment area, for the area south of the nourishment area and for the area north of the nourishment area. Figure 6-17 gives the volume of nourishment area and the areas north and of south of it as a function of time for Section 1.
The volume in Section 1 for the nourishment area before application of nourishment is increasing. After application of nourishment the positive trend remains and the increment is significant. From Figure 6-17 it can be seen, that two years after nourishment (in 2001), the growth rate starts to increase. A jump in the volume can be seen from 2000 to 2001 of the order of 80,000 m$^3$. This also comes in accordance with the analysis of the difference between the absolute volumes measured in 1997 and in 2000. There is a response of the nourishment with a delay of two to three years.

For the area south of the nourishment a jump in the volume can be seen in 1996, right after the beach nourishment application (from R.S.P. 93.50 to R.S.P 91.00, 400,000 m$^3$ of sand were placed). Since then, the volume of this section has been fairly stabilized. For the nourishment area, jump in the volume is observed, two years since completion of the 1998-1999 shoreface nourishment. The response of the nourishment in Section 1 occurred with a two years delay. The increment in the volume of Section 1 can be probably attributed to the shoreface nourishment and it can be concluded that the nourishment gradually shifted landward and increased the volume in the higher parts of the profile. Moreover, the jump in the volume in 1998, can be the effect of the beach nourishment in 1996 (the sand shifted north). In the area north of the nourishment a continuation of the positive trend that existed before nourishment (since 1994) can be seen for the period after placement.

**In Section 2** (Figure 6-18, a definition sketch of the profile volume of Section 2) accretion was calculated before application of nourishment and after application of nourishment this accretion has been increased. This sub section is rather small.
Figure 6-18 Definition sketch of the profile volume of Section 2

Figure 6-19 summarizes the slopes of the trend lines for the periods before and after application of nourishment.

Figure 6-19 Overview of Section 2 volume change trends per transect for the two periods.

The sand gain after placement has been significantly increased especially in the area where the nourishment was applied. In the middle of the nourishment however and to the north there are sand losses. At the area north of the nourishment erosion is also observed.

Section 3 (Figure 6-20, a definition sketch of the profile volume of Section 3) is also a small sub section. Before application the zone volume of Section 3 was in general accreting.

Figure 6-20 Definition sketch of the profile volume of Section 3
Figure 6-21 summarizes the slopes of the trend lines for the periods before and after application of nourishment.

**Comparison before and after nourishment for Section 3**

![Comparison of trend lines for Section 3](image)

**Figure 6-21 Overview of Section 3 volume change trends per transect for the two periods.**

After placement the transects located at the northern half of the nourishment are eroding. The most negative trends after application of nourishment can be seen from transect 88.50 until transect 88.00 that are located in the middle of the nourishment area.

*Section 4* (Figure 6-22, a definition sketch of the profile volume of Section 4) is the 350-500 m zone.

**Figure 6-22 Definition sketch of the profile volume of Section 4**

Figure 6-23 summarizes the slopes of the trend lines for the periods before and after application of nourishment.
Before application the calculated sediment losses are minor, of the order of 2 to $4 \text{ m}^3/\text{m} \text{ year}$ and can only be seen in the southern half of the study area. In the northern half of the study area there is gain of sand of the order of 2 to $5 \text{ m}^3/\text{m} \text{ year}$ . Since the nourishment completed, major changes can be observed. The trends of the transects located at the southern half of the nourishment are positive. The magnitude of the sand that is gained every year for most of the transects around 5 to $10 \text{ m}^3/\text{m} \text{ year}$ . The northern half is in general eroding. The highest sand losses can be seen for transects 88.75, 88.50, 88.25 and 88.00, that are located approximately at the middle of the nourishment area. Moving north the trend remains negative for most of the transects and the sand losses are of the order of 5 to $10 \text{ m}^3/\text{m} \text{ year}$.

Section 5 (Figure 6-24, a definition sketch of the profile volume of Section 6) represents the 500-800 m zone, which is landward of the nourishment area..
The southern half of the under investigation coastal stretch, is eroding before application of nourishment. The sand losses are of the order of 2 to 3 m$^3$/m/year. At the northern half accretion is observed. The trend is positive and the gain of sand is of the order of 2 to 5 m$^3$/m/year. For the post nourishment period, from Figure 6-25, it can be seen that all the trends are negative. The part, landward of the nourishment is eroding. The sand losses are of the order of 10 to 30 m$^3$/m/year. The highest losses can be seen for the northern part of the nourishment area. During the pre nourishment period only the southern half was eroding. For the total coastal stretch there was accretion. Since the nourishment was completed there is a significant volume of sand that is eroding. The magnitude of erosion is significant.

Section 6 (Figure 6-26, a definition sketch of the profile volume of Section 6) is the 800-1000 m zone and it is where the nourishment was placed.

Figure 6-27 summarizes the slopes of the trend lines for the period after application of nourishment (from the year 2000 until 2005).
For this Section, only the data acquired from the nourishment soundings program, are used. For the post nourishment period for all transects, there are losses of sand (only transect 90.50 is the exception). The trend is negative. For transect 92.00, which is located at the southern edge of the study area, the losses are the highest with a magnitude of $45 \text{ m}^3 / \text{m} / \text{year}$. Moving north the losses are decreasing. In R.S.P 90.50 the trend becomes positive and in R.S.P 90.00 becomes negative again and the losses start increasing. Inside the nourishment area (from transect 89.50 until 87.50) the value of the average losses is approximately $20 \text{ m}^3 / \text{m} / \text{year}$. For the transects that are located outside of the nourishment area, at the northern part the losses are almost the same for each transect of the order of $5 \text{ m}^3 / \text{m} / \text{year}$. The total erosion that is calculated after application of nourishment is $100,000 \text{ m}^3 / \text{year}$ (approximately).

Section 7 (Figure 6-28, a definition sketch of the profile volume of Section 6) is the 1000-Seaward boundary zone and is the seaward part of the nourishment area.

Figure 6-27 Overview of Section 6 volume change trends per transect for the post nourishment period, based on nourishment soundings data.

Figure 6-28 Definition sketch of the profile volume of Section 7

Figure 6-29 summarizes the slopes of the trend lines for the period after application of nourishment (from the year 2000 until 2005).
In this Section again the only available data concern the post nourishment period (2000 until 2005). Most of the transects have negative trends. The trends that are located at the southern edge of the nourishment are positive. The zone volume for these transects is increasing after application of nourishment. The highest sand losses can be seen at the northern part of the study area (only the zone volume of transect 86.50 is increasing). The total calculated erosion for Section 7 is of the order of 30,000 m$^3$/year.

Table 6-2 summarizes the calculated accretion or erosion (in m$^3$/year) for each section for both periods. It can be seen there is a significant accretion in Section 1. Major erosion is calculated for Section 5, which is the 500-800m zone. There is a landward shifting of the sediments.

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Table 6-2 The calculated Accretion/Erosion for each section

A plan view of the total study area is given in Figures 6-30 and 6-31. Figure 6-30 presents the sediment gain or losses in m$^3$/m/year in every Section after nourishment. There is not any information about the behaviour of the system concerning the pre nourishment period. It is believed however that also erosion occurred in the area before application of nourishment. Figure 6-31 presents the sediment gain or losses in m$^3$/m/year in every Section as an effect of nourishment.

Landward of the nourishment area, there is a significant gain of sand. Since the nourishment (Section 6) was placed outside the yearly measuring range the main analysis started from Section 5 and landward. Section 5 is eroding since nourishment. The magnitude of the volume
of sand that was lost out of this section (for the nourishment area) from 1999 to 2006 is almost the 59% \((250.000 \text{ m}^3)\) of the volume of the jump. This volume was distributed on the other Sections landward of the nourishment.

The volume of sand that was gained in the later years, in the landward part of the nourishment site (without Section 4) is almost the 80% \((320.000 \text{ m}^3)\) of the jump in the volume. The eroding volume of Section 4 increased the volume of the other Sections. Due to the cross-shore processes, the nourishment volume feeds the landward part of the profile and acts as a feeder berm. There is however in the system a 20% of extra volume. Probably this extra volume that has been found in the system is due to the longshore sediment transport processes. The volume of sand trapped in the lee side of the nourishment (there is dissipation of the wave energy since nourishment acts as a breaker bar).

At the southern edge of the study area sedimentation occurred. Updrift and downdrift of the nourishment erosion is observed. Updrift of the nourishment area the observed erosion is mainly in Section 1 (dune and beach zone volume) and Section 5 (500-800m zone). Downdrift of the nourishment the whole profile is eroding.
### Gain or loss of sediment in m³/m/year after application of the shoreface nourishment

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### Nourishment area

**Figure 6-30** Sediment gain or losses in m³/m/year for each Section after application of nourishment.

**Figure 6-31** Sediment gain or losses in m³/m/year. The effect of nourishment in each Section (For Sections 6, 7 there is not any information for the pre-nourishment period, thus it is not possible to determine the effect of the shoreface nourishment.)
6.7 Definition of the beach quality

In this section, the health and quality of the beach after application of nourishment is investigated by applying the beach width indicator (BWI). Figure 6-32 shows the growth or decrement rate (in \( m / year \)) of the BWI for the pre and post nourishment periods. Figures E.3-1 to E.3-29 in Appendix E.3 present the changes of the beach width indicator per year for each transect.

![Beach Width Indicator](image)

**Figure 6-32 BWI trend for the pre and post nourishment period.**

For the period before application of nourishment the surveys (from 1980 until 1998) indicate for transects 92.00 until 90.50 a positive trend. For the nourishment area volume, for the transects that are at its southern edge, the surveys show a decrement of the BWI. Also for the transects that are at the northern edge of the nourishment area the trends are negative. For the rest transects the BWI did not appear any changes. Moving northward, the rate of decrement for the BWI is approximately of the order of 0.5 \( m/\)year. For transects 85.75, 85.50, 85.25 and 85.00 during the pre nourishment period there were not any changes in the BWI.

For the post nourishment period the picture is different. From Figure 6-33, it can be seen that for transects 92.00 until 90.00 the trend, contrary to the trend during the previous surveys (from 1980 to 1998), is negative and the value of the decrement rate is between 1 and 1.5 \( m/\)year. The BWI is decreasing. For transects 88.50, 88.25 and 88.00 (transects located inside the nourishment area) the decrement rate is between 1.5 and 2 \( m/\)year. From R.S.P. 87.50 (transect located at the northern edge of the nourishment) to R.S.P. 86.50 the surveys (from 1999 to 2006) indicate a positive trend. Finally for transects 86.25, 86.00, 85.75 and 85.50 the trend, as it can be seen from the Figure above, is negative. For the transects that are located at the northern edge of the study area, similarly to the pre nourishment period, the BWI does not present any changes.
Comparing now the BWI length for four different periods (Figure 6-33) 1988, 1998, 1999 and 2006, a decrement can be seen. In 1988 the BWI for most of the transects had its highest value. For the southern half of the coastal stretch the BWI from 1988 until 1999 (just the year after application of nourishment), has not significantly changed. For the northern half there are differences between the 1980 and 1998 values is of the BWI.

Finally it can be said that the nourishment did not positively affect the beach width. Moreover for the transects that are in the middle of the nourishment area the beach seems to have became more narrow compared to the pre nourishment period. Only the dunes seem to benefit from the nourishment whiles the beach volume is decreasing and also the BWI. If the beach becomes steeper, it can be stated that the dunes are increasing on expense of the beach.

6.8 Conclusions

In Katwijk, a shoreface nourishment was applied in the year 1998-1999 (between September 1998 and February 1999). The total volume of the nourishment sand that was used, was 760.000 $m^3$ (which is about 400 $m^3$ per longshore metre of coast). This shoreface nourishment is the first nourishment project applied in the area. In the case of Katwijk, the nourishment was placed outside the yearly measuring range. Therefore, the main research question of the present study; how is the autonomous behaviour of the cross-shore profiles volume changing? cannot be answered. Nevertheless, a number of useful observations can be formulated. The ‘total volume’ is only part of the active volume that stops at the end of the available measurements. It is essential to know that in the Katwijk case the length of the lanes of the profiles are short and conclusions for the ‘total volume’ can not be formulated. What is observed is a small increment of the eroding rate after application. This cannot indicate that the nourishment affected the behaviour and resulted in the increase of the erosion. The dune volume has been increased and in general there is a landward transport of sediments. Part of the nourished volume is considered to have ended up landward at the higher parts of the profile, almost two years after application of nourishment.

In Chapter 3 Section 3.3, a number of basic questions have been formulated. In this Section the answers to these research questions are presented.

How does the application of the shoreface nourishment influence the physical processes that occur in a coastal system? How is the autonomous behaviour of the cross-shore profiles volume changing? Has the behaviour of the cross-shore profile volume
significantly affected since completion of nourishment (gain or loss of sand volume out of a cross-shore profile)?

- The shoreface nourishment resulted on the increment of the volume inside the nourishment area directly after its placement.
- The beach nourishment that was applied in 1996 between R.S.P 91.00 to R.S.P. 93.50 and the shoreface nourishment in 2002 in the same area, possibly affected the transects located south of the nourishment area.

How has the landward part of the profile been affected? How do the higher parts of the profile react to the nourishment? Has the beach and dune volume been increased after application of nourishment?

Does the shoreface nourishment result in beach widening?

- The higher parts of the profile do not have a direct response on the nourishment. There is a delay of two years.
- The shoreface nourishment resulted in the increment of the dune zone volume only in the nourishment area, where the growth rate for the dune foot position is steadily increasing. For the areas north and south of the nourishment area, a continuation of the trend that already existed before the nourishment can be observed. The dunes continue to grow after nourishment but with a slower pace.
- The beach volume in total was not positively affected by the shoreface nourishment.
- The shoreface nourishment did not result in beach widening.

What is the behaviour of the longshore sediment transport, after completion of nourishment, in the area landward of the nourishment? Does the nourishment result in downdrift erosion and updrift sedimentation (salient effect)?

How the nourishment affects the onshore versus offshore sediment transport?

- For the longshore sediment transport, clear conclusions cannot be formulated, since the total profile has not been studied (short length of the lanes). It is possible however that in the area landward of the nourishment, due to the wave energy dissipation, the longshore sediment transport has been decreased and there is volume of sand that has been trapped landward of the nourishment. Figure 6-34 shows the calculated accretion/erosion as an effect of the nourishment, due to the longshore and cross-shore sediment processes. The red line depicts the ideal picture of the salient effect occurred, while the black one depicts the measured accretion/erosion in the area as an effect of the nourishment. The erosion in the updrift might be an indication of the salient effect. Nevertheless concrete conclusions cannot be acquired.

![Figure 6-34 Accretion/Erosion due to the longshore and cross-shore sediment transport processes](image-url)
• The nourishment volume is gradually shifting landward of the nourishment site. There was a quick response of the nourishment, for the ‘total volume’, and thus the nourishment can be considered to be successful. The nourishment fed the study area and the extra volume was mainly preserved in the later years (the nourishment sand gradually ended up at the higher part of the profile). The onshore sediment transport was significantly increased right after nourishment application. The nourished sediments disturb the profile by moving onshore and increasing the volume. Thus, the sediment balance of the cross-shore profiles for the nourishment area was not maintained.

• An overshoot probably occurred in the middle of the nourishment area that resulted on the sudden increment of the volume right after nourishment application and lead to an increase in local erosion in the later years.
7 Analysis of the shoreface nourishment in the area of Noordwijk

7.1 Introduction

In this chapter the effect of the shoreface nourishment that was implemented in the area of Noordwijk, is analyzed and evaluated. Similarly to the Katwijk case, the nourishment was placed outside the yearly measuring range. Consequently, the study area of Noordwijk does not include the nourishment volume. The entire nourishment area was first measured almost two years after completion of nourishment (monitoring survey data). Therefore, the Noordwijk nourishment is studied and analyzed similarly to the Ter Heijde and Katwijk nourishment by using the JARKUS survey data.

From the analysis of JARKUS survey data, as in the Katwijk case, it is not possibly to acquire concrete results relating to the autonomous behaviour of the cross-shore profiles before and after nourishment. Nevertheless, a number of questions such as the magnitude of the response of the nourishment and how the nourishment volume approximately affects the study area might be answered. In the following sections, the same analysis as in Ter Heide and Katwijk is been applied.

7.2 Area under investigation

Noordwijk is a town and municipality in the western part of The Netherlands, in the area of Rijnland. Due to its long sandy beaches, the tourism industry is growing rapidly. The shoreface nourishment in this area was applied in the year 1998 (between January and April). The suppletion sand was placed between RSP 80.50 and RSP 83.50, between the depth contours N.A.P. -5 m and N.A.P. -7 m. Along this coastal stretch no direct human interventions were performed and the shoreface nourishment in 1998 is the first nourishment applied in the area.

The shoreface nourishment was placed in a smooth profile by means of trailer suction hopper dredgers. The sediment was dumped as high as possible on the shoreface. The total volume of the suppletion sand that was used was approximately 1,300,000 m$^3$, which is 400 m$^3$/m. The borrowed sand was coarser in comparison with the naturally present sediment. Its median grain size was almost two times the median grain size of the native sediment. In comparison with Ter Heijde the slope of the coastal profile at Noordwijk is milder. Thus the suppled sand was placed much further offshore. The Noordwijk nourishment area can be classified as a two-breaker bar system, with off shore migrating bars that have a four year (pattern) repeat cycle.

In 2002, a second shoreface nourishment was applied northern, from RSP 80.00 to RSP. 73.00. The total volume of the suppleted sand was 3,000,000 m$^3$, which is 430 m$^3$/m. The study and analysis of the effects of this shoreface nourishment is beyond the scope of the current research. The nourished transects (80.00, 79.75, 79.50, 79.25 and 79.00) however are included in the present study.

The coastal stretch that is going to be studied and analyzed in this chapter includes the transects from R.S.P. 85.00 to R.S.P. 83.75, located south of the nourishment area, the transects R.S.P. 83.50 to R.S.P. 80.50, located in the nourishment area, and the transects R.S.P. 80.25 to R.S.P. 83 79.00, located north of nourishment (Figure 7-1).
The period before nourishment application is chosen as the years from 1980 to 1997. The post nourishment period includes the years from 1998 to 2006 (the nourishment was completed on April 1998 and JARKUS survey performed two months later, thus in the post nourishment period the latter one is included).

**Figure 7-1 Overview of JARKUS transects in the area of Noordwijk**

### 7.3 Analysis of the ‘total volume’ changes

Analogously to the areas of Ter Heijde and Katwijk, the volume evolution in each of the transects has been studied according to the methodological approach described in Chapter 4. The study coastal stretch was not been regularly nourished. In Appendix A.2, Figures A.2-1 to A.2-25, present the ‘total volume’ changes per year and the trend lines for the pre nourishment and post nourishment period. Every period is analyzed separately. The trend lines for both periods, for transects 85.00, 84.75, 84.50, 84.25, 84.00, 83.75, 83.50, 83.25, 83.00, 82.75, 82.50, 82.25, 82.00, 81.75, 81.50, 81.25, 81.00, 80.75 and 80.50, are based on uncorrected values, since there is no nourishment application during these years.

For transects 79.00, 79.25, 79.50, 79.75 and 80.00 (Appendix A.2, Figures A.2-1 to A.2-5) two trend lines can be seen after 1998. The first trend line is from 1998 to 2002 and is based on the uncorrected volumes and the second trend line starts from 2003 to 2006 and is based on corrected values from the nourishment in 2002. Transect 80.25 has never been nourished (Figure A.2-6) and transects from R.S.P 83.75 to R.S.P. 85.00 were only been nourished in the year 2006.

Figure 7-2 presents the volume evolution for transect 82.00 which is located in the middle of the nourishment area. The dashed line depicts the corrected values, the vertical green line shows the starting date of the nourishments and the vertical red line corresponds to the ending date of the nourishments.
The pre nourishment period is from the year 1980 until the year 1997. The post nourishment period is from the year 1999 until the year 2006. A jump in the volume is observed after 1998 (after application of nourishment) though the nourishment volume is not included in these measurements (JARKUS measurements do not cover the entire nourishment area).

7.3.1 Transect by transect analysis

The coastal stretch that is being analyzed, is divided in transects located south of the nourishment area, transects located in the nourishment area, and transects located north of the nourishment area (three sub areas). In Figure 7-3 a definition sketch of the total profile volume is given (the nourishment volume is not included in these profiles, since the yearly surveys did not cover the nourishment area). The analysis showed that in the landward direction the boundary could be taken at -200 m. There were no changes in the shape and the volume of the dunes in the more landward direction.

The transect by transect analysis starts with a brief analysis of the transects located at the edges of each sub area. Transects 85.00 and 83.75 for the area south of the nourishment, the transects 83.50 and 80.50 for the nourishment area, the transects 80.25 and 79.00 for the area north of the nourishment area and also of the transect located at the middle of the nourishment area, transect 82.00, are analyzed.

Figure 7-4 summarizes the slopes of the trend lines for the periods before and after application of nourishment for all the transects that are being studied. The bar plots illustrate
the gain (structural accretion) or sand losses (structural erosion) in \( m^3/m/year \) from R.S.P. 85.00 till R.S.P. 79.00.

![Comparison before and after nourishment for the total volume](image)

**Figure 7-4** ‘Total volume’ trend for the pre and post nourishment period.

**Transect 85.00** (Figure A.2-25, Appendix A.2), is located in the part south of the study area. Before nourishment application the trend line is positive and the sand gain is of the order of \( 25 \ m^3/m/year \). Since application of nourishment this trend remains positive but the sand gain has been significantly decreased.

**Transect 83.75** (Figure A.2-20, Appendix A.2), is located in the part south of the study area, at the northern edge of the first sub area. During the pre nourishment period the losses are minor. After application of nourishment the trend remains negative and the losses have been slightly increased.

**Transect 83.50** (Figure A.2-19, Appendix A.2), is located at the southern edge of the nourishment area. The trend line was positive before nourishment. Since completion of nourishment the trend remains positive and the gain of sand has increased.

**Transect 82.00** (Figure A.2-13, Appendix A.2), is located in the middle on the nourishment area. A negative trend can be seen during the pre nourishment period. After application of nourishment the trend remains negative and the sand losses have been slightly decreased.

**Transect 80.50** (Figure A.2-7, Appendix A.2), is located at the northern edge of the nourishment area. The sand gain for the two periods is the same and is of the order of 16 \( m^3/m/year \).

**Transect 80.25** (Figure A.2-6, Appendix A.2), is located 250m north from transect 80.50. The positive trend that appeared before the placement of the nourishment volume continues after the placement as well. The sand gain has almost been doubled.

**Transect 79.00** (Figure A.2-1, Appendix A.2), is located in the northern edge of the study area. There is gain of sand for both periods. After application of the nourishment, the sand gain has been roughly decreased.

From transect 85.00 to transect 84.00, before the placement of the shoreface nourishment, a positive trend be seen. The rate is decreasing to the north. The gain of sand after placement for the se transects has been significantly decreased. For transects 84.75, 84.25 and 84.00, the trend is negative (losses for transect 84.00 of the order of \( 20 m^3/m/year \)). This is the highest amount of losses that can be seen south of the nourishment area. Transect 83.75 located 250m north of transect 84.00 and just before the first transect of the nourishment area. A
negative trend that can be seen for this transect during the pre nourishment period, that continues after placement. The sand losses have been increased.

Transects 83.50, 83.25, 83.00, 82.75 and 82.50, located in the southern half of the nourishment area, behave the same during both periods. Before application of nourishment there was a small amount of sand gain of the order of 5 to 6 $m^3/\text{m/year}$. Since completion of the nourishment, the trend remains positive and the sand gain is of the order of 15 to 30 $m^3/\text{m/year}$. Transect 82.25 shows a different behaviour. There is gain of sand before nourishment and afterwards sediment losses can be observed. The losses are relatively small. The next transects, transect 82.00 and 81.75, show negative trends for both periods.

In the northern half of the nourishment area the volume is increasing before and after application of nourishment. For transects 81.50, 81.25 and 81.00 the sand gain is significant and of the order of 30 to 35 $m^3/\text{m/year}$. For transects 80.75 and 80.50 that are the last transects located inside the nourishment area the volume increment is almost equal for both periods. For transects located north of the nourishment area the trends are positive for both periods (only for transect 79.25 the trend is negative during the pre nourishment period).

In general the ‘total volume’ in the study area has been increased. Only for the area south of the nourishment the volume has been decreased. The calculated increment can be attributed to the nourishment volume. Though the nourishment was placed outside the study area the volume of the study area was increased after placement probably due to the cross-shore transport of the nourishment sand. For the transects located at the northern part of the study area, the behaviour of the total profile volume seems to have been mainly affected by the shoreface nourishment applied in 2002 (see also Figures A.2-1 to A.2-5, Appendix A.2 that the trends are changing right after the nourishment application in 2002). This however cannot be clearly concluded from the present research. For the area south of the nourishment, the volume is decreasing. It is possible that this decrease is due to the longshore sediment transport from south to north.

7.3.2 Longshore sediment transport

In the case of Noordwijk, there is a significant cross-shore sediment transport as in the case of the Ter Heijde and Katwijk nourishments. Though the nourishment volume is not included in the study area, the changes that occurred in the cross-shore sediment transport, resulted in fluctuations in the coastal profiles. Sediment (from the nourishment) is being moved onshore and feeds the study area. Cross-shore and longshore sediment transport processes taking place on the same time, thus they cannot be studied separately. The same analysis as in Ter Heijde and Katwijk is applied. The ‘outgoing sediment transport’ cannot be clearly studied and defined.
Figure 7-5 Comparison of the ‘outgoing longshore sediment transport’ before and after nourishment.

Figure 7-5 shows a comparison of the ‘outgoing longshore sediment transport’ before and after nourishment. If the sediment transport in cross-shore direction were being disregarded, it could be stated that the ‘outgoing longshore sediment transport’, due to the nourishment has been reduced. From Figure 7-5 it can be seen that before application of nourishment the ‘outgoing longshore sediment transport’ is steadily decreasing towards the north. After application, updrift of the nourishment there is an increment in the ‘outgoing longshore sediment transport’ and negative sediment balances along this coastal stretch occurred (erosion). In the nourishment area, the ‘outgoing longshore sediment transport’ continuous to be negative, but compared to the pre nourishment period, it has been increased. Downdrift of the nourishment area, the ‘outgoing longshore sediment transport’ has been decreased and more sedimentation is observed. The cross-shore sediment transport however, cannot be ignored. The observed increment in the volume might be also due to the onshore sediment transport of the nourishment sand.

7.3.3 Absolute volume analysis

Figure 7-6 presents a comparison between the absolute volume (in \(m^3/m\)), that was gained from 1997 until 1999 and the suppleted sand volume (400 \(m^3/m\)) for the study area.
From Figure 7-6 it can be seen that the effect of the shoreface nourishment is visible in the survey that was performed a year after completion of nourishment (in 1999). Even though the nourishment volume was completely placed outside the study area (similarly to the case of Katwijk nourishment), after placement, the volume in the nourishment area has increased. This increment is of the order of 100 to 150 m$^3$/m, while the nourished volume was of the order of 400 m$^3$/m. At the southern part of the study area, the volume has been decreased after placement. The same can be seen for the northern part.

The absolute total volumes were added for the nourishment area, for the area south of the nourishment area and for the area north of the nourishment area. Figure 7-7 gives the volume of nourishment area and the areas north and of south of it as a function of time.

Figure 7-7 shows that the volume in the nourishment area has increased by a jump that occurred after application of nourishment (from 1997 to 1998). This jump is of the order of 240,000 m$^3$. The volume of sand that was placed in the system during the nourishment project was 1,300,000 m$^3$. Thus almost 18% of the suppled sand came into the measured system. Since the nourishment sand volume was placed completely outside the yearly measuring range, this jump shows that there was no significant response of the nourishment; a small amount of the nourishment volume has shifted landward and increased the ‘total volume’. During the post nourishment period, the ‘total volume’ is increasing almost linearly. The sand losses out of the total profile for most of the transects have been decreased. The volume shows a more stable behaviour. Since 1999, (after the jump in the volume) the ‘total volume’ in the nourishment area has increased by 280,000 m$^3$. This shows that the volume of the jump has largely been conserved in the later years and that the nourishment continuous to feed the total profile. The erosion rate for transects 82.25, 82.00 and 81.00 has been significantly increased.

For the area south of the nourishment, there was a slightly positive trend that after nourishment became negative. The volume for this area is decreasing after placement.

**7.4 Analysis of the dune volume changes**

In this section the dune volume evolution is studied and analyzed. The coastal stretch includes the transects located in the part south of the nourishment area, the transects located in the
nourishment area, and the transects located in the part north of the nourishment. The procedure that is chosen for this analysis is demonstrated in Chapter 4 (Methodological approach). The study period includes, similar to the 'total volume' analysis, two periods. The pre nourishment period, that is from 1980 to 1997 and the post nourishment period from 1998 to 2006 (see Appendix B.2 Dune volume evolution). The calculation of the linear dune volume change trends is based on uncorrected volumes. In Figure 7-8, a definition sketch of the dune volume is given (above dune foot position, NAP+3 m).

Transect by transect analysis

In Figure 7-9 the slopes of the trend lines of the dune volumes for both periods can be seen. A positive trend can be observed for the pre nourishment and post nourishment period from R.S.P 85.00 until R.S.P. 84.50. This positive trend is decreasing to the north for the period before nourishment but for the period after application of nourishment the gain of sand is similar for all these transects and is of the order of \(5 \text{ m}^3/\text{m}^2\text{ year}\). For both periods the trend is positive for transect 84.25. For transect 84.00 the sand losses after nourishment are almost the same as before. For transect 83.75 the growth trend has increased after application of nourishment (the gain of sand is of the order of \(10 \text{ m}^3/\text{m}^2\text{ year}\).

Figure 7-9 Dune volume trend for the pre and post nourishment period.

For all transects that are located in the nourishment area the trend for both periods is positive. For transects 83.50 to 82.50, that are located in the southern half of the nourishment area the
sand volume increment after application of nourishment has almost doubled (in some cases even more).

The highest gain of sand can be seen during the pre nourishment period (and it is much higher that it is during the post nourishment area of the order of $20 \text{ m}^3/\text{m/year}$) is observed for transect 82.25. There is a small gain of sand before application of nourishment for transects 82.00 and 81.75 of the order of $3 \text{ m}^3/\text{m/year}$ and after nourishment the gain has been increased for transect 82.00 and it has been decreased for transect 81.75 (the same holds for transect 81.50). For transects 81.25 to 80.50 that are located in the northern half of the nourishment the sand gain after nourishment is higher that it was before.

The trend line during the pre nourishment area, for all transects out of the nourishment area at its northern part, is positive. The highest gain of sand is observed for transect 80.25 and the lowest for transect 79.25. Since completion of nourishment the trend is negative for transects 79.75 and 79.00. The sand losses however are minor, of the order of $2 \text{ m}^3/\text{m/year}$.

From Figures B.2 in the Appendix B.2, it can be seen that for the transects located in the southern part of the study area (transects 83.75, 84.00, 84.25, 84.50, 84.75 and, 85.00 Figures B.2-20 to B.2-25) the trends changed right after the application of nourishment. The same holds for the transects located in the northern part of the study area (transects 79.00, 79.25, 79.50 and 79.75 Figures B.2-1 to B.2-4). However for the transects located inside the nourishment area the autonomous behaviour of the system had already changed before nourishment application between the years 1994, 1995 (the trend seems to have changed during these years).

The dune foot position has also been determined. Figure 7-10 presents the trend for the dune foot position for the pre and post nourishment periods.

![Dune foot trend for the pre and post nourishment period.](image)

In the southern part of the coastal stretch the dune foot shows a landward migration during the post nourishment period (for transects 84.50, 84.25 and 84.00). This landward retreat rate is of the order of $2 \text{ m/year}$ (for transect 84.50 the retreat is of the order of $1 \text{ m/year}$). From R.S.P. 83.75 and north it can be clearly seen that since application of nourishment the progress speed has been increased. The progressing rate is between 1 and $3 \text{ m/year}$ and is in accordance with the observed dune volume increment (see Figure 7-9). For transect 79.00, that is located at the northern edge of the coastal stretch, after application of nourishment a
landward retreat rate of the order of $1 \text{ m/year}$ has been calculated. The dune volume for this transect has decreased after application of nourishment.

For the area south of nourishment, the nourishment area and the area north of nourishment, the average growth rate is calculated for both periods.

Table 7-1 presents the average growth rate of the dune foot position (seaward migration) for both periods and the difference between them.

<table>
<thead>
<tr>
<th>Areas</th>
<th>Average growth rate in m/year</th>
<th>Increment/Decrement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area south of nourishment</td>
<td>0.9</td>
<td>-0.1</td>
</tr>
<tr>
<td>Nourishment area</td>
<td>0.3</td>
<td>1.9</td>
</tr>
<tr>
<td>Area north of nourishment</td>
<td>0.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 7-1 Average growth rate in m/year for both periods

The highest value of the growth rate is observed ($1.6 \text{ m/year}$) in the area where the nourishment was applied. A decrease of the growth rate of the order of $1 \text{ m/year}$ is observed for the area south of the nourishment. For the area north of nourishment the growth rate remains stable.

The dune foot position is presented for four different years (Figure 7-11). The year 1980 represents the first year of the pre nourishment period and during that year, for all transects the dune foot has its most landward position.

The year 1997 represents the year just before the application of the shoreface nourishment. Compared to the 1980 values, a seaward shifting can be seen in the southern half of the coastal stretch, of the magnitude of 30 m, while in the northern half this seaward shifting is of the magnitude of 20 m. Just in the middle of the coastal stretch, transect 82.25 there was no retreat. The dune foot position remained stable.

In 1998, just a year after the nourishment was applied, the dune foot position remained rather stable. Finally in the year 2006, which is the last year of the post nourishment period, in the southern part of the study area, a landward retreat can be observed compared to the 1997 and 1998 dune foot positions. From transect 84.00 and towards the north, until transect 79.75 the dune foot appears to have its most seaward position, compared to the other years. For the last three transects that are located at the northern part of the coastal stretch, the dune foot position is almost the same with the positions in the years 1997 and 1998 (for transect 79.00 a landward retreat has been calculated).
A major increase in the dune volume in the nourishment area, after application, is observed. Moreover, the analysis of the dune foot position showed that the speed with which the dune foot is shifting seaward, has significantly increased, since the nourishment was completed. It is possible that the shoreface nourishment contributed to the dune volume increment and resulted in the increment of the growth speed of the dunes (the dune foot position is migrating seaward). The dunes became wider since completion of the nourishment and the growth rate has been increased from 0.3 m/year to 1.9 m/year.

7.5 Analysis of the beach volume changes

In this section the beach volume evolution is analyzed. The study area is divided in transects located south of the nourishment area, transects located in the nourishment area, and transects located north of nourishment.

The analysis of the beach volume changes is according to the procedure which is demonstrated in Chapter 4 (Methodological approach). The study period includes two periods: the pre nourishment period, that is from 1988 to 1997 and the post nourishment period from 1998 to 2006 (see Appendix C.1 Beach volume evolution). In Figure 7-12 a definition sketch of the beach volume is given (above MLW level and below dune foot position, NAP+3 m).

Figure 7-12 Definition sketch of the beach volume

In Figure 7-13 the slopes of the trend lines for both periods for the beach volume can be seen.
Figure 7-13 Beach volume trend for the pre and post nourishment period.

Figure 7-13 shows that for the transects located south of the coastal stretch, the positive trend that existed before application of nourishment, continuous after application. From transect 84.00 to transect 83.25, the trend after completion of nourishment is slightly negative of the order of $3 m^3/m/year$. From transect 83.00 until 82.50 the trend after nourishment is positive and the gain of sand is of the order of $5 m^3/m/year$. For the three following transects the trend is again negative and from R.S.P. 81.50 to R.S.P. 80.25 it is positive with only one notable exception, transect 81.25 (the sand losses are of the order of $10 m^3/m/year$ and is the highest value of sand losses for both periods).

In general, for both periods, great fluctuations can be seen from transect to transect. Almost every $1 km$, erosion changes to accretion and vice versa. The beach volume after nourishment increased. In the nourishment area the nourishment positively affected the beach volume and the beach width. The dunes do not seem to be growing on the expense of the beach. Moreover, they seem to benefit more and faster from the nourishment than the beach does.

### 7.6 Analysis of the volume evolution of the Sections 1 to 8

In this section a detailed analysis of the volume changes of the beach/dune volume is applied. Moreover, the shoreface profile volume is divided in sub sections and their volumes are also analyzed. For the case of Noordwijk the shoreface volume is divided in seven sub sections. JARKUS measurements do not cover the entire nourishment area. Only the part landward of the nourishment is included in the available data. The first measurement that includes the entire nourishment area was performed two years later by the monitoring sounding program. Thus two years of information that concern the effect of the nourishment and its behaviour are missing.

For all Sections (1 to 8) the two dataset (JARKUS and nourishment soundings) gave similar results. In the seaward direction the cross-shore profiles are extended approximately until $1.400-1.600 m$. Theses measurements cover the entire nourishment area and the part seaward of it. Section 7 determines the area where the shoreface nourishment was applied in 1998 and it is the $800-1.000 m$ zone, and Section 8, the 1000-Seaward boundary zone, is the part seaward of the nourishment. From the analysis of the nourishment soundings survey data, a complete picture concerning the effect of nourishment in the coastal system can be obtained.
For Section 8, a volume correction is applied for transects 80.00, 79.75, 79.50, 79.25 and 79.00, since in 2001 a shoreface nourishment project was implemented there.

The trend lines for the beach/dune volume analysis (Section 1) are based on uncorrected volumes. In Appendix D.2 plots that show the volume evolution and the trend lines for each section can be seen. In Figure 7-14 a definition sketch of the profile volume of Section 1 is given.

![Figure 7-14 Definition sketch of the profile volume of Section 1](image)

For Section 1 (Figure 7-15 summarizes the slopes of the trend lines for the periods before and after application of nourishment.) accretion was calculated after placement of the nourishment. Before application of nourishment all trends were positive. After nourishment for some transects the trend is negative. At the southern half of the nourishment area the gain of sand has been significantly increased after application of nourishment. Inside the nourishment area the gain of sand has been increased. For transects located in the middle of nourishment area (transects 82.25 and 81.95) the sand gain is less after nourishment. For the southern part of the study area the trend after nourishment is positive but the sand gain has been decreased compared to the sand gain before the application.

![Figure 7-15 Overview of Section 1 volume change trends per transect for the two periods.](image)

For Section 1 a comparison between the absolute volumes measured a year before nourishment application (in 1997) and the absolute volumes measured a year after nourishment application (in 1999) is shown in Figure 7-16. The general picture is that the volume in Section 1 has not been significantly increased. The 'total volume' in the nourishment area did not change. The volume at the part north of the study area has been slightly increased, while at the part south a small decrement can be observed (see also Figure F.2-1, Appendix F.2)
Comparison between the nourishment volume and the volume differences of 1997 and 1999 for Section 1

Figure 7-16 Differences of the absolute volume in Noordwijk between 1997 and 1999 in comparison with the average nourishment volume as indicated, for Section 1

For Section 1 the southern half of the nourishment area appears an increment in the volume of the order of 30 to 40 m$^3$/m while the volume in northern half is decreased (30 to 40 m$^3$/m). The increment is compensated by the decrement. During the first two years it seems that the nourishment did not affect Section 1. In the areas south and north of the nourishment there is an increment in the volume of the order of 40 m$^3$/m.

The absolute volumes of Section 1, were also added for the nourishment area, for the area south of the nourishment area and for the area north of the nourishment area, in order to obtain a global picture of the volume changes for the three areas. Figure 7-17 gives the volume of nourishment area and the areas north and of south of it as a function of time for Section 1.

Figure 7-17 Volume of nourishment area and the areas north and of south of it as a function of time for Section 1. All volumes are scaled in the 2005 volume.

The volume in Section 1 for the nourishment area before application of nourishment is increasing. After application of nourishment the positive trend remains but the growth speed has been increased. From the Figure it can be seen that three years after nourishment (in 2000), a jump in the volume occurred (from 2000 to 2001) of the order of 130.000 m$^3$, 

99
suggesting a response of the nourishment with a delay of three years. After 2001 a positive trend can be seen. For the areas south and north of the nourishment a positive trend that did not change much after nourishment can be seen.

South of the nourishment area the volume of Section 1 was slightly increasing. The volume is conserved and a jump in the volume that occurred in 1996 is probably due the beach nourishment applied in the area. The part north of the nourishment is almost linearly increasing before nourishment and continues afterwards, but it seems to have been affected by the nourishment.

For the nourishment area the jump in the volume in 2000 can be attributed to the nourishment. The nourishment is gradually shifting landward and increases the volume in the higher parts of the profile. Similarly to the cases of Ter Heijde and Katwijk, the higher parts respond to the nourishment with a two-year delay.

_In Section 2_ (Figure 7-18, a definition sketch of the profile volume of Section 6) accretion was calculated before application of nourishment and after application of nourishment the accretion is increased.

**Figure 7-18 Definition sketch of the profile volume of Section 2**

Figure 7-19 summarizes the slopes of the trend lines for the periods before and after application of nourishment.

**Figure 7-19 Overview of Section 2 volume change trends per transect for the two periods.**

Inside the nourishment area the sand gain has been significantly increased. This sub section is rather small.
Section 3 (Figure 7-20, a definition sketch of the profile volume of Section 6) is also a small sub section.

Figure 7-20 Definition sketch of the profile volume of Section 3

Figure 7-21 summarizes the slopes of the trend lines for the periods before and after application of nourishment.

Figure 7-21 Overview of Section 3 volume change trends per transect for the two periods.

For both periods accretion is calculated. The most negative trends after application of nourishment can be seen from transects 82.00 and 81.50 that are located in the middle of the nourishment area.

Section 4 (Figure 7-22, a definition sketch of the profile volume of Section 6) is the 250-340 m zone and is also a small sub section.

Figure 7-22 Definition sketch of the profile volume of Section 4
Figure 7-23 summarizes the slopes of the trend lines for the periods before and after application of nourishment.

![Comparison before and after nourishment for Section 4](image)

**Figure 7-23** Overview of Section 4 volume change trends per transect for the two periods.

Before application of nourishment the trends display a wave pattern. Starting from the southern edge of the study area the first four transects (85.00 to 84.25), have a positive trend. Moving northward until transect 81.75 the trends are negative. The calculated sediment losses are minor, of the order of 2 to 3 $m^3/m/year$. From 81.50 to 80.75 there is a small gain of sand. From transect 80.50 (located at the northern edge of the nourishment area) to transect 79.00 (located at the northern edge of the study coastal stretch) the trend is negative and the calculated losses are of the order of 3-4 $m^3/m/year$. After application of nourishment the wave pattern that the trends follow is clearer and differs from the one that was observed during the pre nourishment period. In the southern part (from transect 85.00 to transect 83.50) all transects have negative trends. The higher losses are observed for transect 84.00. From transect 83.25 north the trends are positive.

*For Section 5* (Figure 7-24, a definition sketch of the profile volume of Section 6) which represents the 340-500 m zone.

![Figure 7-24 Definition sketch of the profile volume of Section 5](image)

Figure 7-25 summarizes the slopes of the trend lines for the periods before and after application of nourishment.
Figure 7-25 Overview of Section 5 volume change trends per transect for the two periods.

The trend is positive updrift of the nourishment area before and after application of nourishment. The increment is major since completion of the nourishment. From R.S.P. 82.50 to R.S.P. 81.50, for the pre nourishment period the trend is negative but the calculated volume losses are minor. From R.S.P. 80.75 until R.S.P. 79.00 the trend is positive and the sand gain is small. For the post nourishment period from R.S.P. 82.50 to R.S.P. 81.50 the trend remains negative but the sand losses have been significantly increased. For transect 81.25 the trend is positive and from R.S.P. 81.50 to R.S.P. 80.50 the trend is negative. Finally from transect 79.75 the trend is positive and moving north, is increasing until the last transect of the coastal stretch, 79.00.

Section 6 (Figure 7-26, a definition sketch of the profile volume of Section 6) is the part landward of the nourishment and includes a small part of the nourishment volume.

Figure 7-26 Definition sketch of the profile volume of Section 6

Figure 7-27 summarizes the slopes of the trend lines for the periods before and after application of nourishment.
For the pre nourishment period almost all the transects have a similar behaviour. The trend is negative during the pre nourishment period. The losses however are minor (magnitude of \(4 m^3/m/year\)). After application of nourishment, significant changes occurred. The transects located at the southern half of the coastal stretch have negative trends. The sediment losses are reducing to the north. The trend is positive for the transects located at the northern part of the coastal stretch. The growth rate is increasing to the north. It reaches its highest value at R.S.P 81.50. From there to the north it decreases until R.S.P 79.00 where the trend is negative. In total erosion was calculated for the post nourishment period.

Section 7 (Figure 7-28, a definition sketch of the profile volume of Section 6) is the 800-1000 m zone. There the nourishment was placed.

Figure 7-29 summarizes the slopes of the trend lines for the period after application of nourishment (2000-2005).
Figure 7- 29 Overview of Section 7 volume change trends per transect for the post nourishment period, based on nourishment soundings data.

For this Section only the data acquired from the nourishment soundings program, are used. In this Section the trends are negative for all transects. For the transects that are located inside the nourishment area the losses are similar. For the transects that are in the southern part of the study area, the losses are less of the order of 9 to 10 m$^3$/m/year. Finally for the transects that are in the northern part of the study area the losses are of the order of 30 to 35 m$^3$/m/year. There is no available data for the pre nourishment period. Thus it is not possible to determine how the shoreface nourishment affected the natural processes in this Section.

Section 8 (Figure 7-30, a definition sketch of the profile volume of Section 6) is the 1000-Seaward boundary zone and is the part seaward of the nourishment area.

Figure 7- 30 Definition sketch of the profile volume of Section 8

Figure 5-31 summarizes the slopes of the trend lines for the period after application of nourishment (2000-2005).
Figure 7-31 Overview of Section 8 volume change trends per transect for the post nourishment period, based on nourishment soundings data.

In this Section again the only available data concern the post nourishment period for the years 2000 until 2005. All transects have negative trends.

Table 7-2 summarizes the calculated accretion or erosion (in $m^3/\text{year}$) for each section for both periods. It can be seen there is a significant accretion in Section 1. Major erosion is calculated for Section 5, which is the 500-800m zone. There is a landward shifting of the sediments.

<table>
<thead>
<tr>
<th>Section</th>
<th>Accretion (+)/Erosion (-) in $m^3/\text{year}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>45.000/50.000</td>
</tr>
<tr>
<td>2</td>
<td>8.000/20.000</td>
</tr>
<tr>
<td>3</td>
<td>5.000/8.000</td>
</tr>
<tr>
<td>4</td>
<td>-4.000/12.000</td>
</tr>
<tr>
<td>5</td>
<td>14.000/2.500</td>
</tr>
<tr>
<td>6</td>
<td>-16.000/-14.000</td>
</tr>
</tbody>
</table>

Table 7-2 The calculated Accretion/Erosion for each section

A plan view of the total study area is given in Figures 5-32 and 5-33. Figure 5-32 presents the sediment gain or losses in $m^3/m/\text{year}$ in every Section after nourishment. There is not any information about the behaviour of the system concerning the pre nourishment period, for Section 7 and 8. It is believed however that also erosion occurred in the area before application of nourishment. Figure 5-33 presents the sediment gain or losses in $m^3/m/\text{year}$ in every Section as an effect of nourishment.

The shoreface profile volume was divided in sub sections in order to obtain a clearer picture of how the distribution of sand occurs and how the shoreface nourishment affects the longshore and cross-shore sediment transport.

Landward of the nourishment site there is a significant gain of sand. Since the nourishment (Section 7) was placed outside the yearly measuring range the main analysis started from Section 6 landward. Of the nourishment volume, 18% was shifted landward (the jump of the order of 240,000 $m^3$ that was observed). Section 6 is eroding since nourishment. The magnitude of the volume of sand that was lost out of this section (for the nourishment area)
from 1998 until 2006 is almost 80% (180,000 m$^3$) of the volume of the jump. This volume was distributed on the other Sections landward of the nourishment. The volume of sand that was gained in the later years, in the landward part of the nourishment site (without Section 6) is almost 370,000 m$^3$, which is more than the volume of the jump. This 140,000 m$^3$ of extra volume, (the difference between the volume that Section 5 lost and the volume that the other Sections gained) found in the system is probably due to the longshore sediment transport processes. Volume of sand trapped in the lee side of the nourishment (there is dissipation of the wave energy since nourishment acts as a submerged breakwater).

Moreover it is clear, similarly to the cases of Ter Heijde and Katwijk that the whole profile is shifting landward. The nourishment volume feeds the landward part of the profile. The onshore sediment transport has been significantly increased.

At the part south of the nourishment erosion is observed. The volume of this area probably moved northward and increased the volume in the nourishment area. Moreover, this part is located between two shoreface nourishments (Katwijk and Noordwijk), so the observed decrement can be attributed to that. Downdrift of the nourishment area there is gain of sand. Possible due the shoreface nourishment applied in 2002 there was a reduction of the wave energy and sediments were trapped in the lee side of the nourishment. This might have resulted in a reduction of the longshore sediment transport and an accumulation of sediments. It is not clear however whether or not this sedimentation can be attributed to the longshore sediment transport or to the cross-shore sediment transport or it is the result of both processes.
### Seaward Boundary

#### Gain or loss of sediment in m$^3$/m/year after application of the shoreface nourishment

| Section 8 | -12 | -11 | -14 | -13 | -23 | -20 | -14 | -16 | -14 | -16 | -19 | -11 | -7 | -13 | -13 | -6 | -9 | -17 | -32 | -25 | -16 | -8 | -14 |
| Section 7 | -7  | -6  | -9  | -9  | -8  | -7  | -24 | -22 | -26 | -27 | -24 | -30 | -25 | -30 | -24 | -13 | -22 | -12 | -30 | -37 | -30 | -25 | -20 | -16 |
| Section 6 | -26 | -24 | -21 | -18 | -21 | -16 | -11 | -11 | -15 | -7  | 4  | 6  | 10 | 10 | 15 | 15 | 14 | 10 | 6  | 10 | 8  | 10 | 5  | 2  |
| Section 5 | -18 | 22  | -21 | 16  | 11  | 11  | 8  | 12  | 19  | 0  | -13 | -21 | -19 | -25 | -5  | 2  | -16 | -29 | -25 | -15 | -11 | 1  | 6  | 14 | 17 |
| Section 4 | -1  | -3  | -6  | -7  | -8  | -5  | -4  | 2   | 5   | 3   | 1   | 6   | 3   | 2   | 9   | 12  | 9   | 11  | 8   | 5   | 3   | 1  | 1  | 2  | 1  |
| Section 3 | -4  | 3   | 5   | 3   | 2   | -1  | 3   | 5   | 3   | 1   | 3   | 1   | -3  | -1  | -3  | 1   | -1  | 1   | -1  | 4   | 3   | 1  | 3  | 3  | 1  |
| Section 2 | 12  | 2   | 3   | -2  | -5  | -5  | 6   | 5   | 9   | 11  | 10  | 2   | -2  | 3   | 6   | 11  | 7   | 9   | 8   | 6   | 3   | 2  | 2  | 1  | 4  |
| Section 1 | 5   | 4   | 4   | -1  | -4  | -4  | 8   | 15  | 10  | 12  | 18  | 15  | 5   | 8   | 1   | 7   | 7   | 20  | 11  | 22  | 18  | 12  | -2 | 6  | 7  | 3  |

### Landward Boundary

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<tr>
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### Figure 7-32

Sediment gain or losses in m$^3$/m/year for each Section

### Seaward Boundary

#### Gain or loss of sediment in m$^3$/m/year - effect of the shoreface nourishment

| Section 8 | -30 | -27 | -20 | -15 | -17 | -11 | -7 | -8 | -11 | -3 | 8 | 9 | 14 | 12 | 18 | 21 | 17 | 12 | 10 | 15 | 12 | 15 | 5 | 10 | 6 |
| Section 7 | -20 | 21  | 15  | 9   | 5   | 5   | 3   | 7  | 16  | 16 | -2 | -13 | -20 | -17 | -23 | -3  | 2   | -16 | -30 | -29 | -18 | -15 | -2 | 2 | 11 | 15 |
| Section 6 | -6  | -8  | -10 | -8  | -6  | -2  | -2  | -2  | -5  | -5  | 6   | 5   | 9   | 11  | 10  | 2   | -2  | 3   | 6   | 11  | 7   | 9   | 8   | 6   | 3   | 2 | 2 | 1 | 4  |
| Section 5 | 3   | 1   | 2   | 1   | 1   | -2  | 3   | 5   | 4   | 1   | 3   | 1   | -3  | -2  | -4  | -1  | -2  | 0   | 0   | 0   | 1   | 1   | -1 | 1 | 2 | -1 |
| Section 4 | 0   | -2  | -3  | -5  | -6  | -5  | 6   | 7   | 9   | 8   | 11  | 2   | -2  | 3   | 6   | 8   | 5   | 8   | 6   | 4   | 2   | -3 | 1 | -1 | -5 |
| Section 3 | -10 | -9  | -4  | -5  | -5  | 8   | 10  | 3   | 7   | 12  | 13  | -13 | 5   | -1  | 1   | 2   | 14  | 1   | 6   | 4   | 2   | -12 | -4 | 6   | 10  |

### Landward Boundary

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### Figure 7-33

The effect of nourishment in each Section (For Sections 7, 8 there is not any information for the pre nourishment period, thus it is not possible to determine the effect of the shoreface nourishment)

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7.7 Definition of the beach quality

The health and quality of the beach after application of nourishment is investigated in this Section 7.7. The beach width indicator is applied (BWI). The growth or decrement rate (in \( m / \text{year} \)) of the BWI for the pre and post nourishment periods is presented in Figure 7-34. Figures E.2-1 to E.2-25 in Appendix E.2 show the changes of the beach width indicator per year for each transect.

![Beach Width Indicator](image1)

**Figure 7-34 BWI trend with respect to the Landward Boundary for the pre and post nourishment period.**

For the pre nourishment period the trend for the BWI is either positive (for the southern part of the study area) with an average growth rate of the order of 0.5 m or it is negative with a decrement rate of the order of 0.5 m. After application of nourishment in the southern part of the study area for transects 84.00, 83.75 and 83.50 the trend is negative. For transects 82.25, 82.00 and 81.75 that are located in the middle of nourishment area (also for transect 81.50 where the decrement rate is of the order of 3 m) and for transects 80.00, 79.75 and 79.00 that are located outside the nourishment area, at the northern part of the study area the trend is negative too.

![Comparison of the BWI position for four different years](image2)

**Figure 7-35 Comparison of the BWI position for four different years**
Figure 7-35 shows the Beach Width Indicator for four different years, 1980, 1997, 1998 and 2006. From transect 85.00 to 84.00 the BWI for the years 1980 and 2006 is almost identical. In 1997 there was an increment. A year later however, a decrease can be observed.

For the transects that are located inside the nourishment area the BWI is almost the same for three different years, for 1980, 1997 (just a year before nourishment) and 1998 (a year after nourishment). For most of the transects, the BWI reaches its highest value in 2006. For transects 82.00 and 81.75 (the transects that are located in the middle of the nourishment area) the BWI in the year 2006 has its smaller value.

Finally for the most northward transects that are situated outside the nourishment area the BWI reaches its highest value in 1997, a year later it starts decreasing again and in 2006 appears to have almost the same value that it had in 1980.

It can be said that the nourishment positively affected the beach width. It seems that the beach width in the southern and northern part of the nourishment area has been significantly increased since completion of the nourishment. For the transects that are in the middle of the nourishment area the beach seems to have become narrower compared to the pre nourishment period.

7.8 Conclusions

In Noordwijk a shoreface nourishment was applied in the year 1998 (between January and April). The total volume of the suppletion sand that was used was approximately $1,300,000 \text{ m}^3$, which is $400 \text{ m}^3/m$. The area where this nourishment project was implemented is an area where no direct interventions by man have been made. In the case of Noordwijk, the length of the lanes, of the measured profiles is short and the nourishment volume is not included in the measured profiles. Thus, the 'total volume’ has not been really measured. Therefore, the main research question of the present study; how is the autonomous behaviour of the cross-shore profiles volume changing? cannot be answered. Nevertheless, a number of useful observations can be formulated. The accreting rate has been significantly increased since completion of the nourishment. This however, similarly to the Katwijk case, cannot be attributed to longshore processes, induced by the nourishment. The dune volume and the beach volume have been increased and the beach width, unlike to the two previous cases (Ter Heijde and Katwijk) has been positively affected by the nourishment.

In Chapter 3 Section 3.3, a number of basic questions have been formulated. In this Section the answers to these research questions are presented.

How does the application of the shoreface nourishment influence the physical processes that occur in a coastal system? How does the autonomous behaviour of the cross-shore profiles volume change? Has the behaviour of the cross-shore profile volume significantly affected since completion of nourishment (gain or loss of sand volume out of a cross-shore profile)?

- The shoreface nourishment resulted on the increment of the volume of the study area and mostly in the area where the shoreface nourishment was applied.
- An increment of the volume at the part south of the study area is observed. The area downdrift of the nourishment area was probably affected by the shoreface nourishment applied in 2002.
How has the landward part of the profile been affected? How the higher parts of the profile react to the nourishment? Has the beach and dune volume been increased after application of nourishment?

Does the shoreface nourishment result in beach widening?

- The higher parts of the profile do not have a direct response on the nourishment. There is a delay of two to three years.

- The shoreface nourishment resulted on the increment of the dune zone volume, only inside the nourishment area where the growth rate for the dune foot position is steadily increasing. A continuation of the trend that already existed before the nourishment can be observed for the dune volume of the areas north and south of the nourishment area. The dunes continue to grow after nourishment but with a slower pace.

- The beach volume in total was slightly increased since application of the shoreface nourishment. This increment cannot be clearly attributed to the shoreface nourishment.

- If the beach volume increment is due to the shoreface nourishment then it can be concluded that the shoreface nourishment resulted in beach widening for the southern and northern part of the nourishment area.

What is the behaviour of the longshore sediment transport, after completion of nourishment, in the lee side of the nourishment? Does the nourishment result in downdrift erosion and updrift sedimentation (salient effect)?

How the nourishment affects the onshore versus offshore sediment transport?

- Similarly to the Katwijk case, for the longshore sediment transport clear conclusions cannot be formulated. In the updrift direction erosion occurred. It can be stated that it is a clear erosion spot since is situated between two nourishments (the Katwijk and the Noordwijk nourishments). In the downdrift direction sedimentation is observed. This accretion might be due to the new shoreface nourishment applied in the area in 2002. Inside the nourishment area the accreting rate has been significantly increased. This is mainly attributed to the cross-shore processes and not to the longshore processes. Thus, we cannot indicate with certainty that the salient effect occurred. Figure 7-36 shows the calculated accretion/erosion as an effect of the nourishment, due to the longshore and cross-shore sediment processes.

![Oblique waves](image)

**Figure 7-36 Accretion/Erosion due to the longshore and cross-shore sediment transport processes**

- The onshore sediment transport was increased right after nourishment application. The nourishment volume is gradually shifting landward of the nourishment site and gradually ending up at the higher part of the profile. The sediment balance of the
entire cross-shore profile has been disturbed. It is quite possible that the feeding processes of the higher parts of the profiles have been increased.
8 General Conclusion and Recommendations

Concise conclusions were provided at the end of every section. The overall conclusions that provide answers to the main research questions are described in this Chapter in section 8.1. In section 8.2 recommendations are given.

8.1 General Conclusions

In this section the conclusions answering the main research questions are described. The main research questions, as already mentioned in Section 1.2 are repeated below.

- How does the application of the shoreface nourishment influence the physical processes that occur in a coastal system? How is the autonomous behaviour of the cross-shore profiles volume changing? Has the behaviour of the cross-shore profile volume been significantly affected since completion of nourishment (gain or loss of sand volume out of a cross-shore profile)?

- How is the landward part of the profile affected? How do the higher parts of the profile react to the nourishment? Has the beach and dune volume been increased after application of nourishment?

- Does the shoreface nourishment result in beach widening?

- What is the behaviour of the longshore sediment transport, after completion of nourishment, in the lee side of the nourishment?

- Does the nourishment result in downdrift erosion and updrift sedimentation (salient effect)?

- How does the nourishment affect the onshore versus offshore sediment transport?

The analysis of the shoreface nourishments applied in the areas of Ter Heijde, Katwijk and Noordwijk showed that there were differences concerning the results for the three areas. This can be attributed firstly to the fact that in Ter Heijde, the nourishment area is part of a dynamic system that can be classified as a one breaker bar system, while in Katwijk and Noordwijk the nourishment areas are parts of a dynamic system that can be classified as a two breaker bar system. Moreover, the nourishment in Ter Heijde was placed on a smooth profile, while in the other two cases; the coastal profiles have a milder slope. The shoreface nourishment in Ter Heijde was placed relatively close to the shore, while in Katwijk and Noordwijk the shoreface nourishment was placed relatively far offshore. Finally, the most important information for the present analysis is that the nourishment volume, in the cases of Katwijk and Noordwijk, was placed outside the yearly measuring range. Thus, the main research question of the present study; how is the autonomous behaviour of the cross-shore profiles volume changing? cannot be answered. Moreover, it cannot be studied the longshore sediment transport and how it was affected by the nourishment.

Below each question is answered separately. It is essential that the conclusions of the total section are treated carefully since the results basically depend on the selected boundaries that determine each study area.
How does the application of the shoreface nourishment influence the physical processes that occur in a coastal system? How is the autonomous behaviour of the cross-shore profiles volume changing? Has the behaviour of the cross-shore profile volume been significantly affected since completion of nourishment (gain or loss of sand volume out of a cross-shore profile)?

From the total volume analysis the following can be concluded:

- For the Ter Heijde case it can be concluded that for the nourishment area the behaviour of the cross-shore profile volume inside the nourishment area was not actually affected by the nourishment, the rate of erosion did not change after application of nourishment. For the cases of Katwijk and Noordwijk due to the fact that the length of the lanes of the profiles are short, conclusions for the ‘total volume’ and how the autonomous behaviour of the cross-shore profile has been affected by the nourishments, can not be formulated (the nourishment volume is not included in the yearly measuring range). The shoreface nourishment however, resulted in the increment of the volume inside the nourishment area, directly after its placement.

- The shoreface nourishment in the Ter Heide seems to have been affected the southern part of the coastal stretch, while in the northern part it is not clear whether or no, the natural processes were mostly affected by the present shoreface nourishment or by the beach and shoreface nourishments applied in the neighboring area. Accretion was observed in both areas. For the Katwijk case the volume in the area south of the nourishment was decreased and at the south edge of the study area, the volume is increased, probably due to the shoreface nourishment in 2002 in the specific area. The area north of the nourishment area was decreased. This area is adjacent with the south area of Noordwijk. The erosion there is possible due to the fact that is located between two nourishments. The volume in the area south of the nourishment area of Noordwijk is increasing. This might be due the shoreface nourishment applied in 2002 in this area.

How is the landward part of the profile affected? How do the higher parts of the profile react to the nourishment? Has the beach and dune volume been increased after application of nourishment?

From the dune, beach and Section 1 volume analysis the following can be concluded:

- The higher parts of the profile do not have a direct response of the nourishment. There is a delay of two to three years for all three areas. There is a landward shifting of the volume (the nourished volume pushes the whole profile).

- The nourishment did not resulted on the increment of the dune volume in the area of Ter Heijde. The system seems to have been positively affected some years before application. Probably the dune reinforcement project in 1986, 1987 resulted in this change. The dune volume in the areas of Katwijk and Noordwijk was increased due to the nourishment and also the speed of the growth rate of the dune foot position (seaward shifting). Moreover, the observed increment in all cases can also be attributed to the Aeolian (wind-induced) sediment transport, since this is the basic mechanism for the formation of the dunes. Especially in the area north of the Ter Heijde nourishment it is more likely that the observed increase is due to the Aeolian sediment transport, since no other mechanism could increase the dune volume.

- The beach volume was slightly increased in the area of Noordwijk.
Does the shoreface nourishment result in beach widening?

From the beach width indicator approach, the beach width was defined and the following can be concluded:

- Shoreface nourishment in general did not result in beach widening, only in the Noordwijk case there was an increase of the beach width.

What is the behaviour of the longshore sediment transport, after completion of nourishment, in the lee side of the nourishment? Does the nourishment result in downdrift erosion and updrift sedimentation (salient effect)?

- From the longshore sediment transport analysis the following can be concluded: Only for the case of Ter Heijde a clear answer can be formulated. The outgoing longshore sediment transport has been decreased. In the updrift and downdrift direction a significant sedimentation is observed. The opposite effect of the salient effect has probably occurred. For the cases of Katwijk and Noordwijk it is not possibly to come up with conclusions. The longshore sediment transport is clearly affected by the cross-shore sediment transport.

How does the nourishment affect the onshore versus offshore sediment transport?

- From the sub sections volume analysis the following can be concluded: In all cases the nourishment volume is gradually shifting landward. Feeding processes of the higher parts of the profile are observed. The onshore sediment transport has been increased. In the cases of Katwijk and Noordwijk there was a quick response of the nourishment, for the ‘total volume’, and thus the nourishment can be considered to be successful. The extra volume was mainly preserved in the later years. The sediment balance of the cross-shore profiles for the nourishment area was not maintained.

8.2 Recommendations

Due to the importance of regular and accurate survey data for the study and analysis of the nourishments the following is recommended:

Before and after application of the shoreface nourishment, sufficient surveys that cover the entire area must be conducted. By this way important information concerning the nourishment behaviour and how it affected the autonomous behaviour of the cross-shore profiles will not be missing. Moreover, an area larger than the nourishment area should be covered by the measurements, during the pre and post nourishment periods. It is important for any kind of analysis to be aware of the processes that taking place in the part seaward of the nourishment.

For a future research the following recommendations can be made:

A distinction as clear as possible, between the longshore and cross-shore sediment transport, must be applied. It is more sufficient to start with the analysis of the changes that occurred in the absolute volumes and continue with the analysis of the trend lines. Moreover, when a trend of a period is been taken, the conclusions might be inaccurate or misleading. Thus, different periods should be studied first, while the definition of the periods should follow. For the changes in the autonomous behaviour of the cross-shore profiles due to shoreface nourishment, it is important that the analysis to be based on coastal stretches where no direct interventions by man have been made.
9 List of References

Lecture Books


CT5309, “Coastal Morphology and Coastal Protection”, lecture book Delft University of Technology.

Other Publications


10 Appendices

The following Appendices are included in the DVD that is provided with the present report:

A: Total volume evolution

B: Dune volume evolution

C: Beach volume evolution

D: Volume changes for Sections

E: Beach Width Indicator evolution in time