DECADAL MORPHODYNAMIC BEHAVIOUR OF THE HOLLAND SHOREFACE

A thesis submitted to Middlesex University
in partial fulfilment of the requirements for the degree of
Doctor of Philosophy

CLAIRE L HINTON

Flood Hazard Research Centre
School of Social Science
Middlesex University

July 2000

ABSTRACT

The shoreface, the 'buffer zone' between the land and sea, is one of the most important coastal regions directly influencing the coastal sediment budget through its role as a sediment sink or source. It therefore has a potentially significant impact upon large-scale (10 km; decades) shoreline movement. However, knowledge of shoreface activity over the medium- (1 km; years) and, more particularly, the large-scale remains scarce, primarily as a consequence of data limitations.

This empirical thesis extends existing knowledge to the large-scale through the observation of the temporal and spatial characteristics of shoreface morphodynamic behaviour over a 32 year period. It takes a data-orientated approach using the unique JARKUS data set which is composed of cross-shore bathymetric profiles covering the entire Holland coast to a maximum offshore distance of 3 km (approximately 16 m depth). The observations made are also used to i) evaluate the ability of existing models to predict shoreface morphodynamic behaviour; and ii) examine the evolution of shoreface activity beyond the data limits.

It is shown that not only is there a cross-shore limit to significant depth change on the upper shoreface (as previously observed in short-scale studies), but over the longer temporal periods ($\geq$ 10 years), the middle and lower shoreface typically undergoes significant erosion. These observations are forthwith named the 'shoreward depth of closure' and 're-opening zone', respectively. The observed shoreface activity has also been classified as a function of the cross-shore extent of the activity as either 'non-', 'partially-' or 'fully-active'. Shoreface activity is strongly spatially- and temporally-dependant, such that i) the Holland coast can be divided into two longshore provinces of similar morphodynamic characteristics; and ii) after 100 years, the north Holland shoreface is predicted to become fully active i.e. there is no cross-shore limit to the activity. Shoreface processes are under the control of internal dynamics e.g. the nearshore bar system, and external forcing e.g. hydrodynamics. The relative significance of these forcings is temporally-dependent; for example the nearshore bar system has a greater relevance on the upper shoreface activity over the shorter time periods.

Although most readily applicable to wave-dominated coastlines with similar characteristics to the Holland coast e.g. a nearshore bar system, the fundamental ideas arising from this work could also be applied to coasts with different environmental conditions e.g. tidally-dominated. Essentially this study shows that shoreface activity is more widespread in the cross-shore than previously appreciated. One consequence is that there will be a greater sediment volume in transport than formerly acknowledged and accounted for in, for example, sediment budgets.

ACKNOWLEDGEMENTS

This thesis is the result of 4 years research whilst at the Flood Hazard Research Centre (FHRC), Middlesex University and in The Netherlands at Rikzwaterstaat (RIKZ) and Delft Hydraulics. All of the work was carried out as part of the PACE (Prediction of Aggregated-scale Coastal Evolution) project which itself is part of the EU-sponsored MAST-III programme under contract number MAS3-CT95-002. During my work I benefited from the support and expertise of many people to whom I am extremely grateful and would now like to mention.

Firstly I would like to thank my supervisor, Dr. Robert Nicholls (FHRC), for the help and guidance he provided and the many open and informative discussions we had. I am also grateful to my second supervisor, Prof. John Handmer (FHRC) for his comments and advice on the thesis. I gratefully acknowledge the staff at the FHRC and technical unit for their support and help during the period of my study.

Furthermore I would like to thank the staff of RIKZ and Delft Hydraulics for extending their welcome and advice during my stay at their Institutions. I am especially thankful to Dr. Daan Dunsbergen (RIKZ) for his time and help in obtaining the JARKUS data set, Dr. Jean-Marie Stam (RIKZ) and Wim Bakker (RIKZ/Delft Technical University) for their discussions on the Holland coast. Bram Roskam (RIKZ) was very helpful in providing and discussing the hydrodynamic data. Prof. Dr. Leo van Rijn (Delft Hydraulics/Utrecht University) is thanked for his discussions on the morphodynamic behaviour of the Holland coast. I am especially thankful to Prof. Dr. Marcel Stive (Delft Hydraulics/Delft Technical University) and Prof. Dr. Huib de Vriend (Delft Technical University/Enschede University) for sharing their knowledge and discussing my work. I also wish to thank them for providing me with the opportunity to use UNIBEST-TC. I am also grateful to Stefan Aarninkhof for his time and collaboration on the work involving UNIBEST-TC.

I would also like to thank Dr. Kathelijine Wijnberg (Utrecht University) for her insight into the morphodynamic behaviour of the nearshore bar system and her colleagues at the Institute for Marine and Atmospheric Research (IMAU) for their comments after a presentation of my work.

My scientific research also benefited from the help and suggestions of many coastal scientists, especially at the PACE workshops and conferences. Thanks extend to all.

Finally I would like to thank my parents for their everlasting encouragement to follow my dreams and their patience after the well used response "not long now".

CONTENTS

FIGURES

TABLES

PLATES

BOXES

APPENDICES

PUBLISHED PAPERS

1) INTRODUCTION

1.1) BACKGROUND TO STUDY

The coastline forms the boundary between the marine and terrestrial environments. It is a highly dynamic zone within which changes, primarily resulting from interactions between the lithosphere, atmosphere, hydrosphere and biosphere, can take place over a range of temporal periods. The dynamic nature of the coast is such that it is vitally important that its changing behaviour[1], through time and space, is understood and can be predicted. The changes which do occur within the coastal system could have a potentially significant impact upon both the ecological and human environments; for example coastal erosion will lead to land loss and possibly the destruction of properties. The classic case study of this is the cliff erosion at Hallsands, Devon, UK in 1912 due to anthropogenic influences. Loss of the feed of shingle to the beach resulted in the removal of protection to the cliff foot, ultimately causing severe cliff erosion and the collapse of Hallsands village into the sea. An understanding of the coastal environment and its complexities, as attained by coastal scientists, should therefore improve the coastal managers and engineers ability (cf. Environmental Transport Regions, 1998) to install schemes with more confidence and success.

It is that region between the beach and shelf which should be taken to represent the 'transition zone', or 'buffer zone' between the land and sea; it is here that the waves have a significant direct impact upon the sea floor through, for example, shoaling. Seaward of this area there are relatively few influences which will have an effect upon the coastline. This zone is most commonly referred to as the shoreface (e.g. Vincent *et al*, 1983; Stive *et al*, 1990; Wright *et al*, 1991; Van Rijn, 1995; Walstra *et al*, 1998) and is illustrated in Figure 1.1 using an example of a cross-shore profile from the Holland coast. Other terms used to describe this region are i) the inner shelf (e.g. Wright, 1995) and ii) the offshore (e.g. Komar, 1998). For the purpose of this study the term shoreface is used as it has been shown (e.g. Van Rijn, 1997) to be practical for the study area; indeed most, if not all, studies of this coastline (the Holland coast) use the term 'shoreface'. Hence the terminology of this study will be in keeping with that of existing ones on the Holland coast. The definition of the shoreface, as used here, is given in Box 1.1. The shoreface makes an important long-term contribution to the coastal sediment budget as it will be acting as either a sink or source of sediment from/to the active zone; for example the dominant onshore transport of the Holland coast (Walstra *et al*, 1998) means that this shoreface acts as a sediment source for the active zone. However, the dominant longshore transport also means that the majority of this sediment is

[1] or the morphodynamic result of the interaction between the existing morphology, hydrodynamics and sediment transport of the coastal system (see Box 1.3)

transported northwards (Van Rijn, 1995) and so does not act as nourishment for the active zone. It should be noted that if there was no shoreface feed then it is probable that the active zone (and beach) would erode at a greater rate than at present. The role of the shoreface also means that it can potentially act as a control upon the long-term shoreline movement.

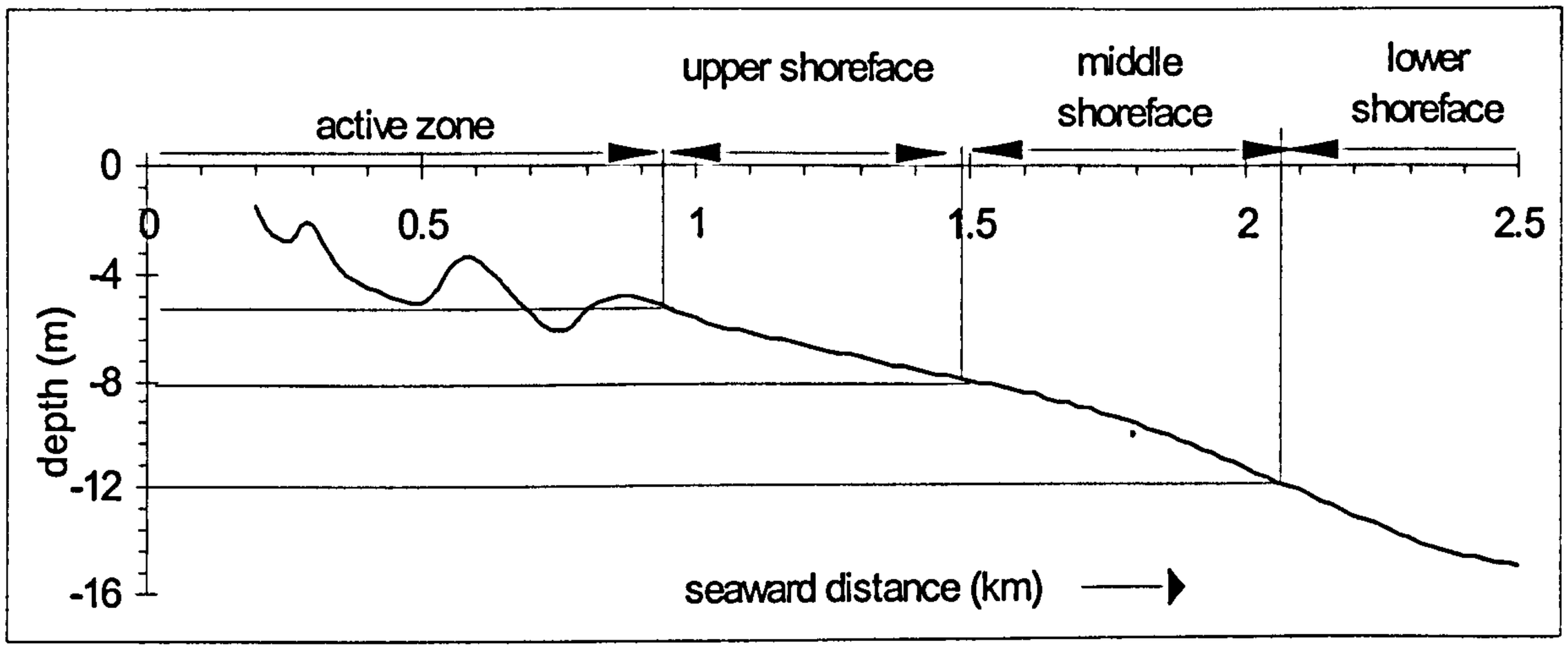


Figure 1.1. Definition sketch of the shoreface using a cross-shore profile from the Holland coast.

Box 1.1, The definition of the shoreface as used in this study :

'the fixed offshore zone bound on the landward side by the seaward slope of the outer breaker bars and bound on the seaward side by the transition from a concave profile to a nearly horizontal bottom'
(Houwman and Hoekstra, 1994).

It is important that the response of the coastal region, especially the shoreface, to different forcings can be anticipated over all scales; "*in addition to being fundamental to understanding the morphodynamics of beaches, the spatial and temporal behaviour of the beach profile has direct application in coastal engineering projects involving beach nourishment and the siting of coastal structures*" (Larson and Kraus, 1994). It is becoming increasingly obvious that information of long-term coastal behaviour is vital, especially with the increasing pressure placed upon this environment. An example of such a pressure is that of climate change which leaves as one of its signatures rising sea levels; the global rise is predicted to be approximately 0.2 m by 2030

(regional variations will exist) (Houghton, 1991). However, this does not mean that there is any less requirement for smaller scale information; upscaling of knowledge over the small- and medium-scales (Table 1.1) i.e. process-knowledge, provides useful details for understanding and prediction over the large-scale. The interaction between these scales, defined within the Large Scale Coastal Evolution concept of Stive *et al* (1990), is given in Figure 1.2.

SCALE DESCRIPTION	MORPHODYNAMIC (LONGSHORE) LENGTH SCALE	TIME SCALE
Geological-Scale	100 km	centuries
Large-Scale	10 km	decades
Medium-Scale	1 km	years
Short-Scale	100 m	storms-seasons

Table 1.1. Description of the three scales adopted from the Large Scale Coastal Evolution concept of Stive *et al* (1990) in addition to the geological-scale. These are illustrated in Figure 1.2.

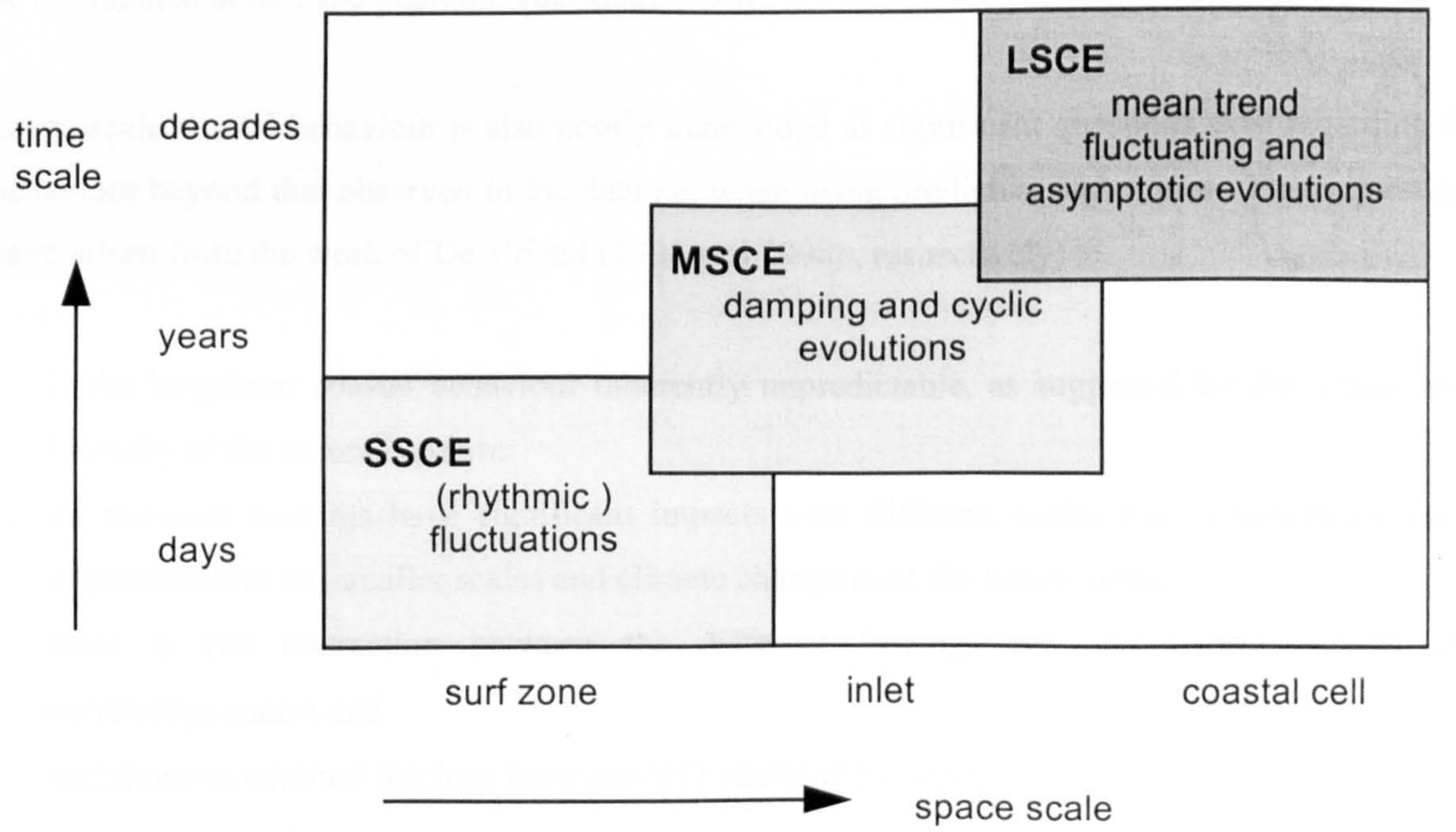


Figure 1.2. Coastal evolution scales (taken from Stive *et al*, 1990)

At present there is little information available of coastal behaviour over the medium- and large-scale. This is primarily the result of a lack of good quality, long-term data sets which are required not only i) to allow the observation of coastal behaviour, but also ii) to validate and calibrate

models which attempt to reproduce and predict this behaviour. Typically, long-term data sets are derived from maps discovered in archives and used to determine long-term changes in shoreline position. Though useful in calculating shoreline change, they should be used with caution as the accuracy of the data source is difficult to determine. Long-term data sets should, ideally, include high quality bathymetric and hydrodynamic data. In addition, such data sets should be available at a number of different locations with sufficient resolution in time and space. The number of these data sets are limited, although expanding (Table 1.2). One of the largest data sets of this kind exists for the low-lying, densely populated Netherlands coast where a coastal morphodynamic monitoring system has been in operation since 1963. This extensive data set is called JARKUS, an acronym for annual soundings (in Dutch 'JAaRlijkse KUStlodingen' (Ruessink, 1998)). The JARKUS data set was primarily collected for coastal zone management purposes (RIKZ[2]) but has also proven useful to coastal scientists investigating coastal behaviour e.g. nearshore bar behaviour (Wijnberg, 1995). In the former case, analysis of the bathymetric data led to the implementation of the 1990 'dynamic preservation policy' which aimed to fully control erosion until 1995 and consequently resulted in 10^6 million cubic meters of sediment being placed on the coast (Louisse and Kirk, 1990). The most important aspect of this policy was that the shoreline of the Netherlands be maintained at its 1990 position[3] (de Ruig, 1998).

Large-scale coastal behaviour is also poorly understood as significant questions exist regarding the behaviour beyond that observed in the data i.e. when using predictive techniques. These questions have arisen from the work of De Vriend (1991 and 1998b, respectively) :

1. is the long-term coastal behaviour inherently unpredictable, as suggested by the strong non-linearity of the natural system;
2. do different forcings have significant impacts over different scales e.g. is turbulence more important over the smaller scales and climate change over the longer term;
3. what is the interaction between the different forcings e.g. the hydrodynamics and morphodynamics; and
4. variations in external forcings have and will continue to occur.

These questions are examined in more detail in Chapter 2. The conclusion drawn is that, in combination with data limitations, they have resulted in a large knowledge gap as it has proven

[2] RIKZ or Rijkswaterstaat, the Dutch National Institute for Marine and Coastal Management
[3] A review of this coastal defence policy in 1995 showed that it was successful; considerable dune and beach loss no longer occurs (de Ruig, 1998).

hard to upscale process knowledge[4] to change on a longer timescale (cf. De Vriend, 1993). This problem has been concentrated upon over the past 15 years: an example of a recent research project is the EU MAST-III PACE (Prediction of Aggregated-scale Coastal Evolution) project (De Vriend, 1997a; 1998a).

SITE	LINCON-SHIRE (UK)	JARKUS (Netherlands) (short)	JARKUS (Netherlands) (extended)	LUBIATOWO (Poland)	SYLT ISLAND (Germany)
LENGTH OF COAST (km)	38	500	500	2.7	35
NO. PROFILES	18	2500	500	5 to 28	70
LONGSHORE SPACING (m)	1000 to 2000	200 to 250	1000	100	500
CROSS-SHORE DISTANCE	intertidal (80 m offshore)	dune & beach (1000 m offshore)	coastal profile (2.5 to 5 km offshore)	dune to -5 m (800 m offshore)	dune to MLW
DURATION (yrs)	31	36	32	35	114
DATES	1959 to 1990	1963 to 1999	1965 to 1997	1964 to 1999	1870 to 1984
TIME INTERVAL	1 month	1 year	3 to 5 years	6 months	5 to 10 years

Table 1.2. Examples of the largest-scale profile and bathymetric data sets (taken from Hamm, 1999).

It is the aim of this coastal science thesis (Box 1.2; 1.3) to expand upon the limited knowledge of medium- and large-scale coastal behaviour by concentrating on the morphodynamic (Box 1.3) activity[5] of the Dutch shoreface[6]. Temporal and spatial resolutions, in combination with accessibility, led this author to use the JARKUS data set to achieve this aim (Chapter 3). This data exists for the entire Netherlands coast, covering both tidally- and wave-dominated environments. However, in order to avoid the complication of inlet processes, and to encourage comparision between the bulk of research on shoreface morphodyanmics, it is the Holland coast (Figure 1.3) which is studied here. In particular it is the shoreface between Callantsoog and Schevingen which

[4] as observed from short-term field experiments
[5] morphodynamic activity is identified by significant depth changes, where 'significant' is dependant upon the criterion selected to identify the depth change
[6] as already stated the shoreface is an extremely important part of the coastal region due to its role i) as a 'buffer zone'; ii) in sediment budgets; and iii) in shoreline movement.

constitutes the study area. Hence the large-scale behaviour of a wave-dominated, uniform coast uninterrupted by tidal inlets can be accurately ascertained; inclusion of more northern and southern profiles of the Holland coast will include tidal effects from the Marsdiep inlet and the Rotterdam Waterway (these features are all shown in Figure 1.3). The results from this study can :

1. be compared with the majority of existing research on this topic;
2. be integrated with the short-scale knowledge already available on other, similar, coastlines; and
3. act as a 'bridge' between the short-/medium- and geological-scale shoreface knowledge which exists for this environment.

Box 1.2, the aim of this study:

determine the spatial- and temporal-characteristics of *shoreface morphodynamic behaviour* over the *medium-* and *large-scales*, paying particular attention to the latter.

In more detail, this investigation of large-scale shoreface behaviour will provide invaluable information on the different timescales of shoreface response to forcings. At present the general assumption that the shoreface response is temporally dependent is based upon medium-term data sets (e.g. Wright *et al*, 1985) and modelling work (e.g. Stive and De Vriend, 1995). By using the JARKUS data set, this research will either confirm or reject this assumption based upon 32 years worth of field data. In addition, it is hoped that not only will the results i) support the output of existing long-term models e.g. the Advection-Diffusion Model (Niedoroda *et al*, 1985); but also provide details of shoreface morphodynamic behaviour for application to generic shoreface studies. For example not only should the concepts obtained be useful to other coastal researchers who have limited information on the morphodynamic behaviour of a shoreface of similar characteristics but it should also prove invaluable to coastal managers who wish to further understand the temporal- and spatial-development of 'their' shoreface (again with similar characteristics to the Holland shoreface).

Box 1.3, definitions of the key words used in Box 1.2 :

Shoreface : *the fixed offshore zone bound on the landward side by the seaward slope of the outer breaker bars and bound on the seaward side by the transition from a concave profile to nearly horizontal bottom* (Houwman and Hoekstra, 1994) (as given in Box 1.1).

Morphodynamic: *the form and structure of the coastal system*

Behaviour : *the morphodynamic result of the interaction between the existing morphology, hydrodynamics and sediment transport of the coastal system*

Medium-scale : *temporal period greater than years; morphodynamic length scale greater than 1 km (*Stive *et al,* 1990*)*

Large-scale : *temporal period greater than 10 years; morphodynamic length scale greater than 10 km* (Stive *et al*, 1990)

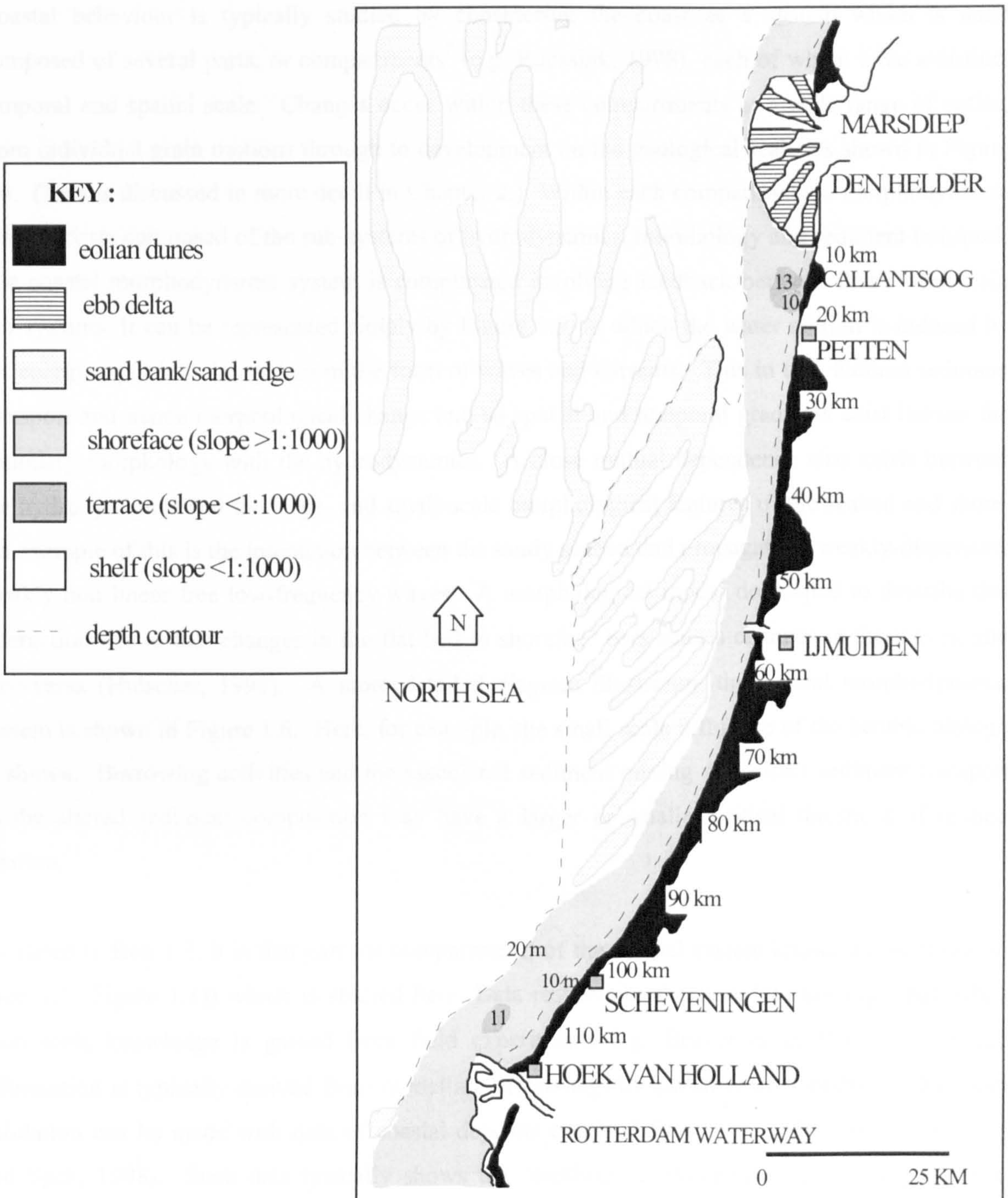


Figure 1.3. The study area : the Holland coast (adapted from Wijnberg, 1995). Distance is measured from the north to the south as indicated.

1.2) THE COASTAL SYSTEM

Coastal behaviour is typically studied by considering the coast as a system which is itself composed of several parts, or compartments[7] (e.g. Ruessink, 1998), each of which have a distinct temporal and spatial scale. Changes occur within these compartments at a wide range of scales, from individual grain motions through to development on the geological scale, as shown in Figure 1.4. (This is discussed in more detail in Chapter 2.) Within each compartment, a morphodynamic system exists composed of the sub-systems of hydrodynamics, morphology and sediment transport. The coastal morphodynamic system is complicated involving feedback between these three main sub-systems. It can be represented simply by Figure 1.5, in which the water motion is induced by the energy input into the system in the form of waves and currents. This in turn induces sediment transport and hence morphological change and so spatial and temporal gradients exist linking the boundary morphology with the hydrodynamics. A close mutual dependence also exists between the hydrodynamics and the large- and small-scale morphological features of the seabed and shore. An example of this is the interaction between the sandy seabed and propagating, weakly-dispersive, weakly non-linear free low-frequency waves. A morphological model developed to describe this interaction shows that changes in the flat bed to shoreface bars causes changes in the waves, and vice-versa (Hulscher, 1998). A more detailed diagram illustrating the coastal morphodynamic system is shown in Figure 1.6. Here, for example, the small-scale influence of the benthic biology is shown. Burrowing activities and the associated sediment mixing will affect sediment transport as the altered sediment composition may have a larger or smaller critical threshold of motion iniation.

As stated in Box 1.2, it is that part (or compartment) of the coastal system known as the shoreface (Box 1.1; Figure 1.1)) which is studied here. Data restrictions (section 1.1) are such that, whilst short-scale knowledge is gained from field experiments e.g. Beaver *et al* (1999), large-scale information is typically derived from modelling efforts e.g. Buijsman *et al* (1998b). In the latter, validation can be made with data of coastal deposits obtained from core borings (e.g. Cleveringa and Spek, 1998). Such data typically shows the coastline development through the position of coastal deposits within the core. Of the short-scale shoreface studies, the majority have focused upon differences in wave- and tidal-currents and sediment transport between fair-weather and

[7] the definition of compartment is a section of the coastal system which has a distinct temporal and spatial scale e.g. the shoreface, tidal inlets, beach, active zone (see glossary). The concept of the compartment is adopted in the ASMITA model which consists of three parts; the tidal basin; ebb-tidal delta; and adjacent coast (Buijsman *et al*, 1998b)

storm conditions (e.g. Vincent *et al*, 1983; Wright *et al*, 1986; Snedden *et al*, 1988; Gracia *et al*, 1998; Beaver *et al*, 1999). These have shown that the initiation of sediment transport only occurs during extreme events i.e. storms. The most significant large-scale modelling efforts have been made using behaviour-orientated models (BOM) which are able to predict the shoreface and shelf behaviour over periods from decades to millennia (Cowell *et al*, 1995; Niedoroda *et al*, 1995; Stive and De Vriend, 1995; Buijsman and Stive 1998). Validation between model results and field data generally agree although some discrepancies do still exist. For example the Advection-Diffusion Model (ADM) of Niedoroda *et al* (1995) tends to underestimate the Holocene progradation of the beach at Haarlem, The Netherlands (Buijsman *et al*, 1998a). All the models suggest that the shoreface is active over the large-scale. (These results are discussed further in Chapter 2). The shoreface behaviour of the Holland coast, as observed in this study, was primarily identified using the morphological concept of 'depth of closure' (Box 1.4).

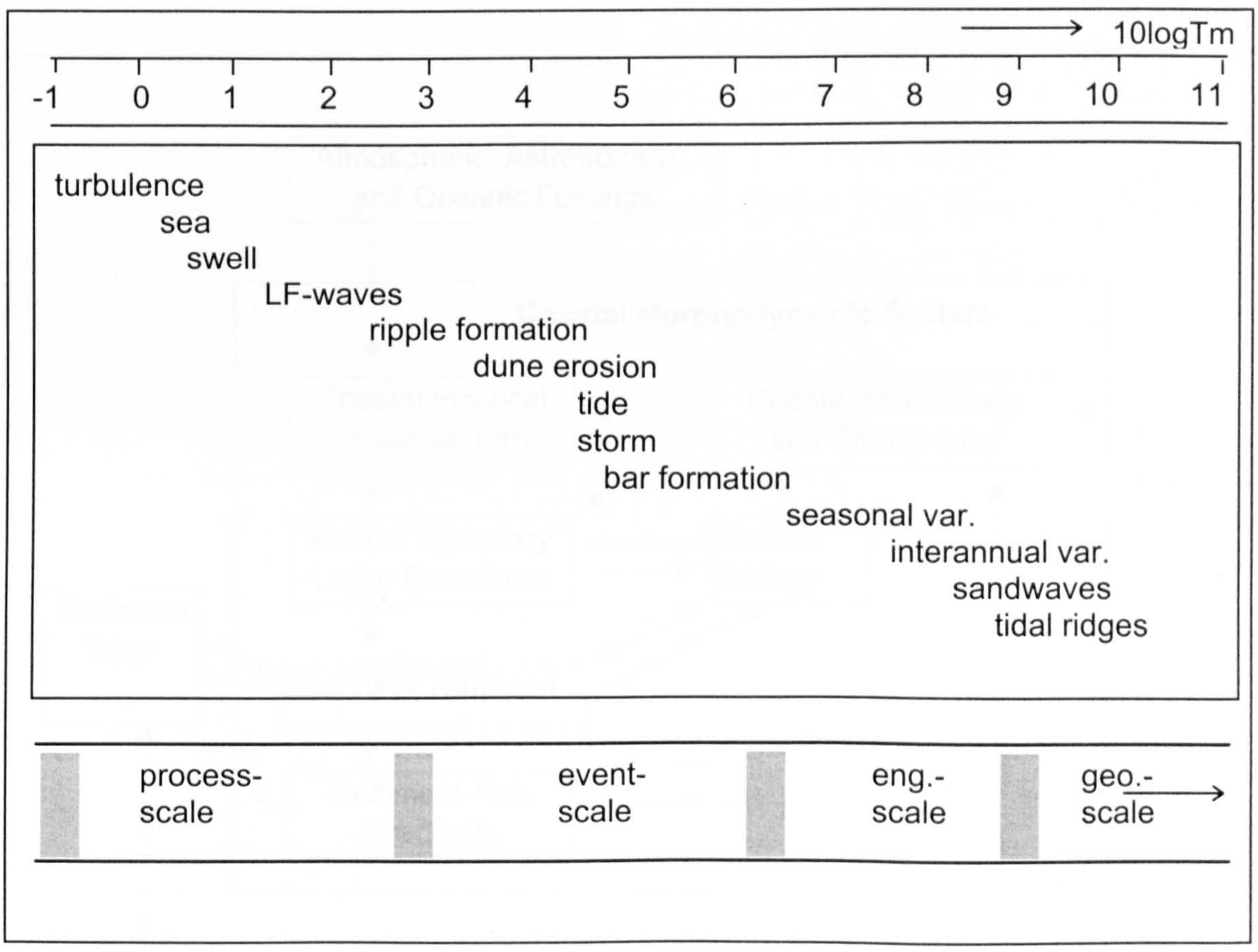


Figure 1.4. Scale range in coastal morphology (De Vriend, 1998).

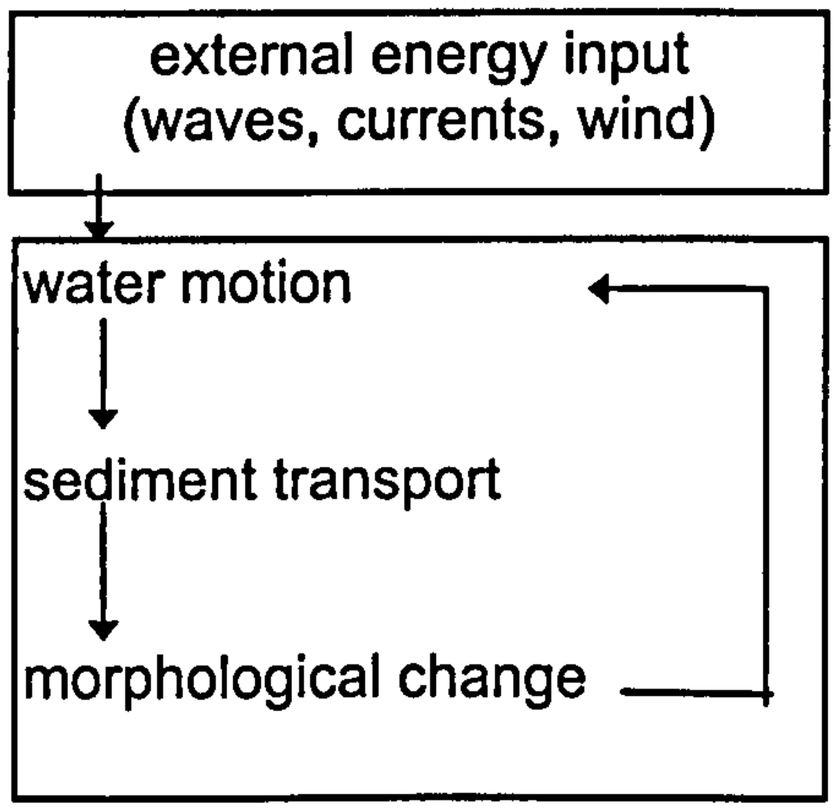


Figure 1.5. The coastal morphodynamic system which is found within each of the compartments of the coastal system (taken from Ruessink *et al*, 1998). It comprises hydrodynamic processes, the resulting sediment transport and hence morphological change linked by the feedback changing morphology has on the hydrodynamic processes.

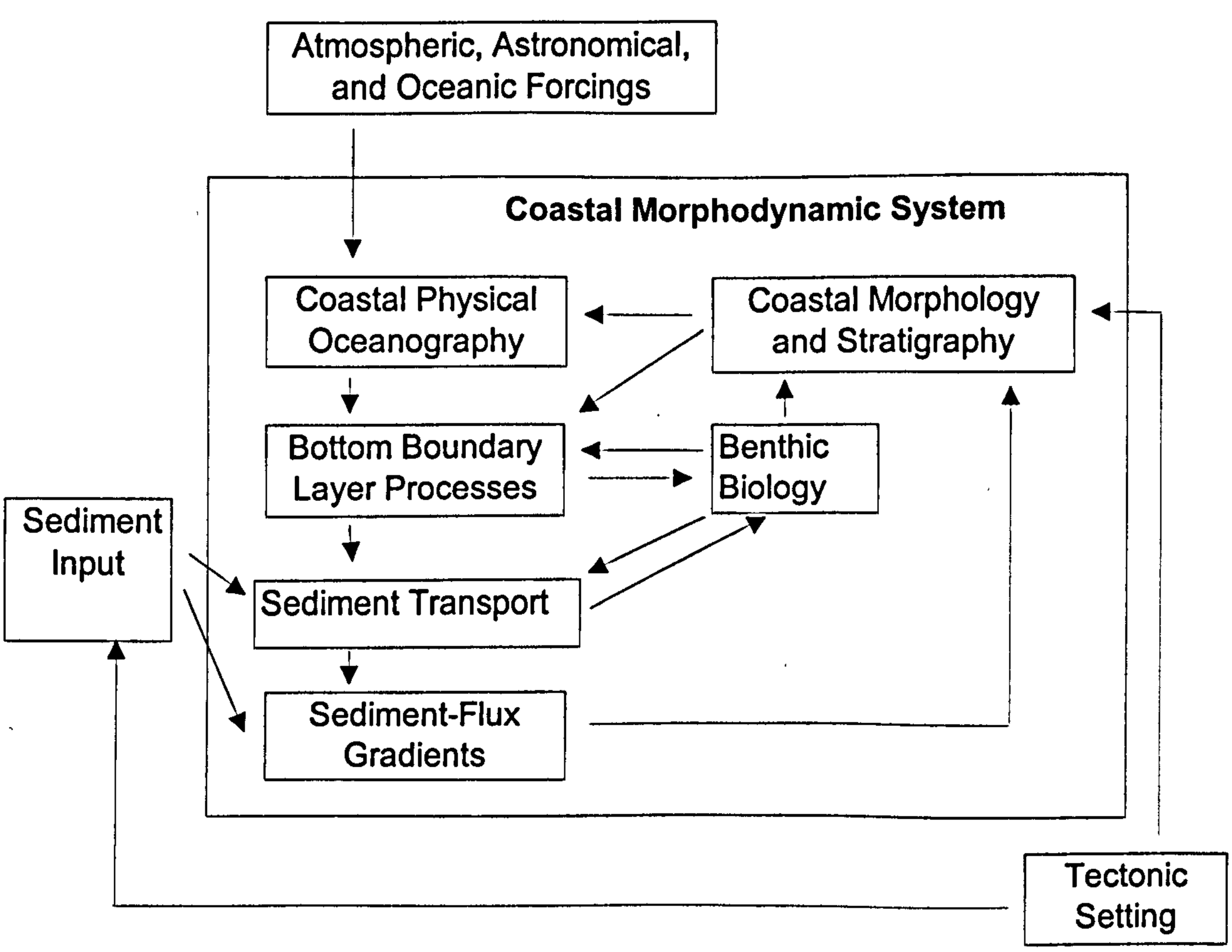


Figure 1.6. Flow diagram illustrating the idealised elements and linkages in a coastal morphodynamic system (taken from Wright, 1995).

Box 1.4, the working definition of depth of closure :

the seaward limit of significant depth change but not the absolute limit to cross-shore sediment transport (Nicholls *et al*, 1996).

Here 'significant' is dependant upon the criterion selected to identify the depth change; larger change criterion e.g. 0.25 m, allow a greater margin of change than a smaller change criterion e.g. 0.06 m and so Dc will typically be located at a more shoreward position.

Depth of closure (Figure 1.7) has been previously studied at short- and medium-scales as a result of data limitations (see section 1.1). It is typically found on the upper shoreface i.e. in water depths less than 8 m. A specific example is that of the Ebro Delta where Dc is found at 6.5 m depth over a 4 year period (Garcia *et al*, 1998). Closure is shown to be temporally-dependant over these scales i.e. as the time period increases, then the depth of closure also increase. In addition it has been shown that different forcings, in the form of bar dynamics and wave action, act as controls upon closure, in which the latter is constrained by the former (e.g. Hinton and Nicholls, 1998). This study, through the investigation of the large scale morphodynamic behaviour of the shoreface, also investigates the behaviour of depth of closure over the large-scale, as it is an integral characteristic of the shoreface.

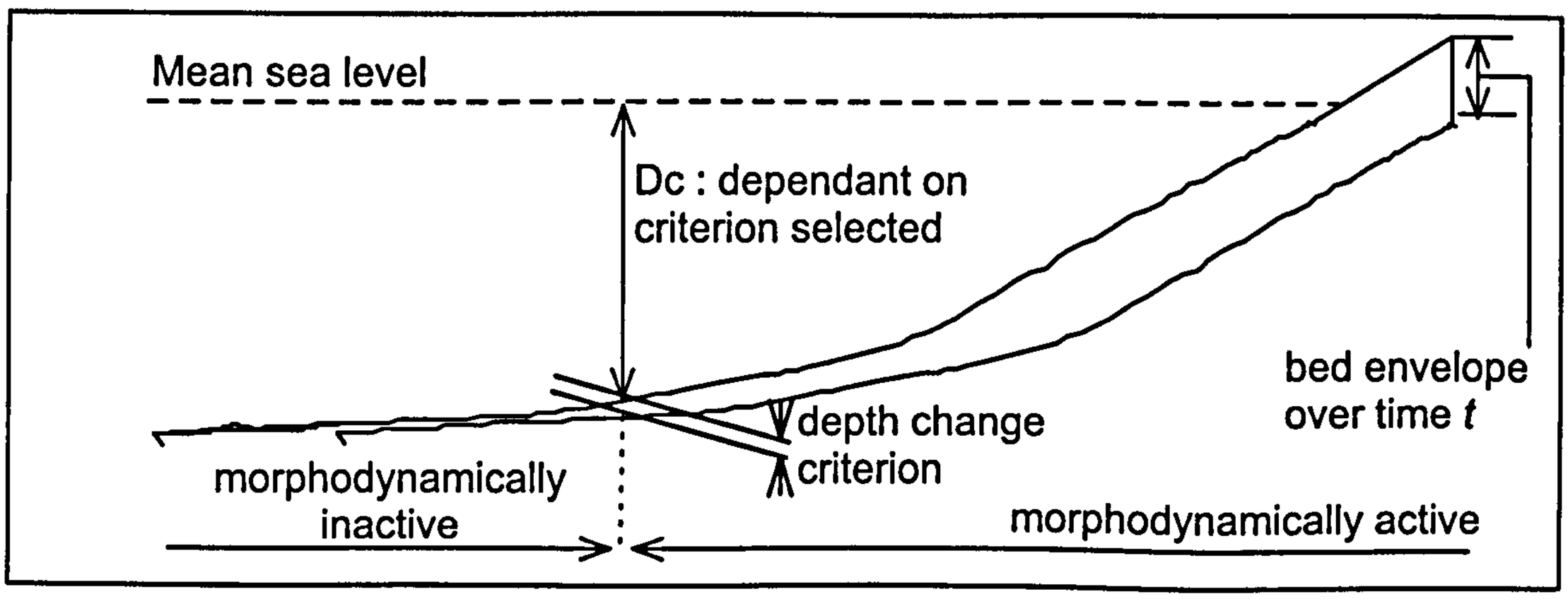


Figure 1.7. Zonation of a cross-shore profile over time *t* where Dc represents the seaward limit of significant depth change using the depth change criterion shown(after Hallermeier, 1978).

1.3) RESEARCH OBJECTIVES

As already stated, the aim of this research to expand existing knowledge of coastal behaviour, especially over the large-scale (Box 1.2). This is achieved by focusing on the morphodynamic behaviour of the Holland shoreface using the large-scale JARKUS data set. Based on the preceding sections, the following four research objectives have been formulated :

1. Determine the temporal and spatial variability of the morphodynamic behaviour of the Holland shoreface, over the medium- and large-scales (years to decades).

    - Can the depth of closure be identified on the shoreface? If so, what is the nature of its temporal and spatial evolution?

    - If the depth of closure is identified, can its working definition (Box 1.4) be applied to the shoreface over all scales? If not, what is a more appropriate description for the significant (and insignificant) depth changes observed on the shoreface?

    - Is the middle and lower shoreface a morphodynamically active region? Over what temporal and spatial scales, if any, can activity be observed?

    - How does the morphodynamic activity of the middle and lower shoreface influence the coastal sediment budget i.e. the relative role of shoreface erosion versus accretion?

2. Determine the causes and controls upon the shoreface morphodynamic behaviour along the Holland coast over the medium- and large-scales.

    - What morphodynamic and hydrodynamic controls exist upon the shoreface behaviour? What is the interaction of these controls over the scales investigated?

    - Do anthropogenic influences act as a control upon the morphodynamic activity? In particular does the largest engineering intervention, the

IJmuiden harbour moles ,(Figure 1.3) influence morphodynamic activity? If these controls are relevant, how do they influence the shoreface activity?

3. Evaluate the ability of existing models to predict shoreface morphodynamic behaviour.
   - Can the medium- and large-scale depth of closure be predicted using the time-dependent analytical Hallermeier (1977, 1978) model (Chapter 2)? What are the limitations, if any, of this model?
   - Can a process-based model (UNIBEST-TC; Chapter 5) designed for the short-term evolution of a cross-shore profile be used to identify shoreface behaviour over this and larger scales? What are the limitations of upscaling a short-term model in this way?
4. Examine how the shoreface behaviour may evolve beyond the data limit.
   - What timescales are inferred for shoreface evolution using extrapolation techniques?

These research questions are addressed using a strategy incorporating both data- and model-orientated approaches, as shown in Figure 1.8. Initially the data was examined for evidence of the depth of closure and subsequently morphodynamic behaviour over the entire cross-shore profile, to the data limits (approximately 16 m water depth). Using the observed results as validation, the models could then be tested for their ability in reproducing specific parts of the shoreface behaviour. Extrapolation of the trends calculated from the observations were also made. The details of the data-oriented and model-orientated approaches of this study, based upon the JARKUS data set, are clearly illustrated in Figure 1.9. Within this thesis three shoreface zones are identified (Chapter 2), ultimately resulting in the upper shoreface being separated from the middle and lower for ease of description. It is important to note that the shoreface zones are linked within feedback systems which interact at different scales and in practise must not be considered as separate entities.

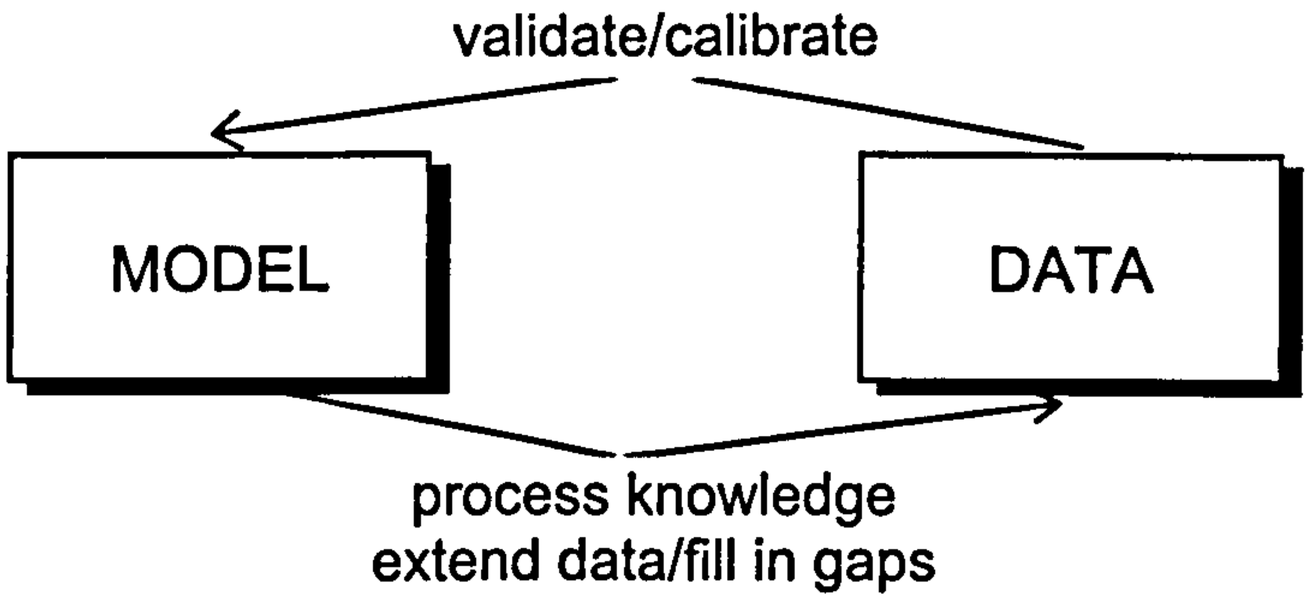


Figure 1.8. Links between data- and model-approaches within coastal research.

1.4) THESIS OUTLINE

It is intended that this thesis presents a detailed evaluation of the shoreface behaviour of the Holland coast. The following outlines each of the chapters :

The background to this research is introduced in **Chapter 1.** This includes not only the importance of large-scale coastal behaviour in today's research but also how this thesis aims to expand upon existing knowledge. Hence the approach that this study takes and the expected outcomes are also discussed.

Before an investigation can proceed it is vital that all existing research relevant to the study is known and understood. There are three main topics which are relevant here; i) large-scale coastal behaviour; ii) morphodynamic shoreface behaviour; and iii) the processes which control this behaviour. Each are thoroughly discussed in **Chapter 2** after introduction in Chapter 1.

Chapter 3 discusses the large-scale bathymetric data set used in this study; the JARKUS data set. Calculations of the resolution through time and space and measurement accuracy have been made. Consequently, the methods of measurement used since 1963 are also described.

The Holland coast is particularly uniform, both hydrodynamically and morphodynamically. Localised morphodynamic features do exist e.g. natural terraces. In addition, due to the coastal vulnerability to erosion, numerous anthropogenic influences have occurred here e.g. beach nourishment schemes. All are described in **Chapter 4.**

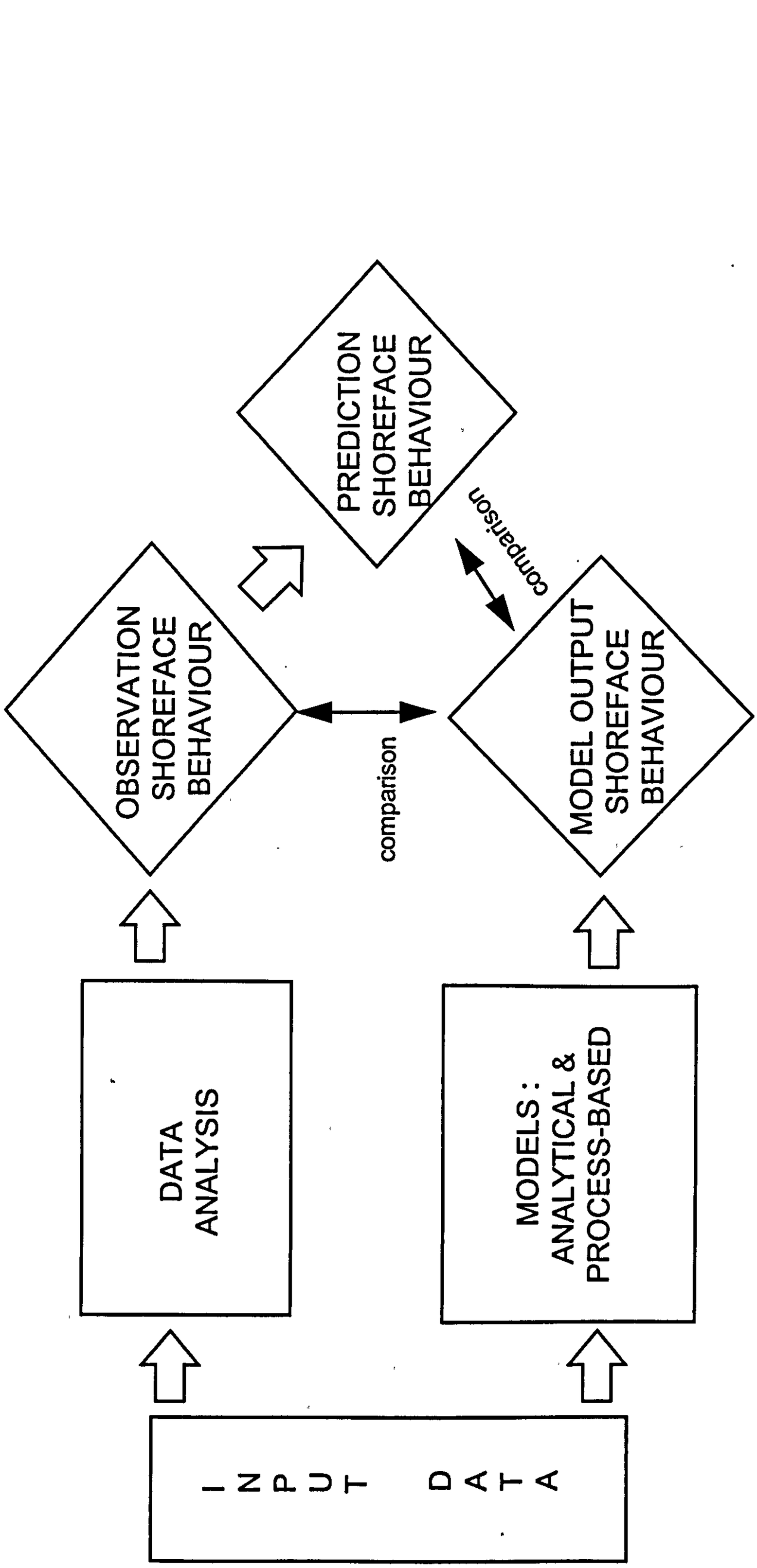


Figure 1.9. Flow diagram showing the data- and model-orientated approaches adopted in this study. The JARKUS data set is i) analysed in order to allow observations of the shoreface behaviour; and ii) used as input in two models (the analytical Hallermeier (1977, 1978) model and the process-based UNIBEST-TC model). In addition the observations of shoreface behaviour are used to predict shoreface behaviour over the large- and very-large-scales. Results from the data-oriented and model-orientated approaches are compared.

The large temporal and spatial extent of the JARKUS data set, in addition to its resolution means that a huge amount of bathymetric data is available for analysis. Therefore the methods used here have been selected due to their ability to i) sufficiently analyse the data; and also ii) adequately deal with the large quantity of data. These methods are described and critically analysed in **Chapter 5.** In addition the selected predictive tools are described along with their appropriate limitations.

Observations of the spatial and temporal variability of the shoreface behaviour derived from the analysis of the JARKUS data set are discussed in **Chapter 6.** The observations are sub-divided into those concerned with i) the depth of closure; and ii) the middle and lower shoreface behaviour. All are described as a function of both time and space (alongshore and cross-shore) for the medium- and large-scale.

The potential causes and controls of the observed shoreface behaviour are investigated in **Chapter 7.** These take the form of both the hydrodynamics and morphodynamics. Also examined is the possible influence of the largest anthropogenic feature, the IJmuiden harbour moles.

Predictive techniques are important to provide knowledge beyond data limits (in this instance 32 years[8]) or where data is limited e.g. for a coast where only 2 years of bathymetric data exists. Therefore predictive techniques are tested which are potentially useful in both circumstances. The results derived from the use of three methods are described in **Chapter 8.** The methods used are; i) the analytical Hallermeier (1977, 1978) model; ii) the process-based UNIBEST-TC model; and iii) extrapolation based upon observed trends.

The use of the JARKUS data set, both as a source of observations of shoreface behaviour and as a predictive tool, has resulted in a wealth of knowledge, the majority of which has not been previously available. It is important to provide links between the observed feedback and potential forcings; although some of this has not been possible in a quantitative sense because, for example long-term near-bed current measurements do not exist for the middle/lower shoreface, hypothesis can be suggested and tested qualitatively. Comparisons between predictions and observations have also been made and lead to conclusions concerning the potential of the tested techniques. Both the observations and predictions, with reference to all relevant studies, are discussed in **Chapter 9.** In addition future work is suggested.

[8] 32 years represents the temporal limit of that section of the JARKUS data set used here; the extended JARKUS data set (Table 1.2; Chapter 3).

Chapter 10 discusses the conclusions which can be made from this study in addition to the limitations of this work.

2) THE SHOREFACE : TIMESCALES; PROCESSES AND MORPHODYNAMIC BEHAVIOUR

2.1) GENERAL INTRODUCTION

As stated in Chapter 1, this thesis will help fill the knowledge gap between the short- and geological-scales (Table 1.1) that presently exists for the shoreface (Box 1.1); it is important to understand the behaviour of this region over all scales due to its direct contribution to the coastal sediment budget and the potential control upon long-term shoreline movement (section 1.1). This is to be achieved by investigating the morphodynamic behaviour of the Holland shoreface over the medium- and large-scales (Box 1.2). Hence there are three topics pertinent to this research; i) large-scale coastal behaviour; ii) the morphodynamic behaviour of the shoreface; and iii) the processes which control this behaviour. This chapter therefore reviews the existing literature in the context of this study (section 1.3).

2.2) LARGE-SCALE COASTAL BEHAVIOUR

Coastal behaviour is generally studied by considering the coast as a system in which numerous compartments exist. Within each compartment there is a morphodynamic system (composed of hydrodynamics; morphology; and sediment transport) (see section 1.2). The systems' development is temporally- and spatially-dependant and is often positively coupled i.e. the time scale increases with the spatial scale; a result of the sediment quantities to be displaced and the depths at which this occurs (Wijnberg, 1995). This is related to the assumption of the 'primary-scale relationship' (Figure 2.1.) (De Vriend, 1991):

> *"a process of a certain scale will be in dynamic interaction with coastal behaviour within a certain scale".*

Outside this scale, the process is noise for coastal behaviour on a larger scale and is an extrinsic factor (boundary condition) for coastal behaviour on a smaller scale. Therefore at different scales, a different energy input becomes significant. When simplified the primary-scale relationship suggests that, for each scale level, a different morphodynamic system exists. The implications of this are that different aspects of the hydrodynamics, morphodynamics and sediment transport will

be important at different scales, suggesting that the morphological development of a system through time and space is controlled by:

1. the scales of variation in the forcing energy input i.e. the hydrodynamics; and
2. the scales of variation in the boundary condition, which are in turn controlled by the morphodynamic system on the larger-scale (Wijnberg, 1995).

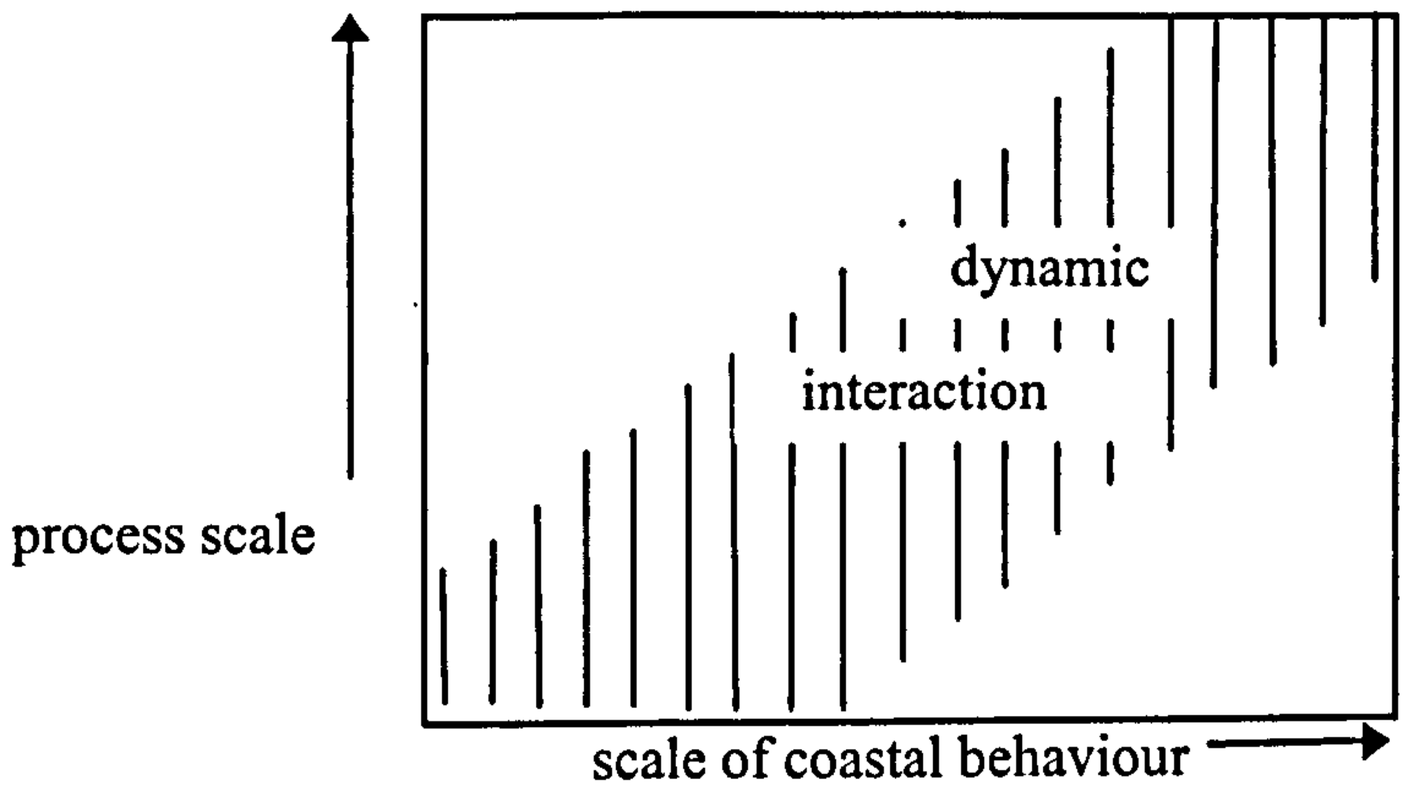


Figure 2.1. Primary scale relationship (De Vriend, 1991).

This relationship is a logical deduction if one considers the forcing and feedback of the coastal system over the short-, medium- and large-scale. For example profile changes over a small time period e.g. 1 day, can be explained using hourly hydrodynamic and water level data. Such changes over a longer period e.g. 5 years, are more likely to result from the overall hydrodynamic climate than individual waves.

The concept behind the primary-scale relationship forms the basis for the coastal-tract cascade which also takes as its assumption the idea that coastal processes and behaviour can be separated on the basis of scale (Cowell *et al*, 2000). The coastal tract was primarily devised to aid the modelling of low-order (10^2 to 10^3 years) coastal change. It is discussed in more detail in section 2.3.5.

Large-scale coastal behaviour is both poorly understood and difficult to predict (Chapter 1). The lack of long-term data sets (Table 1.2) means that the i) observation of long-term trends; and ii) calibration and validation of long-term models, are difficult to achieve to a high degree of

accuracy. Additionally, uncertainties exist within the coastal behaviour beyond that observed in the data, such as those shown in Table 2.1. Hence predictability limits exist :

> *"central to such an effort[1] is the evaluation of the degree of uncertainty related with the prediction, and particularly with the time and space scale of such prediction. When such uncertainty exceed a certain threshold to be defined with reference to the specific application, then we can argue that the limit of predictability has been reached"* (Capobianco, 1998).

turbulent motion	=	unpredictable
turbulence	≠	mean flow
sediment motion	=	unpredictable
grain motion	≠	transport
small bedforms	=	unpredictable
bedforms	≠	roughness
nearshore bars	=	unpredictable
bars	≠	mean profile

Table 2.1. Examples of inherent uncertainties which could occur in a deterministic sense (De Vriend, 1998). Taking the example of the sediment motion; grain motion can be used to determine sediment transport over the small-scale but, because the sediment motion is inherently unpredictable over the large-scale, grain motion cannot be used to predict sediment transport over this scale. (The predictability limits of these examples are also shown in Figure 2.3; see later)

The uncertainties which exist are now discussed in more detail :

1. is the long-term behaviour inherently unpredictable as suggested by the strong, non-linearity of the system?
   - simply, non-linearity is such that a small variation at $t = 1$ may grow into a large variation at $t = 100$. The non-linearity leads to inherent uncertainties (De Vriend, 1998) as :

[1] the *effort* being the prediction of long-term coastal behaviour

i) inherent unpredictability, or chaotic behaviour. This indicates that seemingly random behaviour exists in the coastal system, which cannot be solved from equations. Recent work does suggest that it is possible to gain information directly from data, which otherwise suggest a chaotic system, rather than indirectly from modelling. This is done using 'strange attractors' which exist in phase space where the dimensions can have any physical quality [2] (Pool, 1989). (However, for long-term behaviour, this will obviously require long-term data sets which are, as already stated, scarce);

ii) uncertainty in model parameters. If it is uncertain which processes are significant over the scale *x*, then there must be uncertainties concerning which parameters are required in the model, for example grain size; and

iii) uncertainties in the forcing (see points 2) and 3)).

2. do different forcings have significant impacts over different scales (De Vriend, 1991) ?

- if confirmed, then forcings which are negligible on the smaller scales may be significant over the larger scales. Indeed, it has been shown (Wright *et al*, 1985) that the state, profile configuration and sand storage of the beach and surf zone system results from the time-integration of numerous processes which have different spatial- and temporal-scales.

3. what is the interaction between external forcings and internal dynamics[3]?

- forcings can be divided into external forcings e.g. hydrodynamics, and internal dynamics e.g. morphodynamics. It has been suggested (Hinton and Aarninkhof, 1998) that the relative contribution of each not only differs between scales, but that those which occur on the macro-scale act as global forcing, or boundary conditions to the meso-scale, as illustrated in Figure 2.2. Non-linear dissipative systems can be maintained in states far from equilibrium due to self-organisation

[2] taking the example of Pool (1989), to describe the weather one may look in phase space with the dimensions of temperature and wind velocity. To represent how weather changes with time, one would draw a curve in phase space where each point on the curve is indicated by the temperature and wind velocity at a particular time. It should be noted that there is no restriction on the number of dimensions which the phase system can have, for example a four-dimensional phase space may encompass temperature, pressure, wind velocity and humidity.
[3] see glossary for precise definitions

i.e. the scales or perturbations which evolve upon the unstable basic state are controlled by the internal dynamics of the system, rather than the applied forcing (Swart and Falqués, 1998). The 'balance' between external forcing and internal dynamics has been investigated on short- and medium-scales and the interaction between them is shown to vary depending on the scenario. For example the behaviour of the two most inner bars of a three bar nearshore system is controlled by the internal dynamics of this system, in the form of the outer bar. Morphological changes in the outer bar are, however, controlled by hydrodynamic forcings (Hinton and Aarninkhof, 1998).

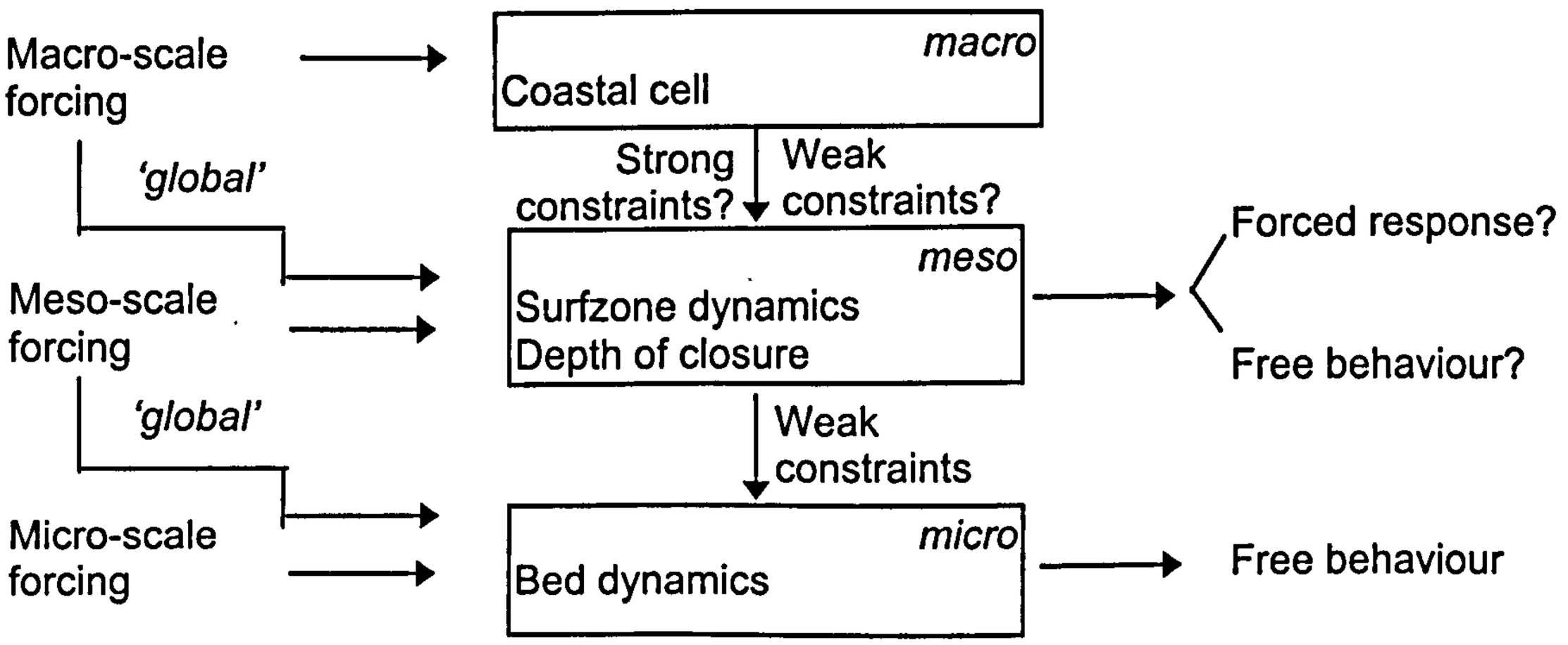


Figure 2.2. Schematised dynamics of a coastal system at various spatial/temporal scales. On the macro-scale level, the forcing can be, for example, sea-level rise and large-scale structures i.e. harbour moles. On the meso-scale level, forcings are waves and tides. The micro-scale forcing represents local, often anthropogenic, effects. Each of these forces can act as a global force on the lower scale level. (Hinton and Aarninkhof, 1998).

4. variations in external forcings have and will continue to occur
   - It has been shown that the non-linearity of the coastal system can lead to difficulty in understanding long-term coastal behaviour. However, the 'ease' with which observed non-linear trends e.g. exponential trends, can be used to predict behaviour beyond the data limits is fundamentally dependant upon the variation within these trends i.e. how much deviation from the mean trend line occurs? An additional point which needs to be considered here is whether future variations are

predictable. The forcings which need to be considered are both natural and anthropogenic. One example of the former is given in the following :

> a key topic in today's research is climate change and variability. Work within this field is reviewed by the IPCC[4] and incorporates many areas of research which both influence and are affected by the climate change for example increasing greenhouse gases (Houghton, 1991) and coastal zone management (Eid and Hulsbergen, 1991). Consideration of all possible influences has lead to the conclusion that "*there is no firm evidence that the global climate has become more variable over the last few decades*" (Houghton, 1991). However, other studies show that local variability does occur *"what is clear is that the North Sea and northeast Atlantic region is liable to bigger variation of its climate than have hitherio been appreciated"* (Lamb, 1985). The difference in opinion could result not only from the different study areas (and so the different data bases) but also the techniques used, for example Lamb (1985) uses a recorded history of sea flood disasters over the last few centuries whilst the IPCC typically concentrates upon indicators of sea-level change e.g. tidal gauges. Climate variability can be observed through storminess, here an increase represents an increase in wave intensity. It is shown that over the last 500 years there has been variations of storminess in the northeast Atlantic over time periods from years to decades (Lamb, 1991). However, it has also been concluded that, although a roughening in the storm climate has occurred in the last 40 years (cf. Carter and Draper, 1988), the present intensity of the climate is comparable with that observed at the beginning of this century (WASA, 1998).

Hence, within the natural coastal system the variation of forcings are shown to be either constant or changing through time.

One way in which the predictability limits can be extended is to use the idea of a 'scale cascade' (De Vriend, 1997). As illustrated in Figure 2.3a each feature of the cascade (as determined by its scale) has a predictability limit through time and space. Long-term prediction through modelling could therefore, in theory, be obtained through the aggregation of models through each step i.e.

[4] IPCC = International Panel for Climate Change

through upscaling, Figure 2.3b. However, such an approach is still in its infancy and the predictability limit not yet determined .

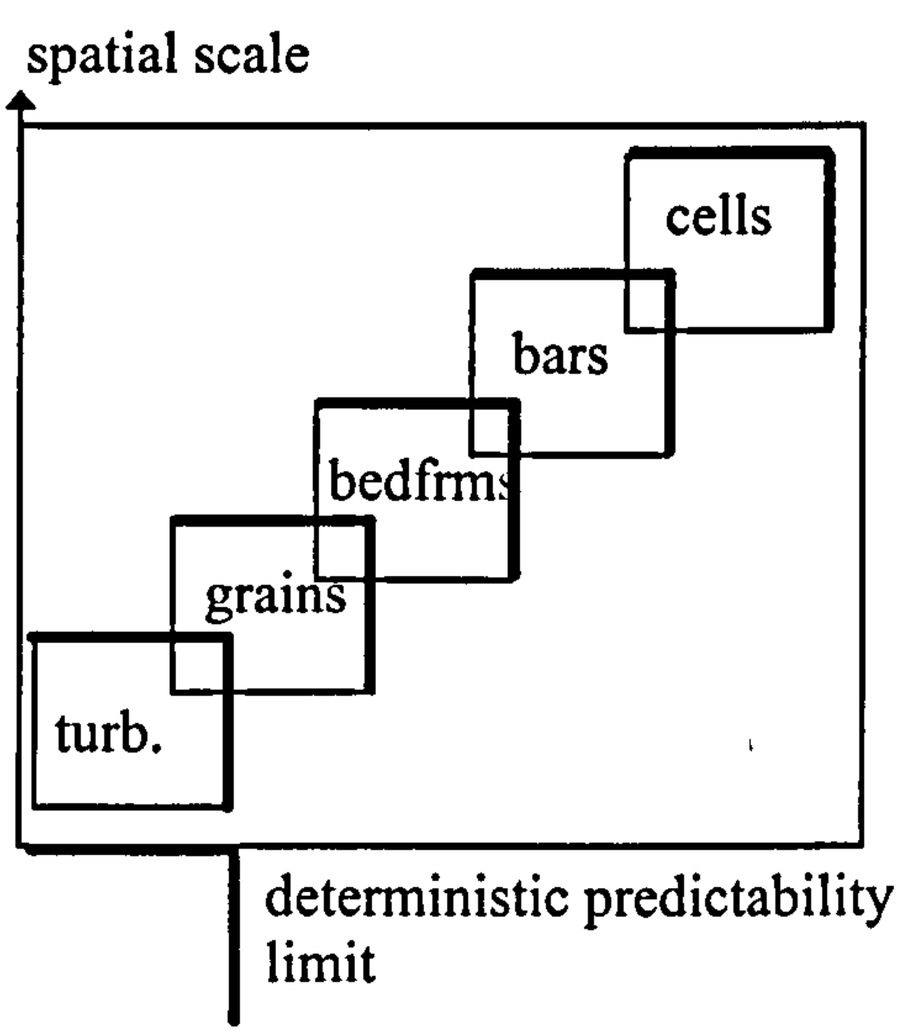


Figure 2.3a. Scale cascade (De Vriend, 1997).

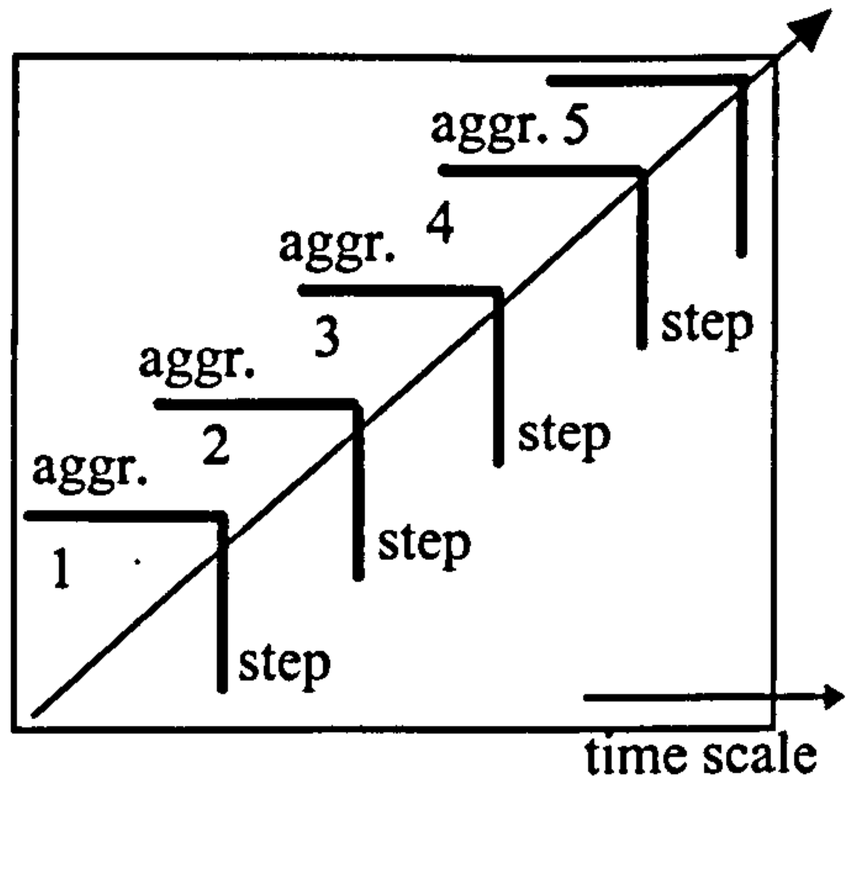


Figure 2.3b. Scale cascade and modelling (De Vriend, 1997).

2.3) MORPHODYNAMIC BEHAVIOUR OF THE SHOREFACE

2.3.1) INTRODUCTION

It is the aim of this section to review all existing literature which is important to our understanding of the shoreface, as it relates to this study. The format taken is therefore to discuss not only existing process-knowledge but also i) the short- to long-term morphodynamic behaviour of the shoreface (including the depth of closure concept[5]); and ii) the geological scale morphodynamic behaviour of the shoreface.

[5] see section 1.2 for introduction

2.3.2) SHOREFACE PROCESSES

The shoreface is most commonly divided into three zones (Figure 1.1), the boundaries of which are distinguished using depth values largely dependent upon the wave climate of the shoreface of interest (values used in this study relate to the Holland coast). These zones are :

1. the upper shoreface. In this study the upper shoreface has as its seaward boundary the seaward slope of the outer breaker bars and its seaward boundary at 8 m water depth. Other studies e.g. Stive *et al*, 1990, take the first dune row as the shoreward boundary and term this zone the active zone. This zone is the most dynamic and profile changes can be observed from bathymetric measurements over a short period;
2. the middle shoreface. This zone extends from the 8 m to 12 m water depth and is where transports are typically wave-dominated. The morphodynamic changes in this, and the lower shoreface, are weakly varying i.e. response times are much slower than on the upper shoreface (cf. Wright *et al*, 1985); and
3. the lower shoreface. The shoreward boundary is located at 12 m water depth and the seaward boundary by the transition from a concave profile to a nearly horizontal bottom. The depth of the seaward boundary is approximately 20 m. The morphodynamic characteristics are similar to the middle shoreface, though the transports are typically tidally-dominated, particularly at the seaward boundary.

Cross-shore divisions of the shoreface have also been made according to the dominant processes, as described in Table 2.2. These divisions (Niedoroda *et al*, 1985) are illustrated in Figure 2.4 and are such that the most seaward division, the geostrophic zone, occurs seaward of the Dutch shoreface.

The sediment transport processes which occur on the shoreface are well-documented, especially on the short-scale (Niedoroda *et al*, 1985; Brink, 1987; Wright, 1995). They differ from the three zones (upper; middle; and lower shoreface) such that wave-related transport is more significant on the upper shoreface and tide-related transport important on the lower shoreface (Table 2.3). Indeed :

> "*the processes which dominate the sediment transport at different times and places on the shoreface should be a function of the relative wave and current action*" (Niedoroda *et al*, 1985).

ZONE	DESCRIPTION
friction-dominated	friction forces are greater than the scale of the Coriolis effect. Typically extends from the surf zone to 10 m water depth.
transition	is the gradation zone between the friction and geostrophic zones. Typically extends from 10 to 20 m water depth.
geostrophic zone	surface and bottom Ekman boundary layers are separated by a region of unaffected geostrophic flow. Typically does not extend shoreward of 20 to 40 m water depths.

Table 2.2. Division of the shoreface according to Niedoroda *et al* (1985).

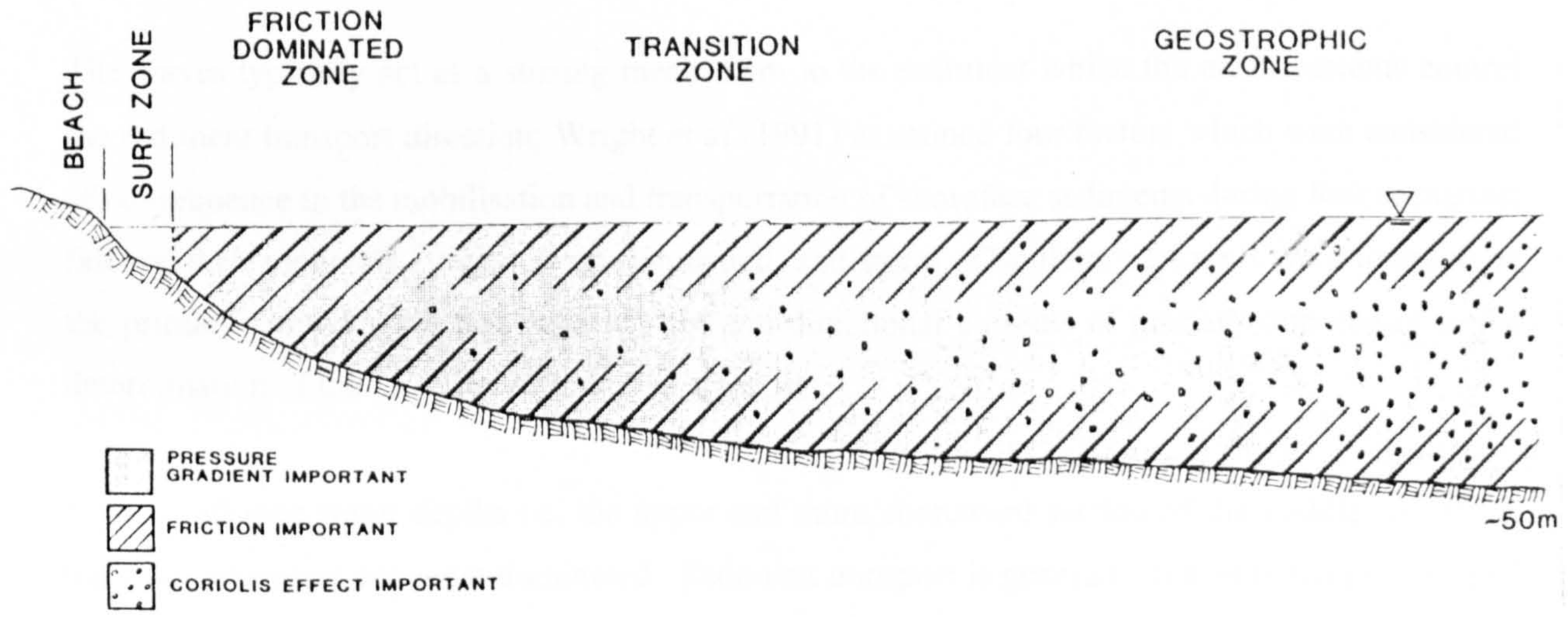


Figure 2.4. Schematic of the major dynamic zones and layers of the coastal boundary layer (Niedoroda *et al*, 1985).

REGION OF SHOREFACE	DOMINANT PROCESS
Upper	Breaking waves Wind-induced currents Longshore drift
Middle	Wave shoaling Wave asymmetry Upwelling/downwelling (Tidal currents)
Lower	(Wave asymmetry) Upwelling/downwelling Tidal currents

Table 2.3. Simplified list of sediment transport processes which occur on the shoreface as a result of hydrodynamic forcing (adopted from Stive *et al*, 1990). The processes in brackets are less significant in the appropriate shoreface region.

The waves typically act as a stirring mechanism to the sediment whilst the mean currents control the sediment transport direction; Wright *et al* (1991) examined four factors which were considered of consequence in the mobilisation and transportation of shoreface sediments during four scenarios; fair-weather; moderate energy; swell-dominated; and storm. Oscillatory currents were found to be the primary control upon bed agitation and uni-directional currents of primary importance in the determination of the direction of sediment transport.

In the shallower water depths i.e. the upper and more shoreward section of the middle shoreface, transport processes are wave-dominated. Sediment transport is generally concentrated near the bed and typically occurs as bedload transport. This occurs in close interaction with small bedforms e.g. ripples, and tends to be dominant where mean currents are relatively weak compared to the wave motion (Walstra *et al*, 1998). Suspended transport is to be expected when the turbulence-related mixing capacity of the tide- and wind-driven mean currents increase and is observed during storms on the Dutch shoreface (Walstra *et al*, 1998). Ripple-related vortices can also induce suspended sediment transport.

In the deeper water depths, transport processes are tidally-dominated. This is because the symmetrical nature of waves in deeper water means that, in wave-dominated environments, net sediment transport by oscillatory motion is small in depths greater than 10 to 15 m (Niedoroda and Swift, 1981; van Rijn, 1995, 1997). Additional middle and lower transport processes are

upwelling and downwelling; coast parallel winds cause surface layers to 'deflect' away from the coastline resulting in shore-normal slopes of the mean surface level. Water therefore comes from below the surface to replace the water deflected away, so satisfying the equation of continuity (cf. Pond and Pickard, 1983).

It is morphodynamical theory rather than process knowledge that long- and geological-scale models take as their basis (see sections 1.2; 2.3.5) e.g. Niedoroda *et al* (1985). This is due to a lack of observations over these scales. However, it has been concluded that the long-term sediment transport is under the greatest influence of fairly large, but not too infrequent, waves, in combination with tidal currents between mean neap and maximum spring tide (Soulsby, 1987).

2.3.3) SHORT- TO MEDIUM-TERM MORPHODYNAMIC BEHAVIOUR OF THE SHOREFACE

The shoreface is shown to be an important compartment within the coastal system (see Chapter 1); for example there is concern that severe erosion of the Holland coast could lead, in the extreme, to the undermining of the coast. As outlined in Chapter 1, data limits are such that the study of shoreface behaviour (both as process and form) based upon observations is restricted to the short- and medium-scales.

There are essentially two techniques used to observed the shoreface behaviour. The first is through the deployment of instruments[6], these are typically used to measure current flow rates and sediment concentration, and so provide process-knowledge. However the time period of instrument deployment is typically short due to restrictions enforced by i) temporal lengths of recording equipment; ii) destruction due to severe environmental conditions e.g. storms; and iii) interference by, for example, fishermen. Hence this method is mainly used for event- and short-term field experiments. The second technique is to compare, or aggregate, bathymetric profiles, this has a greater potential for understanding behaviour over longer time periods i.e. the large-scale. However, the number of long-term data sets of this kind are limited (Table 1.2) and so previous studies remain focused on the short- and medium-scales. It should be noted that the aggregation of profiles will reveal shoreface behaviour, not the acting processes.

[6] examples of today's instrumentation are i) the optical backscatterance (OBS) sediment concentration meters (Wright *et al*, 1986); and ii) ENDECO current meters, which are axial-flow-inducted impellor devices capable of recording mean current speed and direction (Snedden *et al*, 1988).

The instrumentation-based experiments show that short-term shoreface activity is only observed during high-energy events and not during fair-weather[7] periods. The most prominent studies which have lead to this conclusion are based upon the US Atlantic coasts' shoreface and are summarised below :

1. at 10 m water depth on the Long Island shoreface little sand transport is observed during fair-weather conditions, whilst during storm conditions the sediment transport is significant and has a large onshore component (Vincent *et al*, 1983);
2. at 8 m water depth on the shoreface at Duck, N.Carolina the range of elevation change amounted to greater than 15 cm during a 10 day northeaster[8]; '*The amplitude of bed response over the mid shoreface to a typical northeaster maybe appreciable*' (Wright *et al*, 1986);
3. at 12, 18, 34, 74 and 140 m water depth on the central Texas shelf, current meters indicated that the threshold for sand transport was not exceeded during fair-weather periods and during this time sediment entrainment was limited to water depths less than 10 m (Figure 2.5). However, the sediment transport threshold was exceeded at 12, 18 and 34 m water depth during storm conditions (Snedden *et al*, 1988); and
4. instrumentation at 13 m water depth was pushed 2 km to the shore by benthic processes during a storm at Duck, N.Carolina (Wright, 1993).

Observations of storm-induced morphodynamic activity also exist for the shelf environment; Smith and Hopkins (1972) placed current meters at 3 m above the bed in water depths of 50 m and 80 m for a 1 year period. It was found that significant sediment transport only occurred during storms; current speeds up to 60 cm s^{-1} were observed to transport approximately 6 $m^3hr^{-1}m^{-1}$ of the shelf length during these times.

[7] fair-weather is the term used to describe low energy conditions.
[8] northeaster distinguishes the extra-tropical storm from the hurricane

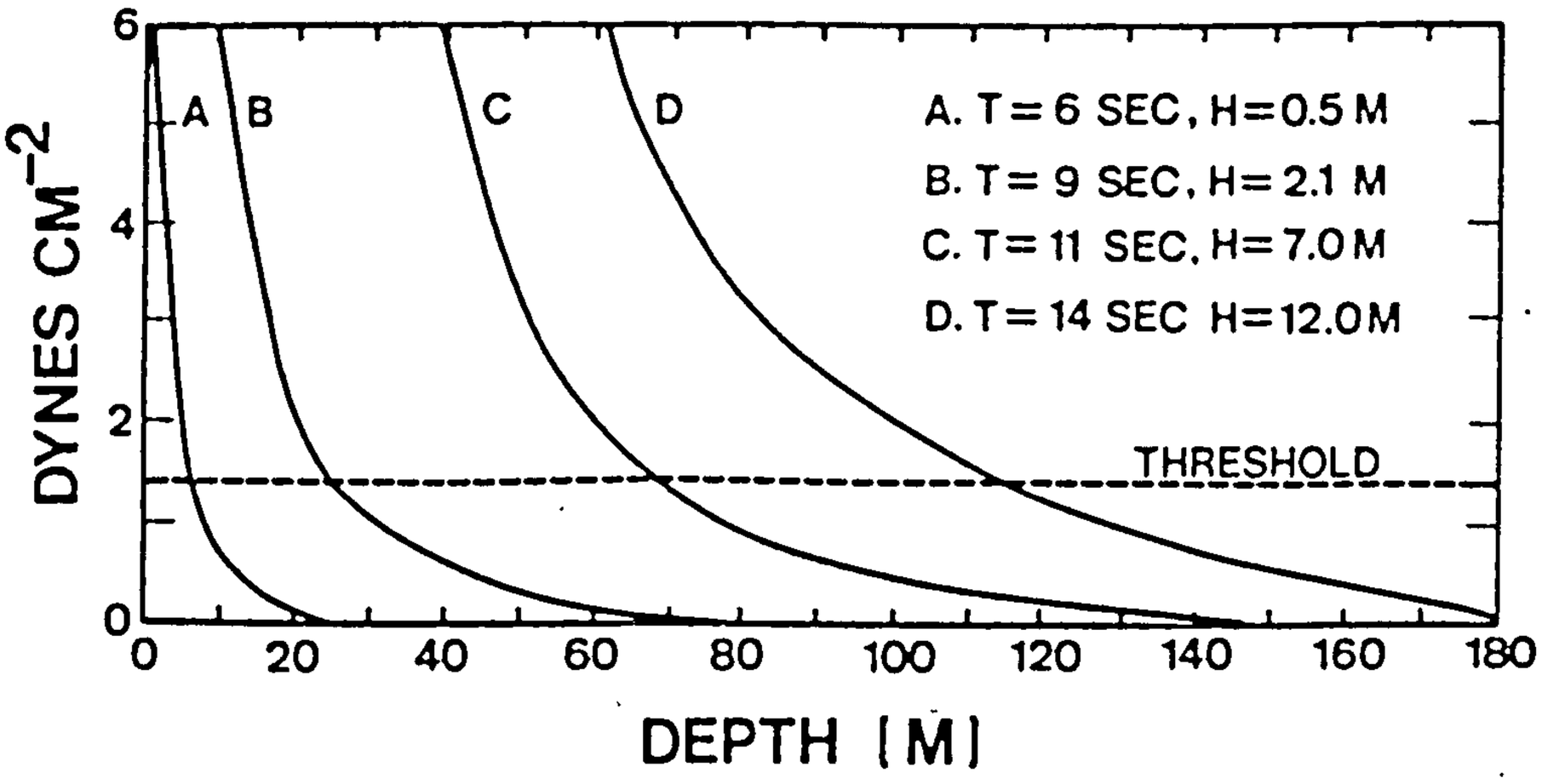


Figure 2.5. Boundary shear stress induced by wave-orbital motion versus water depth for four different wave conditions. Case A represents the significant deep-water wave height and period typical of fair-weather conditions; Case B is the measured wave parameters for the September 1984 storm; Case C is Hurricane Allen (1980); Case D is Hurricane Carla (1961). The dashed line is the threshold of motion for 68-micron sand. The intersection of the dashed line and the stress curve represents the maximum water depth where waves of a particular event are capable of entraining the 68-micron sand (taken from Snedden *et al*, 1988).

Studies based upon the aggregation of bathymetric profiles suggest that, over the small- and medium-scales, no significant[9] activity occurs on the middle or lower shoreface (e.g. Garcia *et al*, 1998; Hinton and Nicholls, 1998; Hinton *et al*, 1999). For example, Garcia *et al* (1998) observed that significant[10] depth changes are restricted to a maximum depth of 6.5 m over a 4 year period at the Ebro Delta, Spain. These depth values are typical of those at which activity has been observed during the experiments previously described. Indeed the two conclusions at first appear to contradict each other; the event-dependant cross-shore limit to significant depth change is observed at 4 m NGVD[11] at Duck, N.Carolina using surveyed bathymetric profiles before and after Hurricane Felix (August, 1995). However, sonar altimetry recorded 11 $\pm$ 2 cm of accretion at 8 m over the same period (Beaver *et al*, 1999). This can be deemed the result of differing techniques;

[9] according to the change criterion selected
[10] according to the change criterion of 0.1 m
[11] NGVD = National Geodetic Vertical Datum = 8 cm below Mean Sea Level (MSL) (Nicholls *et al*, 1998a).

the first set of experiments described are point-experiments i.e. they have a stationary space but moving time window whilst the bathymetric ones are stationary in both time and space i.e. they are a snapshot of the cross-shore profile. The point-experiments may purely indicate a bedform moving through the view-frame, or could represent instrumentation displacement due to, for example, scour. However, if they do show significant sediment transport it is clear that the resulting bed elevation change is not observed through the comparison of bathymetric plots. Hence, individual events i.e. irregular storms, whilst iniating sediment transport are not frequent enough to induce significant bathymetric change over the small- and medium-scales. This suggests that cumulative regular events may be of more importance. Indeed, Soulsby (1987) concluded that it is regular events rather than extreme conditions, such as the infrequent storm, are relatively unimportant contributions to long-term sediment transport. This is due to the fact that, although the transport potential is high during extreme events, the frequency is too low to result in significant bathymetric changes.

The cross-shore limit to the significant depth change, as observed using bathymetric profiles, is known as the depth of closure (Dc) (Figure 1.4). It does not represent the absolute boundary to cross-shore sediment transport and is a morphological not a sedimentological concept. This point is to be remembered when considering the meaning and implications of Dc. For example if one was to assume that closure represents the absolute limit to cross-shore sediment transport, as in the case of Pilkey *et al* (1993) *"the depth beyond which no net offshore or onshore transportation of sediment occurs"*, one could expect to observe Dc on the shelf and not the upper shoreface (over the short-scales). However, the observation made in existing studies that the short-term Dc is on the upper shoreface (< 8 m depth), coupled with the idea of Pilkey *et al* (1993), could lead to doubt in the validity of the concept :

> *"there is indisputable evidence against the existence of closure depth"* (Pilkey *et al*, 1993).

The above conclusion of Pilkey *et al* (1993) only holds in light of the corresponding Dc definition, which is itself more alike to definitions of the geological concept of wave base (Table 2.4). Evidence exists which shows Dc (as defined in Box 1.4) to be a valid concept over the short- and medium-scales, as discussed more thoroughly in the next section.

2.3.4) THE MORPHODYNAMIC CROSS-SHORE LIMIT TO SIGNIFICANT DEPTH CHANGE ON THE SHOREFACE :SHORT- TO MEDIUM-TERM

2.3.4.1) INTRODUCTION

The Dc concept was primarily introduced by Bruun (1962) where it was used as the seaward boundary in a shoreline change model in response to rising sea level. Since 1962, closure has been

i) calculated as a function of that wave height exceeded 12 hours per annum (therefore defining Dc on an annual basis) (Hallermeier, 1977; 1978);
ii) identified from bathymetric profiles over different scales (e.g. Everts, 1978; Birkemeier, 1985; Nicholls *et al*, 1996; Rozynski, 1998);
iii) further used as a seaward boundary in coastal models (e.g. Edelman, 1968; Willis and Price, 1975; per comm. Blanco, 1999); and
iv) adapted for sediment budgets and associated coastal engineering applications (e.g. Hands and Allison, 1991; Davison *et al*, 1992).

This section will discuss the Dc concept including not only its evolution but also its characteristics and the controls which act upon it.

2.3.4.2) DEPTH OF CLOSURE DEFINITIONS

Dc has evolved from the geological concept (Table 1.1) of wave base which represents the maximum depth of wave action over this scale (Table 2.4). Closure is used in preference to wave base in today's coastal research and management because of its greater relevance i.e. it is more useful to know the cross-shore limit of significant depth change over medium- and large-scales (coastal management scales) than over geological scales.

The first definition of Dc, as used by Bruun (1962) was :

'limiting depth between predominant nearshore and offshore material and littoral drift characteristics'

This definition has been refined since this as a result of increased knowledge of the concept i.e. concerning its characteristics and the controls which act upon it. Dc definitions, used since 1962 to the present, are given in Table 2.5. It can be seen that, with one exception, they all are

essentially based upon the same idea. This exception is that of Pilkey *et al* (1993), here is the one case where an absolute limit to the cross-shore sediment transport is included in the definition. This definition can be seen to be on par with the wave base concept and as shown in section 2.3.3 suggests that closure is located in great depths e.g. on the shelf. It is also apparent from more recent work on the time-dependence of Dc that values associated with these definitions must be accompanied by a corresponding time-period (this is discussed in the following section).

AUTHOR	DATE	DEFINITION
Gulliver	1899	'ultimate depth of a platform of marine abrasion'
Fenneman	1902	'depth to which wave action ceases to stir the sediments'
Rich	1951	'greatest depth to which the bottom is stirred by waves during storms'
Dietz and Fairbridge	1968	'downward limit to which waves can move bottom particles'

Table 2.4. Early definitions of 'wave base'.

2.3.4.3) CONTROLS UPON DEPTH OF CLOSURE

The most significant contribution to understanding, and predicting, Dc was by Hallermeier (1977, 1978). This method of prediction has been adopted in studies of micro-tidal, wave-dominated sites, for example Duck, N. Carolina, US.

Hallermeier (1977, 1978) defined two cross-shore zones:

1. the littoral zone, characterised by increasing bed stresses and sediment transport, caused by waves near breaking and induced fluid circulations; and
2. the offshore zone in which wave shoaling is the dominant process and bed agitation is relatively moderate.

AUTHOR	DATE	DEFINITION
Edelman	1968	'depth of effective motion'
Willis and Price	1975	'the depth below which beach changes resulting from alongshore transport are negligible'
Hallermeier	1977	'maximum water depth for nearshore erosion by extreme waves conditions, as exceeded 12 hours per annum'
Dean	1983	'depth of effective motion/limit of offshore adjustment'
Birkemeier	1985	'minimum water depth at which no measurable change in bottom elevation occurs'
Inman *et al*	1993	'the asymptotic merging of summer and winter profiles'
Pilkey *et al*	1993	'the depth beyond which no net offshore or onshore transportation of sediment occurs'
Nicholls *et al*	1996	'seaward limit of significant depth change'
Capobianco *et al*	1997	'seaward limit of the profile envelope'

Table 2.5. Definitions of the 'depth of closure' concept through time.

The boundary between the two zones marks the seaward limit of intense bed agitation by shoaling wave action, d_l, (Dc) and can be described by a critical sediment entrainment factor (ϕ_c) in the form of a Froude number, Eq. 2.1 :

$$\phi c = \frac{u_b^{\,2}}{\gamma' g \varepsilon d} \qquad \text{(Eq.2.1)}$$

where Ub = maximum horizontal fluid velocity at water depth d according to linear wave theory;

d = water depth;

γ' = ratio of density difference between sediment and fluid to fluid density;

g = acceleration due to gravity; and

ε = number less than unity.

The assumptions that $\varepsilon = 0.03$ and $\phi_c = 1$ for the onset of intense wave agitation for fine sands are taken. Therefore Eq.2.1 becomes Eq.2.2 :

$$\phi_c = \frac{u_b^{\,2}}{\gamma' g d} = 0.03 \qquad \text{(Eq.2.2)}$$

The critical value makes the assumption that d_l generally lies seaward of the surf zone implying that the peak near bottom fluid kinetic energy per unit sediment grain volume is sufficient to raise an immersed grain a distance $0.015d$ above the bed. Taking the above assumptions and the linear theory for shoaling waves, Eq.2.2 can be analytically approximated. This produces an expression for the calculation of Dc, Eq.2.3.

$$d_l = 2.28H_s - 68.5\left(\frac{H_s^{\,2}}{gT_s^{\,2}}\right) \qquad \text{(Eq.2.3)}$$

where d_l = maximum water depth for nearshore erosion by extreme (12 hrs per annum) wave conditions, or Dc;

H_s = the non-breaking (significant) wave height that is exceeded 12 hrs per annum;

T_s = associated wave period; and

g = acceleration due to gravity.

Results from Eq.2.3 were tested against laboratory measurements of water depth at an erosive wave cut into 'beach slopes'. The correlation coefficient showed a linear relationship between D_C and the wave cut at the 99.9% confidence level, Figure 2.6. Eq.2.3 was also tested through comparison with observed values of Dc from three published field studies; the Gold Coast, Australia; Torrey Pines, California, USA; and Avondale, Florida, USA (Table 2.6).

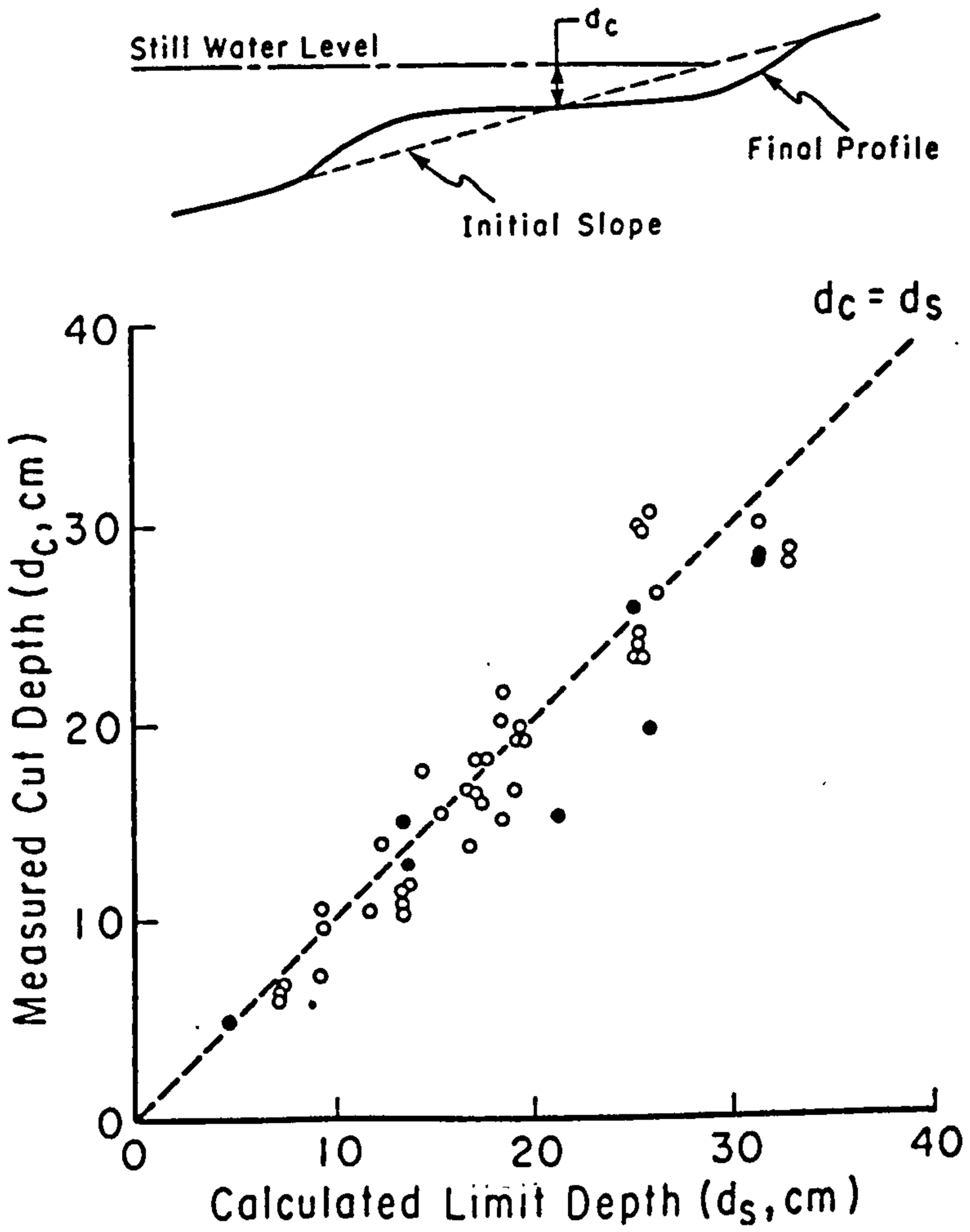


Figure 2.6. Measured profile cut depth, dc, versus the calculated limit depth, ds (taken from Hallermeier, 1978).

Hallermeier's (1977, 1978) model of the cross-shore profile was extended through division into three shore-parallel zones (Hallermeier, 1981), Figure 2.7;

1. the littoral zone, extending to the seaward limit of intense bed activity caused by extreme near-breaking waves and breaker-related currents;
2. shoal zone, a buffer zone where surface wave effects have an immediate effect (sand transport processes result in the deposition of sand from flanking zones); and
3. offshore zone, which has relatively deep water with respect to surface wave effects on the bed.

Unlike the model of 1977 and 1978, this model has not been completely validated with laboratory or field results. Although the boundary between the littoral and shoal zone, represented by Dc, has been tested (as already discussed) the boundary between the shoal and offshore zone remains untested. It can be suggested that this boundary, representing the maximum water depth for motion iniation by median wave conditions, is similar to the depth known as wave base (Table 2.4).

LOCATION/ PROFILE LINE	OBSERVED Dc (m)	CALCULATED Dc (m)
Gold Coast, Australia:		
Letitia	8.7	8
Greenmount	>7.8	
Thigan	7.8	
Palm	9	
Broadbeach	10.5	
The Spit	9.3	
Avondale, Florida, USA:		
The Pier	4.5	4.1
Torrey Pines, California, USA:		
North	6.9	7.3
Indian	7.6	
South	7.6	

Table 2.6. Observed vs. calculated Dc for three field sites (adopted from Hallermeier, 1978)

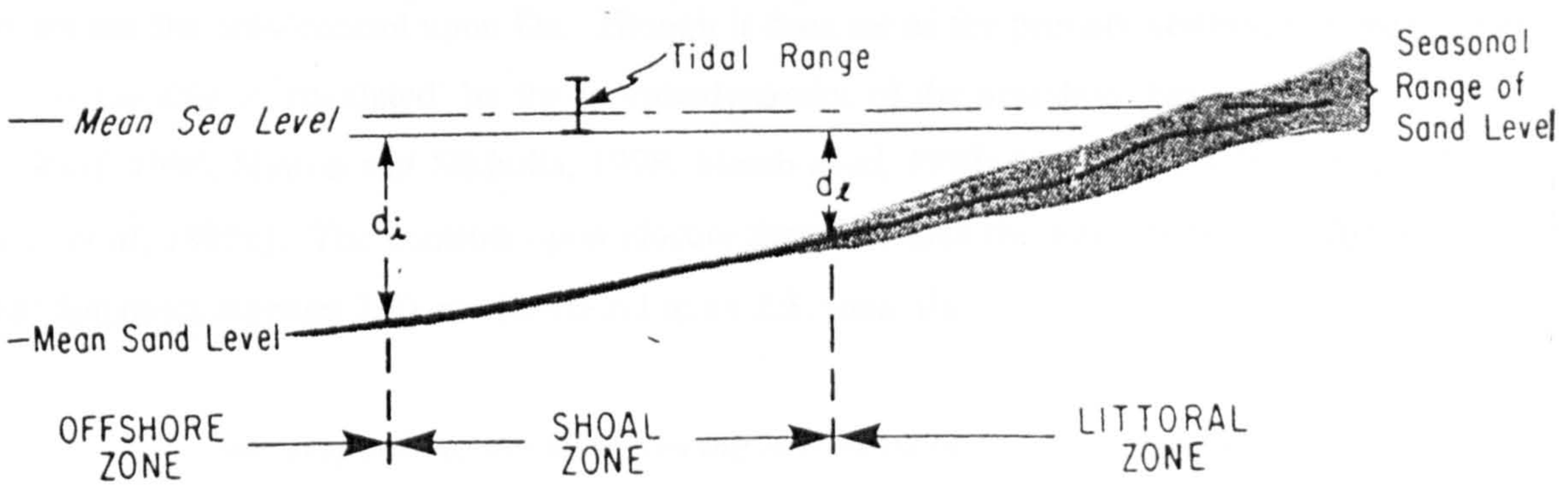


Figure 2.7. Proposed annual zonation of seasonal beach profile; di is the maximum water depth for motion iniation by median wave conditions and dl is the maximum water depth for nearshore erosion by extreme (12 hrs per annum) wave conditions (taken from Hallermeier, 1981).

This work clearly shows that wave characteristics are the major control upon depth of closure; wave height and wave period have long been recognised as the dominant forces in beach processes (King, 1951; Hallermeier, 1977; Sunamura and Kraus, 1983). In developing the relationship between wave height and period and Dc (Eq.2.3), several variables were not found to be important in acting as controls; grain size; beach slope; tank water depth; Stokes number; wave non-linearity; and wave number. Additional field testing of selected variables from this list was performed in recent investigations; slope control was shown to have no effect upon Dc at Duck, N.Carolina (Nicholls and Birkemeier, 1998). However the slope at Duck is relatively low (0.006 to 0.01) and it may be that on profiles with steeper slopes this variable does act as a control. Indeed, doubt is placed upon rejecting the local controls of beach slope and grain size (Capiobianco *et al*, 1998).

The control of volume change upon Dc has also been examined over the annual period at Duck, N.Carolina (Nicholls and Birkemeier, 1997). Here all observed annual residual[12] closure values[13] greater than 3 m (relative to MLW[14]) were compared with the corresponding annual volume changes. A significant negative relationship$_{(95\%\ confidence)}$ was found between the two variables suggesting that on eroding profiles Eq.2.3 overestimates Dc whilst on accreting profiles it underestimates closure. However this control has only been investigated for i) two cross-shore profiles; ii) a maximum volume change of $<\pm$ 300 m^3m^{-1}; and over an annual period. Increases in spatial and temporal scale in addition to investigation on a more/less active coast may produce different results.

Studies on micro-tidal, wave-dominated coasts over the small- and medium-scales[15] show that the waves are not the only control upon Dc. Though it does act as the primary control, the response of Dc to this variable is 'regulated' by the morphodynamics of the nearshore bar system (Hinton and Aarninkhof, 1998; Hinton and Nicholls, 1998; Marsh *et al*, 1998; Nicholls and Birkemeier, 1997; Nicholls *et al*, 1998b). The controls upon closure therefore take the form of external forcings and internal dynamics (section 2.2), as shown in Figure 2.8, such that :

> "*the response to the wave forcing is constrained by the internal dynamics of the morphological system*" (Nicholls *et al*, 1998b)

[12] residual closure = calculated closure (using Eq.2.3) - observed closure
[13] when using change criteria of 6 cm and 30 cm
[14] MLW (Mean Low Water) = 0.42 m below NGVD
[15] scale restriction results from data limitations, as previously discussed

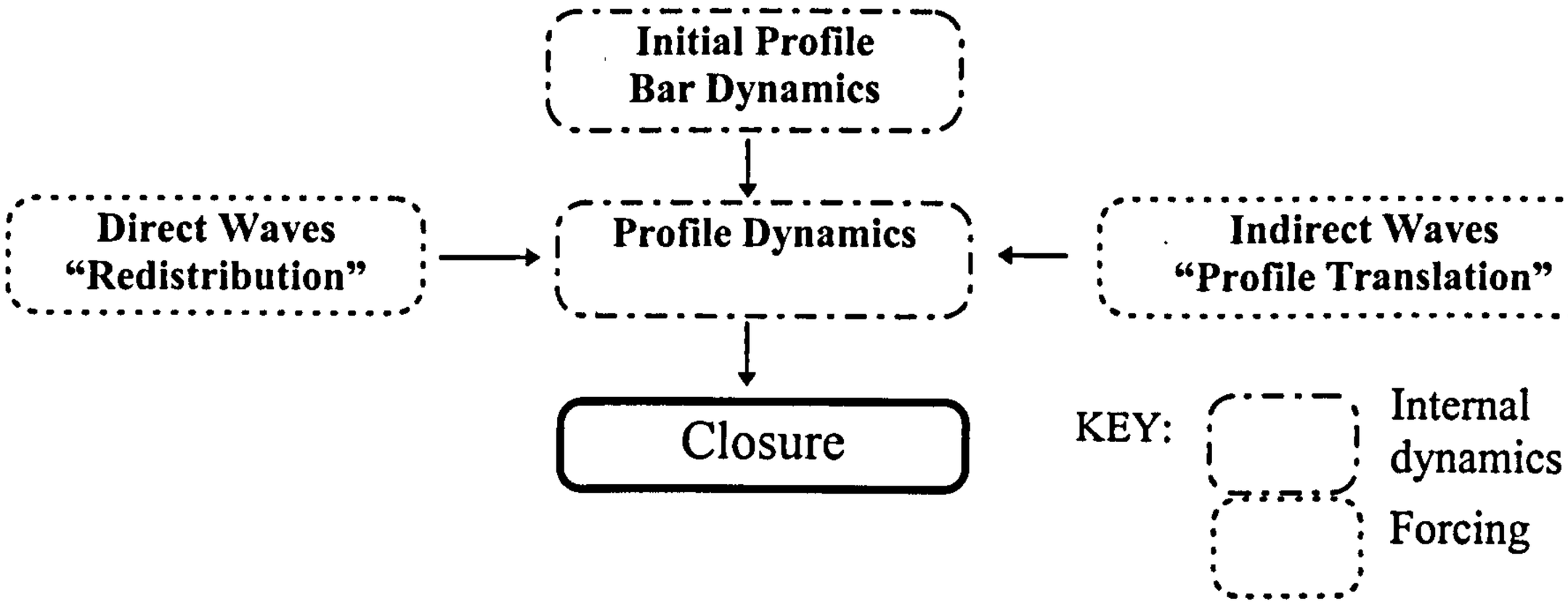


Figure 2.5. A conceptual model showing the major controls on closure at short- and medium-scales (adopted from Nicholls *et al*, 1998).

As already discussed, these controls have been determined for micro-tidal, wave-dominated, sandy coastlines. Although these coasts do compose the majority of the worlds coasts (cf. Davis, 1984), coasts with different environmental settings do exist e.g. southern England has a tidally-dominated, shingle coastline. Application of these results to such sites should be carried out with caution.

2.3.4.4) EVALUATION OF THE HALLERMEIER (1977, 1978) MODEL

In order that Eq. 2.3 can be used with confidence, agreement must exist between calculated and observed values. Much research has been performed into this on small- and medium-scales and the results are reviewed here.

An altered version of Bruun's (1962) shoreline change model was used to investigate processes of shore erosion at the Great Lakes (Hands, 1983). It was found that the ultimate shore erosion was equivalent to Dc, which was determined from accurate repetitive profiling over 7 years. Eq.2.3 was also applied to the Great Lakes and the calculated values found to act as a offshore limit to the observed Dc. The overprediction of Dc for erosive cases has been observed elsewhere e.g. Nicholls and Birkemeier (1997) (this section).

Birkemeier (1985) also tested Hallermeier's (1978) work using data collected at Duck, N. Carolina, US over a 2 year period. Here it was found that Eq.2.3 overestimated the observed Dc

by, on average, 1.4 m. As a result, an alternative expression derived empirically (Eq.2.4) was produced through linear approximation. As would be expected from such an approach, Eq.2.4 yielded a higher degree of accuracy between observations and predictions; on average 0.4 m.

$$d_l = 1.75H_e - 57.9\left(\frac{H_e^2}{gT_e^2}\right) \qquad \text{(Eq.2.4)}$$

where H_e = nearshore storm wave height exceeded 12 hrs per annum;

T_e = associated wave period; and

g = acceleration due to gravity.

By adopting the same approach, Eq.2.4 was further simplified to Eq.2.5. Using only H_e, an average difference of 0.5 m between observations and predictions was yielded.

$$d_l = 1.57H_e \qquad \text{(Eq.2.5)}$$

It should be noted here that Birkemeier's (1985) equations (Eq.2.4 and Eq.2.5) are simply the result of site specific adjustment of Hallermeier's (1977, 1978) (Eq.2.3) and so should be used with caution for sites other than Duck, N.Carolina, US.

In the majority of cases, calculated values from the Hallermeier (1977, 1978) model prove to act as an offshore limit to the observed value, Table 2.7. The exception is for the event-scale accretional cases when Eq.2.3 tends to underpredict closure as a result of the domination of onshore transport and accretion in the active zone (Nicholls *et al*, 1998a). However, it can be argued that this is not a significant problem as accretional cases result in a positive sediment budget in the nearshore region.

The method of prediction, as described here, does have one major limitation (Nicholls *et al*, 1996; 1998a); it has been derived for wave-dominated study sites e.g. Duck, N.Carolina, USA. It can therefore be hypothesised that, in those situations e.g. the UK coastline, where factors other than waves e.g. tides, are the dominant physical process, the Hallermeier (1977, 1978) model will not be applicable. It would be expected that terms describing the threshold of sediment movement under tidally-induced currents will need to be incorporated in such predictive expressions for those tidally dominated shorelines, whilst in other instances wave-current interactions will need to be accounted for.

OBSERVED Dc (m)	CALCULATED Dc (m)	TEMPORAL PERIOD	SITE/ AUTHOR
4.8	6.3	event - erosional	Duck, N.Carolina, USA/ Birkemeier (1985)
4.0 4.1 6.4 6.8 7.0 8.0	2.4 5.9 10.0 9.2 9.3 10.0	event - accretional event - erosional 1 yr 2 yr 4 yr 8 yr	Duck, N.Carolina, USA/ Nicholls *et al* (1998a)
5.5	9.3	1 yr	Terschelling, The Netherlands/Marsh *et al* (1998)

Table 2.7. Examples of observed and calculated values of Dc for different time periods from three locations clearly showing that the Hallermeier (1977, 1978) model overpredicts closure observed using a variety of change criterion; for example the Dc at Duck is observed using a 0.06 m change criterion whilst that at Terschelling, The Netherlands a 0.25 m change criterion. The values represent the mean value of all published values for the appropriate temporal period.

2.3.4.5) ALTERNATIVE METHODS TO DETERMINE DEPTH OF CLOSURE

The Hallermeier (1977, 1978) model remains, to date, the most frequently used predictor of Dc. Alternative methods have been proposed (Hallermeier, 1981) which enable the prediction of closure through the observation of other features of coastal behaviour. However the testing of these methods with field observations typically produce uncertainties regarding their reliability. It therefore appears that Eq.2.3 remains the most accurate predictor of Dc. The alternative methods are :

1. Geometric limits:

The transition from irregular to regular bathymetric contours could be expected to mark the depth of closure. Here the transition would be the result of the depth limit to the effective action of waves on the bed. This method was proposed by Dietz (1963) and tested by Everts (1978) using 49 different profiles from the Atlantic and Gulf coasts. However, problems arose; for example 14 % of profiles had contours shore-parallel at the cross-shore limit (30.5 km).

An additional geometric limit is the junction between two characteristic cross-shore profile sections; the curved shoreface and the plane ramp (Figure 2.9). This junction is taken to represent the cut-off region of significant active modification of the profile by the

hydrodynamic climate. As with the previous geometric limit problems do exist; the main complication is that the two sections join asymptotically and on a very gradual slope (Everts, 1978). Comparison between results from the two methods show that the depth values do not agree. Everts (1978) concluded that the shoreface-ramp transition is the more consistent method; depths are in the range of 5 to 20 metres.

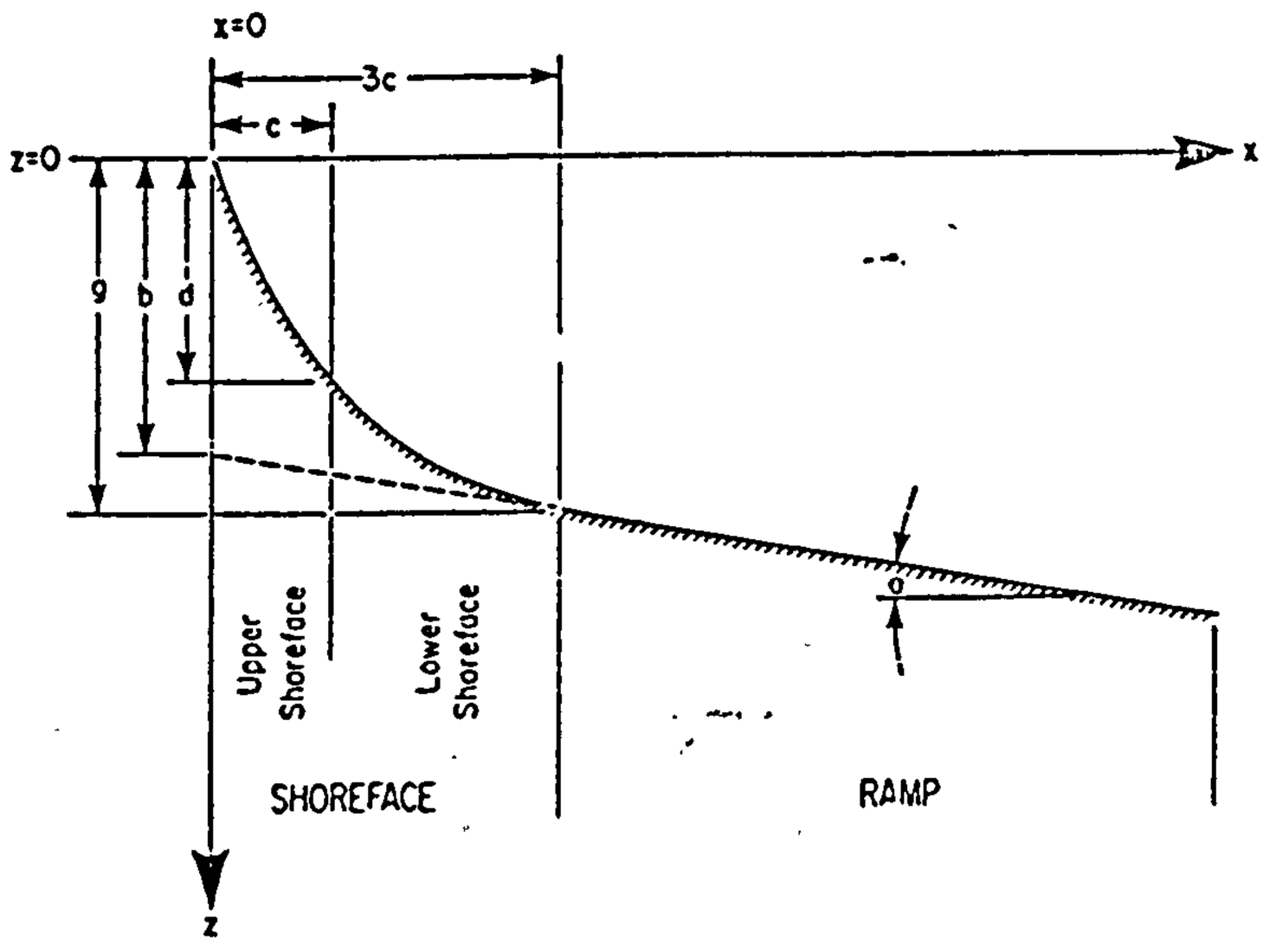


Figure 2.9.. Definition sketch of an idealised linear continental shelf profile showing the planar, seaward dipping ramp sector and concave-up shoreward sector (taken from Everts, 1978)

2. Sediment characteristics:

Cross-shore variation in grain size is apparent (Komar, 1999). Generally, the coarser grain sizes are located in the zone of most intense wave activity and the finer towards deeper water and shoreward across the active zone. Distinct breaks in grain characteristic could therefore be used as an indicator of the importance of wave-dominated transport. Studies have shown that this is the case; Pilkey and Frankenburg (1964) reported a boundary between recent and relict sediments at a depth of approximately 11 m on the Georgia Continental Shelf, USA; similarly Gordon and Roy (1977) report a relict-recent boundary at a depth of approximately 18 metres in the Newcastle Bight, Australia.

An additional sediment characteristic is that of heavy mineral concentration. It has been shown (Koomans *et al*, 1998) that on the shoreface of the Dutch Island Ameland a maximum concentration of heavy minerals is located at 7.5 m water depth, decreasing to a depth of 11 m and remaining constant towards deeper water (Figure 2.10). This coincides with the long-

term range of Dc from 7.5 to 10.5 m, as calculated using Eq.2.3 for the adjacent island of Terschelling (Marsh, 1998).

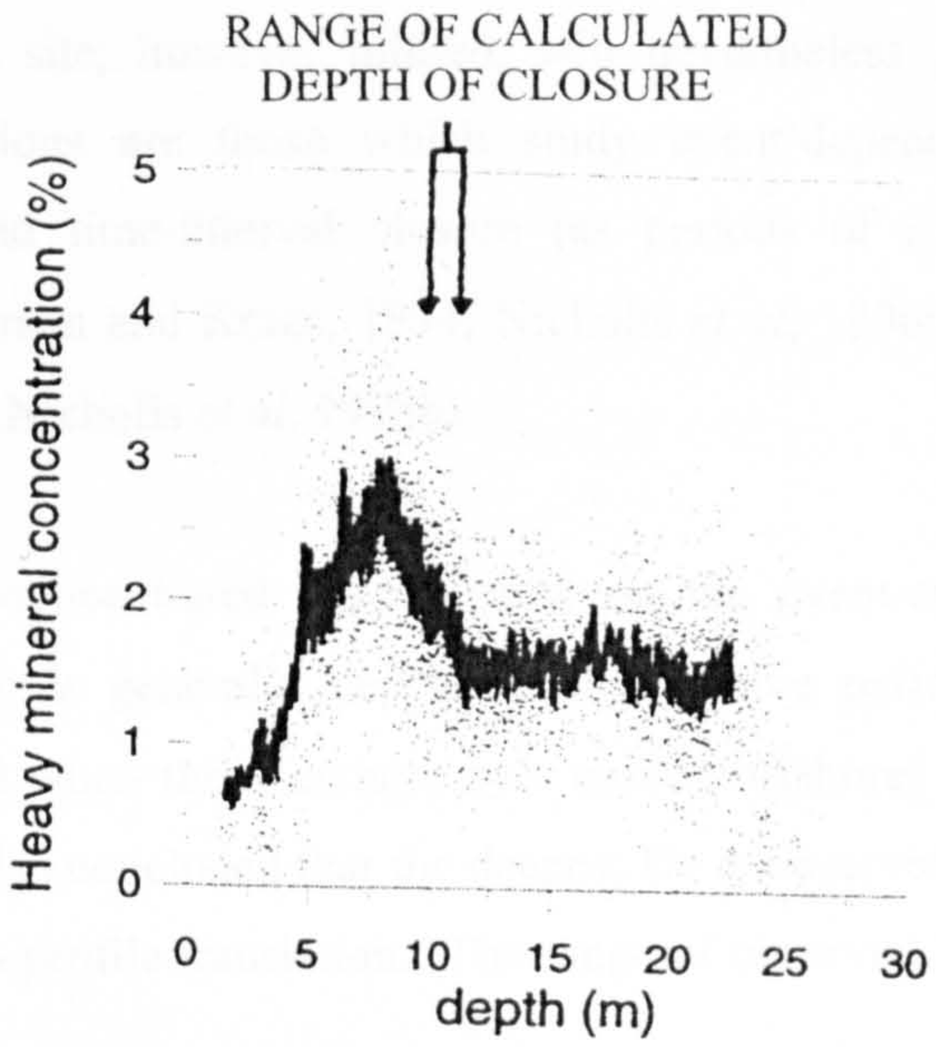


Figure 2.10. Heavy mineral concentration over water depth of measurements before the coast of the Dutch Island Ameland. The line represents a running average through the data points (adopted from Koomans, 1998).

3. Null-point hypothesis.

Another proposed alternative approach is to combine wave and sediment processes in the form of wave energy, grain size and beach slope. These are combined in the null-point hypothesis (Cornaglia, 1977); each grain size has a position of dynamic equilibrium at which the forces acting upon it (waves causing onshore motion and gravity causing offshore motion) are balanced. It is argued that the null-point will be located in deeper water for larger wave energy, bottom slope or smaller sediment density and size (Cornaglia, 1977). However, many other predictions of this model have been proven to be incorrect (for example the prediction that coarser grains move offshore and finer grains onshore) and so it should be used with much care (Komar, 1998).

2.3.4.6) SCALE DEPENDENCE OF DEPTH OF CLOSURE

Data set limitations (Chapter 1) clearly influence the spatial and temporal scales of an investigation. Spatial scales are typically more restricted than the temporal; for example four cross-shore profile lines are measured at Duck, N.Carolina over the medium-term (Lee *et al*, 1995). The study of Dc through time at any site, however limited, will nevertheless give insight into its behaviour. Prominent investigations are those which study event-dependant closure (as erosional and accretional cases) and time-interval closure (as periods of *t* years) using data from Duck, N.Carolina, USA (Larson and Kraus, 1994; Nicholls *et al*, 1996; Nicholls and Birkemeier, 1997; Nicholls *et al*, 1998a; Nicholls *et al*, 1998b).

Studies which have concentrated upon closure on the event-scale have shown that, of those measurable cases, Dc is generally deeper during erosive periods (here the profile change is classified as erosional when the nearshore bars moved offshore) (Nicholls *et al*, 1998a). During these periods it was also concluded that the deepest Dc is observed during the most energetic wave events[16] in addition to profile translation. The range of observed Dc values and the corresponding controls are :

1. erosive cases show Dc to be in the range 2.7m to 7.8m below NGVD (using a 6 cm criterion) and under the control of pre-storm morphology;
2. accretional Dc is in the range 2.1m to 5.2m below MLW[17] (using a 6 cm criterion) and is under the primary control of shoaling, rather than breaking, waves; and
3. annual closure has a range of 5 m to 8 m below MLW and represents an integration of accretional and erosional processes.

It has been found that the temporal-dependence of closure is such that as the temporal period increases, Dc increases. This is illustrated in Table 2.8 which shows that percentage of cases which close over a time period of *t* years (within the cross-shore data limits); a decrease in the closing cases suggests that fewer cases exhibit Dc within the data limits i.e. it moves offshore.

[16] as would be expected from the Hallermeier (1977, 1978) model
[17] MLW = Mean Low Water = 42 cm below NGVD

TIME PERIOD (yrs)	% CASES CLOSING (using 6 cm criterion)
1	65
2	60
4	44
8	3

Table 2.8. Percentage of time-interval Dc at less than 8 m water depth, for two cross-shore profiles located at Duck, N.Carolina, USA, as a function of time interval (from Nicholls *et al*, 1998).

It is therefore shown that Dc is temporally-dependent. To allow calculation of Dc over *t* years Eq.2.3 has been developed, producing an analytical expression, Eq.2.6 (Stive *et al*, 1992) :

$$d_{e,t} = 2.28H_{e,t} - 68.5\left(\frac{H^2_{e,t}}{gT^2_{e,t}}\right) \qquad \text{(Eq.2.6)}$$

where $d_{e,t}$ = the Dc over *t* years;

$H_{e,t}$ = the non-breaking significant wave height that is exceeded 12 hours per *t* years, (100/730t)% of the time;

$T_{e,t}$ = the associated wave period; and

g = the acceleration due to gravity.

Our understanding of the Dc concept has therefore evolved substantially in the last decade; it is now apparent that the time-dependence of Dc cannot be ignored and values are worthless unless accompanied by a corresponding time period.

2.3.4.7) PRACTICAL APPLICATIONS OF THE DEPTH OF CLOSURE CONCEPT

There are numerous applications of Dc in the field. The four main ones are discussed below :

1. Beach nourishment projects.

This is perhaps the most common the use of Dc. One of the major considerations to be taken when designing such a project is the determination of the required volume of material; sufficient volume must be placed to nourish both the sub-aerial and sub-aqueous beach (Davison *et*

al, 1992). It is therefore necessary to know the depth to which the profile will develop after the fill material is deposited. The lower limit of the active profile is given by Dc, and it is important that the depth is as accurate as possible as subtle differences will result in large differences in fill material volume; for every 1m difference in Dc there is approximately a 9 to 12% variation in the beach fill estimate (Hansen and Lillycrop, 1988). Dc is incorporated in a translation method in which the volume of material required is calculated by 'translating' the entire representative profile seaward by a dimension equal to the desired berm width. The seaward boundary of the translation is given as Dc. The minimum fill material volume is therefore the volumetric difference between the original and translated profile. When using the translation method over the standard design an approximate increase of 60% in fill material is required, hence showing the importance of the incorporation of an accurate value of Dc in such projects (Hansen and Lillycrop ,1988). It should also be noted that the development of the profile in the seaward direction will slow down with time, though it is not yet possible to accurately predict when the process will stop.

Beach nourishment is also carried out by the construction of mounds at depth. It has been found that there are two positions at which they can be placed; active and stable. Placement in the active zone provides material for onshore feed. The use of Hallermeiers (1981) zonation of the sub-aqueous profile has enabled a conservative estimate of these two positions to be determined, allowing coastal protection schemes which use mounds to have a more beneficial effect than has been the case in previous years (Hands and Allison, 1991).

2. Coastal models.

As previously mentioned, the determination of shore response to changing sea-level can be performed using a model based on the Bruun model (1962). Hands (1981) predicted a response of the profiles to the changing water levels of the Great Lakes where Dc was shown to represent the depth to which the profile no longer responded to these changes; at Lake Michigan profile response was evident to a depth of 9m over a 6 year period (Hands, 1977). An estimation of the height of the profile response was obtained through the summation of Dc and the average backshore height. Other examples of the inclusion of Dc in coastal models are :

1. the small-scale beach response model of Edleman (1968). This model is based on pre- and post-storm profiles from the Holland coast and equated Dc (see Table 2.5) to the breaking depth; and
2. the medium-scale beach plan shape model of Willis and Price (1975). Dc (see Table 2.5) was found, from wave basin studies, to be approximately equal to twice the breaking depth.

However, Dc was shown to be constant in practise[18] and so was assumed to be constant in this model i.e. independent of wave height.

It is important that the Dc value used in the model is as accurate as possible, so requiring precise bathymetric surveying/ prediction techniques. If the Dc in such a model as used on the Great Lakes was to be inaccurate then the profile response of the shoreface to changing water levels would be over/under-estimated.

3. Extraction of marine aggregates.

Extraction of marine aggregates is a growing industry, in addition its reverse, marine disposal, could be seen to increase in intensity as land fill sites are used up. It is therefore important that any activities of this kind are conducted sufficiently seaward of Dc so that the natural processes which act within the coastal system are unaffected. Examples of the processes which could be affected are:

1. sediment transport, both on- and offshore. The removal of marine aggregates within the active littoral zone could result in a reduction of natural feed for the shore which in turn will result in coastal retreat;
2. wave refraction. This would result in a wave shadow shoreward of a hole and wave concentration at elevated regions; and
3. wave reflection. This would tend to shelter the shore contained in the wave shadow of either a hole or mound.

All these effects will act not only upon the immediate shore but also that surrounding it; a well-known example of the effect of the reduction of natural marine feed to the coast line is that of Hallsands, South England, in which the whole village fell to the sea (see section 1.1). The effect of these two industries can be minimised by restricting the activity to areas seaward of Dc.

Field surveys of the inactive/active zone

The application of Dc also extends to the location of nearshore wave gauges and similar equipment. It would be advisable to place the gauge seaward of Dc as almost all surface waves will be

[18] e.g. experiments performed at Worthing Beach, UK revealed that shingle movement did not occur seaward of the 10 m water depth during winter periods (short-scale). The authors took the assumption that if sediment was not moved during these high-energy periods, then this depth limit could be used over all scales. As the results of this study and work after 1975 indicate such an assumption is dangerous and invalid.

unbroken here and so waves incident to the littoral zone will be accurately measured, in addition the equipment will not be influenced by significant changes in bottom elevation. The concept also becomes important when planning hydrographic surveys, both near- and off-shore. For those nearshore, the survey should extend out to D_C so that complete coverage of the active zone is obtained, whilst for those offshore, equipment should be sufficiently sensitive to detect small changes in the bathymetry so that the survey data is of high enough accuracy.

2.3.5) LONG- AND GEOLOGICAL TERM MORPHODYNAMIC BEHAVIOUR OF THE SHOREFACE

It has been shown using modelling techniques (Stive and De Vriend, 1995; cf. Wright, 1995) that over scales equal to and greater than the large-scale, the entire shoreface profile is active. However the response of the dynamic profile will take place at different temporal scales; the lower shoreface has a longer response time than the upper. This implies (Cowell and Roy, 1998) that the lower shoreface controls macro-scale problems which are important to coastal management issues e.g. shoreline position. It is therefore important that knowledge of the large- and geological-scale shoreface behaviour exists. However, bathymetric and process-based data sets are such that shoreface characteristics over these scales can not be observed. Rather, they can be inferred from existing knowledge used in conjunction with geological measurements e.g. core borings, and large-scale modelling efforts.

The most promising models for this task (cf. Buijsman *et al*, 1998a) are the behaviour-orientated models (BOM) listed below :

1. the Advection Diffusion Model (ADM) of Niedoroda *et al* (1995);
2. the Panel model of Stive and De Vriend (1995);
3. the Aggregated Scale Morphological Interaction between a Tidal inlet system and the Adjacent coast model (ASMITA) of Stive *et al*, 1997); and
4. the Shoreface Translation Model (STM) of Cowell *et al* (1995).

The characteristics of these models both differ, for example the STM is a continuum model whilst the ASMITA a box model, and correlate, for example the ADM and ASMITA have the same three transport terms (advection; diffusion; slope-dependent). These long-term models take different assumptions when calculating the coastal evolution over 10 to 10^{3to6} years. For example Stive and De Vriend (1995) take the assumption that the shoreface zones respond to the forcings at different

rates, as inferred by Wright (1995). Meanwhile the ASMITA (Stive *et al*, 1997) takes the assumption that each of the morphological elements within it have a beginning equilibrium state which after disturbance (by, for example, sea-level rise) will subsequently be re-attained.

Although comparisons between observed evolutions[19] and that computed are not in 100% agreement, these models add invaluable knowledge to our understanding of the long-term shoreface behaviour as they provide confidence in the processes which are used to predict the observed behaviour. Examples of the differences which exist are :

1. the ADM underestimates the Holocene beach progradation at Haarlem, The Netherlands; and
2. the Panel model overestimates the middle shoreface slope of the Subboreal/Subatlantic evolution.

In order to further improve the model results it is important that the parameters, if changed, are done so to a realistic setting and are based upon sensible assumptions. This is because, although final results may be correlate more closely with observations, the new parameters may not be valid in practise. Indeed, any model can be improved by changing its values and relative importance of dynamics and inputs; for example a study validating four coastal dynamic models found that all the results agreed well with the chosen[20] observed shoreline behaviour after the values of model settings were changed (cf. Symytkiewicz *et al*, 1997). This danger has been avoided in at least one of the models; although the Panel model (Stive and De Vriend, 1995) did not agree 100% with observed evolutions (see earlier), changes to the model dynamics and inputs were not made because the authors were concerned about the lack of relevant data.

All the models show that the shoreface is active over the long- and geological-scales in response to various forcings. For example the ADM shows that the cross-shore profile i) straightens with an increasing rate of sea-level rise and hydrodynamic forcing; and ii) exhibits more curvature with an increase in sediment input and grain size.

The use of these models to predict the long-term morphodynamic behaviour of the shoreface has a potential impact upon the understanding of Dc. As already discussed (section 2.3.3 and 2.3.4) knowledge of this morphodynamic concept is concentrated upon the short- and medium-scales as a result of data limitations. This understanding could be extended to the long- and geological-scales

[19] as determined from, for example, historical waterline position data and ^{14}C gradients (Stive and De Vriend, 1995)
[20] the two harbours of Kolobrzeg and Wladyslawowo, Poland.

not only through the analysis of long-term data sets (e.g. the JARKUS data set) but also through the use of models such as the ADM. Indeed, preliminary investigations have been performed on the evolution of Dc from time scales of 1 year to 10 000 years (Nicholls *et al*, 1998c). Three environmental inputs (sea-level rise; hydrodynamic intensity; sediment input) have been changed over this time period and the resulting effects upon the Dc of an equilibrium profile analysed. It is shown that for all three scenarios, as the time period increases then so does Dc such that, after 100 years, the profile is active to, at a minimum, the lower shoreface, as illustrated in Figure 2.11. After 10 000 years the profile is active to the shelf. This reinforces the previous conclusions that Dc is a time-dependent concept (see section 2.3.4).

A new approach to the problem of long-term coastal modelling has been derived taking as its basis the concept behind the primary-scale relationship (De Vriend, 1991) (section 2.2). It is termed the 'coastal tract cascade' and provides a "*framework for the aggregation of process and spatial dimensions in modelling low-order* (10^2 to 10^3 years) *coastal change*" (Cowell *et al*, 2000). The aim of the cascade is to enable the correct application of existing BOM (see earlier) by distinguishing those processes significant to the modelling of coastal change and those which act as boundary conditions or noise. The coupling of the knowledge of the important processes and the models characteristics will potentially result in the more widespread, correct application of BOMs. Although the cascade does not significantly aid towards the extension of existing predictability limits the comprehensive combination of spatial- and temporal-concepts has produced a protocol for model application to site-specific coastal problems.

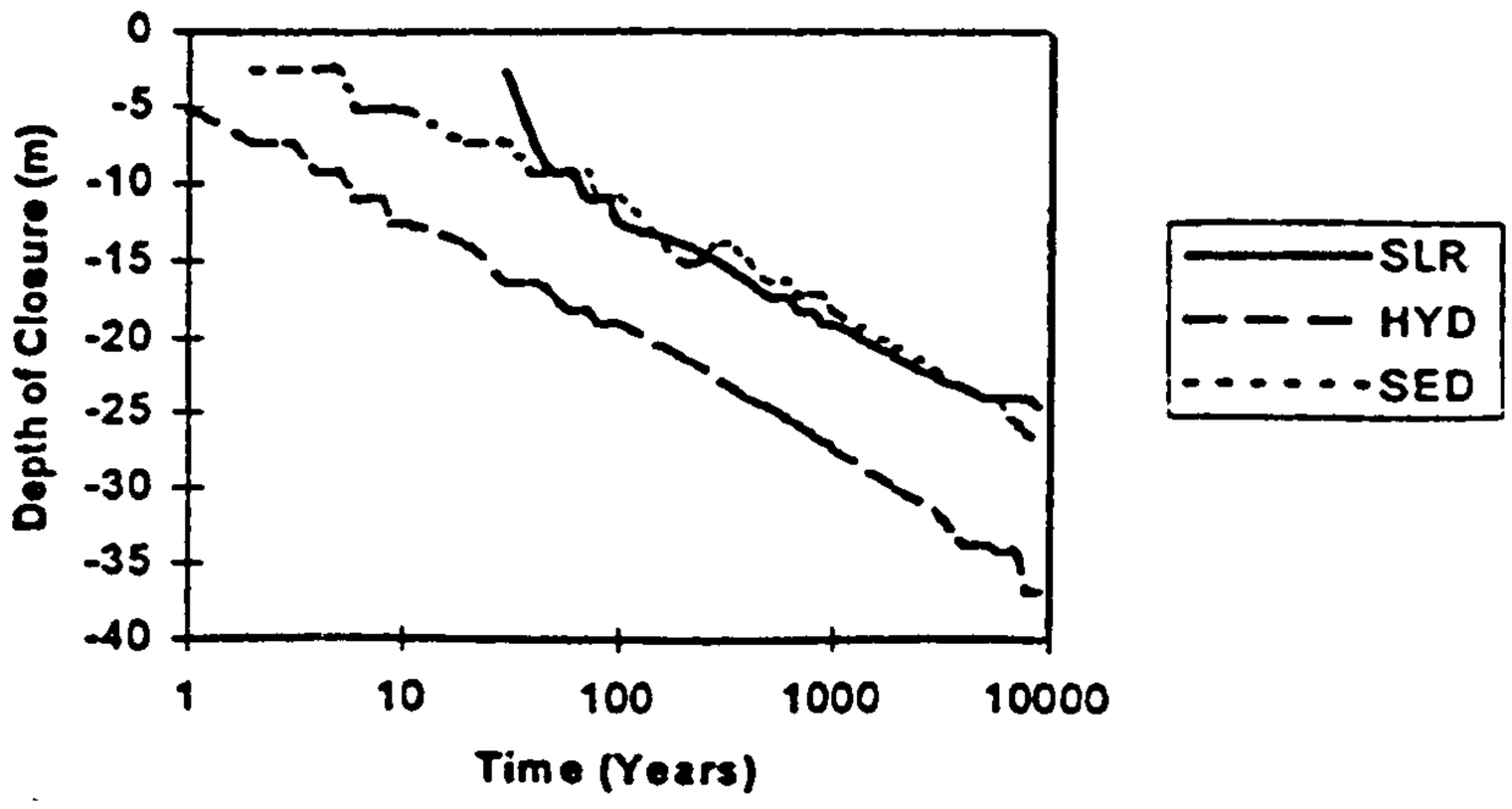


Figure 2.11. Closure evolution's following changes in three environmental inputs of the ADM model. The inputs are; sea-level rise (SLR); hydrodynamic intensity (HYD); and sediment supply (SED) (taken from Nicholls *et al*, 1998c).

3) THE DATA SET : JARKUS

3.1) INTRODUCTION

As stated in Box 1.2, it is the aim of this thesis to determine the medium- and large-scale characteristics of the shoreface morphodynamic behaviour through time and space. In order to achieve this, a large-scale data set, with sufficient temporal and spatial resolution was required. Accessibility and resolution details led to the use of the large-scale JARKUS data set (Table 1.2) which contains cross-shore bathymetric profiles for the entire Netherlands coast. The JARKUS data set was initially collected by RIKZ for coastal zone monitoring and management purposes, so ensuring adequate coastal defence policies were implemented e.g. the 1990 'dynamic preservation policy' (de Ruig, 1998; section 1.1). The qualities of this data set e.g. measurement accuracy, has subsequently resulted in its incorporation in many coastal research projects (e.g. Wijnberg, 1995; van Rijn, 1995; 1997; Marsh *et al*, 1998). All the details of the JARKUS data set are now discussed.

3.2) TEMPORAL AND SPATIAL RESOLUTION

3.2.1)INTRODUCTION

The spatial and temporal resolution of a data set is one of its most important characteristics and could pose a problem over all scales. For example poor temporal resolution represents few measurements through time within the measurement period and will result in an inadequate data set. Similarly a poor spatial resolution could also incur problems; two measurements across a cross-shore profile at for example, the shoreline and 1 km offshore over a time period *t*, will, whilst providing information about the evolution of these two points, not enable details to be derived concerning the characteristics across the entire shoreface.

The JARKUS data set is one of the few available long-term data sets (Table 1.2) which, for the purpose required in this study, has a good spatial and temporal resolution. This data set has two sections, both of which have a shoreward cross-shore boundary represented by the fore-dune. The difference between them is a result of the cross-shore distance from the shoreward to seaward boundary and the spatial and temporal resolution. Details of both sections are given in Table 3.1.

Examples of the two sections are given in Figure 3.1, where the difference in the seaward boundary is clearly shown. It should be noted that preliminary investigations within this study, focusing upon the identification of the depth of closure (Dc; Box 1.4) led to the dominant use of the extended profiles. These investigations found that the short profiles did not extend sufficiently seaward to identify Dc[1].

	TEMPORAL		SPATIAL	
	EXTENT	RESOLUTION	EXTENT*[1]	CROSS-SHORE / LONGSHORE RESOLUTION*[2]
SHORT PROFILES ($JARKUS_S$)	1963 - present	1 year	dune to minimum 0.8 km offshore	5 m near waterline 20 m remaining shoreface/ 0.25 km
EXTENDED ('DOORLODINGEN') PROFILES ($JARKUS_E$)	1965 - 1997	5 years to 1990 3 years to 1997	dune to minimum 2.5 km offshore	5 m near waterline 20 m upper/mid shoreface 40 m lower shoreface/ 1 km

*1 The details of the spatial extent give the minimum distance offshore. The more recent profiles extend beyond this for example measurements of the extended profiles do occur up to 4 km offshore.

*2 The resolution details are for the majority of profiles. There is however a general trend that the more recent profiles have a greater cross-shore resolution over the shoreface e.g. 10 to 20 m cross-shore spacing.

Table 3.1. Details of the JARKUS data set.

[1] when using the sddc self-selecting tail method; Chapter 5

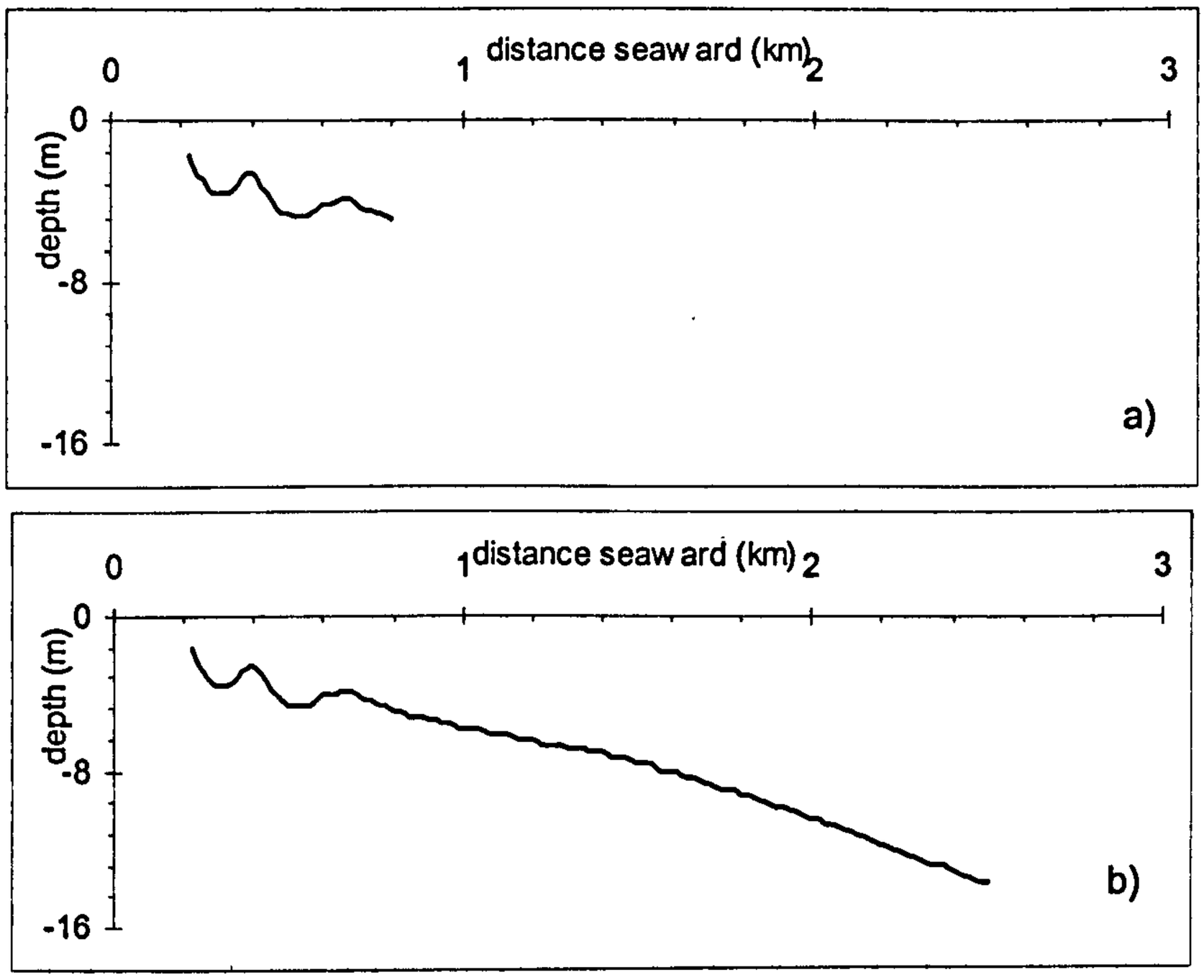


Figure 3.1. Examples of the two sections of the JARKUS data set for profile km 77; a) the short data; and b) the extended (doorlodingen) data. Data is from 1970.

3.2.2) TEMPORAL RESOLUTION

The temporal resolution of the JARKUS data set ranges from 1 to 5 years; annually for the short profiles and 3 to 5 yearly for the extended profiles (Table 3.1).. As this research focuses upon the medium- and large-scale, the lack of short-scale resolution does not pose a problem. Indeed, such information regarding the morphodynamic behaviour of a wave-dominated shoreface can be obtained from existing short-scale studies (e.g. Snedden *et al*, 1998; Chapter 2). However, a preliminary investigation into the short-scale morphodynamic behaviour of the Holland shoreface was undertaken using a process-based model (Chapter 5 and 8).

The cross-shore bathymetric profiles are typically surveyed (relative to NAP[2]) in the spring and summer months, as illustrated in Figure 3.2. This implies that there is a potential for seasonal bias as it is generally accepted that, in wave-dominated environments, the spring and summer months are typically less stormy than the autumn and winter months (Komar, 1998; Lee *et al*, 1998). This

[2] NAP = Normal Amsterdams Peil which is approximately equal to Mean Sea Level.

is shown in Figure 3.3 which gives the significant wave height for a mean year between 1979 and 1991, as recorded at one of the wave stations off the Holland coast. Additionally profiles which have been surveyed in a more than average stormy spring could resemble those surveyed in a less than average stormy winter. However, as the focus of this work is on the medium- and large-scales, seasonal bias should not play a role in the trends observed over these scales; the morphodynamic behaviour investigated occurs over temporal periods greater than seasonal changes. In addition, preliminary investigations showed that the profiles undergo steady morphodynamic changes over these time periods, rather than abrupt ones indicating that there is no seasonal effects. Even if seasonal bias were to be a factor the methods chosen to analysis the data (Chapter 5) will remove it.

3.2.3) SPATIAL RESOLUTION

The spatial resolution of $JARKUS_{S+E}$[3] (Table 3.1) needs to consider both longshore and cross-shore spacing. The longshore spacing of the cross-shore profiles is marked by a permanent base of beach poles known as the RSP ('Rijks Strand Palen lijn') reference line. The poles are numbered relative to their distance from Den Helder (Figure 1.4) and within this study each profile is labelled according to this distance. For example km 81 represents the profile located 81 km south of Den Helder at Noordwijk aan Zee. $JARKUS_E$ profiles longshore spacing of 1 km is sufficiently adequate to investigate the shoreface morphodynamic behaviour of the Holland coast between Callantsoog (km 16) and Schevingen (km 97) (see Chapter 1 and 4).

As shown in Table 3.1, the cross-shore resolution varies from the waterline (5 m) to the seaward boundary (40 m) of the profile. In order that all profiles have the same cross-shore spacing, selected at 20 m, between consecutive measurements, the interpolation method of cubic splining has been used. The cross-shore spacing has proven to be adequate for identifying the shoreface behaviour, particularly on the middle and lower shoreface where a horizontal change of 20 m typically represents a vertical change of no more than 0.1 m.

[3] $JARKUS_{S+E}$ = short and extended data sets

km \ year	65	70	75	80	85	90	93	97
16	5	5	2	5	7	5	8	10
17	5	5	2	5	7	8	8	10
18	5	5	2	5	7	8	8	10
22	4	5	2	6	7	8	9	11
23	4	5	2	7	7	8	9	11
24	4	5	2	7	7	8	9	11
25	4	5	2	10	7	8	9	11
27	4	5	2	10	9	8	7	11
28	4	5	2	10	9	8	7	11
29	4	5	2	10	9	8	6	11
30	4	5	2	10	9	8	6	11
31	3	5	2	10	9	8	6	11
32	3	5	2	10	9	8	6	11
33	3	5	2	10	9	8	6	11
34	3	5	2	10	9	8	6	11
35	3	5	2	10	9	8	6	11
36	3	5	2	10	9	8	6	11
37	3	5	2	10	9	8	6	11
38	3	5	2	10	9	8	6	11
39	3	5	2	10	9	8	6	11
40	3	5	2	10	9	9	6	11
41	3	5	2	10	9	9	4	3
42	3	5	2	10	9	9	4	3
43	3	5	2	10	9	9	4	3
44	3	5	2	10	9	9	4	3
45	3	5	2	10	9	9	4	3
46	3	5	2	10	9	9	4	3
47	3	5	2	10	9	9	4	3
48	3	5	2	10	9	9	4	3
50	3	5	2	10	9	9	4	3
51	4	5	2	10	9	9	4	3
52	4	5	2	10	9	9	4	3
53	4	5	2	10	9	9	4	3
57	4	5	2	9	10	9	3	3
58	4	5	2	9	7	9	3	3
59	3	5	2	9	7	9	3	5
60	3	5	2	9	7	9	3	5
62	3	5	2	9	7	10	3	7
63	3	5	2	9	7	10	3	7
64	3	5	2	9	7	10	3	7
65	3	5	2	9	7	10	3	7
66	3	5	2	9	7	10	3	7
67	3	5	2	9	7	10	3	7
68	3	5	2	9	7	10	3	7
69	3	5	2	9	7	10	3	7
70	3	5	2	9	7	10	3	7
71	3	5	2	9	7	10	3	7
72	-	4	8	10	10	5	3	7
73	-	4	8	10	10	5	3	9
74	-	4	8	10	7	5	3	9
75	-	4	8	10	7	5	3	9
76	-	4	8	10	7	5	3	8
77	-	5	8	10	7	5	3	8
78	-	5	8	10	7	5	3	8
79	-	5	8	10	7	5	3	8
80	-	5	8	10	7	5	3	8
81	-	6	8	10	7	5	3	8
82	-	10	8	10	7	5	3	8
83	-	10	8	10	7	5	3	8
84	-	10	8	8	7	5	3	8
85	-	10	8	8	7	5	3	8
86	-	10	8	8	7	5	3	8
87	-	6	8	8	6	5	3	8
88	-	6	8	8	6	5	3	8
89	-	9	8	8	6	5	3	8
90	-	6	8	8	6	5	3	8
91	-	6	8	8	6	5	3	8
92	-	6	8	8	6	5	3	8
93	-	6	8	8	6	5	3	7
94	-	6	8	8	6	5	3	7
95	-	6	8	8	6	5	3	7
96	-	6	8	8	6	5	3	7
97	-	6	8	8	6	5	3	7

KEY :

1	jan
2	feb
3	mar
4	apr
5	may
6	jun
7	jul
8	aug
9	sept
10	oct
11	nov
12	dec
-	no data

Figure 3.2. The month of surveying for each profile for the period 1965 to 1997. The shadings are made according to the season of surveying. It can be observed that the majority of measurements are taken in the spring and summer months.

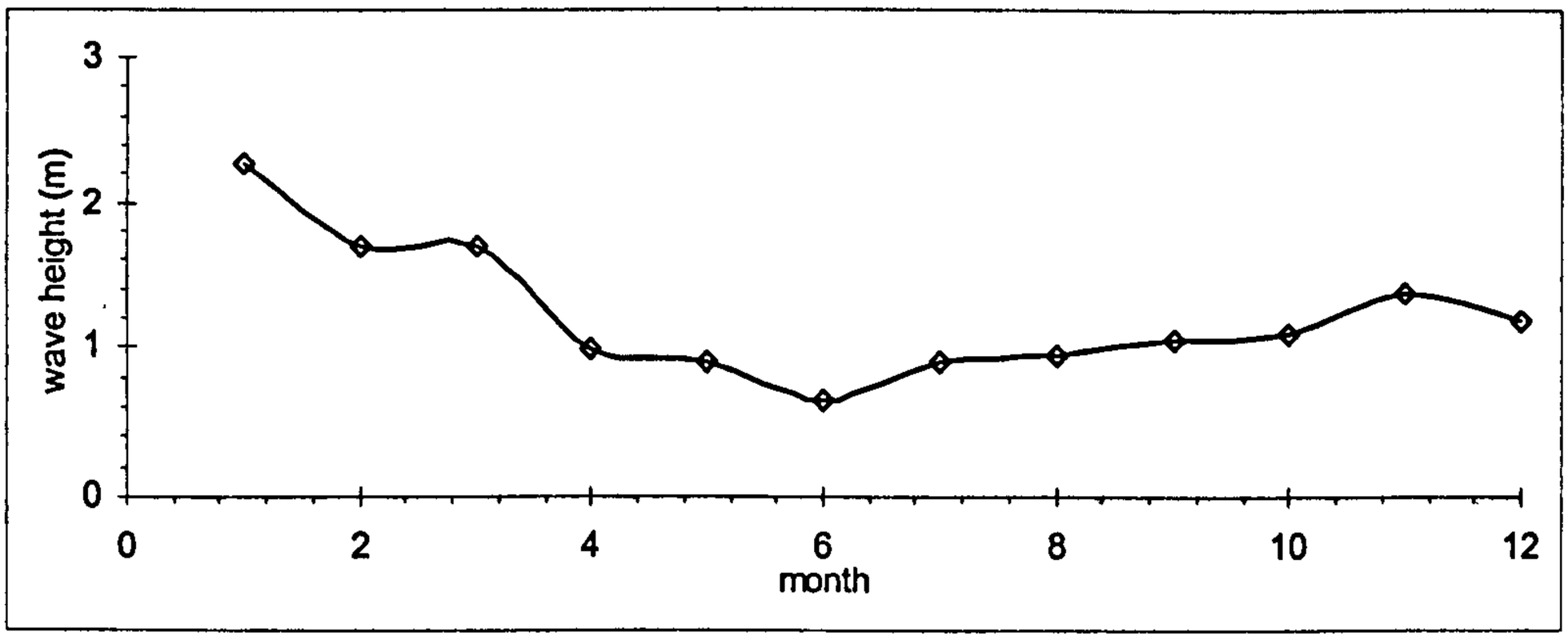


Figure 3.3. The mean annual significant wave height for the period 1979 to 1991. Taken from station YM6 (see Section 4.3). It is clear that the spring and summer months are generally least stormy and the winter is highly stormy.

3.3) MEASURING TECHNIQUES AND MEASUREMENT ACCURACY

The cross-shore bathymetric profiles of $JARKUS_{S+E}$ are composed of both sub-aerial and sub-aqueous parts. The former covers the dune and beach whilst the latter the active zone and shoreface (this study only uses the sub-aqueous parts). Details of the measurement techniques and the resulting measurement accuracy have been taken from discussion with users of the data set (Wijnberg, 1999) and in the case of the latter from translated Dutch reports and the summaries of Wijnberg and Terwindt (1995).

3.3.1) MEASUREMENT TECHNIQUES

The nature of the sub-aerial and sub-aqueous environments demands that different techniques are used to measure the bathymetry. These methods have evolved since 1963 in step with technological advances. The techniques used in the two cross-shore parts are :

1. Sub-aerial. Levelling was initially used until 1977. Since this time, until very recently, photogrammetry was employed. Laser altimetry is now used after tests and evaluation proved successful; and

2. Sub-aqueous. Ship-based echo-sounding has been used since 1963. However the original DECCA[4] positioning system has been replaced with GPS[5].

It should be noted that a new measurement technique is currently being tested at Egmond aan Zee (km 42) as part of the KUST 2000 project[6]. This technique is capable of measuring both the sub-aerial (from the dune foot) and the sub-aqueous (to a maximum depth of approximately 6 m[7]). It is known as the WESP ('Water En Strand Profiler') (Plate 3.1) and has the potential of producing highly accurate bathymetric measurements (approximately 0.02 m). The WESP can be regarded as the European sister of the American CRAB (Coastal Research Amphibious Buggy) (Birkemeier and Mason, 1984).

3.3.2) DATA SET ACCURACY

It is important that the measurement accuracy of the JARKUS data set is known so that not only can one be sure that the correct analysis is being used, but also so that one can be confident that a real bathymetric change has occurred.

The measurement accuracy of $JARKUS_{S+E}$ is documented to be 0.25 m. This has been derived from both analysis of the JARKUS data set and the stochastic and systematic errors which arise from the measurement techniques. These errors (Table 3.2) were used in the study of Nanninga (1985) to calculate a measurement accuracy of 0.25 m. It has also been shown that the sounding accuracy of the depth values is approximately 0.15 m which increases to 0.25 m when ship-dependant errors are taken into account, for example errors such as those which arise when determining the sea surface elevation relative to NAP (Wijnberg and Terwindt, 1995).

The measurement accuracy has also been calculated within this study (Chapter 5) using a different approach; the standard deviation value of all the bathymetric measurements of one cross-shore profile i.e. 1965 to 1997, was calculated. This was repeated for all longshore profiles. The resulting standard deviation value was less than, or equal to, 0.25 m, and consistent with a vertical measurement accuracy of 0.25 m; bathymetric changes of this value represent a 66 % confidence that a real change has occurred in the bathymetry.

---

[4] DECCA = positioning system based upon the triangulation of long-wave radio signals
[5] GPS = Global Positioning System based upon satellite technology
[6] KUST 2000 = the research project of RIKZ which aims to improve morphodynamic knowledge of the Dutch coast
[7] depending on the wave height at the time of measurement

ERROR	EXPLANATION
water level	measured and calculated from ordnance level to the water surface at the ship position
squat	result of falling water around a moving ship
zero line	difference between transducer and sea bottom
waves and swell	-
incorrect positioning	-

Table 3.2. Stochastic and systematic errors, as included in the study of Nanninga (1985).

3.4) SUMMARY

The spatial and temporal resolution and extent of the accurate (0.25 m) JARKUS data set has meant that it is particularly suitable for this study. The analysis of 81 km of cross-shore bathymetric profiles has enabled the shoreface morphodynamic behaviour (to a depth of approximately 15 m) of the Holland coast to be investigated over a 32 year period.

Plate 3.1. The 'WESP' (Water En Strand Profiler)

4) THE STUDY AREA : THE HOLLAND COAST

4.1) GENERAL INTRODUCTION

One of the few large-scale data sets in existence is the JARKUS data set (Table 1.2; Chapter 3). The accessibility of this data, in combination with its temporal and spatial resolutions and extent, led to its selection for use in this study. The JARKUS data set covers the entire Netherlands coast which is essentially divided into three sub-systems (Figure 4.1) each of which has distinct characteristics :

1. the northern Dutch *Wadden Sea* coast which is made up of a series of barrier islands, large inlets and active tidal delta regions;
2. the central '*closed*' (i.e. uninterrupted by tidal inlets) *Holland coast*; and
3. the southern *Delta Region* coast which is made up of large active and inactive tidal delta regions due to the natural and anthropogenic opening and closing of the coast.

Figure 4.1. The Netherlands coast (taken from Dijkman *et al*, 1990).

It is the second sub-system, the closed Holland coast (Figure 1.3) which is studied here (section 1.1). It is bound in the north by the Marsdiep, a tidal inlet which has considerable influence on coastal behaviour due to the presence of a large ebb tidal shoal, from km 0 to, approximately, km 12, as observed from bathymetric profiles. In the south, the Rotterdam Waterway acts as a boundary between the closed coast and Delta Region; the Waterway causes the deposition of sediment directly to the north in the dune, breaker and active zones due its interruption to longshore drift (De Ruig and Louisse, 1991; Van Rijn, 1995a, 1995b). This concave coast faces the southern part of the North Sea. At present the Holland coast is prograding in the centre and retreating in the north and south. The progradation is interpreted to be the result of onshore sediment exchange from the shelf and shoreface to the surf zone (Wiersma and Van Alphen, 1988; Stive, 1987, 1989, 1990). Regradation in the north is due to sediment loss through the Marsdiep Inlet to the Wadden Sea and in the south due to net northward longshore losses enhanced by the Rotterdam Waterway (Dijkman *et al*, 1990; Stive *et al*, 1990; Van Rijn, 1995a, 1995b).

More specifically it is the shoreface between Callantsoog (km 16) and Schevingen (km 97) which is taken as the study area (Chapter 1). Hence the shoreface of a wave-dominated, uniform coastline backed by dunes and uninterrupted by tidal inlets (e.g. the Marsdiep Tidal Inlet) is investigated. Major morphologic characteristics are; i) multiple bars located along the coastline obliquely to the shore and; ii) shoreface-connected ridges found in the centre of the coastline (km 35 - 65). Anthropogenic features are the Hondsbossche and Pettermer seawall (km 20 - 26) and IJmuiden harbour moles (km 55/56), in addition to relatively minor beach nourishment's. This chapter aims to describe all relevant characteristics of the study area, as outlined above.

4.2) GEOLOGICAL HISTORY : HOLOCENE EVOLUTION

The Holocene evolution of the Holland coast, as summarised in Figure 4.2, is described below.

At the end of the last ice age, the melting of the ice sheets induced the rapid sea-level rise which ultimately resulted in the fast transgression of the coastal barrier. The North Sea began to flood reaching the Dutch coastline around 7500 BP[1]. The coastline at this time was located approximately 25 km west of its present position (Zitman *et al*, 1990). Subsequently, east- and south-ward migrating back-barrier lagoons were established which were separated from both i) the precursor of the present Wadden Sea by a Pleistocene high (the Texel High) and ii) the southern

[1] BP = Before Present

Delta Region by the Rhine-Meuse Delta (de Boer *et al*, 1997). These features are assumed to have acted as sediment divergence points upon which longshore transport was superimposed (Stive *et al*, 1999b). During this sea-level rise the coastline retreated.

Around 5000 BP the rate of sea-level rise gradually decreased, reaching its present value. At the same time the rate of sediment supply became constant resulting in the sedimentation of the tidal basin. Tidal inlets progressively closed from north to south, until 3200 BP when the last major inlet (the Bergen Inlet) closed, ending the east-west directed tidal flow. At this time, the sediment supply to the back-barrier lagoons ceased and the barrier began to prograde into an 8 km wide 'closed' (see 4.1) system upon which the Older Dunes were formed. These changes caused shoreface steepening (Beets *et al*, 1992); a process argued to still be continuing today (Stive *et al*, 1990) (Figure 4.3). Simultaneously to barrier progradation was the retreat of the two headlands by erosion; since 2000 BP the Rhine-Meuse no longer acted as a sediment source. In addition, washovers and breakthroughs caused the Texel High to develop into a sink for the south and a source for the Wadden Sea (Stive *et al*, 1999a). From 1000 to 400 BP (Zitman *et al*, 1990) the Younger Dunes, which today back the present coastline, were formed on top of the Older Dunes.

The main events in the late Holocene evolution were therefore;

1. the transformation from an open, tidally-dominated coast to a closed, wave-dominated coast in the Subboreal; and
2. the change in the barrier movement from transgressive to regressive in the late Atlantic/early Subboreal (Beets *et al*, 1992).

This evolution was controlled by the interaction of i) hydrodynamics, which determined rate and direction of sediment transport; ii) rate of sea-level rise; and iii) the morphology of the transgressional surface. The combination of ii) and iii) primarily determined the location of sediment sources and sinks (Beets *et al*, 1992).

GEOLOGICAL TIME		YEARS BP	YEARS AD	SEA-LEVEL	EVENT IN COASTAL EVOLUTION
PLEISTOCENE		10 000			
H O L O C E N E	PREBOREAL	9 000		-25m	8700 BP: S. North Sea formed 8300 BP: connection between S & N North Sea
	BOREAL	8 000	5 500 BC	-15m	7800 BP: coastline approx. 25 km west of present location
	ATLANTIC	7 000 6 000 5 000			on average, coastline retreats & barrier isles formed in east of country 5000 BP: interconnection of barrier isles in east; formation of old dunes; mouth of Rhine active; coastline 8 km east of present location & advancing
	SUBBOREAL	4 000 3 000	3 850 BC 1 100 BC	-4.5m -3.0m -1.7m	3200 BP: closure of Bergen Inlet coastal advance to end & retreat begins; Rhine mouth inactive
	SUBATLANTIC	2 000 1 000 0	AD 1987	-1.0m NAP	+ 500 AD: breakthrough of dunes in south + 1100 AD: breakthrough of dunes in north-west + 1000 - 1600 AD: formation younger dunes

Figure 4.2. Time table with the main events in the development of the Dutch Coast (Zitman *et al*, 1990)

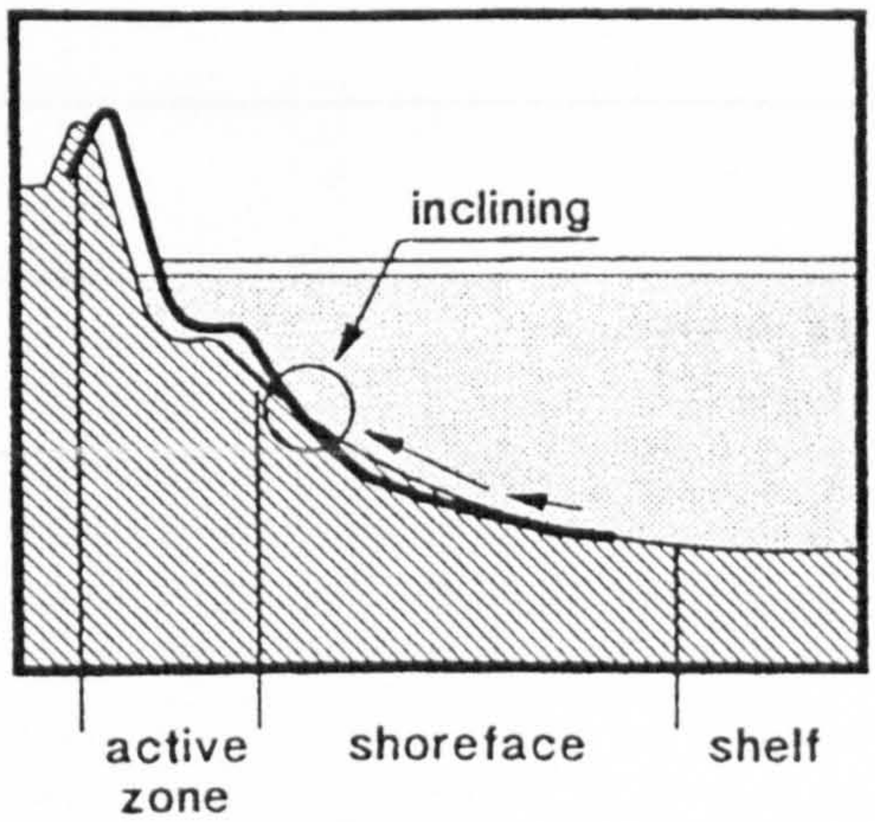


Figure 4.3. Typical behaviour of the shoreface showing the processes of shoreface steepening (taken from Stive *et al*, 1990).

4. 3) PRESENT HYDRODYNAMIC CHARACTERISTICS

4.3.1)BACKGROUND

The hydrodynamic climate of the Netherlands (from the Wadden Sea to the Delta Region) has been monitored since 1979:

1. wind direction and speed have been measured at hourly intervals and are available for the period 1979 to 1995; and
2. wave parameters (direction; height; period) have been measured at 3-hourly intervals and are available for the period 1979 to 1991.

There are three stations which are relevant to this study; 1) ELD (Eierland); 2) MPN (Meetpost Noordwijk); and 3) YM6 (IJmuiden-06). Their positions along the Holland coast are shown in Figure 4.4. The second station originally used wave poles (which measure water level fluctuations using an array of vertical sensors) whilst ELD and YM6 used latter wave-rider buoys; all were replaced by directional wavec buoys between 1985 and 1989. Wind data is only available for YM6 and is measured at a land station. The details of the three stations are given in Table 4.1.

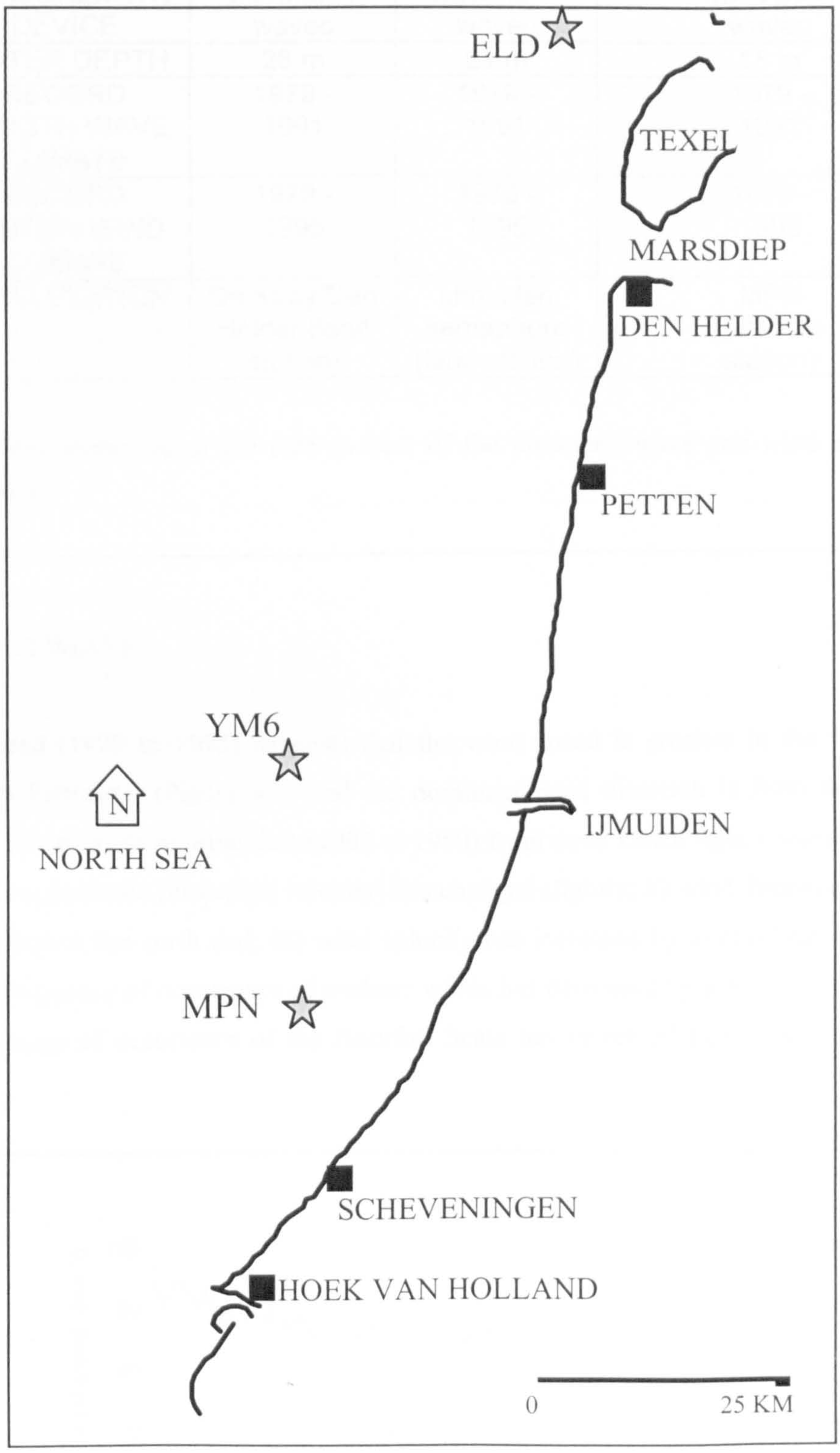


Figure 4.4. Position of the three measurement stations used in this study (as shown by the stars).

	EIERLAND (ELD)	IJMUIDEN06 (YM6)	MEETPOST NOORDWIJK (MPN)
MEASUREMENT DEVICE	waverider/ wavec	waverider/ wavec	wave pole/ wavec
WATER DEPTH	26 m	21 m	18 m
RECORD LENGTH WAVE CLIMATE	1979 - 1991	1979 - 1991	1979 - 1991
RECORD LENGTH WIND CLIMATE	1979 - 1995	1979 - 1995	1979 - 1995
WIND STATION	De Kooy/Den Helder (land station)	IJmuiden semaphore (land station)	MPN (offshore station)

Table 4.1. Some properties of the data sources of the presented wave and wind climate (after Wijnberg, 1995).

4.3.2) WIND CLIMATE

The mean speed (1979 to 1995) suggests that the wind speed is greatest in the winter season (November to February) (Figure 4.5) and the dominant wind direction is from the south-west (Figure 4.6). The analysis of wind data (1905 to 1980) from three Dutch light vessels revealed that the i) annual wind climate (direction; velocity) has changed slightly; ii) wind direction has changed by a few degrees to the north and; iii) wind velocity has increased by approximately 1 ms^{-1}. In addition, the frequency of occurrence of onshore winds has decreased by a few degrees, whilst the highest percentage of occurrence of the Beaufort Scale has increased from 3 to 4 (Hoozemans, 1990).

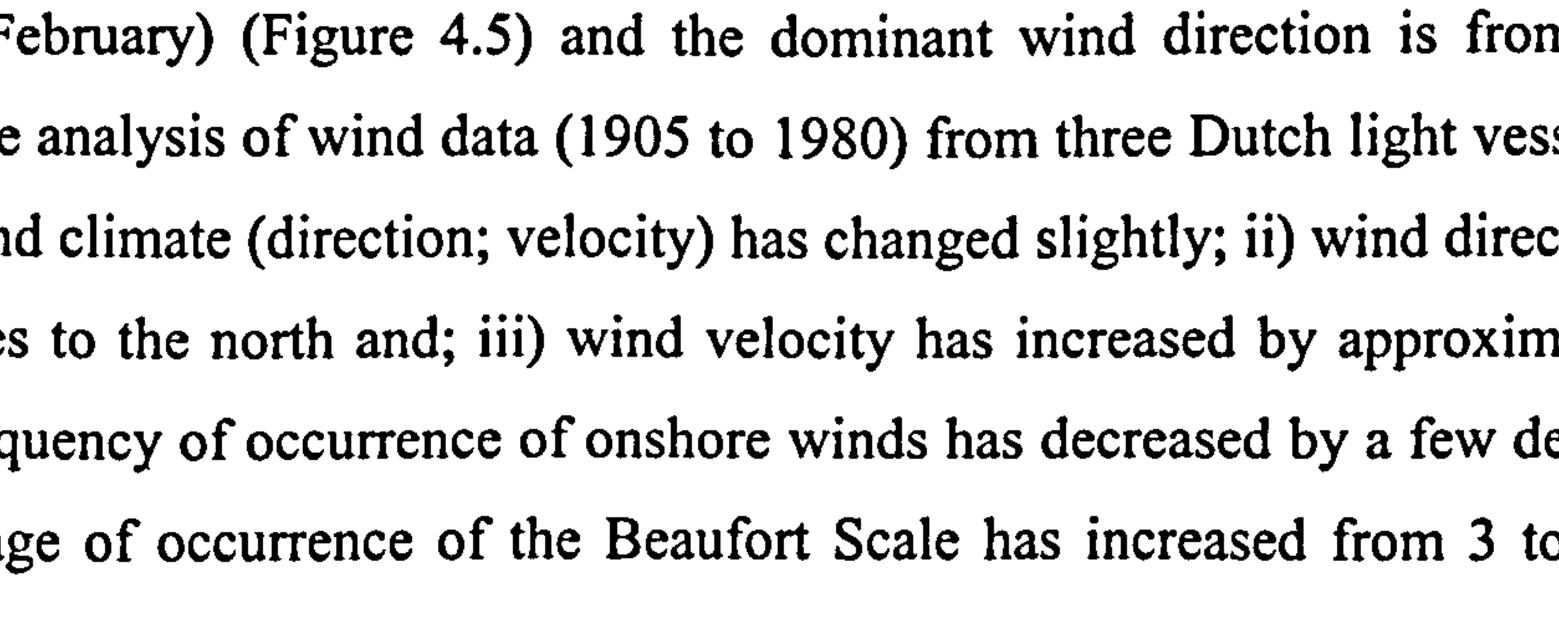


Figure 4.5. Mean annual wind speed for the period 1965 to 1995, taken from station YM6. It can be seen that the wind speed is greatest in the autumn and winter months.

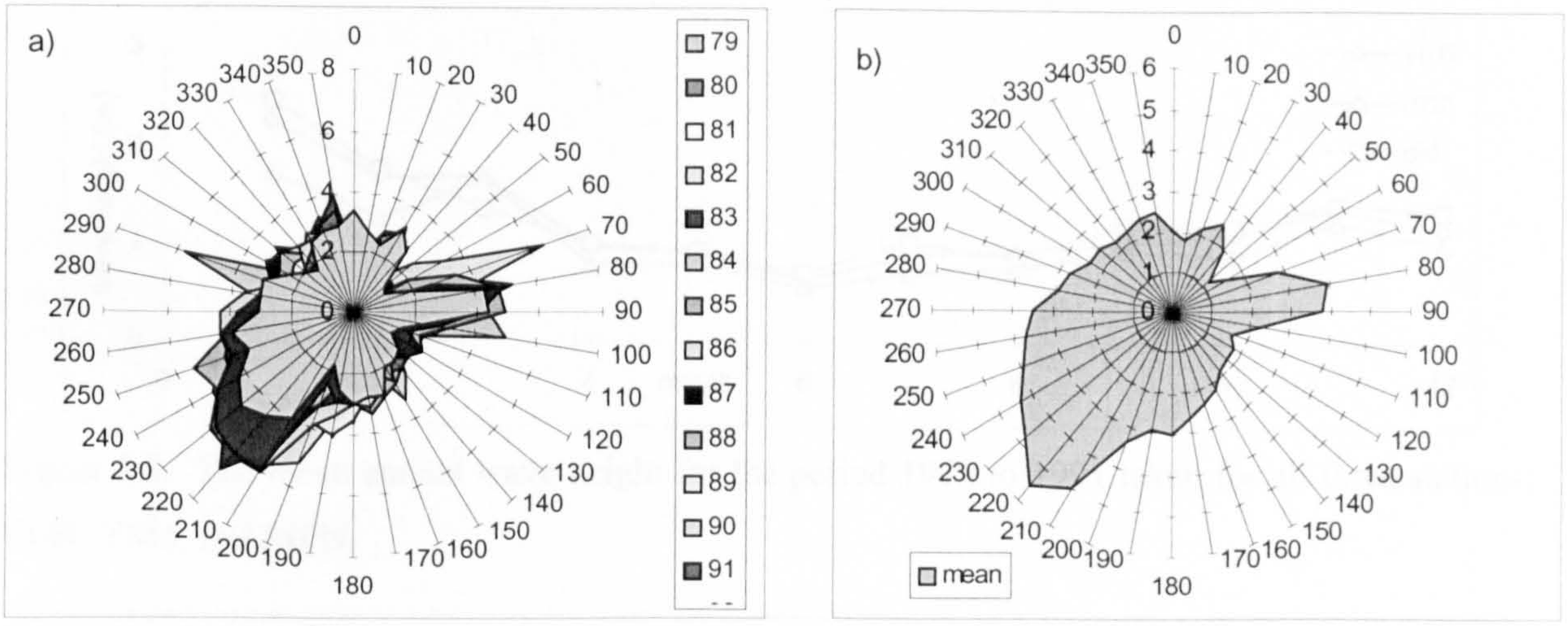


Figure 4.6. Wind direction for the station YM6 a) for the period 1979 to 1995; and b) the mean of the period 1979 to 1995. The dominant wind direction can be seen to be from the south-west.

4.3.3) WAVE CLIMATE

The wave environment is mainly controlled by the wind climate (Figure 4.7). The annual mean wave height is 1.2 m (associated wave period 5 sec.) whilst the extreme annual wave height is 5.3 m (associated wave period 7.7 sec.) (Roskam, 1988). The wave climate is similar alongshore; deviations in wave height from north to south are in the order of 0.2 m (Figure 4.8). Waves mainly approach the coast from the south-west and north-north-west (Figure 4.9a); this directional spectrum is similar alongshore (Figure 4.9 b and c).

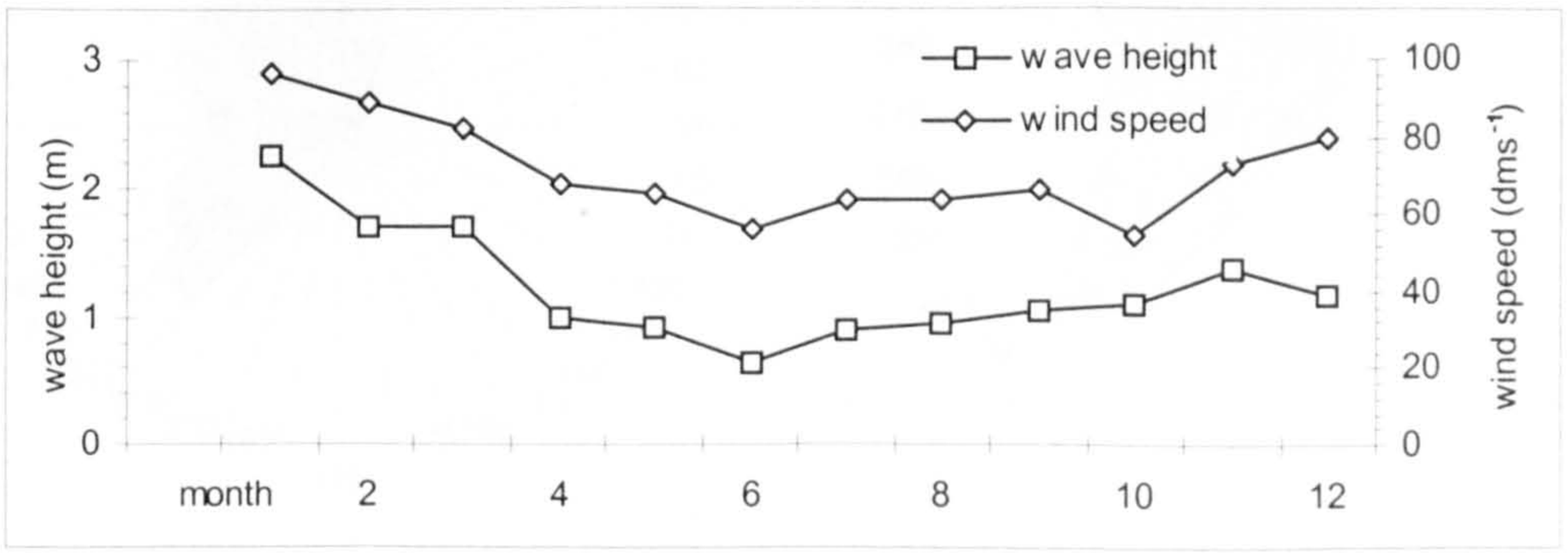


Figure 4.7. The relation between the mean annual wave height and wind speed for the period 1979 to 1990/5, taken from the station YM6. It can be seen that the wave climate is mainly controlled by the wave climate .

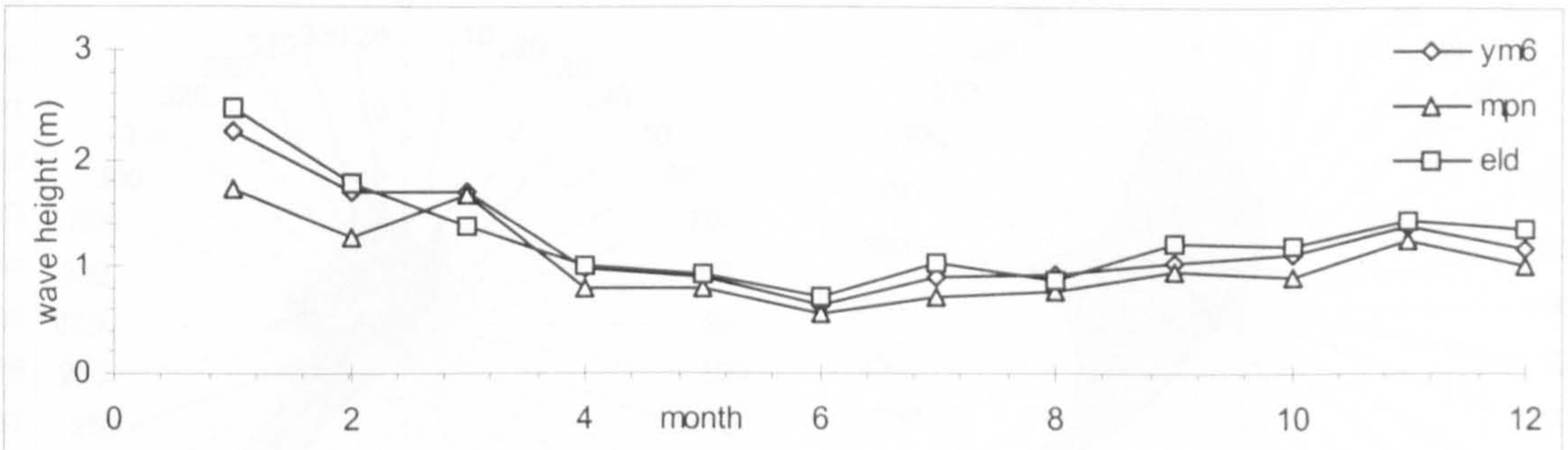


Figure 4.8. The mean annual wave height for the period 1979 to 1991 taken for all three stations; ELD; YM6; and MPN.

Seasonal variation is apparent in the wave climate; wave height is greatest in the winter months (November to February) than in the summer (April to August); 1.63 m and 0.87 m respectively (station YM6).

Swell is present in the wave climate as energy found in the low-frequency part of the spectrum (0.03 to 0.10 Hz) and forms approximately 20% of the wave energy spectrum. In addition, the contribution of swell to the wave climate is a little greater in the north (Figure 4.10) and there is a decrease in swell conditions to the south (per. comm. Roskam, 1998).

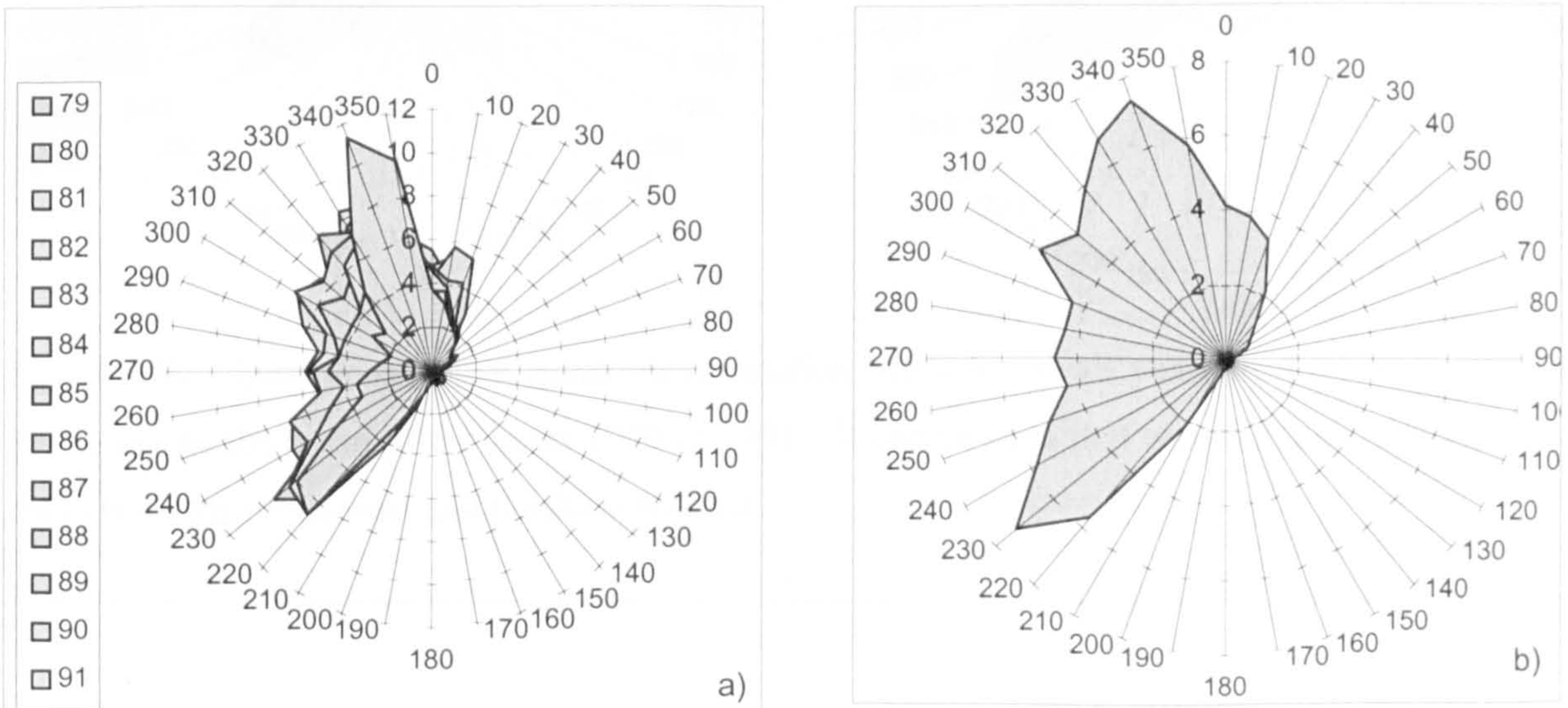


Figure 4.9a. Directional wave spectrum for station YM6 for a) all years in the period 1979 to 1991; and b) the mean of the years 1979 to 1991. It can be seen that waves mainly approach the coast from the south-west and north-north-west.

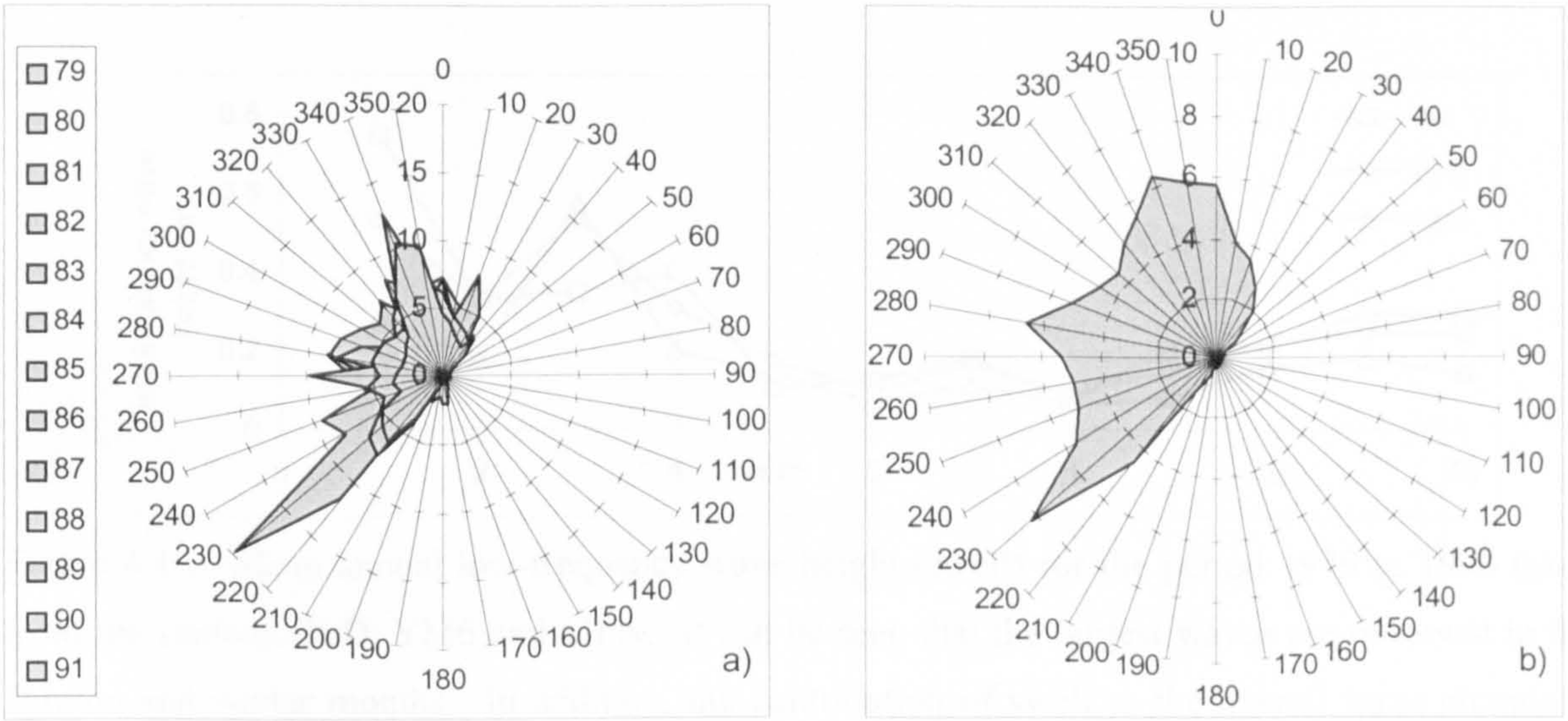


Figure 4.9b. Directional wave spectrum for station ELD for a) all years in the period 1979 to 1991; and b) the mean of the years 1979 to 1991. It can be seen that waves mainly approach the coast from the south-west and north-north-west.

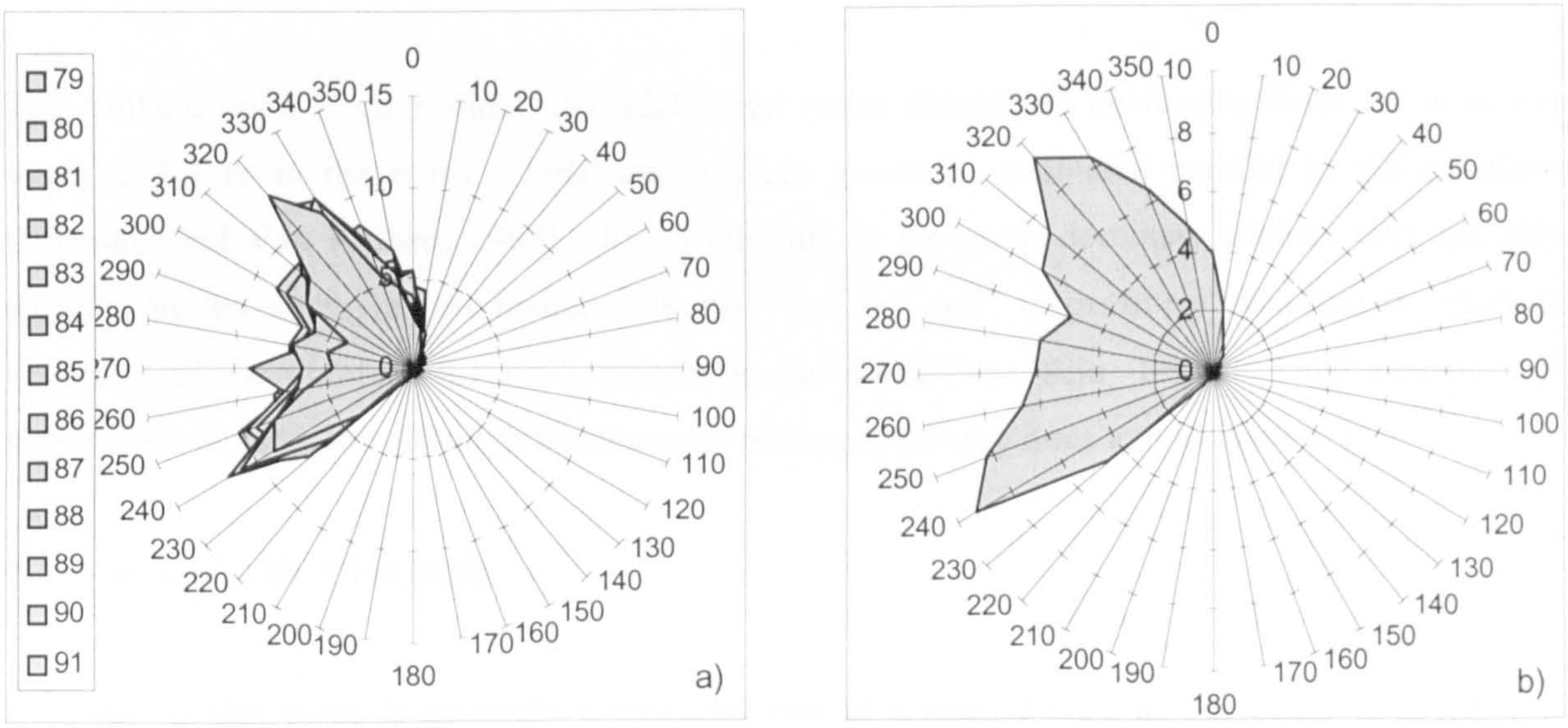


Figure 4.9c. Directional wave spectrum for station MPN for a) all years in the period 1979 to 1991; and b) the mean of the years 1979 to 1991. It can be seen that waves mainly approach the coast from the south-west and north-north-west.

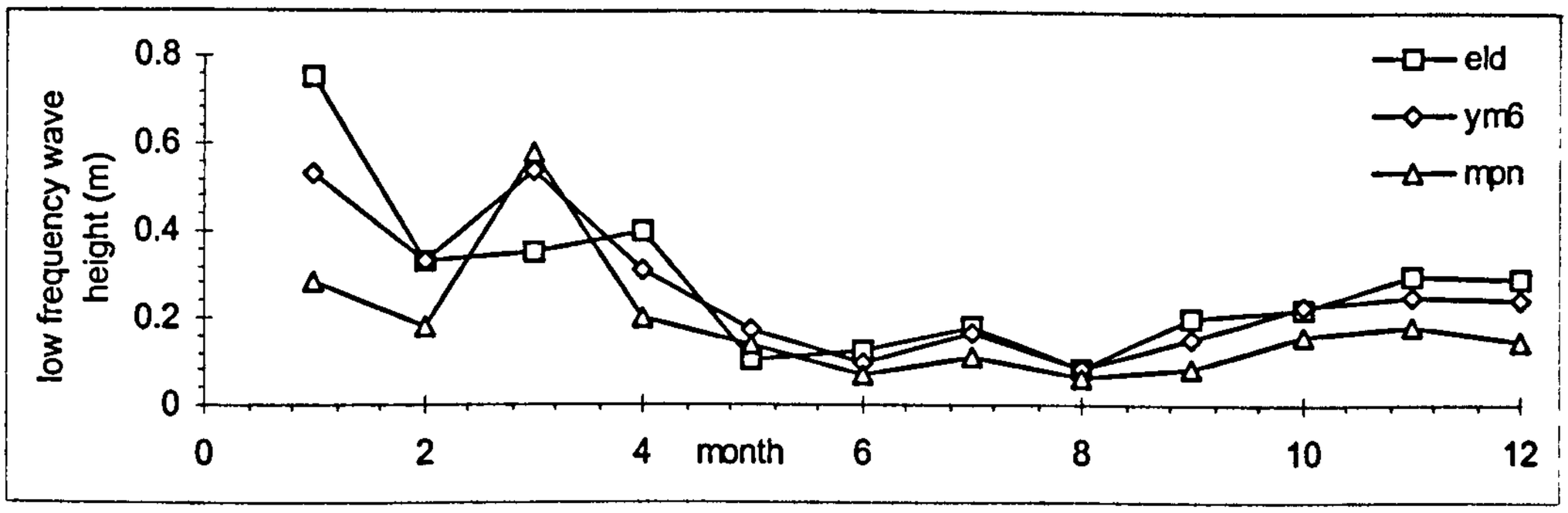


Figure 4.10. Mean annual low-frequency wave height (swell) for the period 1979 to 1990 taken from the stations ELD, YM6 and MPN. It can be seen that the largest waves are observed in the autumn and winter months. In addition, the contribution of swell to the overall wave climate is greatest in the north of Holland, decreasing to the south.

4.3.4) TIDES

The Holland coast is micro-tidal; the tidal range varies alongshore decreasing from 1.7 m in the south to 1.4 m in the north. Tidal currents are generally orientated parallel to the coastline (Wiersma and Van Alphen, 1988). Flood currents in the north dominate slightly over the ebb currents in the south; approximately 0.8 ms^{-1} and 0.7 ms^{-1} respectively resulting in residual velocities of the order of 0.1 ms^{-1} directed to the north (Van Rijn, 1997). Tidal currents are asymmetric alongshore, although the character of the asymmetry does vary (Figure 4.11).

4.3.5) SEA-LEVEL CHANGE

It is shown that there is currently a sea-level rise at a rate of 0.20 m per century. Predicted scenarios give an expected rise of 0.60 m per century and a pessimistic rise of 0.85 m per century (Louisse and Kirk, 1990).

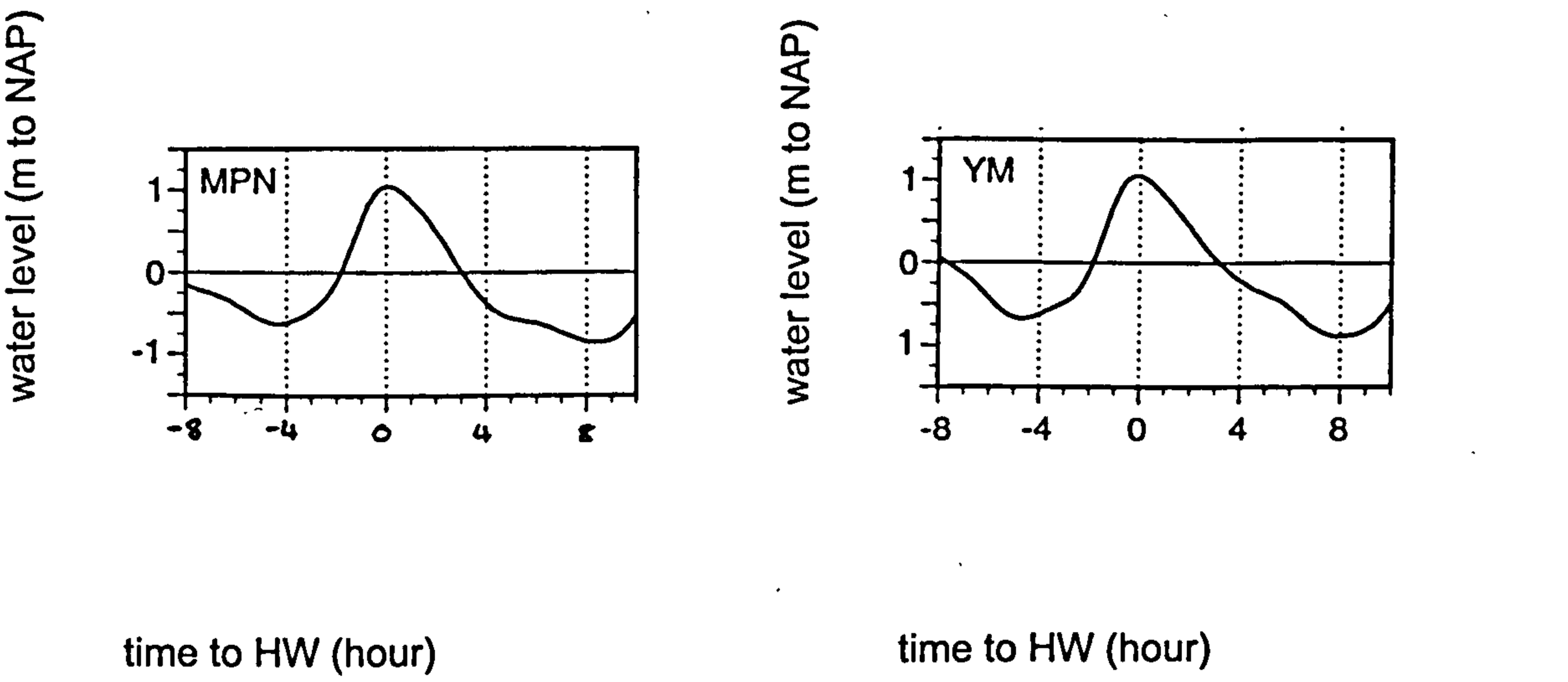


Figure 4.11. Tidal curves along the Holland coast for the stations of MPN and YM6 (taken from Wijnberg, 1995).

4.4) PRESENT MORPHOLOGICAL AND SEDIMENTARY CHARACTERISTICS

4.4.1) INTRODUCTION

As described in Section 4.3, the Holland coast has a particularly uniform hydrodynamic environment in the longshore. Similarly it has a uniform morphodynamic and, to a smaller extent, sedimentological environment. This environment consists of a sand barrier system which is fronted by the beach and active zone which contains a nearshore bar system composed of 2 to 3 bars (Short, 1992). However, unlike the hydrodynamic environment, localised features do exist. This section will discuss all features, taking the most shoreward first.

4.4.2) THE SUB-AERIAL SYSTEM

4.4.2.1) DUNES

The most dominant feature of this part of the Holland coast is the dune system which acts as a barrier between the sea and low-lying land. With the exception of the coastal stretch dominated by

the Hondsbossche and Pettermer seawall (km 20 - 26), the entire Holland coast is backed by dunes.

The dune system width varies from 0.1 km to more than 5 km and a mean maximum height of 20 to 30 m (although an extreme height of 50 m has been recorded). It has been shown (Stive *et al*, 1996) that the decadal behaviour of the dune/beach interface is correlated with both the reoccurrence frequency of the migratory nearshore bar system (see section 4.4.3) and the cumulative effects of the episodic wave events.

The majority of the dunes are under the influence of anthropogenic controls which act to stabilise and so decrease sediment loss (cf. de Ruig, 1998). One example of dune stabilisation is that of the planting of dune grass. In addition, schemes have been implemented where inlets are created within the dunes and a lagoon formed (Helmer *et al*, 1996; Waterman *et al*, 1998); such an experimental scheme has been introduced at km 31.

4.4.2.2) BEACH

The beach system is typically defined as including both the sub-aerial beach and the active zone (Short, 1992). The latter contains the nearshore bar system, which is the most significant morphodynamic feature of the beach system and is described in Section 4.4.3. The state of the sub-aerial beach is, as with the active zone, controlled by the wind waves generated in the North Sea. It is typically 43 m wide and has a mean slope of 1:15 (Stive *et al*, 1996). Sediment budget studies (see section 4.4.4) have shown that the beach acts as a sediment source in Noord-Holland and a sediment sink in Zuid-Holland.

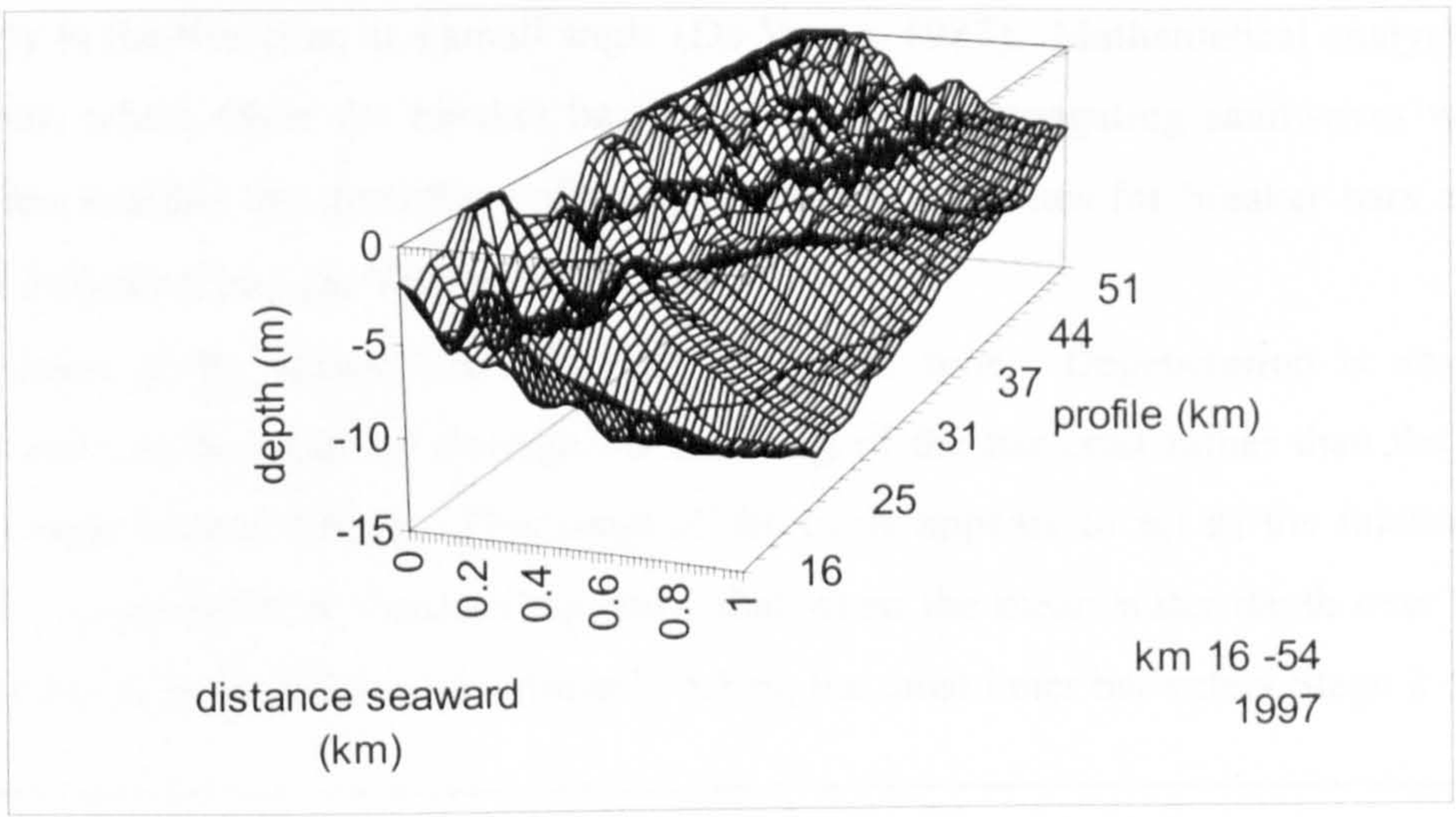
4.4.3) THE SUB-AQUEOUS SYSTEM

4.4.3.1) THE ACTIVE ZONE : THE NEARSHORE BAR SYSTEM

Multiple bars are present along the entire alongshore distance of the Holland coast (with the exception seaward of the IJmuiden harbour moles (km 55/56)) and extend to a maximum depth of approximately 8 m (Figure 4.12). The shape and number (two to five) of bars vary alongshore; it appears that a gentle beach slope results in a greater number of bars (De Vroeg *et al*, 1998). It has been suggested (Bakker *et al*, 1998) that the relative distance between the breaker bars is regulated by the resonance systems of long-periodic waves; surf beat[2] (Symonds *et al*, 1982).

[2] Breaking of alternating high and low waves results in a shoreward directed pulse of varying strength. The surf zone water reacts by an oscillation of the wave group period resulting in the generation of standing waves whose amplitude increases shoreward. The oscillation amplitude depends on whether the surf beat period agrees with the resonance frequency to which the breaker bar system is tuned.

Hence the breaker bars react more to the wave climate than the instantaneous wave characteristics.



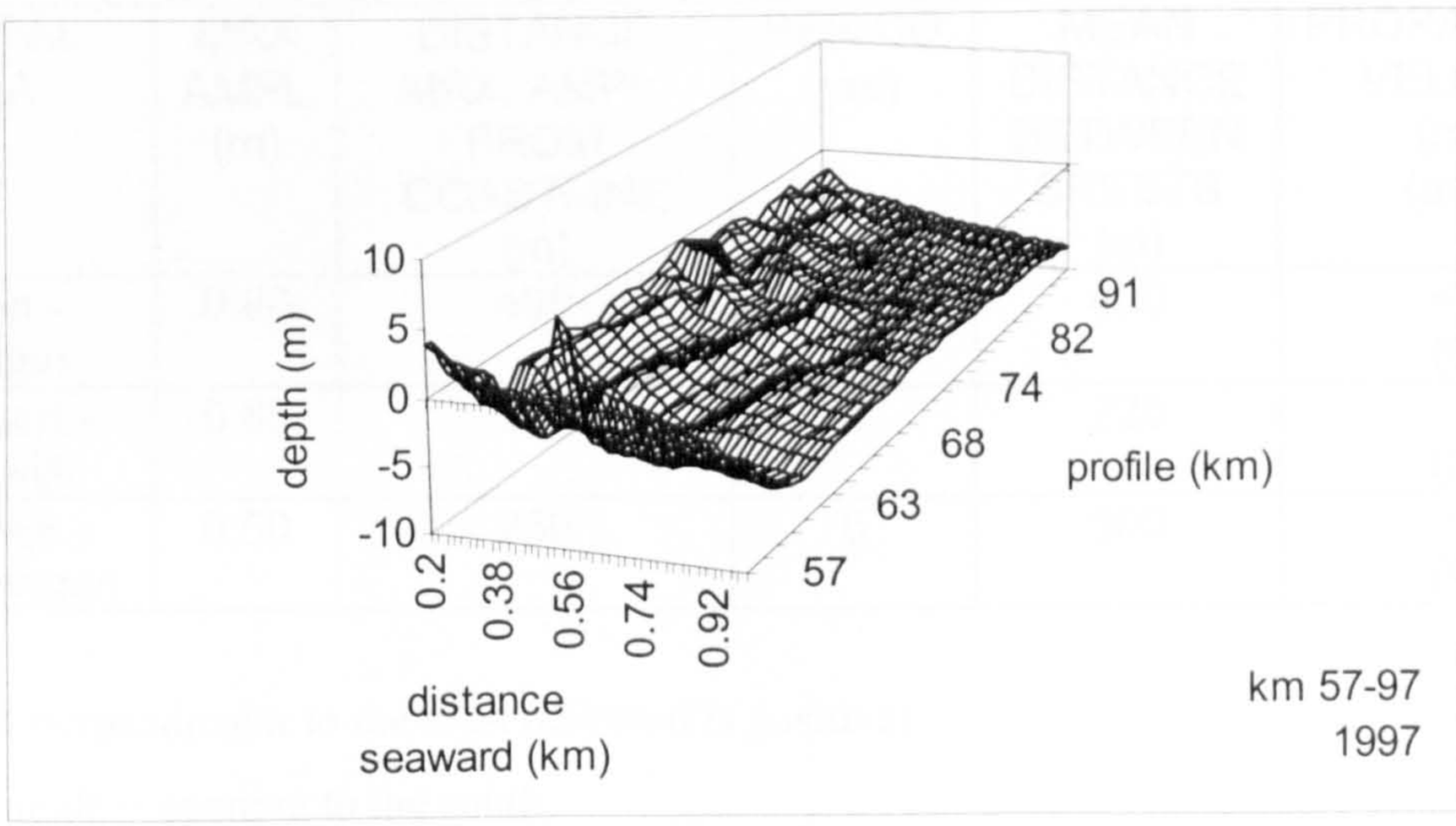


Figure 4.12. Bathymetry of active zone showing breaker bars.

The bar system passes through a three stage cycle during its existence which has also been observed at other locations e.g. Terschelling, The Netherlands (Ruessink, 1998):

1. *generation* close to the shoreline, during which the bar may remain within the inner 0.3 km of the nearshore bar system for several years;
2. net seaward *propagation* through the active zone up to 1.3 km offshore. The seaward propagation of the bar results in the cross-shore redistribution of sediment, and is orientated obliquely to the shoreline at a small angle (De Vroeg, 1987). Mathematical analysis of coastal behaviour, which takes the breaker bars to be seaward propagating sandwaves with straight crests, has enabled the derivation of some characteristic values for breaker bars as shown in Table 4.2 (Bakker and De Vroeg, 1988); and
3. *degeneration* at the seaward boundary of the active zone. Degeneration is an irreversible process and can be observed through the lowering of the bar crest rather than the infilling of the landward located trough. This stage of the cycle appears to act as the iniation of a new cycle i.e. experiments at Terschelling show that when the mean water depth over the crest of the outer bar is greater than approximately 5.5 m, the most inner bar enters Stage 2 of the cycle.

COASTAL AREA	MAX AMPL (m)	DISTANCE MAX. AMPL. FROM COASTLINE (m)	PERIOD (yrs)	MEAN DISTANCE BETWEEN CRESTS (m)	PROPAGATION VELOCITY (m/yr) (angle)
Bergen - IJmuiden	0.90	400	ca. 20	400	< 28 (0°)[1]
Zandvoort - Noordwijk	0.65	330	4	225	57 (2°)[2]
Noordwijk - Scheveningen	0.50	250	5	300	62 (0°)[1]

[1] : measured perpendicular to the crest (seaward is positive)

[2] : positive angle = opening to the south

Table 4.2. Average calculated characteristic values for breaker bars for some coastal areas (from Bakker *et al*, 1998)

Morphologic analysis of available cross-shore profile data ($JARKUS_s$) has also revealed alongshore differences in the decadal morphologic behaviour of the bars; five regions were distinguished bound by anthropogenic structures (Wijnberg, 1995). The investigation, performed using the data-reduction technique of eigenfunction analysis, showed i) different time scales of bar

migration; and ii) the along- and cross-shore migratory patterns. The two main multiple bar regions observed in the study area of this research (km 5 - 55 and km 57 - 100) (Figure 4.13) both

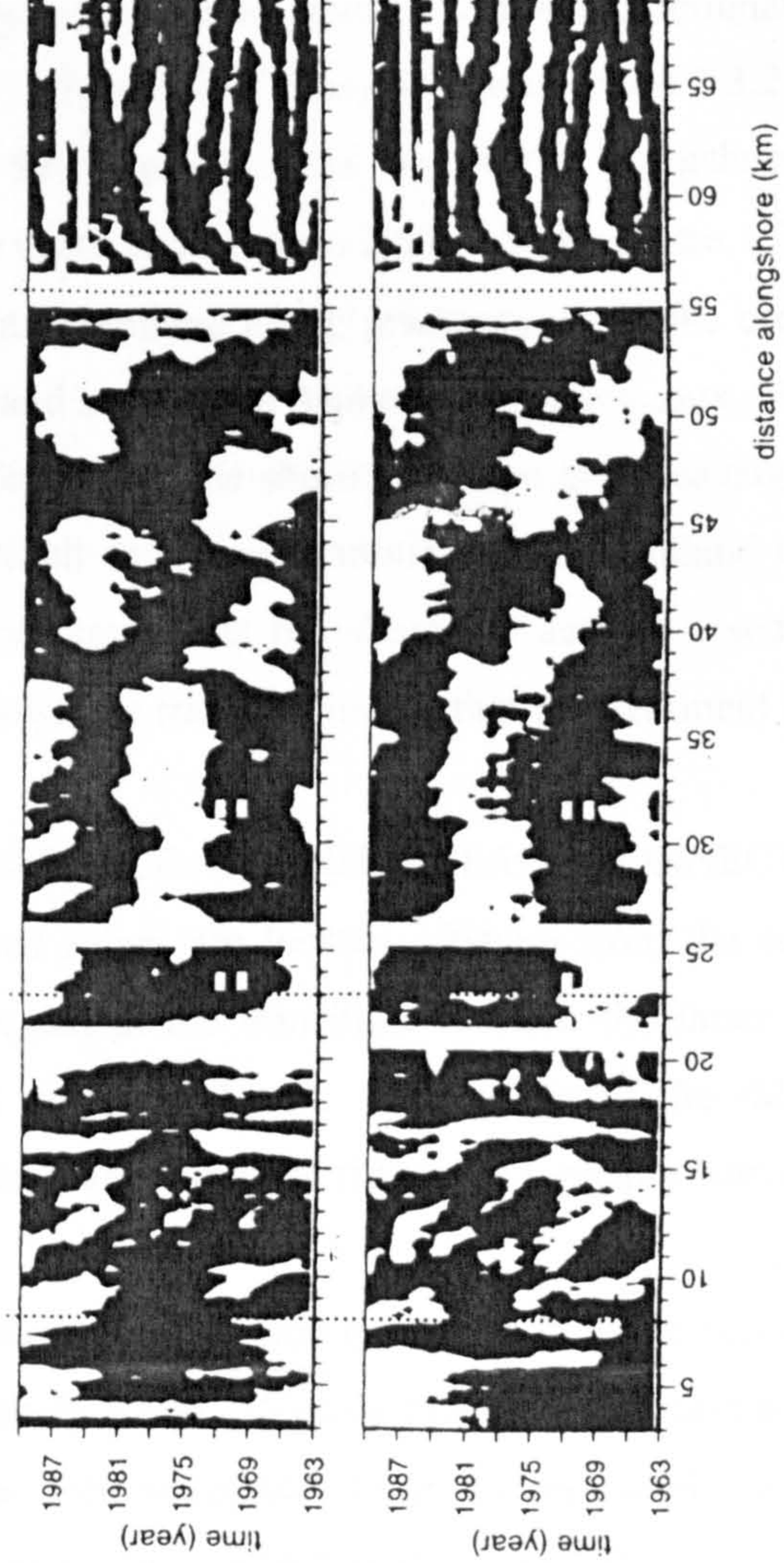


Figure 4.13. The two main multiple bar regions along the Holland coast observed using eigenfunction analysis (taken from Wijnberg, 1995).

undergo the three stage cycle described earlier, however they do migrate offshore at different rates. The morphological cycle repeats every 15 years in Noord-Holland (km 5 - 55) and every 4 years in Zuid-Holland (km 57 - 100). This three stage behaviour over these time scales has also been observed in the nearshore bar zone of Terschelling, The Netherlands (Ruessink and Kroon, 1994). The mechanism of the cyclic behaviour contains a strong morphologic feedback indicating that no cyclic external forcing is required; it is hypothesised that the cyclic behaviour is governed by the outer bar. This has been observed in model simulations of coastal behaviour investigating the differing influences of forcing induced behaviour and internal dynamics (Aarninkhof *et al*, 1998; Hinton and Aarninkhof, 1998).

4.4.3.2) THE SHOREFACE : CHARACTERISTICS

The shoreface (Box 1.1; Figure 1.1) is an important section of the coast (Chapter 1). The sediment transport processes which occur upon it are wave-dominated at the shoreward boundary and tidally-dominated at the seaward boundary (see section 2.3.2). The position of the shelf/shoreface boundary dictates the shoreface slope and varies alongshore, decreasing from approximately 10 km offshore in the north and south to 2.5 km in the centre. Therefore, the mean shoreface slope is steepest in the central Holland coast; gradients are of the order of 1:200 as compared to those of 1:700 in the north and south (Van Alphen and Damoiseaux, 1989). Long-term studies (e.g. Stive *et al*, 1990) have inferred that the shoreface slope is increasing and this has led to concern that this could ultimately result in the undermining of the Holland coast. Sediment budget studies (see section 4.4.4) have shown that the shoreface acts as a sediment source for the Holland coast; however the net longshore transport means that this sediment is ultimately transported northwards.

4.4.3.3) THE SHOREFACE : THE SHOREFACE-CONNECTED RIDGES

Shoreface-connected ridges are located offshore from the central Holland coast (Appendix 4.1). The ridges are located at the transition between the inner shelf and shoreface in water depths typically from 14 to 15 m (NAP). The height of the ridges varies between 1 and 6 m, the wavelength between 1 and 4 km and ridges are typically between 10 and 35 km long.

The shoreface-connected ridges slowly migrate in the direction of the flood current (northwards) at a rate of approximately 1 myr^{-1} (Van de Meene, 1984), and are associated with the large-scale (see Table 1.1). It has been suggested, from studies based upon other, similar, shorefaces, that the individual ridges have a direct effect on shoreline behaviour in the vicinity of the intersection of the ridge with the shoreface over the long-term (Everts, 1985; Rine and Ginnsburg, 1985). It has been shown, through observational and modelling techniques, that the ridges are of a sufficient

morphodynamic scale to influence the flow around them. Over the large-scale, the residual pattern is dominated by the northwards directed dominant flood current and a persistent density-driven, shoreward directed residual current flow close to the bed (Van de Meene, 1984).

4.4.3.4) THE SHOREFACE : THE NATURAL TERRACES

A localised shoreface characteristic is that of two natural terraces[3] located at km 15 approximately 0.6 km seaward and extending to 3 km offshore (Figure 4.14). The terraces are found at water depths of 10 and 13 m (NAP), the shallowest of which is called the 'Pettermer Polder'. It is suggested that they are produced by a 4000 year old erosion- resistant clay and peat layer deposited during the Holocene evolution of the Holland coast (Bakker *et al*, 1998). Surface sediment samples show the terrace to be covered by relatively coarse sand (Eisma, 1968; Wiersma and Van Alphen, 1988). Strong currents (> 20 cms^{-1}) are required to erode both these sediment classes (Graf, 1971).

4.4.4)SEDIMENT CHARACTERISTICS AND BUDGET

4.4.4.1) SEDIMENT CHARACTERISTICS

The shoreface sediments are non-cohesive, medium- to well-sorted and have a median grain size of 0.150 to 0.300 mm (Eisma, 1968; Van Alphen *et al*, 1990; RGD, 1998). The upper 1 m of sediment is generally finer to the north of IJmuiden (0.150 to 0.210 mm) than to the south (0.210 to 0.300 mm) (RGD, 1998), as shown in Appendix 4.2 which shows the upper 1 m of sediment along the Holland coast. This main grain size boundary coincides with i) a general change in grain size in the sands on the shelf seaward of the shoreface; ii) a decrease in beach gradient to the north; and iii) the presence of the harbour moles. Points i) and ii) suggest that south of IJmuiden only small amounts of reworked sands are present, with most sands coming from the sea (Eisma, 1968). An area of relatively coarse sands (0.5 to 2 mm) is found seaward of Petten; the Pettermer Polder (Wiersma and Van Alphen, 1988).

[3] Here a terrace is defined as an almost flat area attached to the shoreface, with a minimum surface area of 1 km and standing proud of the adjoining slope on its seaward side by more than several metres (Van Alphen and Damoiseaux, 1989).

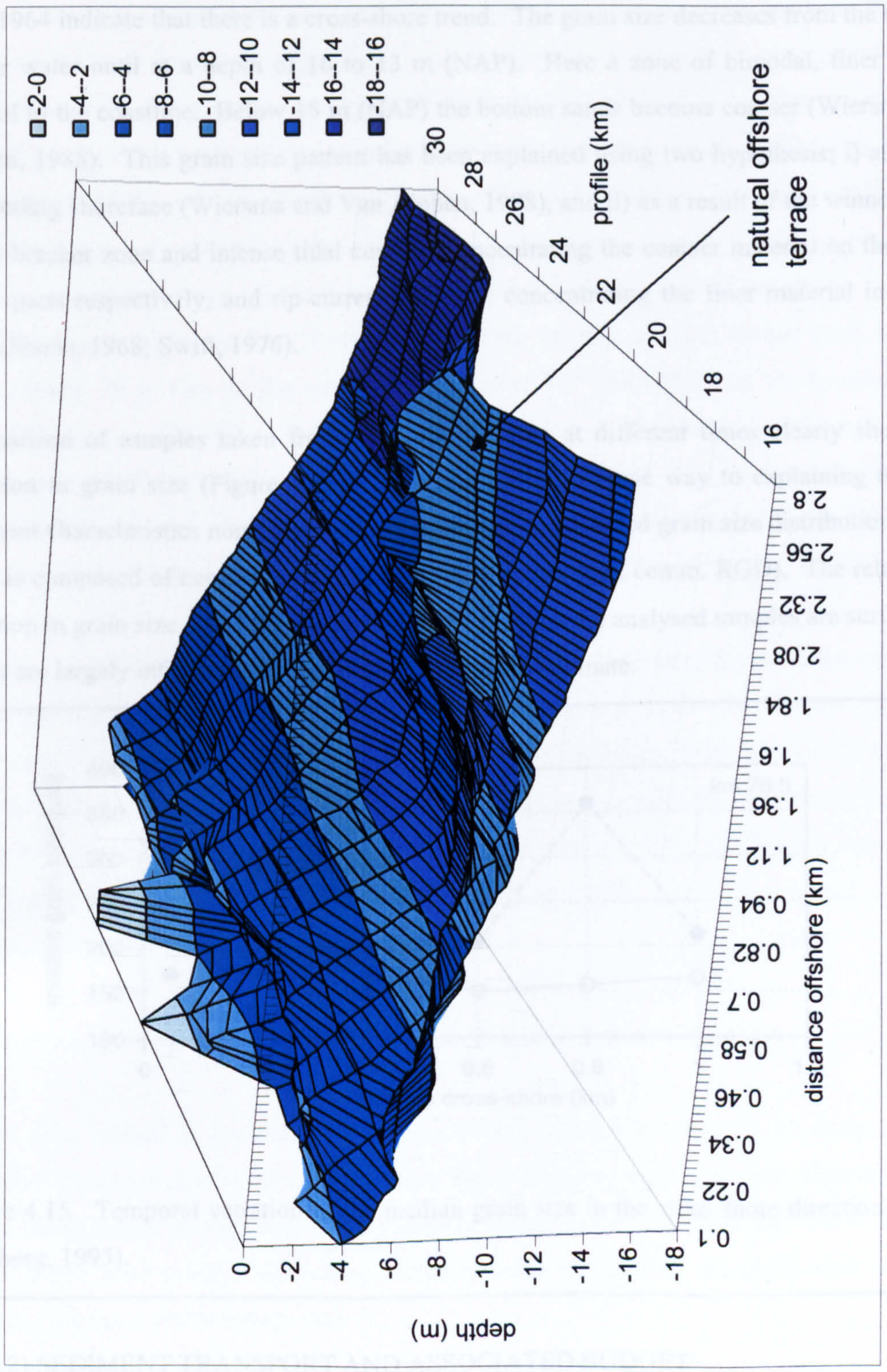


Figure 4.14. Bathymetry of the Holland coast from km 16 to 30 clearly showing the natural terrace from km 16 to 22. (Data taken from 1970).

Within the two sub-sections of the Holland coast (north and south of IJmuiden) there appears to be no distinct alongshore trend of sediment characteristics, as observed in previous studies e.g. Short (1992). Detailed analysis of cross-shore transects at six locations (km 23; 45; 53; 66; 81; 100) from 1964 indicate that there is a cross-shore trend. The grain size decreases from the surf zone to deeper water until at a depth of 10 to 13 m (NAP). Here a zone of bimodal, finer sands exist parallel to the coastline. Below 15 m (NAP) the bottom sands become coarser (Wiersma and Van Alphen, 1988). This grain size pattern has been explained using two hypothesis; i) as a result of the eroding shoreface (Wiersma and Van Alphen, 1988), and ii) as a result of the winnowing effect in the breaker zone and intense tidal currents concentrating the coarser material on the upper and lower parts respectively, and rip-current 'fall-out' concentrating the finer material in the middle parts (Eisma, 1968; Swift, 1976).

Comparison of samples taken from the same location at different times clearly show seasonal variation in grain size (Figure 4.15). This could also go some way to explaining the differing sediment characteristics north and south of IJmuiden; the detailed grain size distribution map of the RGD is composed of cores ranging over the last 40 years (per. comm. RGD). The relatively large variation in grain size could also be related to the fact that the analysed samples are surface samples which are largely influenced by the local hydrodynamic climate.

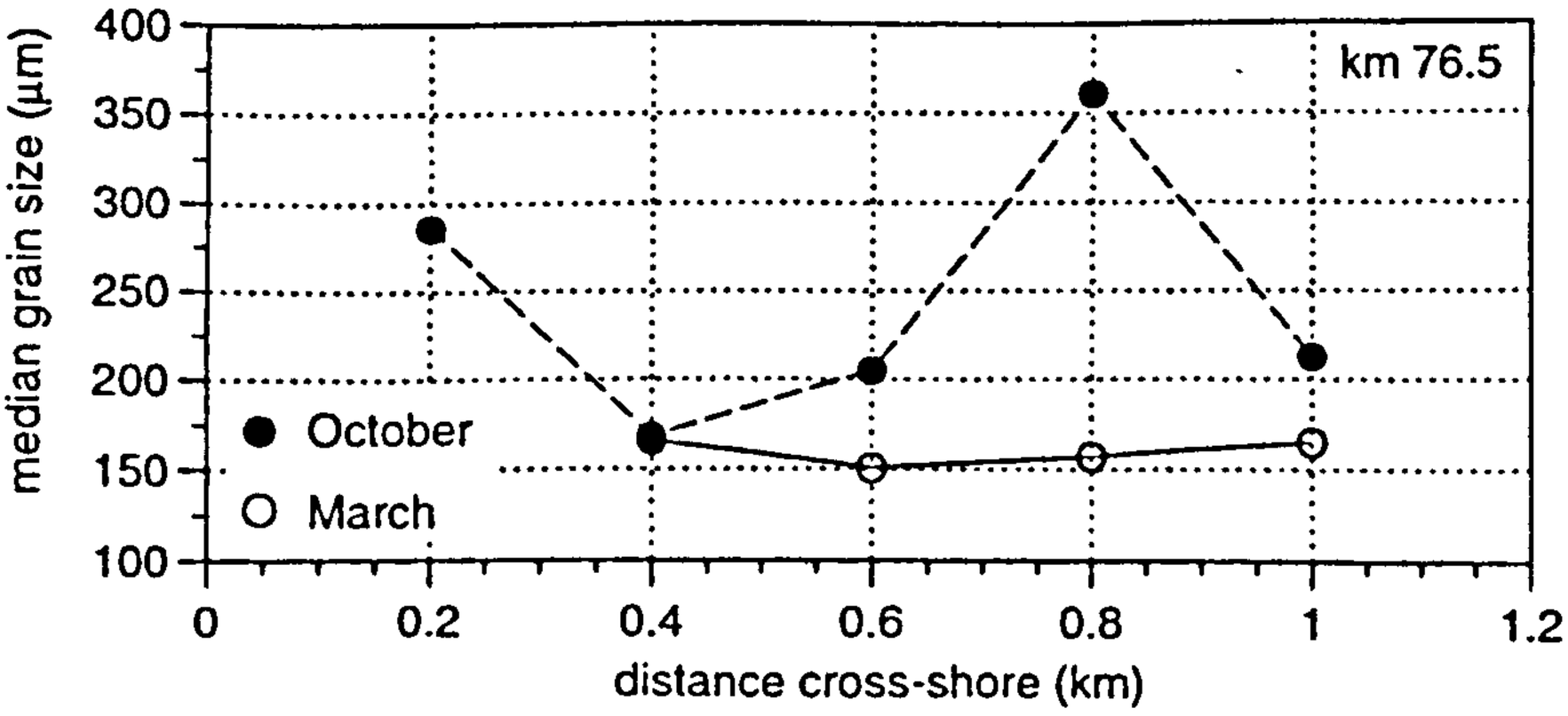


Figure 4.15. Temporal variation of the median grain size in the cross-shore direction (taken from Wijnberg, 1995).

4.4.4.2) SEDIMENT TRANSPORT AND ASSOCIATED BUDGET

The studies discussed in the following are those relevant to this study as they focus on the medium/large-scale shoreface behaviour. It should be noted that the majority of these studies are

written in Dutch, and so where translation has not been possible summaries are taken from the reports of Van Rijn (1995) and Wijnberg (1995).

Sediment transport and the associated sediment budget of the Holland coast, has been the subject of much research over the last decade. These investigations based upon the sediment transport of the closed coast have shown that the dominant cross-shore transport is onshore-directed and the dominant long-shore transport is northwards-directed (Roelvink *et al*, 1990; Van Rijn, 1995; Walstra *et al*, 1998). An important conclusion which can be drawn from such work is that the shoreface acts as a significant source of sediment to the active zone in which the majority of the longshore transport occurs. It should also be noted that the northward longshore transport also occurs in deeper water resulting from tidal currents, for example net annual rates at depths of approximately 20 m vary in the range 25 to 73 $m^3m^{-1}yr^{-1}$ (depending on the location along the coast) (Walstra *et al*, 1998). Transport rates are greater in shallower waters; there is a sharp increase in cross-shore transport towards the 8 m depth contour as a result of increasing wave-induced streaming and short-wave asymmetry. The longshore transport also increases here, resulting from wave-domination in the form of breaking waves (Roelvink *et al*, 1990).

A number of studies have been carried out on the sediment budget and associated changes along the Holland coast, as shown in Table 4.3. It is not possible to compare the detailed results of these studies, only the general ones; for example the erosive/accretionary behaviour of different sections along the coast. This is the result of different along- and cross-shore boundaries being used to identify the control volume; for example Ruig and Louisse (1991) divided the cross-shore into three zones (dune and beach, breaker and shoreface) whilst Van Vessem and Stolk (1990) considered the cross-shore profile as a single unit.

The general trends which are drawn from past studies are summarised below :

1. the dune region is generally gaining sediment, through entrapment by dune management activities, although north of IJmuiden they also undergo erosion over short distances;
2. the beach region undergoes accretion south of IJmuiden and erosion in the Noord- Holland;
3. the active zone exhibits alternating accretory/erosive behaviour along the coast (a result of it being the most active zone); and
4. the shoreface undergoes net erosion along the entire Holland coast.

STUDY	BASIS	CORREC -TION* ?	LONG-SHORE AREA	CROSS-SHORE ZONES	RESULTS
De Ruig (1989)	JARKUS database[1] 1963-86 :km 0-102 1975-86 :km 102-118	yes	km 0 -118. calculations every 1 km	dune & beach → surf (0 - 0.8 km offshore) → shoreface (0.8 - 2.5 km offshore) →	km 0 - 118 = balance → accretion → erosion[*] → erosion[*] ([*] accretion km 50 - 60)
Van Vessem & Stolk (1990)	JARKUS database[1] 1965 - 1984	yes	km 0 - 118 divided into km 0 - 55 km 56 - 118	upper boundary = maximum measured height in year lower boundary = maximum measured depth in year	km 0 - 118 = balance km 0 - 55 = erosion km 56 - 118 = accretion
De Ruig & Louisse (1991)	JARKUS database[1][2] 1963 - 1990	yes	km 0 - 118	upper boundary = most landward measurement lower boundary = most seaward measurement also : dune & beach → breaker → lower shoreface →	km 0 - 118 = balance km 0 - 40 = erosion km 40 - 90 = accretion km 90 - 118 = erosion → accretion → erosion → erosion
Van Rijn (1997)	JARKUS database[1] 1964 - 1992	yes	km 0 - 118	beach & surf (+3 - -3 m) middle shoreface (-3 - -8 m) lower shoreface (-8 - -20 m)	km 0 - 118 for beach & surf = erosion km 0 - 50 = erosion km 50 - 60 = accretion km 60 - 108 = erosion km 108 - 118 = accretion
Hinton (1998)	JARKUS database[1][2]. 1970 - 1990	yes	km 16 - 97	dune (1st dune to +3 m) → beach (+3 - -1m) → surf (-1 - -8 m) → middle shoreface (-8 - -12m) → lower shoreface (-12 - -14m) →	km 16 - 97 = erosion → accretion → erosion

Key : (1) = annual data set; (2) = five-yearly data set; * = correction for beach nourishment

Table 4.3. Summary of sediment budget studies of the Holland coast.

Considerable accretion has also been shown to be occurring immediately north and south of the IJmuiden harbour moles, whilst in neighbouring sections erosion is apparent.

4.5) ANTHROPOGENIC INFLUENCES

4.5.1) COASTAL PROTECTION

The Holland coast has been influenced by numerous hard and soft coastal protection schemes since the 16th century, (as shown in Figure 4.16) in an attempt to ensure that i) the low-lying land (much of which is under sea level) remains free from flooding; and ii) the coastline remains at its 1990 position (de Ruig, 1998).

4.5.1.1) THE HONDSBOSSCHE AND PETTERMER SEAWALL (km 20 - 26)

This is the largest hard protection scheme and was originally built in the middle of the 16th century. It has since been relocated to a more landward position due to the erosion of the adjacent dune system; the last relocation was in 1823 (Wijnberg, 1995). Bathymetric measurements show that the seawall protrudes 0.1 km seaward from the present coastline.

4.5.1.2) GROYNES

Groynes have been built on eroding parts of the coastline. Within the study area they are found both seaward of and attached to either end of the Hondsbossche and Pettermer seawall. These were constructed from the late 19th century to early 20th century. The groynes have a length of approximately 0.2 km and are found with a typical alongshore spacing of 0.2 km. Integration of the mean erosion of protected and unprotected coastal stretches of eroding beaches which become more and more protected with groynes, show that the building of the groynes reduced coastal erosion (Bakker *et al*, 1998). However, those groynes seaward of the seawall are ineffective in directly influencing sediment transport due to their location relative to the natural beach line (Short, 1992).

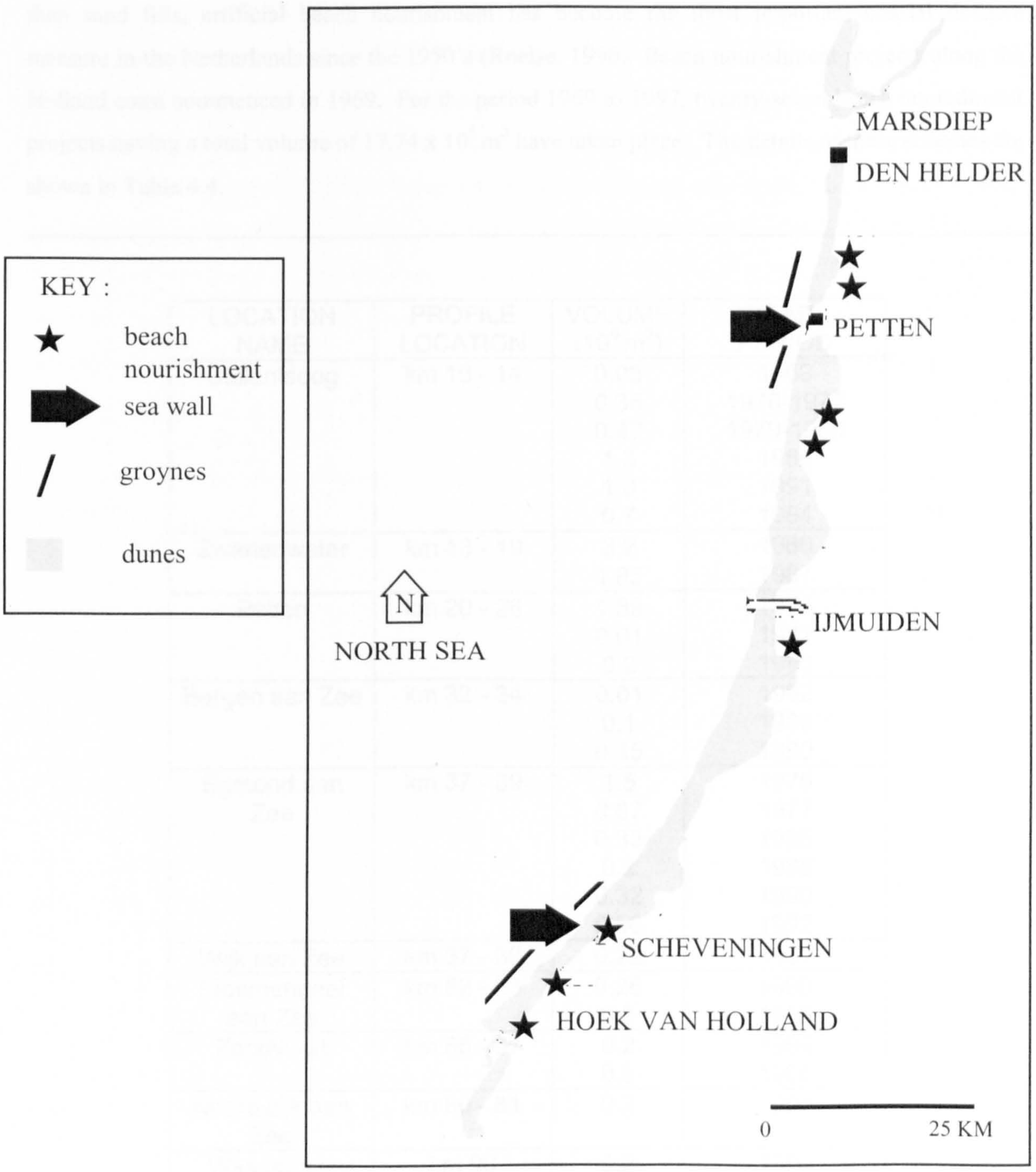


Figure 4.16. Location of coastal protection schemes.

4.5.1.3) BEACH NOURISHMENT

With the demand for more environmentally friendly coastal defences, coupled with technical developments in the dredging industry and groyne and seawall schemes becoming more expensive than sand fills, artificial beach nourishment has become the most important coastal defence measure in the Netherlands since the 1950's (Roelse, 1990). Beach nourishment projects along the Holland coast commenced in 1969. For the period 1969 to 1997, twenty-seven beach nourishment projects having a total volume of 17.74 x 10^6 m^3 have taken place. The details of these schemes are shown in Table 4.4.

LOCATION NAME	PROFILE LOCATION	VOLUME (10^6 m^3)	YEAR/ PERIOD
Callantsoog	km 10 - 14	0.05 0.35 0.47 1.3 1.0 0.7	1969 1976-1977 1979-1980 1986 1991 1994
Zwanenwater	km 13 - 19	3.2 1.85	1986 1987
Petten	km 20 - 26	1.89 0.01 0.2	1971 1987 1993
Bergen aan Zee	km 32 - 34	0.01 0.1 0.45	1982 1989 1990
Egmond aan Zee	km 37 - 39	1.5 0.87 0.33 0.2 0.32 0.56	1976 1977 1985 1988 1990 1992
Wijk aan Zee	km 37 - 39	0.22	1991
Bloemendaal aan Zee	km 62 - 63	0.26 0.5	1990 1995
Zandvoort	km 65 - 67	0.2 0.8	1994 1996
Noordwijk aan Zee	km 80 - 81	0.2	1997
Wassenaar	km 96	0.2	1996

Table 4.4. Nourishment projects in Holland 1969 - 1997 (taken from Roelse (1990) and unpublished data of RIKZ (1999)).

4.5.2) OTHER ENGINEERING WORKS

The closed Holland coast is interrupted by one major anthropogenic structure; the IJmuiden harbour moles (km 55/56),as shown in Plate 4.1, act to 'cut' the coast into two distinct sections. The aim of these moles is to prevent sedimentation in the shipping channel. The 1.5 km long moles were first constructed in the period 1865 to 1879. In the period 1962 to 1967 the northern mole was extended by a further 1 km and the southern by 1.5 km. Since construction, the coastal region to the north and south of the harbour moles has undergone considerable accretion as a result of interruption to the northwards longshore transport. Plans have been developed (Waterman *et al*, 1998) which accelerate the sediment accretion to the south of the harbour moles by creating a new dune and beach system. These plans also include the development of a large yachting marina, tourism and recreation centre, freshwater lake and a new nature reserve (as shown in Figure 4.17).

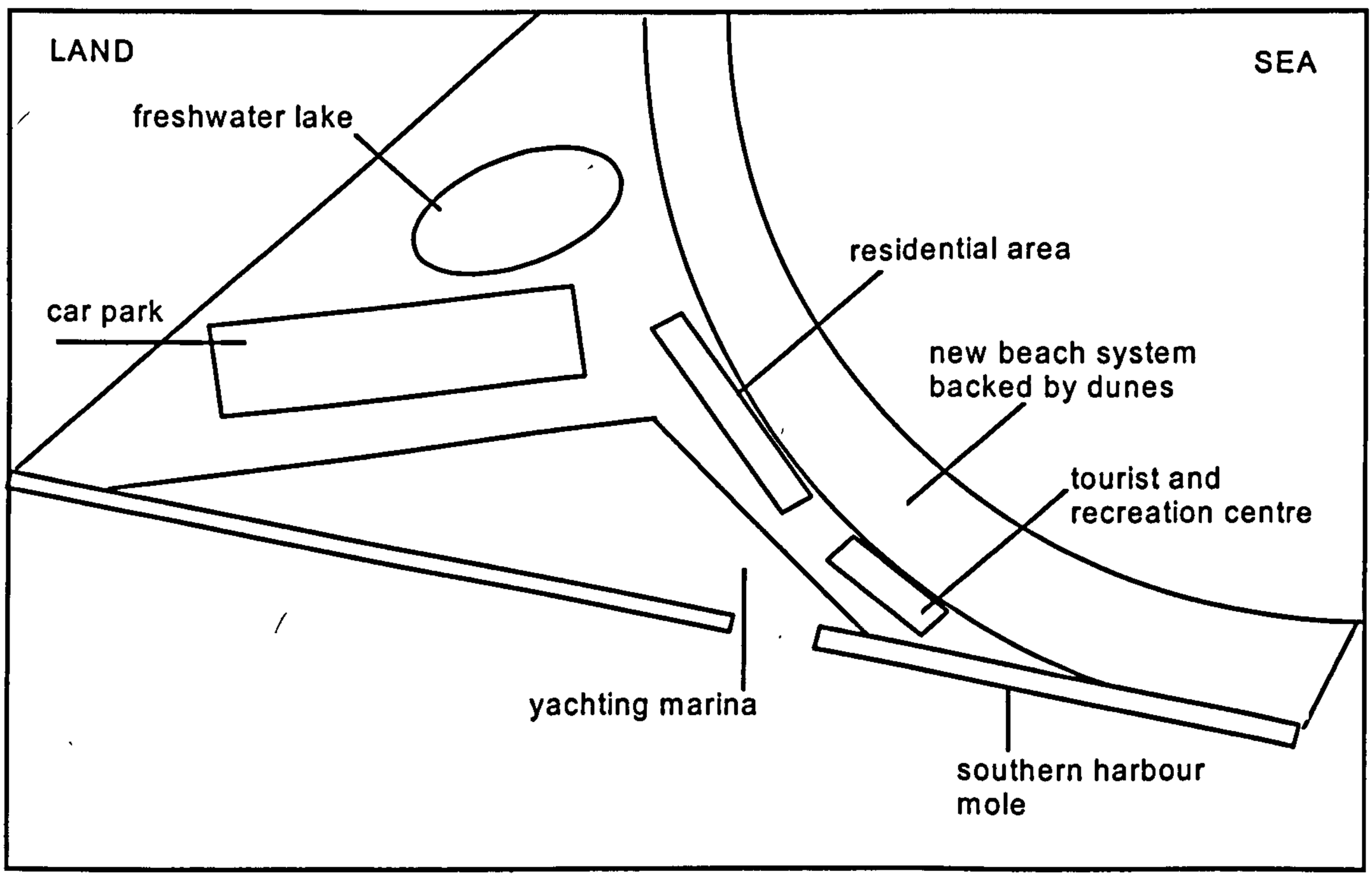


Figure 4.17. Schematisation of the recent plans to develop south of the IJmuiden harbour moles (taken from De Ruig, 1998).

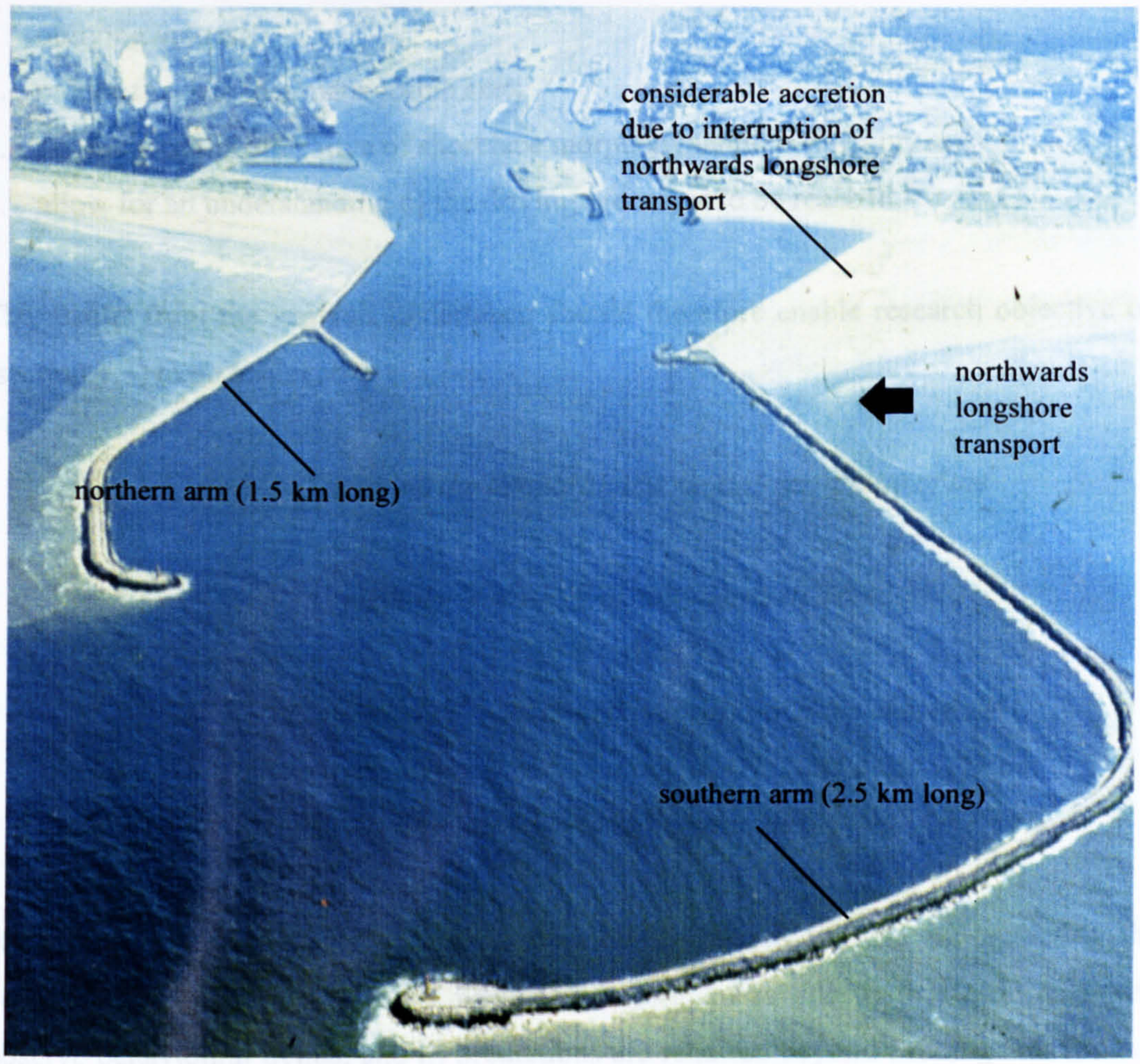


Plate 4.1. The IJmuiden harbour moles (km 55/56)

5) METHODOLOGY

5.1) INTRODUCTION

The JARKUS data set comprises a vast quantity of bathymetric data (Chapter 3) for example, at a minimum, one cross-shore profile will have a total of 960 values. Hence methods need to be selected which can :

1. adequately deal with the large quantity of data without producing results which are biased by outlying values;
2. reduce the data to a manageable size;
3. produce results indicative of shoreface morphodynamic behaviour; and
4. allow for an understanding of the driving processes to be reached.

The results from the analysis undertaken should therefore enable research objective one and two (section 1.3) to be achieved :

Determine the temporal and spatial variability of the morphodynamic behaviour of the Holland shoreface, over the medium- and large-scales (years to decades).

Determine the causes and controls upon the shoreface morphodynamic behaviour along the Holland coast over the medium- and large-scales.

However, there also exists a need to develop techniques capable of predicting the observed behaviour. This need is greatest when i) a coastline has little bathymetric data with which to observe behavioural trends; and ii) predictions are required beyond existing data limits. Therefore this study also tests available techniques for the prediction of shoreface behaviour in order to meet research objective three (section 1.3):

Evaluate the ability of existing models to predict shoreface morphodynamic behaviour

In addition observed trends are projected beyond the data limit (32 years) i.e. from the large- to geological-scale so that the fourth research objective (section 1.3) can be met :

Examine how the shoreface behaviour may evolve beyond the data limit

This chapter describes and critically analyses all the methods used in this research. They are divided into two categories; i) observation techniques; and ii) predictive techniques.

5.2) OBSERVATION TECHNIQUES

5.2.1) INTRODUCTION

These techniques were primarily selected to identify depth of closure and so significant depth changes on the upper shoreface (Box 1.4; Figure 1.8). As preliminary results emerged, this research developed into a study of the entire shoreface (within the data limits) meaning that the techniques must also be successful in identifying middle and lower shoreface behaviour.

For the purpose of this study shoreface behaviour is defined within this study as either *active* or *inactive*. This categorisation of shoreface behaviour is dependent upon the change criterion selected e.g. if the bathymetric change from t_0 to t_1 was less than the selected change criterion, x, then the shoreface behaviour is inactive. The change criteria are selected according to the measurement accuracy, so whilst activity could be observed if using a smaller change criterion, it will could result from measurement error rather than actual bathymetric change .

Two methods have been selected to identify shoreface behaviour and are discussed in the following sections. (Further evaluation of these methods is given in Appendix 5.1). The analysis was performed for all available profiles over a range of temporal periods; 5, 10, 15, 20, 25, 28 and 32 years within the period 1965 to 1997.

5.2.2) STANDARD DEVIATION OF DEPTH CHANGE METHOD

The standard deviation of depth change, or sddc, method originated from the work of Kraus and Harikai (1983) who used it to identify the depth of closure at Oria Beach, Japan. It is a simple method particularly effective in dealing both with large data sets and removing bias from outlying

values. The effectiveness of the method increases as the number of profiles increase, reducing the error influence e.g. an sddc calculation over 20 years uses five sets of years (1965; 1970; 1975; 1980; 1985) whilst over 5 years two sets (1965; 1970) are used. In order to eliminate errors the maximum number of sddc values are calculated for each temporal period and the average taken in order to eliminate errors. This is illustrated in Table 5.1 which gives the combination of years used for each temporal period in order to produce the maximum number of sddc values. Hence errors which may be introduced through the use of a small number of years in one calculation (e.g. the period of 5 years) will be reduced through the calculating the mean of the maximum number of combinations of years (e.g. the period of 5 years has a maximum combination of 5 sets of years). Alternatively, errors which may be introduced by only using one combination of years (e.g. the period of 20 years has a maximum combination of 1 set of years) will be reduced by including a large number of years in one calculation (e.g. the period of 20 years has 5 sets of years in one calculation).

TEMPORAL PERIOD (yrs)	YEAR COMBINATION (Y.C.)	SDDC VALUE USED
5	1965-1970; 1970-1975; 1975-1980; 1980-1985; 1985-1990;	(Σ(Y.C.))/5
10	1965-1975; 1975-1985; 1970-1980; 1980-1990	(Σ(Y.C.))/4
15	1965-1980; 1970-1985; 1975-1990.	(Σ(Y.C.))/3
20	1965-1985; 1970-1990.	(Σ(Y.C.))/2
25	1965-1990.	(Σ(Y.C.))/1
28	1965-1993.	(Σ(Y.C.))/1
32	1965-1997.	(Σ(Y.C.))/1

Table 5.1. The combination of years used for each temporal period in order to produce the maximum number of sddc values. The final sddc value is calculated from the mean of the all the available sddc values (calculated from the combination of years above).

The sddc method is implemented by calculating the 'variation in the standard deviation of elevation ... as a function of the cross-shore distance for *x* number of profiles from the same alongshore location'. This is illustrated in Figure 5.1.

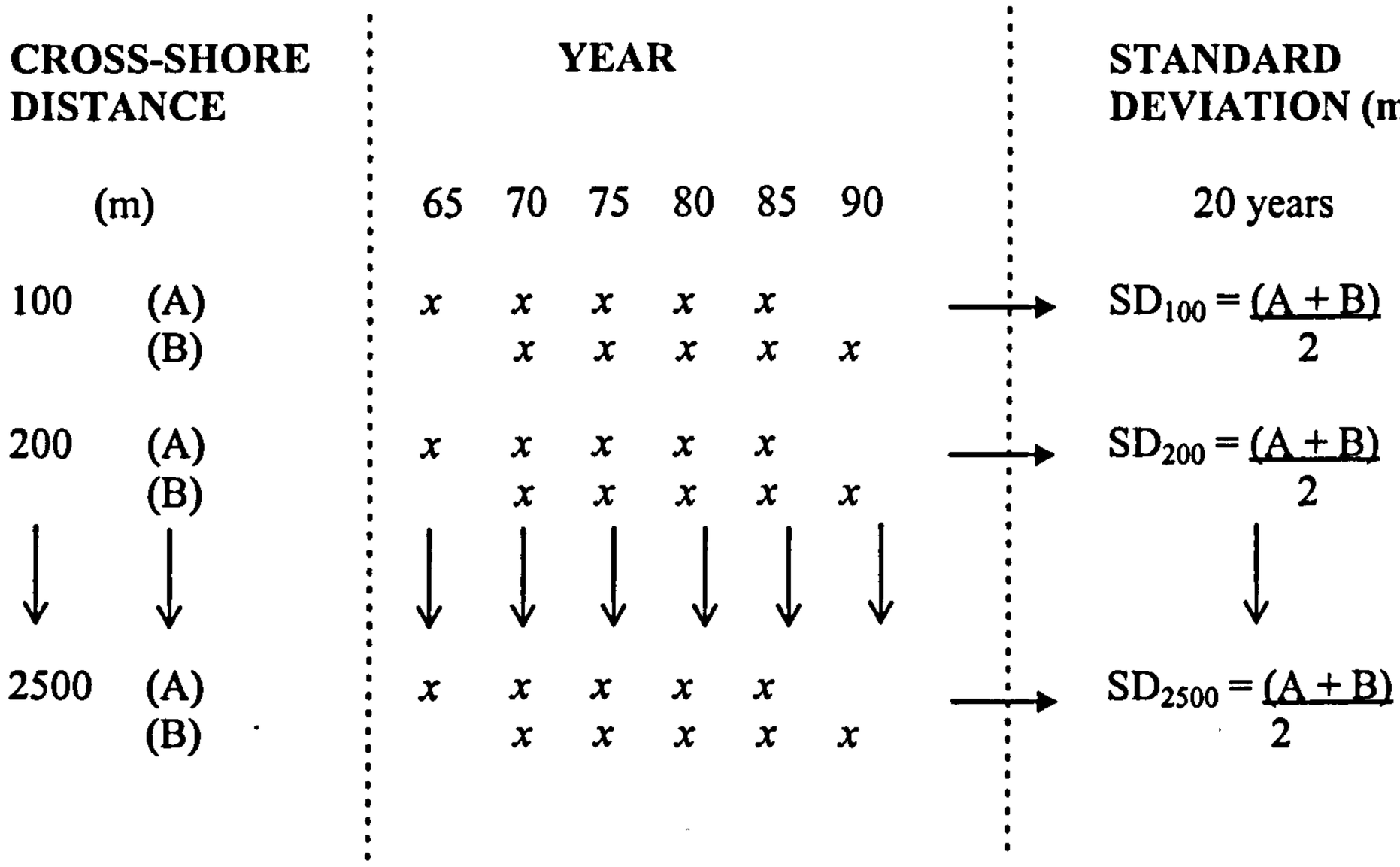


Figure 5.1. The principle of the sddc analysis. Sddc values are calculated from the appropriate years within the chosen temporal period, in this instance 20 years. They are calculated for each possible combination at each cross-shore location. The sddc value used to observe the shoreface behaviour is calculated form the mean of the combinations.

Once the sddc values were calculated, it then remained for the locations of 'activity' and 'inactivity' to be identified. This was performed by plotting all sddc values in the cross-shore and then applying two identification techniques:

1. a *self-selecting, constant yet non-zero tail*, Figure 5.2a. When this tail is observed, it is concluded that the shoreface is inactive. However, the point at which the shoreface is observed to become inactive could be argued to be subjective and so a second method was used, as described below;

   a *fixed standard deviation value,* Figure 5.2b. Inactivity is identified when the standard deviation falls below a fixed value; in the example given a value of 0.25 m is used which represents a 66% confidence that a real change in the bathymetry has occurred. This takes the assumption that the data measurement errors are normally distributed with a standard deviation of 0.25 m (section 3.3). Two additional values have been used; 0.5 m and 0.75m which respectively represent a 95% and 99% confidence that a real bathymetric change has occurred. It is important that more than one criterion is used as it will ensure that a real bathymetric change is observed. However, the 0.75m cases were not investigated further after preliminary

analysis showed that in the majority of cases, even the active nearshore bar system would be considered inactive using this value (Figure 5.3).

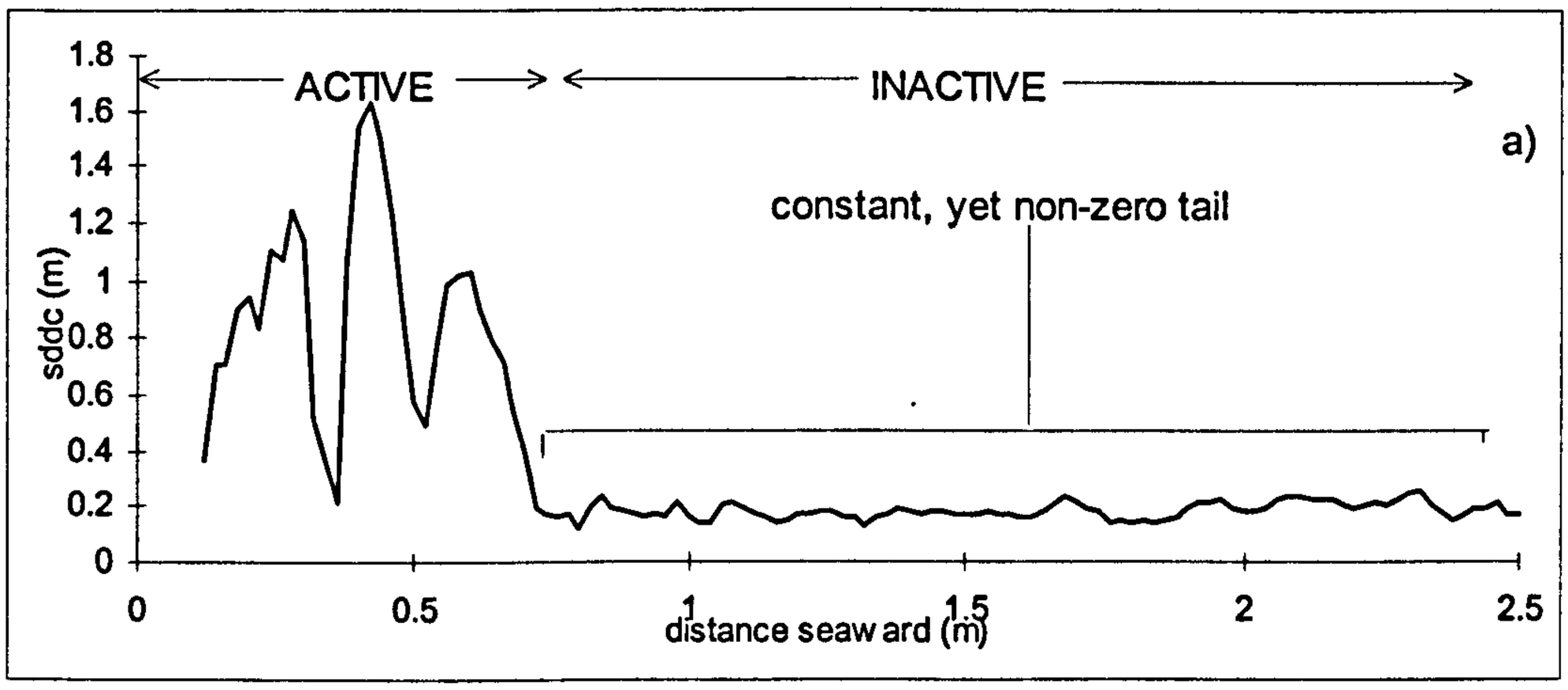


Figure 5.2. The two identification techniques used in conjunction with the sddc analysis are illustrated here using two examples of profiles along the Holland coast. a) is the self-selecting, constant yet non-zero tail and b) the fixed standard deviation value.

The observed variation in standard deviation in the nearshore zone mainly relate to bar morphodynamics whilst those further offshore equate to shoreface morphodynamics.

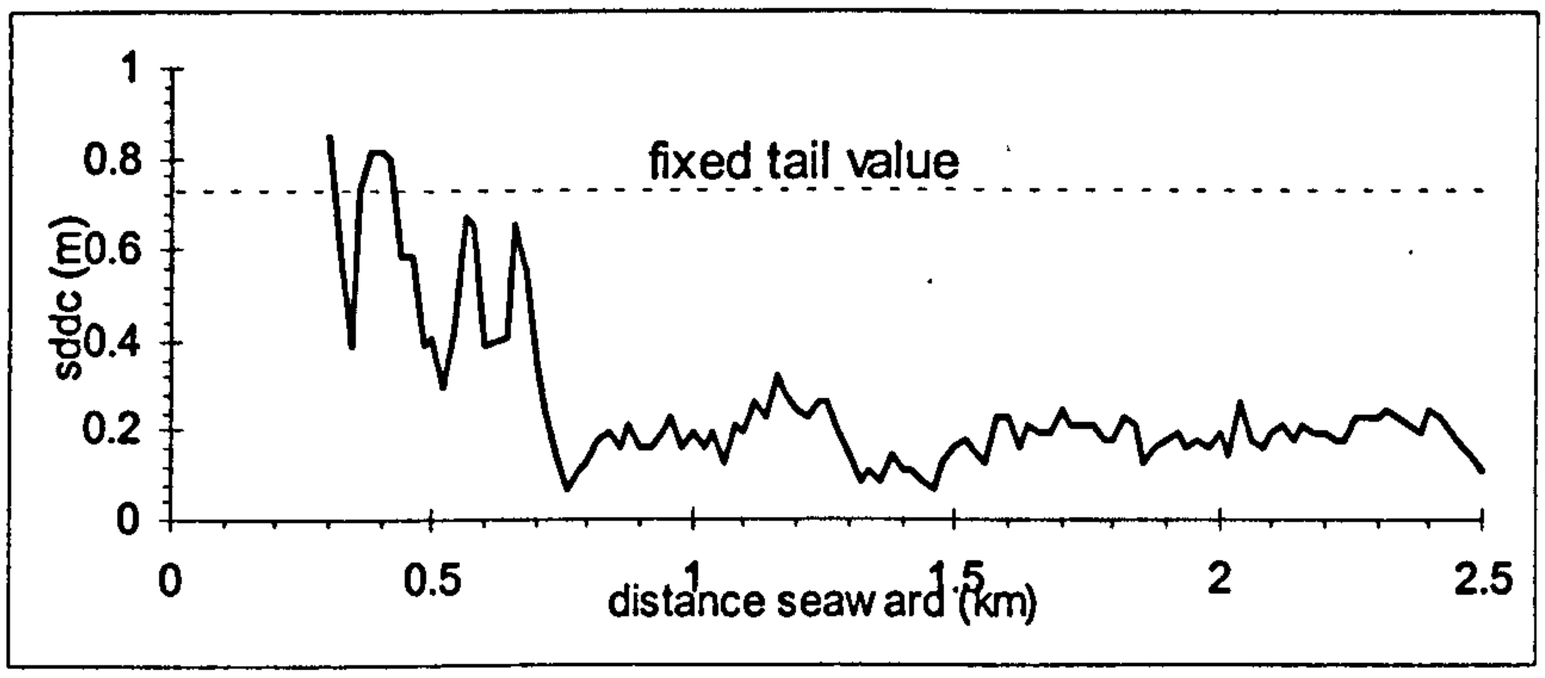


Figure 5.3. The use of the standard deviation fixed tail value 0.75 m results in the majority of profiles being defined as inactive.

5.2.3) FIXED DEPTH CHANGE METHOD

The fixed depth change, or fdc, method was originally used in studies to identify depth of closure (e.g. Nicholls *et al*, 1996). It was easily adopted in this study to identify shoreface activity/inactivity. Two profiles are taken from the same location, but different years, and when the depth variation between them is less than, or equal to, the selected criterion then the shoreface behaviour is classified as inactive. This is illustrated in Figure 5.4. The three change criterion of the sddc fixed standard deviation value were used here; 0.25 m; 0.5 m; and 0.75m (see Section 5.2.2).

Though this method has proved successful in identifying the shoreface behaviour, as shown through the comparison of the sddc and fdc results, it does have two major drawbacks. The first originates from the fact that it depends upon comparison between only two profiles; an error in one or both can result in an inaccurate classification of the profile behaviour. Although the impact of this error is reduced by using the maximum number of combinations of years for each temporal period, and then taking the mean, this problem cannot be entirely eradicated. The second drawback is that as this method is highly sensitive to the depth values of the two profiles, each combination may produce different depths which are active/inactive. This problem is overcome by classifying the behaviour based upon the activity of the majority of profiles.

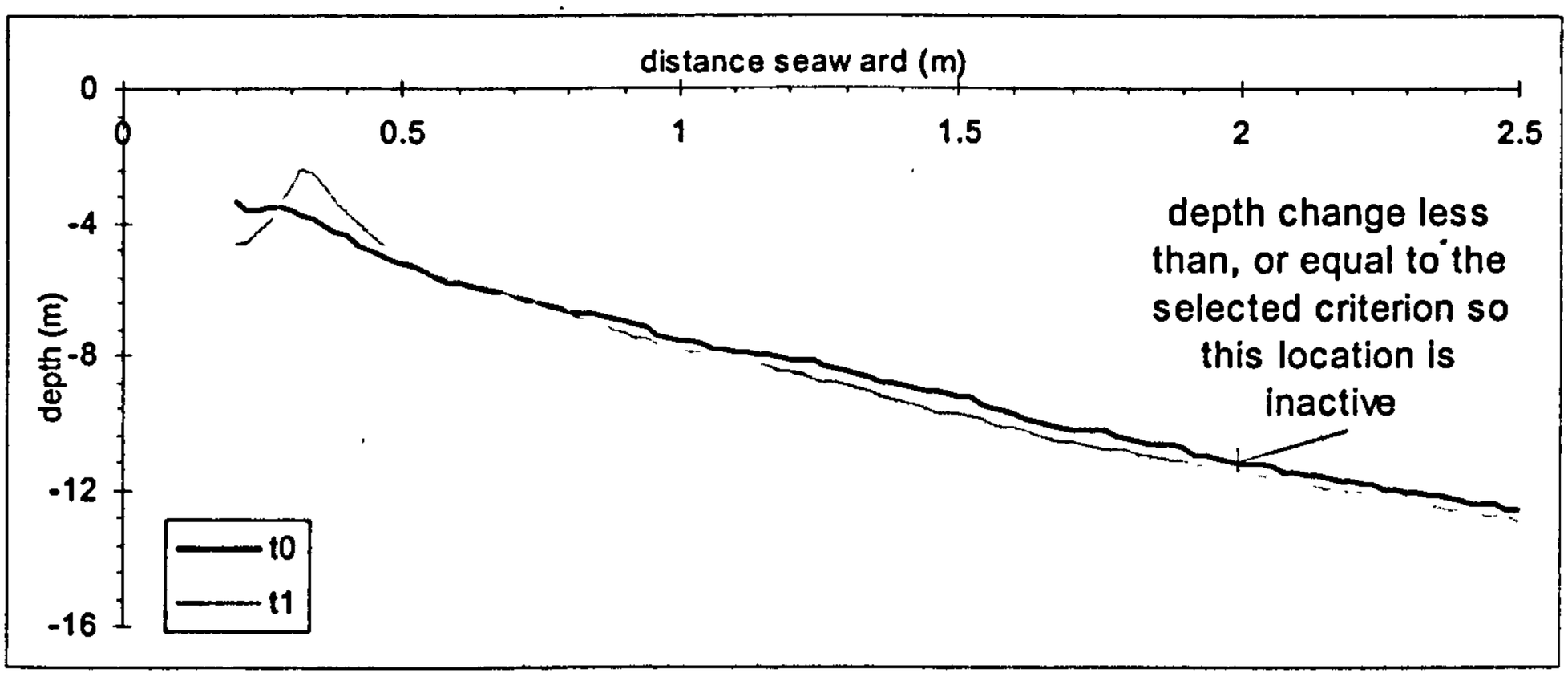


Figure 5.4. Example of the use of the fixed depth change method

5.3) PREDICTIVE METHODS

5.3.1) INTRODUCTION

The ability of two existing models designed to predict shoreface morphodynamic behaviour has been tested within this study. This has been done through the comparison of observed (as derived using the methods of Section 5.2) and calculated values of activity/inactivity. In addition the observed behaviour is projected beyond the data limits. The techniques used are discussed in the following sections.

5.3.2) HALLERMEIER (1981) MODEL

The analytical Hallermeier (1981) model is used to calculate one particular part of shoreface behaviour, the depth of closure. It was developed from a critical sediment entrainment factor in the form of a Froude number in order to calculate the maximum water depth for nearshore erosion by extreme wave conditions, or Dc. The development of this model is shown in Section 2.3.4 and it is the time-dependent form, Eq.2.6 which is used in this study.

The hydrodynamic input required for the model takes the form of i) the non-breaking significant wave height that is exceeded 12 hours per t years (100/730t)% of the time; and ii) the associated wave period. This data was taken from three hydrodynamic measurement stations off the Holland

coast; ELD; YM6; and MPN (see Section 4.3). Preliminary analysis using the routine of Westlake (1995) and the data of YM6 showed that it is not necessary to transform the data to a shallow water (near breaking) time series according to linear wave theory; Figure 5.5.

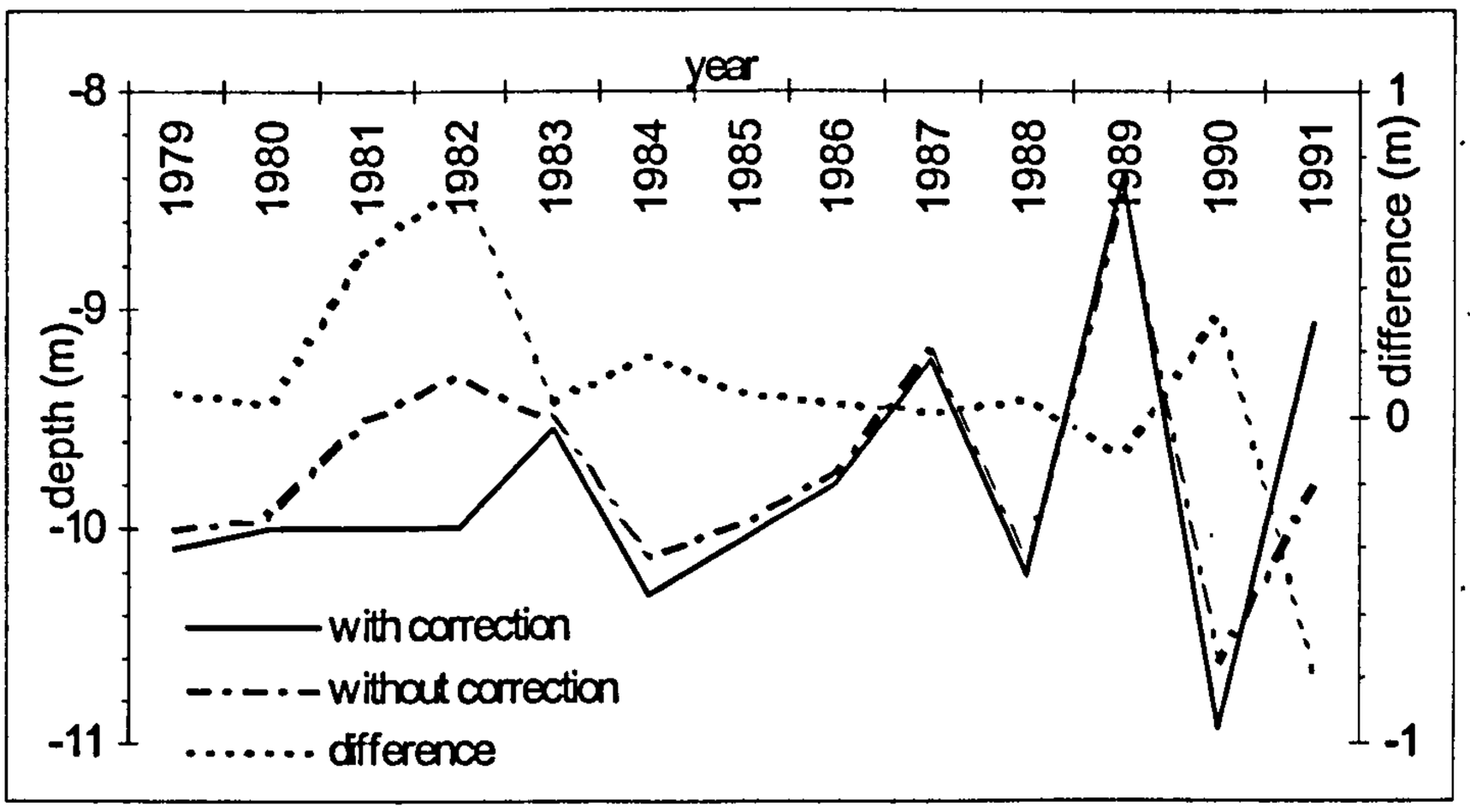


Figure 5.5. Comparison between the output of the Hallermeier (1977, 1978) model for two scenarios; with (solid line) and without (dot-dashed line) the shallow water correction for the annual period. It can be seen that there is little difference between the outputs (black line).

Calculations of Dc are made for three temporal periods; 1; 5; and 10 years. As with the sddc method, the maximum number of combinations possible are used for each temporal period and then the mean calculated; this is illustrated in Figure 5.6 which takes the example of the 10 year temporal period. $Dc_{1,5 \text{ and } 10}$ values were calculated for each of the three stations and then alongshore smoothing was performed. This produced a Dc value for each alongshore profile so allowing the observed value of Dc for each profile to be compared with a predicted value of Dc for the corresponding time period.

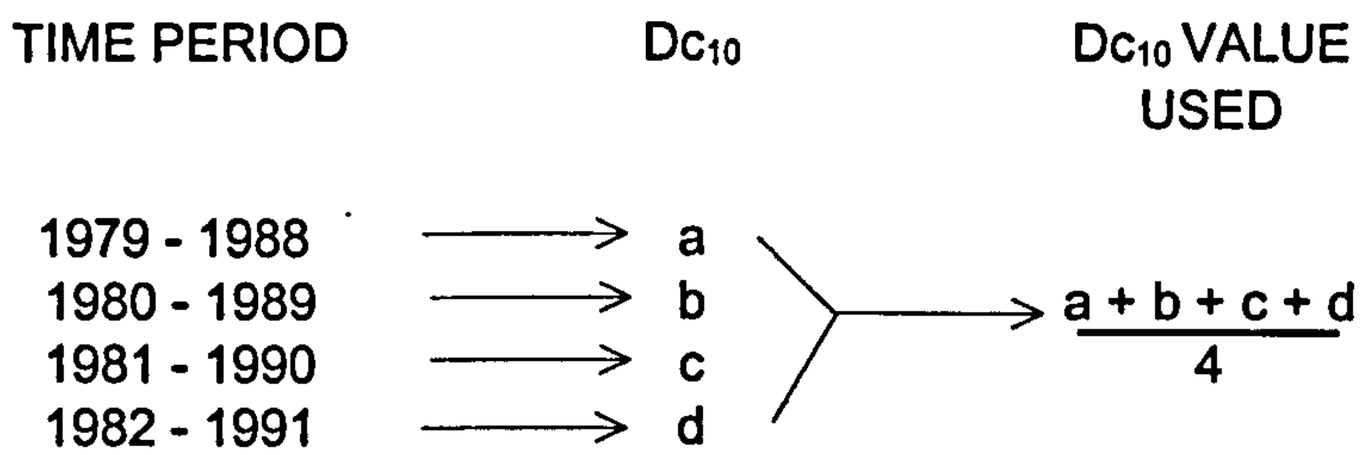


Figure 5.6. The method of calculation for the Hallermeier (1981) model. Values are calculated from the appropriate years within the chosen temporal period, in this instance 10 years. They are calculated for each possible combination. The Dc value used is then calculated from the mean of the combinations.

5.3.3) UNIBEST-TC MODEL

UNIBEST-TC is a process-based model capable of reproducing the short-term evolution of cross-shore profiles, from the shoreline to the offshore boundary. Examples of the integral parts of the evolution are bathymetric changes and sediment transport (both cross-shore and longshore). The model consists of five sub-models as shown in Figure 5.7 and summarised in Appendix 5.2.

The model's ability to predict the short- to large-scale evolution of a single (real) cross-shore profile was tested here through the comparison with the profile's observed evolution (as defined using the categories of 'activity' and 'inactivity'). The evolution of the selected profile (km 81; see later section) was performed for ten 10 year periods. The bathymetric output for 12 temporal periods (1 month; 0.5 year; 1 year; 1.5 years; 2 years; 2.5 years; 3 years; 3.5 years; 4 years; 5 years; 7.5 years; and 10 years) was taken and the sddc (fixed standard deviation value) analysis performed. However, as the runs were observed (through comparison with the JARKUS data) to incorrectly predict (as illustrated in Figure 5.8) the evolution of the middle and lower shoreface this analysis was only performed for the upper shoreface i.e. it was only used to identify the depth of closure. After performing the sddc analysis comparisons between the observed Dc and calculated Dc for periods greater than 1 year were made using both the annual and extended data sets. The results from the analysis for the periods less than 1 year were used as an indication of how Dc evolved from the short-scale.

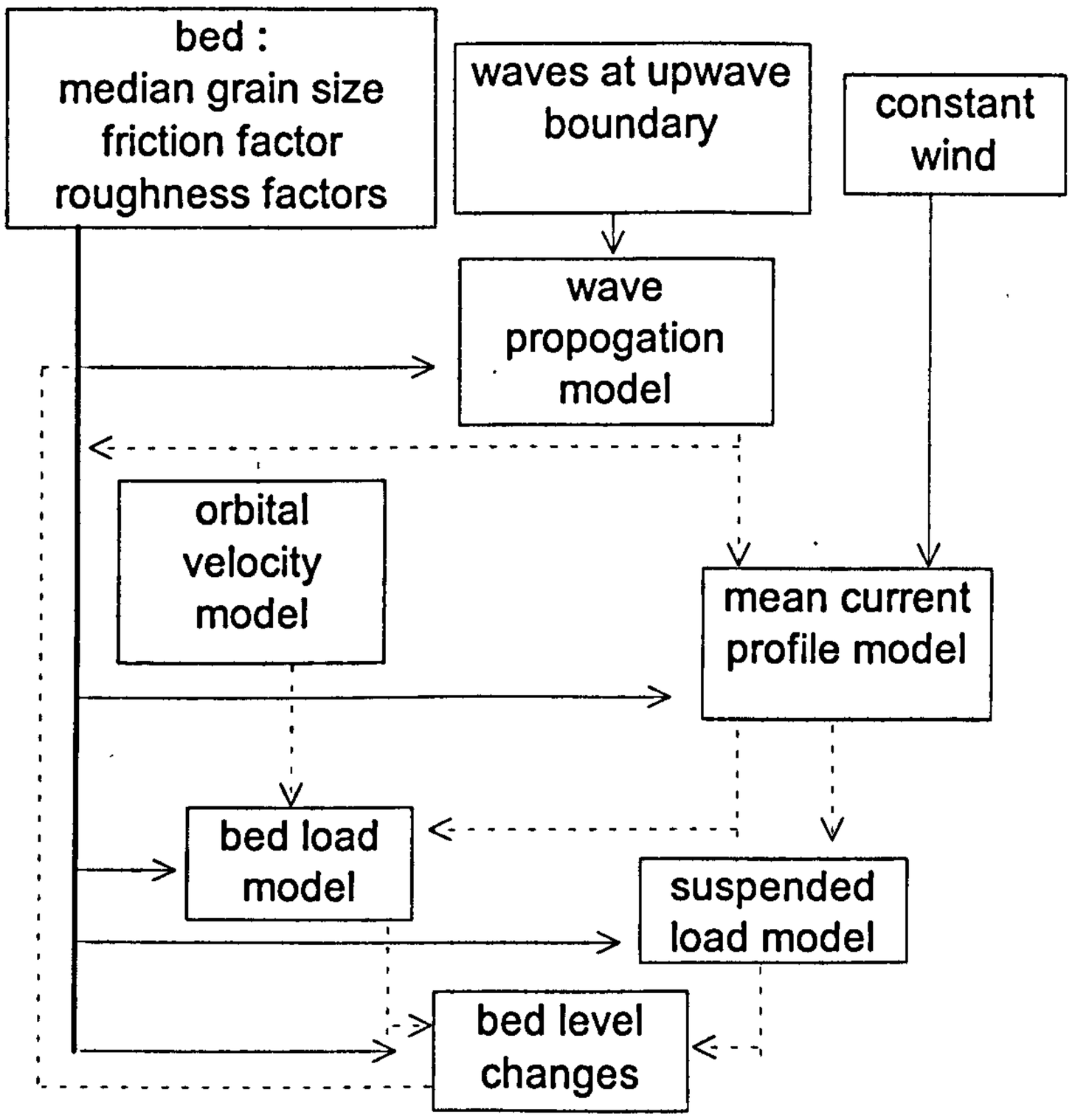


Figure 5.7. Overview of UNIBEST-TC sub-models (adopted from Bosboom *et al*, 1997)

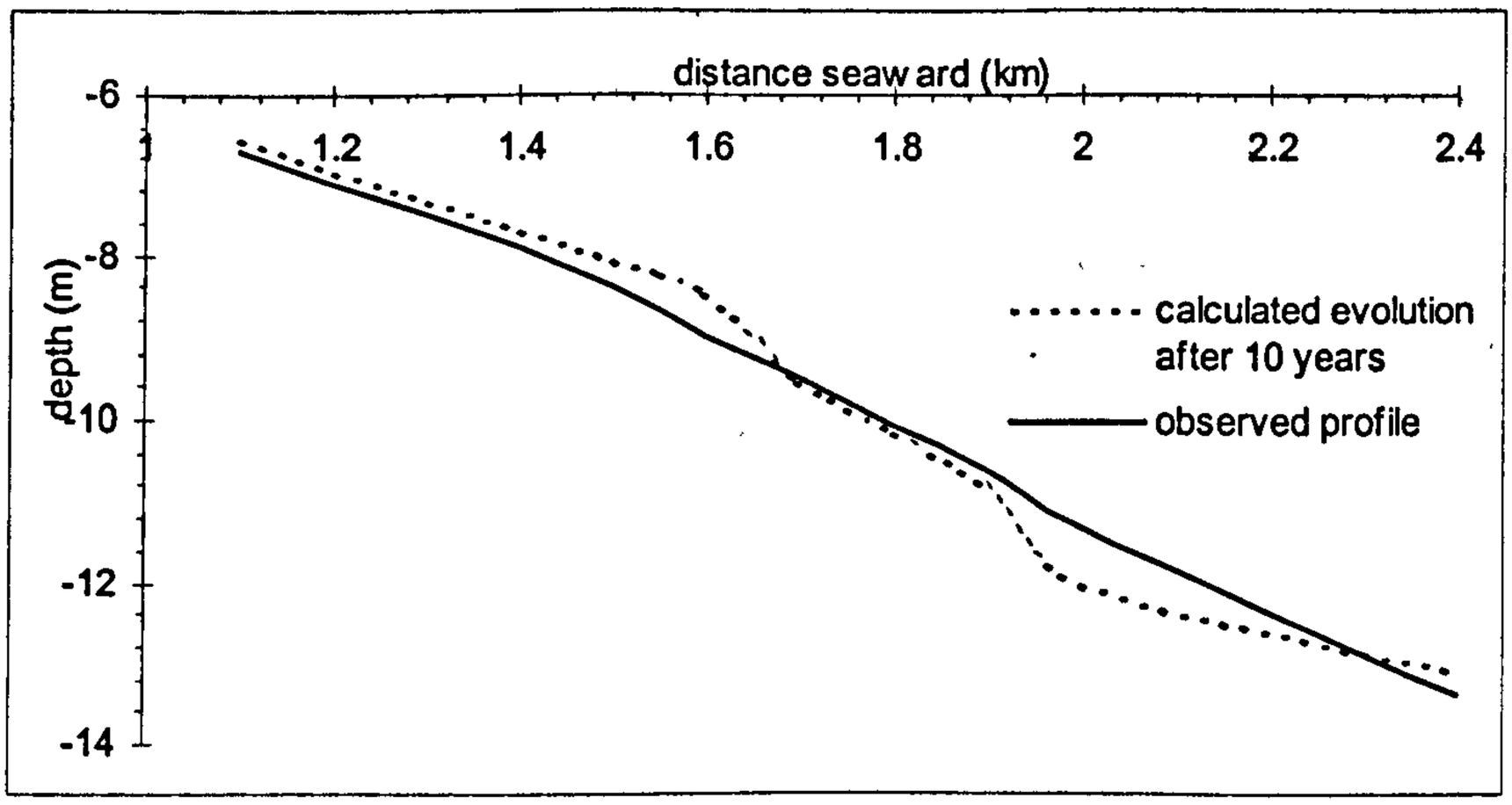


Figure 5.8. An example of the observed and calculated evolution of km 81, highlighting the disagreement between the evolution at the middle and lower shoreface.

UNIBEST-TC does have some limitations which must be considered before conclusions can be made. In addition it is important to note the model set-up and the calibrations performed. These are discussed below.

5.3.3.1) MODEL LIMITATIONS

The predictive abilities of models such as UNIBEST-TC over the long term remain relatively untested. Uncertainties exist regarding the quality of output if the model were to be run on the long term. This is the result of a lack of knowledge regarding coastal morphological development due to i) the strong non-linearity of the system; ii) the interaction between forcing at different scales; and iii) the interaction of forcing and internal dynamics of the system (see Section 2.2). In addition, process-based models designed on the short- and medium-term have a number of inherent errors. This is the result of the equations which make up the model being applicable on the short-term. Though insignificant on the time scales for which they have been designed, they become larger and more significant over the long-term. Projects, for example NICOP, are currently investigating the use of such models to predict long-term behaviour.

5.3.3.2) MODEL SET-UP: HYDRODYNAMIC INPUT

5.3.3.2.1)WAVE CLIMATE

A 12-year (1979 - 1991) wave climate (Roskam, 1988) was used derived from 3-hourly wave measurements taken from the wave station MPN (see section 4.3). Different time series were generated, taking in to account the frequency of occurrence of various wave height classes and directional sectors as observed from the Roskam climate. Consequently, the resulting realisations have the same statistical properties, even though the sequence of the wave conditions differs. The time series includes information not only on wave height and angle of incidence, but also on the associated wave period and storm surge level. Time series have only been calculated for wave angles within the incoming 180^{o} sector. When translating the deep water time series to the seaward boundary of the model (at 3.5 km offshore, equivalent to 15 m water depth), the effects of shoaling and refraction were taken into account.

5.3.3.2.2) TIDE

Tidal influences were not included in this study, although this exclusion is unrealistic in the 'real' world, their inclusion would have resulted in a proliferation of model runs. The expected morphological effects of ignoring the tide is a greater erosion close to the waterline and the formation of a steep berm (Southgate, 1995).

5.3.3.2.3) MODEL SET-UP: MORPHODYNAMIC INPUT

Profile km 81 was used. The model grid starts at -14.9 m (NAP) and continues to + 5 m (NAP). The horizontal grid spacing decreases towards the shore so that a higher resolution is reached in the active zone. This yields a total of 147 grid points.

5.3.3.2.4) MODEL CALIBRATION

The model has been calibrated in previous studies with emphasis placed on replicating nearshore behaviour (Reniers and Roelvink, 1995) through, for example comparison between predicted and observed behaviour. The default values within each of the sub-models have been derived from experiments at Terschelling, the Netherlands. For this investigation settings have been used which reproduce the characteristic 4 year cyclic bar behaviour observed at km 81 and reasonable morphologic changes across the shoreface.

In addition, a series of computations were made to determine what time step should be used in order to optimise both the accuracy of results and the computational time. Time steps tested were; 0.0625; 0.125; 0.25; 0.5; 1; 2 and 4 days. As the boundary conditions for these computations were sampled at 4 day intervals, chronology effects are absent and all differences attributed to numerical effects. As a result, a 1 day time step was selected for the long-term(10 years) runs.

5.3.4) EXTRAPOLATION BEYOND THE DATA LIMITS

Extrapolation has been used to extend the observations made of the shoreface morphodynamic behaviour beyond the 32 year limit of the JARKUS data set. Although this method is relatively simple it will enable orders of magnitude of shoreface evolution to be determined e.g. when closure exists on *x*% of profiles along the Holland coast.

The assumption taken here is that :

> the large-scale coastal behaviour over temporal periods greater than the 32 years will not deviate from the trends observed over periods less than, or equal to, the 32 years.

Potential violations of this assumption are :

1. variation in the future hydrodynamic climate. As introduced in Chapter 2, there are two schools of thought on this topic; one believes that evidence points towards an increased variation in the hydrodynamics, particularly in the form of storminess (e.g. Carter and Draper, 1988) whilst the other concludes that there is no such evidence (e.g. Houghton, 1991);
2. variation in sea-level rise. Current rates of sea-level rise for the Holland coast are i) at present 0.20 m per century; ii) expected 0.60 m per century; and iii) pessimistic 0.90 m per century (Louisse and Kirk, 1990);
3. declining sediment supply from shoreface. The reduction of this supply would suggest that the profile would be reaching equilibrium, although it is unlikely that this will occur as current evidence shows variability in forcings; a condition which must be removed if equilibrium is to be reached. Existing investigations show that the Holland shoreface acts as a sediment supply (e.g. Walstra *et al*, 1998), changes in the supply could result in changes in the morphodynamic behaviour of the shoreface (e.g. a decline would result in increased shoreface steepening). Under these circumstances the projections made within this chapter would become void; and
4. the occurrence of a future major anthropogenic influence. An example of such an anthropogenic influence is that of the 'Island-In-The-Sea', one of the options being researched as a new location for Schipol Airport.

5.4) SUMMARY

The methods discussed here, both for the observation and prediction of shoreface morphodynamic behaviour, have been successfully used in previous studies (e.g. Marsh *et al*, 1998). They are used in this research with a clear understanding of both positive and negative characteristics e.g. UNIBEST-TC was primarily developed for the short-term profile evolution.

6) OBSERVATIONS ON THE DECADAL BEHAVIOUR OF THE HOLLAND SHOREFACE

6.1) INTRODUCTION

This chapter analyses the observations of the shoreface morphodynamic behaviour of the Holland coast (Figure 6.1). It focuses upon research objective one (section 1.3) :

Determine the temporal and spatial variability of the morphodynamic behaviour of the Holland shoreface over the medium- and large-scales

by addressing the research questions below :

Can the depth of closure be identified on the shoreface? If so, what is the nature of its evolution through time and space?

Is the concept of the depth of closure meaningful to describe the morphodynamic behaviour of the shoreface?

Is the middle and lower shoreface a morphodynamically active region? Over what temporal and spatial scales, if any, can activity be observed? Is there a scale-dependency? What does the morphodynamic behaviour represent?

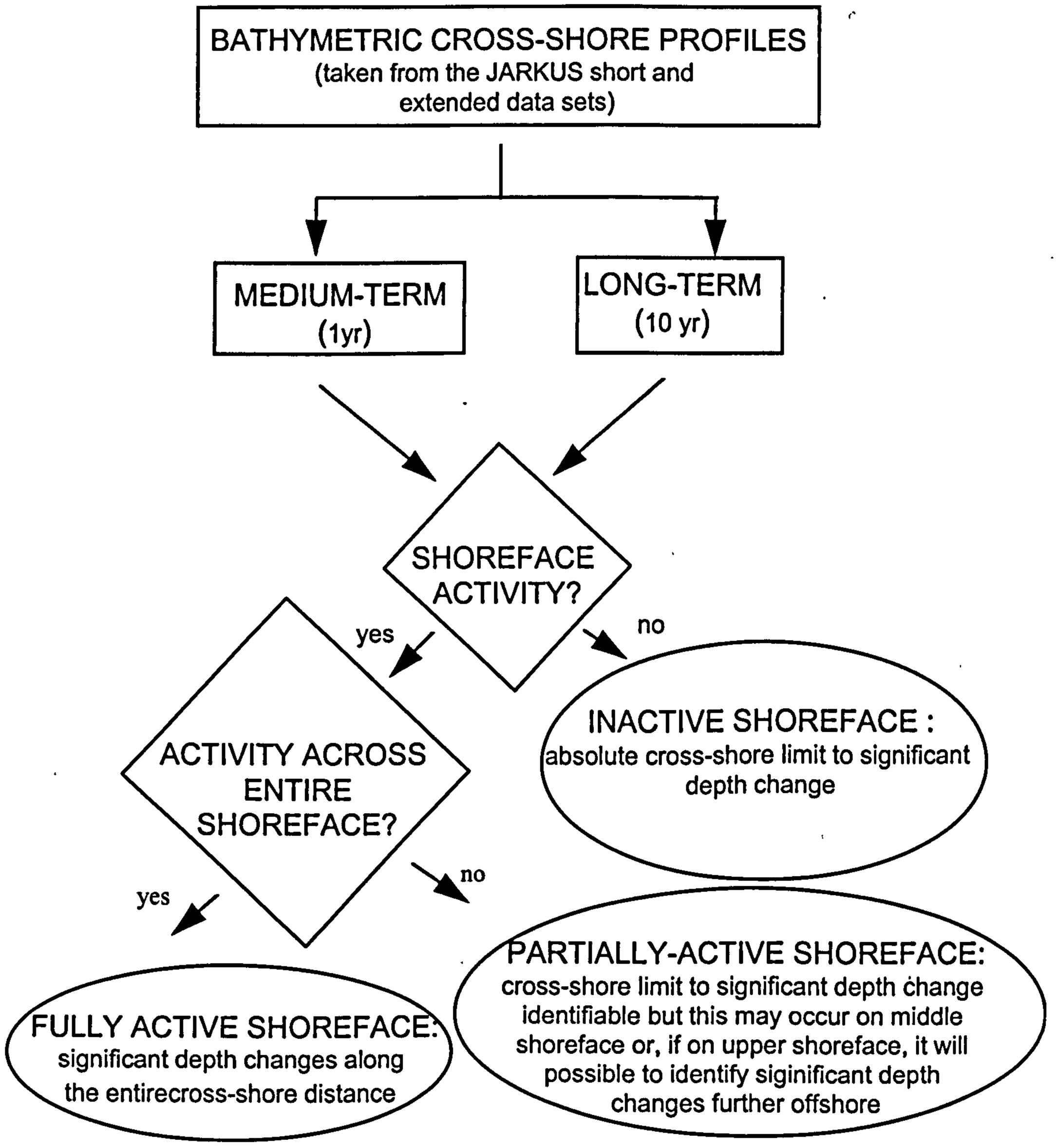


Figure 6.1. Flow diagram showing the data-orientated approach. Analysis of the JARKUS data set was carried out over the medium- and large-scales. The shoreface was observed to be either active (fully or partially) or inactive.

The analysis techniques used upon the JARKUS data set are such that the shoreface morphodynamic behaviour is defined as either 'active' or 'inactive' (Chapter 5). Previous work based upon the aggregation of bathymetric profiles (e.g. Nicholls *et al*, 1996; Garcia *et al*, 1998) suggests that there is a seaward limit to significant depth change, or activity (Dc) on the upper

shoreface over the small- and medium- scales (Chapter 2). The examination of this study's results clearly show that this is not the case; indeed over the 5 year period, a minimum of 85%[1] of profiles exhibit closure (see section 6.2.3 for further details). This is especially true over the long-term (Hinton *et al*, 1999). In some instances, not only does the profile 1) become inactive at some distance *x* from the shore on the upper shoreface, but then 2) becomes active, usually exhibiting 3) inactivity towards its seaward boundary. This behaviour can be seen most clearly using the sddc results as illustrated in Figure 6.2. These phenomena are hereafter classified as :

1. the *shoreward closure* (Dc_s). The limit to significant depth change, but not the absolute limit to cross-shore sediment transport, as located on the upper shoreface (in water depths of 8 m or less);
2. the *re-opening point* (Ro) and associated *re-opening zone*; the shoreward point of significant depth changes which occur on the middle/lower shoreface is known as the 're-opening point'. The cross-shore zone in which these changes can be observed is known as the re-opening zone; and
3. the *middle/lower shoreface closure* ($D_{cm/l}$). The seaward limit to the re-opening zone, observed within the data limits.

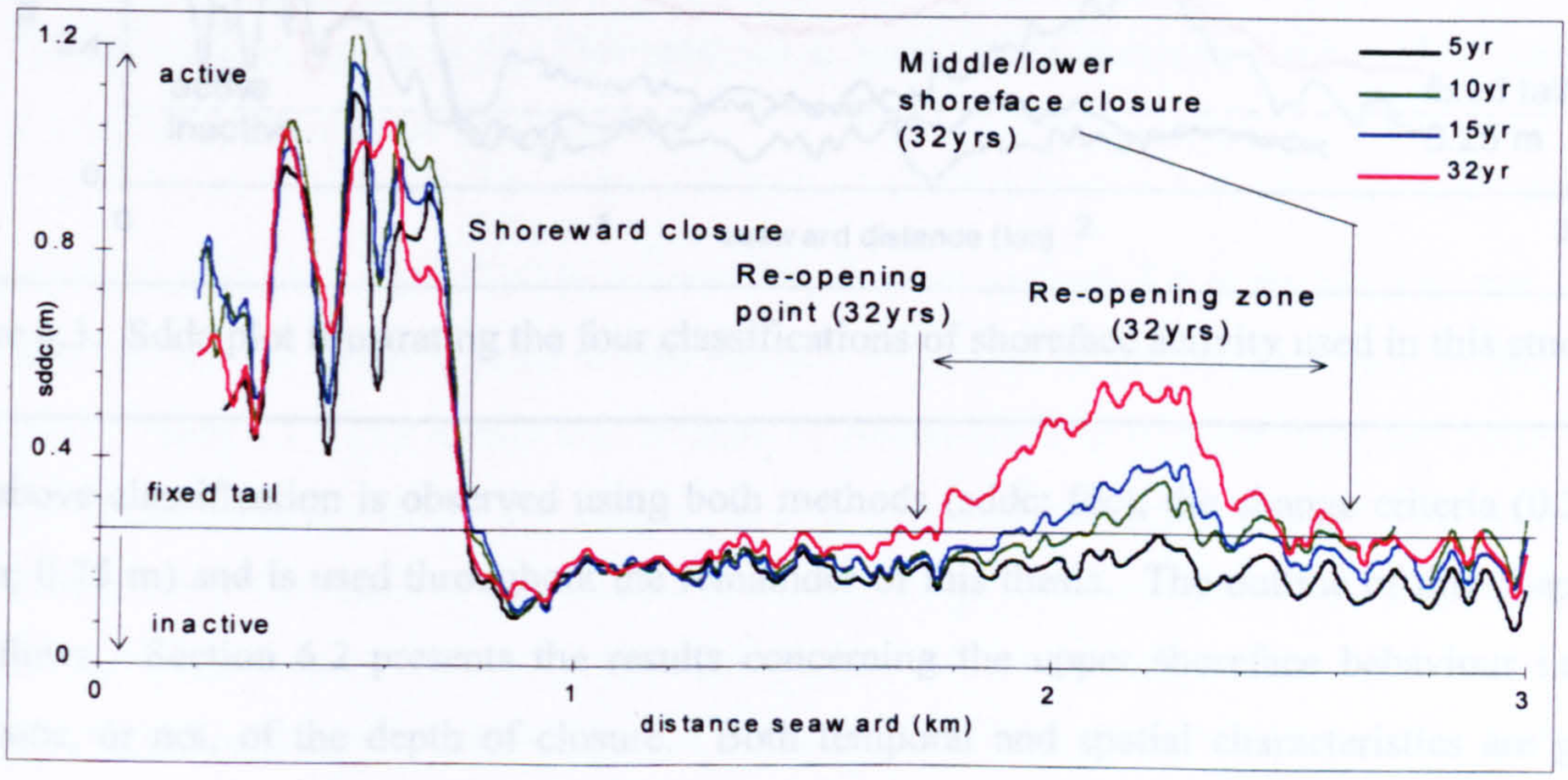


Figure 6.2. Standard deviation of depth change plot which clearly shows re-opening and the subsequent closure for time periods of 15 and 25 years (km 69).

[1] taking the sddc method, change criterion 0.25 m

The identification of the 're-opening zone' has led to the classification of four types of shoreface behaviour which are observed to exhibit both spatial and temporal patterns (as shown in Figure 6.3):

1. an *inactive shoreface*. No morphodynamic activity is observed seaward of Dc_s;
2. a *shoreward partially-active shoreface*. The shoreface is active until the middle/lower shoreface;
3. a *seaward partially-active shoreface*. The shoreface exhibits re-opening i.e. the profile must first exhibit a Dc_s in order to re-open and may exhibit closure towards the seaward limit of the profile; and
4. a *fully-active shoreface*. Morphodynamic activity occurs along the entire shoreface i.e. the profile does not exhibit a shoreward closure.

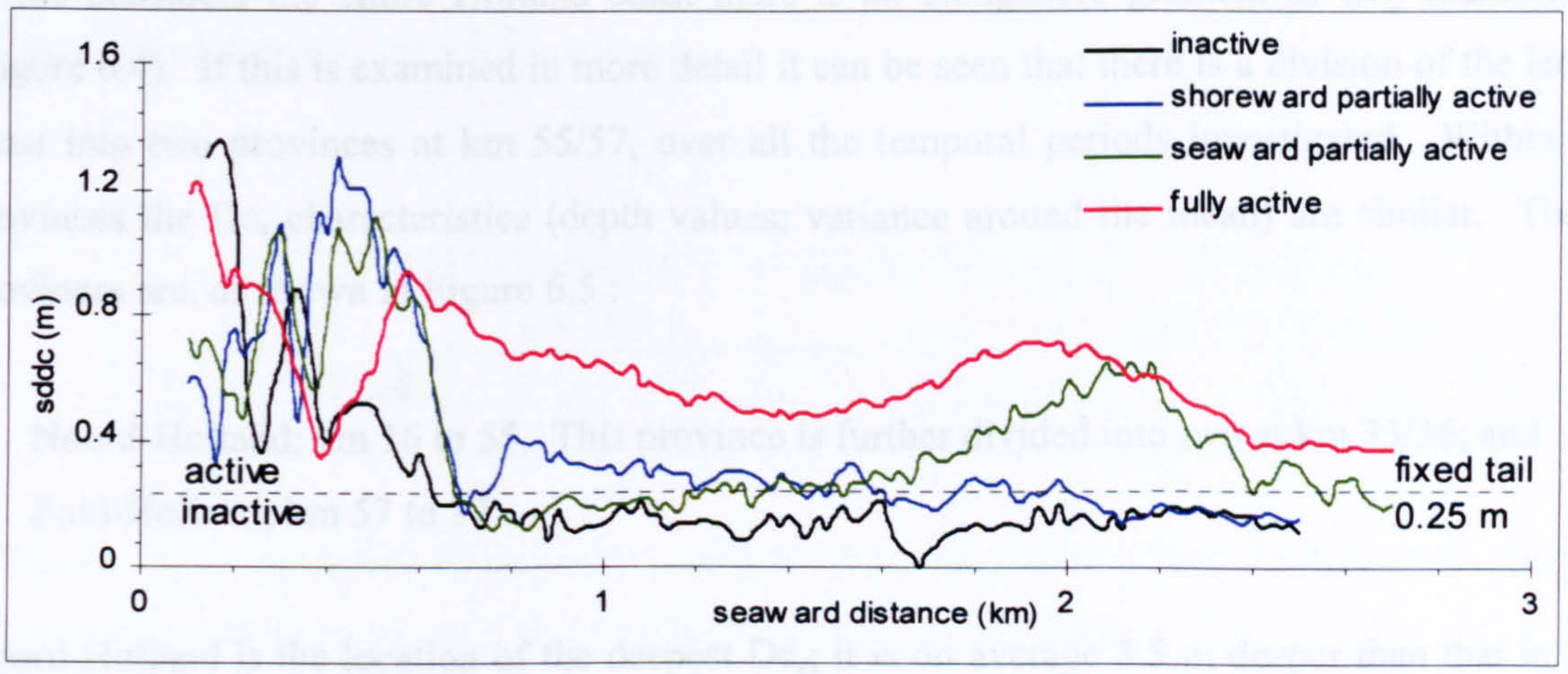


Figure 6.3. Sddc plot illustrating the four classifications of shoreface activity used in this study.

The above classification is observed using both methods (sddc; fdc), the change criteria (0.25 m; 0.5 m; 0.75 m) and is used throughout the remainder of this thesis. The outline of this chapter is as follows. Section 6.2 presents the results concerning the upper shoreface behaviour i.e. the existence, or not, of the depth of closure. Both temporal and spatial characteristics are given. Details are also given of the compatibility of the annual and extended sections of the data set. The spatial and temporal characteristics of the middle and lower shoreface behaviour are given in Section 6.3, including all four types of shoreface activity in addition to the seaward boundary of activity. The final section discusses all the results in the context of the research objective and questions given at the beginning of this chapter.

6.2) UPPER SHOREFACE BEHAVIOUR : DEPTH OF CLOSURE

6.2.1) INTRODUCTION

A depth of closure has been observed on the upper shoreface of the Holland coast. As already stated in Section 6.1, it is often preceded in the cross-shore by shoreface activity on the middle and/or lower shoreface and has therefore been re-classified as the 'shoreward depth of closure' (Dc_s). It is typically the only cross-shore phenomenon (of those stated in the previous section) that can be observed over short-temporal periods and the shoreface activity over longer temporal periods means that the Dc_s may not be observed. Spatial and temporal variations of Dc_s are apparent within the data set and are discussed in more detail in the following sections.

6.2.2) SPATIAL BEHAVIOUR

If one considers the entire Holland coast there is an alongshore gradient of Dc_s characteristics (Figure 6.4). If this is examined in more detail it can be seen that there is a division of the Holland coast into two provinces at km 55/57, over all the temporal periods investigated. Within these provinces the Dc_s characteristics (depth values; variance around the mean) are similar. The two provinces are, as shown in Figure 6.5 :

1. Noord-Holland; km 16 to 55. This province is further divided into two at km 35/36; and
2. Zuid-Holland; km 57 to 97.

Noord-Holland is the location of the deepest Dc_s; it is on average 3.5 m deeper than that in Zuid-Holland (indeed the deepest value within Holland is located in the northern sub-division of this province), Table 6.1. The further sub-division of Noord-Holland is based upon the occurrence of closure; although depth values are similar[2] to both the north and south of km 35/36, to the north there are fewer occurrences of this characteristic, Table 6.2. This indicates that the upper shoreface of the most northern part of the studied Holland coast is the most active. The shallowest values of Dc_s are located in the most southern part of the studied Holland coast (however the range of values within this province is not large). An additional difference between the two provinces is that of the variance of Dc_s; the greatest range of the shoreward closure is observed in Noord-Holland. These characteristics are quantified in Table 6.1 which clearly shows the differences between the two provinces.

[2] the difference in mean values (20 years) between the northern and southern province is 0.9m

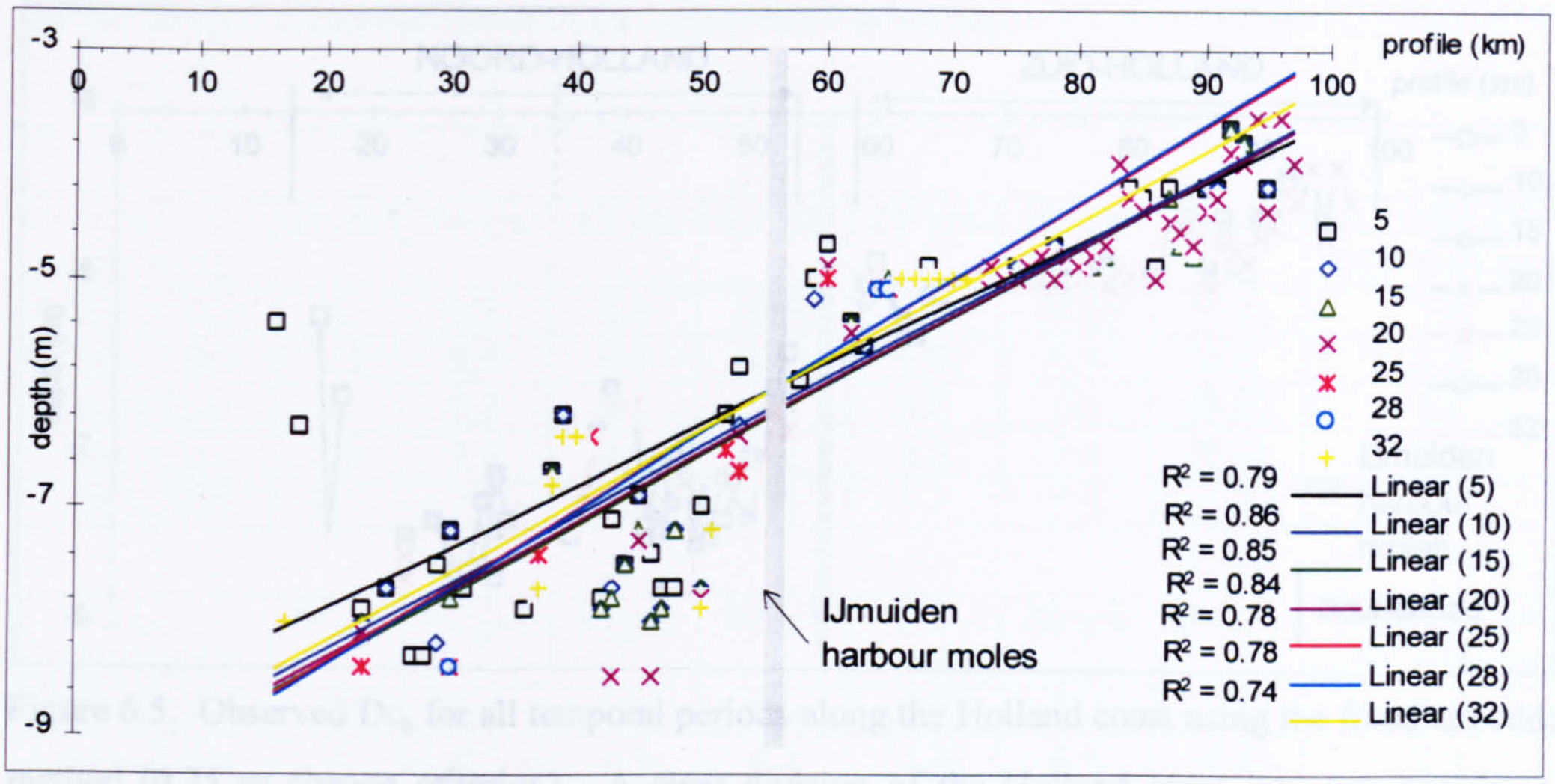


Figure 6.4. Linear trendlines for Dc_s values from each temporal period for the entire Holland coast; the longshore gradient is clear. The thick grey line represents the IJmuiden harbour moles and the division between the two provinces.

REGION NAME	REGION EXTENT	MEAN DEPTH (m)	STANDARD DEVIATION (m)
Noord-Holland	km 16 - 54	7.3	0.8
Zuid-Holland	km 57 - 97	4.9	0.4

Table 6.1. Characteristics of Dc_s over a 20 year temporal period within the two main provinces. These values are observed using the sddc method criterion of 0.25 m.

TEMPORAL PERIOD (yrs)	5	10	15	20	25	28	32
km 16 - 35/36	67	33	20	20	20	13	7
km 35/36 - 54	100	94	94	71	53	35	35
FACTOR	1.5	2.8	4.7	3.5	2.6	2.7	5.3

Table 6.2. Occurrence (%) of Dc_s in the two sub-provinces of Noord-Holland. It is clear that Dc_s is 'more common' in the southern sub-province. Note : factor represents the multiplication factor from the northern to southern sub-division. These values are observed using the sddc method criterion of 0.25 m.

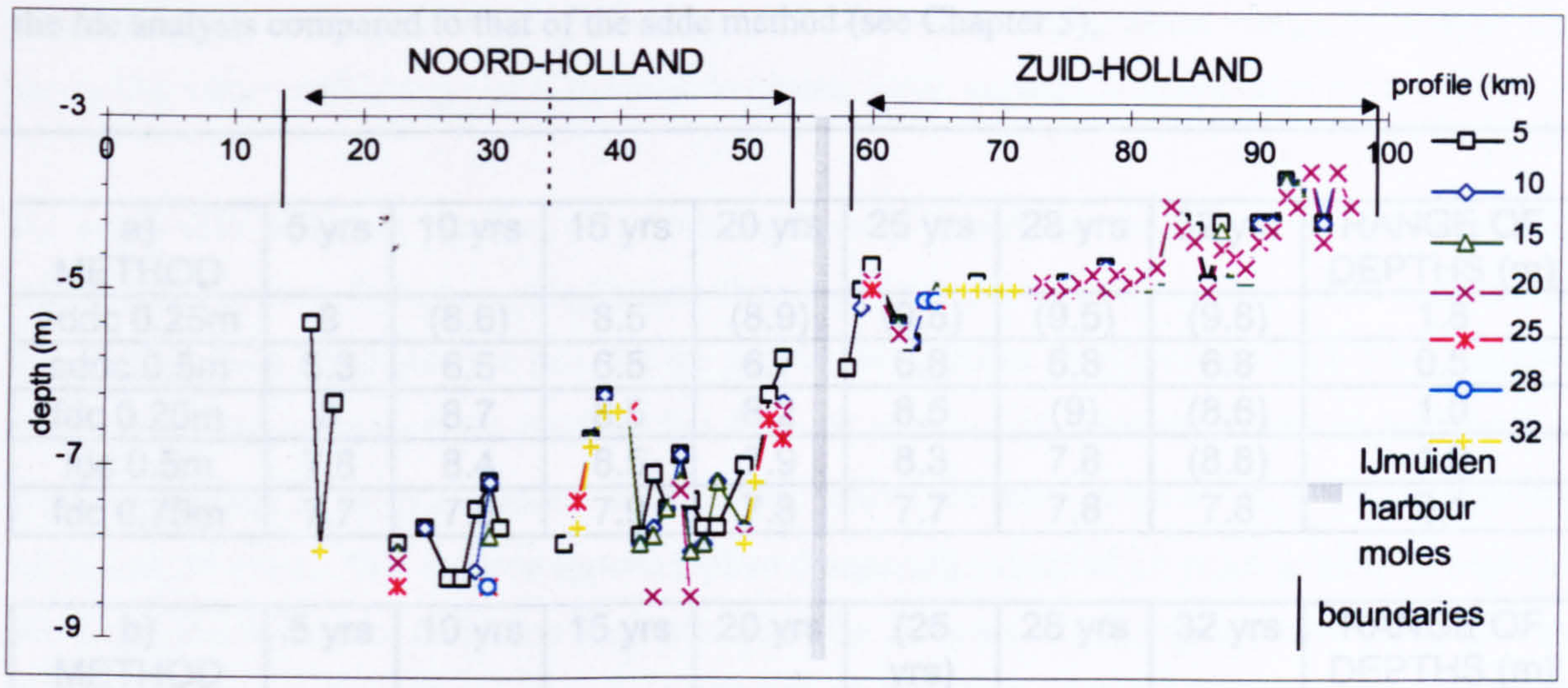


Figure 6.5. Observed Dc_s for all temporal periods along the Holland coast using the fixed tail sddc method (0.25 m change criterion). A clear division of the Holland coast into two provinces, Noord- and Zuid-Holland, can be seen; in the former province values are deeper and more varied than in the latter province. Dc_s also has a lower occurrence in this region. The dashed line shows the division of Noord-Holland into two sub-provinces based upon the occurrence of closure; km 16 to km 35/36 has a much smaller occurrence of Dc_s than in km 35/36 to km 55. The thick line represents the IJmuiden harbour moles and the division between the two provinces.

6.2.3) TEMPORAL BEHAVIOUR

The temporal behaviour of Dc_s has been investigated through the examination of both its characteristics (i.e. depth values) and occurrence (as a percentage). The division of the Holland coast, as described in section 6.2.2, is supported by results concerning the temporal dependence of Dc_s. This dependence is now discussed in more detail.

6.2.3.1) CHARACTERISTICS DERIVED FROM THE EXTENDED DATA SET ($JARKUS_E$)

The value of Dc_s typically increases with an increasing temporal period, however deviations around this trend do occur as illustrated in Table 6.3. The significance of the overall temporal trend is a function of the technique used (Table 6.4); a strong temporal dependence of Dc_s is shown by the correlation values calculated from observations made using the sddc fixed tail method. However this trend is clearly less significant when using the results of the fdc technique.

The difference between the results of the two methods is a consequence of the greater sensitivity of the fdc analysis compared to that of the sddc method (see Chapter 5).

a) METHOD	5 yrs	10 yrs	15 yrs	20 yrs	25 yrs	28 yrs	32 yrs	RANGE OF DEPTHS (m)
sddc 0.25m	8	(8.6)	8.5	(8.9)	(9.5)	(9.5)	(9.8)	1.8
sddc 0.5m	6.3	6.5	6.5	6.7	6.8	6.8	6.8	0.5
fdc 0.25m	8	8.7	8.5	8.2	8.5	(9)	(8.6)	1.0
fdc 0.5m	7.8	8.4	8.5	7.9	8.3	7.8	(8.8)	1.0
fdc 0.75m	7.7	7.9	7.9	7.8	7.7	7.8	7.8	0.1

b) METHOD	5 yrs	10 yrs	15 yrs	20 yrs	(25 yrs)	28 yrs	32 yrs	RANGE OF DEPTHS (m)
sddc 0.25m	4.7	4.7	4.8	4.9	(6.8)	5.2	5.7	1.0
sddc 0.5m	4	4.1	4.1	4.2	(4.9)	4.4	4.6	0.6
fdc 0.25m	5.2	5.2	5.1	5.3	(5.7)	5.1	5.2	0.2
fdc 0.5m	5	5	5	5	(5.4)	4.9	5	0.1
fdc 0.75m	5.1	5.1	5.1	5.1	(5.2)	5	5.2	0.2

Table 6.3. Mean depths of the observed Dc_s within each of the two main provinces, using all methods. a) = Noord-Holland; b) = Zuid-Holland. It can be seen that the greatest depth increase occurs in Noord-Holland. Note that the sudden increase in values in Zuid-Holland after the 25 year period results from missing data for this period for profiles km 72 to 97.

REGION	SDDC : 0.25m	SDDC : 0.5m	FDC : 0.25m	FDC : 0.5m	FDC : 0.75m
Holland	0.80	0.87	0.44	0.42	0.68
Noord-Holland	0.97	0.96	0.56	0.31	0.10
Zuid-Holland	0.64	0.78	0.20	0.15	0.24

Table 6.4. Correlation coefficients at the 95 % confidence level between temporal period and observed mean Dc_s for all methods.

Although the correlation coefficients typically indicate a strong temporal dependence of Dc_s, the actual increase in depth over the 32 years is not that large. For example the mean values (derived using the fdc change criterion of 0.5 m) for Noord- and Zuid-Holland increase by 1 m and 0.1 m respectively (Table 6.3). This observation is best illustrated using gradients of the overall trendline of which the greatest, as shown in Table 6.5, is $-0.09myr^{-1}$. It is interesting to note that

the greatest gradients i.e. the largest temporal increases, are observed with the smallest change criterion. This is because the largest change criterion allows the greatest margin of change and hence Dc_s values will always be at the most landward point, regardless of temporal period.

As previously stated in Section 6.1, both methods give similar results of the observed Dc_s; differences between them are typically less than 1 m for each temporal period. This is shown in Figure 6.6 which highlights the fact that the profiles in southern Zuid-Holland have the shallowest Dc_s values; missing data from 1965 for km 72 to 97 means that calculations for the profiles over temporal periods 25 and 32 years are not possible. Hence the mean value of Dc_s is greater than that of 20 and 28 years. This is more apparent when comparing values of 25 years as after 32 years all the Dc_s values will have increased more than after the 28 years. The temporal trends also indicate similar behaviour of Dc_s for each method (Table 6.6). Depths and trends are generally of a lower value when a greater change criterion is used i.e. 0.75 m. The largest change criterion allows a greater margin of change and as a result the range of Dc_s values with increasing temporal period decreases. This conclusion is observed throughout the study and will not be highlighted further.

REGION	SDDC : 0.25 m	SDDC : 0.5 m	FDC : 0.25 m	FDC : 0.5 m	FDC : 0.75 m
Holland	-0.09	-0.03	-0.06	-0.04	-0.02
Noord-Holland	-0.07	-0.02	-0.02	-0.04	0
Zuid-Holland	-0.04	-0.02	0	0	0

Table 6.5. Gradients (myr^{-1}) of the trendlines fitted to values of mean Dc_s from 5 and 32 years. These illustrate that the temporal increase in Dc_s is not great.

TEMPORAL PERIOD (yrs)	SDDC : 0.25 m		SDDC : 0.5 m		FDC : 0.25 m		FDC : 0.5 m		FDC : 0.75 m	
	N	Z	N	Z	N	Z	N	Z	N	Z
5	8	4.7	6.3	4	8	5.2	7.8	5	7.7	5.1
32	9.8	5.7	6.8	4.6	8.6	5.2	8.8	5	7.8	5.2

Table 6.6. Mean depth values of Dc_s for the two provinces using both methods; fixed tail sddc (criteria 0.25m and 0.5 m) and fdc (criteria 0.25 m, 0.5 m and 0.75 m). Here N = Noord-Holland, Z= Zuid-Holland.

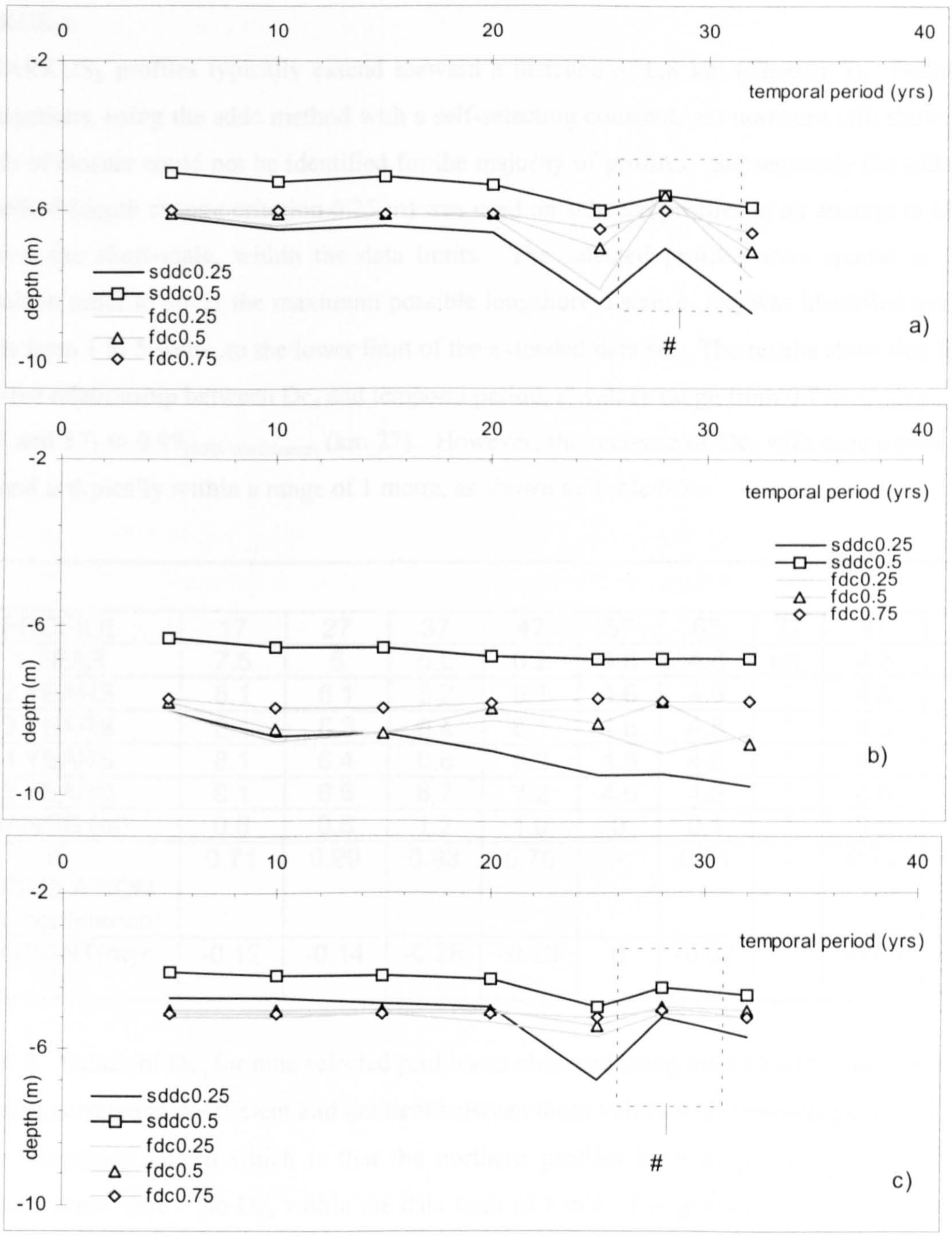


Figure 6.6. Mean values of the shoreward closure for each temporal period using both methods (sddc; fdc) and all criteria (0.25m; 0.5m; 0.75m). Mean values are shown for; a) km 16 to 97; b) km 16 to 55 (Noord-Holland); km 57 to 97 (Zuid-Holland).

- this sudden increase in Dc_s values is a consequence of the missing data from 1965 for km 72 to 97. Combined with the slightly (Table 6.1) shallower values (Figure 6.5) for these profiles the resulting mean values of Dc_s are deeper than those mean values which include km 72 to 97.

6.2.3.2) CHARACTERISTICS DERIVED FROM THE SHORT (ANNUAL) DATA SET ($JARKUS_S$)

The $JARKUS_S$ profiles typically extend seaward a distance of 0.8 km (Chapter 3). Preliminary investigations, using the sddc method with a self-selecting constant, yet non-zero tail, showed that a depth of closure could not be identified for the majority of profiles. Subsequently the sddc fixed tail method (depth change criterion 0.25 m) was used on selected profiles in an attempt to identify Dc_s over the short-scale, within the data limits. The selected profiles were spaced at 10 km intervals in order to cover the maximum possible longshore distance. Dc_s was identified over time periods from 1 to 5 years, to the lower limit of the extended data set. The results show that there is a positive relationship between Dc_s and temporal period; r^2 values range from $0.71_{(95\% \text{ confidence})}$ (km 17, 67 and 87) to $0.99_{(95\% \text{ confidence})}$ (km 27). However, the increase of Dc_s with time period is not great and is typically within a range of 1 metre, as shown in Table 6.7.

PROFILE	17	27	37	47	57	67	77	87	97
1 YEAR	7.5	6	5.5	6.2	4.6	4.8	n/c	4.3	3.2
2 YEARS	8.1	6.1	6.2	6.1	4.6	4.8	"	4.5	3.6
3 YEARS	8.1	6.3	6.4	6.1	4.6	4.8	"	4.5	3.7
4 YEARS	8.1	6.4	6.6	6.3	4.6	4.8	"	4.5	3.7
5 YEARS	8.1	6.6	6.7	7.2	4.6	4.9	"	4.5	3.8
RANGE (m)	0.6	0.6	1.2	1.0	0	0.1	"	0.2	0.6
r^2 CORRELATION (95% confidence)	0.71	0.99	0.93	0.75	-	0.71	-	0.71	0.88
GRADIENT(myr^{-1})	-0.12	-0.14	-0.28	-0.23	0	-0.02	-	-0.04	-0.13

Table 6.7. Values of Dc_s for nine selected profiles as observed using the $JARKUS_S$ data set and the associated correlation coefficient and gradient between these values with temporal period. There is a clear longshore pattern which is that the northern profiles have deeper Dcs values than the southern values. (n/c = no Dc_s within the data limit (5.1 m)). The gradient is calculated from the best fit linear trendline using all values.

The increase is especially small in Zuid-Holland and is so consistent with that observed over temporal periods greater than 5 years. The small temporal increase of Dc_s is supported by the gradients of the relationship which are typically no greater than -0.14 myr^{-1}. The gradients are greater than those calculated from observations of Dc_s from 5 to 32 years (Table 6.5). This

suggests that the increase in Dc_s is greatest during the smaller temporal periods i.e. the temporal relationship is non-linear (see Chapter 8).

These results also support the earlier observation (Figure 6.5) that there is a distinct longshore pattern of Dc_s; the Holland coast can be divided into two at km 55/56, so separating deeper, more variable values (Noord-Holland) from the shallower, more constant values (Zuid-Holland).

6.2.3.3) OCCURRENCE

The percentage occurrence of the shoreward closure was only calculated over the medium- and large-scales for profiles between km 16 to 71 due to missing data from 1965 for the profiles km 72 to 97. The missing data meant that calculations for the temporal periods 25 years and 32 years were not possible and would strongly influence final results. It was found that as the temporal period increases the percentage of profiles which exhibit a shoreward closure decreases (Table 6.8, Figure 6.7). This relationship is strongly significant at the 95 % confidence level for both methods (Table 6.9), although the relative significance decreases as the change criterion increases (see earlier sections). Note that those profiles which do not exhibit Dc_s over the medium-scales are mainly found in Noord-Holland.

METHOD	0 yrs	5 yrs	10 yrs	15 yrs	20 yrs	25 yrs	28 yrs	32 yrs
sddc 0.25m	100	85	73	71	60	46	33	30
sddc 0.5m	100	96	98	98	96	98	93	93
fdc 0.25 m	100	100	76	52	96	72	16	12
fdc 0.5m	100	100	96	96	100	96	68	35
fdc 0.75m	100	100	100	100	100	100	96	84

Table 6.8. Percentage occurrence of Dc_s for km 16 to 71 for each temporal period using all methods.

	sddc : 0.25m	sddc : 0.5m	fdc : 0.25m	fdc : 0.5m	fdc : 0.75m
CORRELATION COEFFICIENT (95% confidence)	0.93	0.55	0.79	0.73	0.64

Table 6.9. Correlation coefficients (r^2) for the exponential relationship between percentage occurrence of Dc_s and temporal period for km 16 to 71, using all methods.

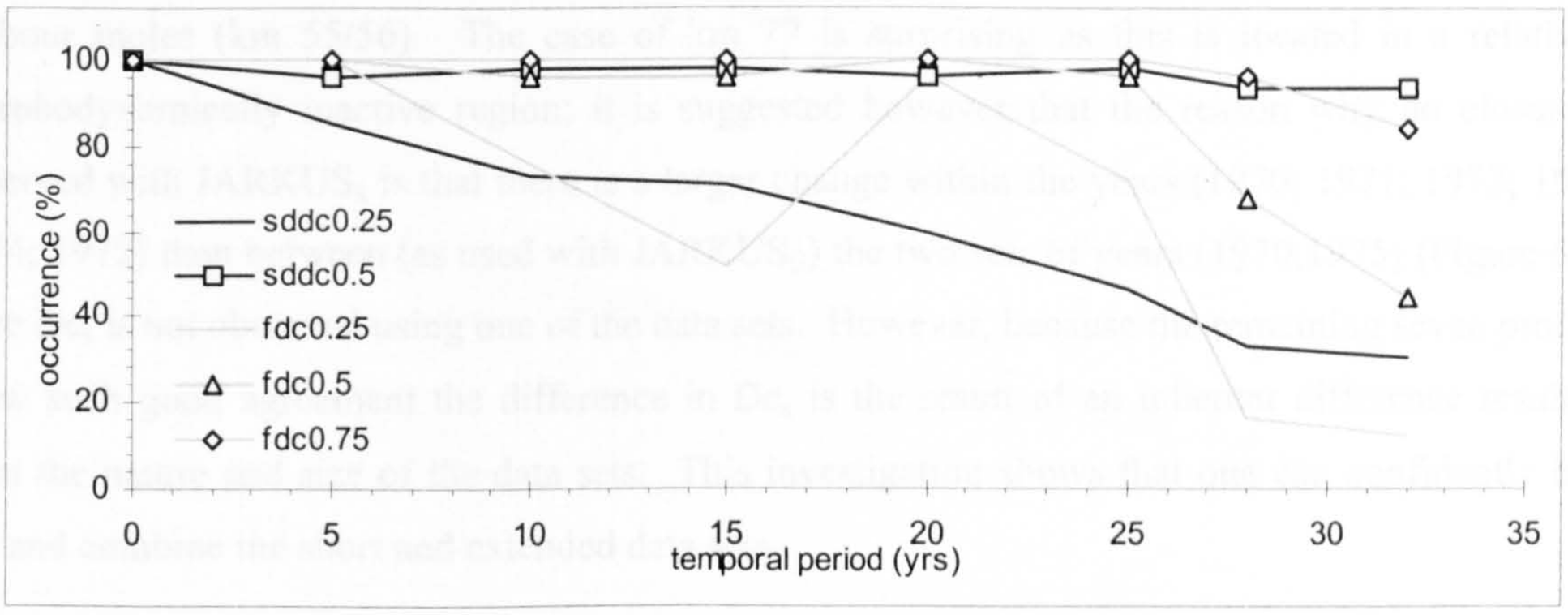


Figure 6.7. Percentage occurrence of the shoreward closure for each temporal period using both methods (sddc; fdc) and all criteria (0.25 m; 0.5 m; 0.75 m) between km 16 and 71. The fdc values can be seen to fluctuate more than the sddc. This is the result of the fdc's greater sensitivity to depth changes (see Chapter 5).

6.2.4) COMPARISON OF OBSERVED Dc_s USING THE SHORT ($JARKUS_S$) AND EXTENDED ($JARKUS_E$) DATA SETS

Section 6.2 discusses the results of the analysis of both $JARKUS_{S+E}$ regarding Dc_s characteristics. It is important that the Dc_s values observed from both data sets agree as not only will this provide reliance in the results presented but it will also add to the confidence in the accuracy of the annual and extended profiles; a large variation in the observed Dc_s would suggest that deviations in the bathymetric data exists between the two data sets, casting doubt on their reliability.

Hence a comparison has been made between the observed Dc_s values over a 5 year period from i) the annual JARKUS data set; and ii) the extended JARKUS data set. The Dc_s values were derived using the sddc fixed tail method (change criterion 0.25 m) and represent a 5 year running mean through the data from 1965 to 1997.

The results show (as illustrated in Table 6.10 and Appendix 6.1) that of those profiles which close within the data limits, 100 % of Dc_s values agree within 1 m. An additional observation is that the data sets of Zuid-Holland have a better agreement (Dc_s values agree within 0.3 m) than those in Noord-Holland (Dc_s values agree within 0.6 m). This suggests that, because the annual and extended profiles are not measured at the same time, Noord-Holland is more dynamic than Zuid-

Holland. Only two profiles, km 57 and 77, do not show agreement; it is suggested that in the case of the former (km 57) this results from the nature of the profile due to its proximity to the IJmuiden harbour moles (km 55/56). The case of km 77 is surprising as this is located in a relatively morphodynamically inactive region; it is suggested however that the reason why no closure is observed with JARKUS$_s$ is that there is a larger change within the years (1970; 1971; 1972; 1973; 1974; 1975) than between (as used with JARKUS$_E$) the two sets of years (1970;1975) (Figure 6.8). Here Dc_s is not observed using one of the data sets. However, because the remaining seven profiles show such good agreement the difference in Dc_s is the result of an inherent difference resulting from the nature and size of the data sets. This investigation shows that one can confidently both use and combine the short and extended data sets.

PROFILE	17	27	37	47	57	67	77	87	97
ANNUAL Dc_s (m) :									
sddc 0.25m	8.1	7.6	6.9	7.2	4.6	4.9	*n/c*	4.5	3.8
sddc 0.5m	7.5	6.0	5.7	6.3	2.9	4.7	*n/c*	4.4	3.3
EXTENDED Dc_s (m) :									
sddc 0.25m	8.0	8.3	7.4	7.7	*n/c*	5.0	4.8	4.2	4.0
sddc 0.5m	7.6	6.1	6.4	6.7	*n/a*	4.9	4.4	4.1	3.5
DIFFERENCE (m) :									
sddc 0.25m	0.1	0.6	0.5	0.5	-	0.1	-	0.3	0.2
sddc 0.5m	0.1	0.1	0.7	0.5	-	0.2	-	0.3	0.2

Table 6.10. Comparison between the Dc_s of nine selected profiles over a temporal period of 5 years, as observed from the short and extended JARKUS data sets. *n/c* = no closure observed within the data limits (km 57 = 11.1 m; km 77 = 5.1 m); *n/a* = no activity observed.

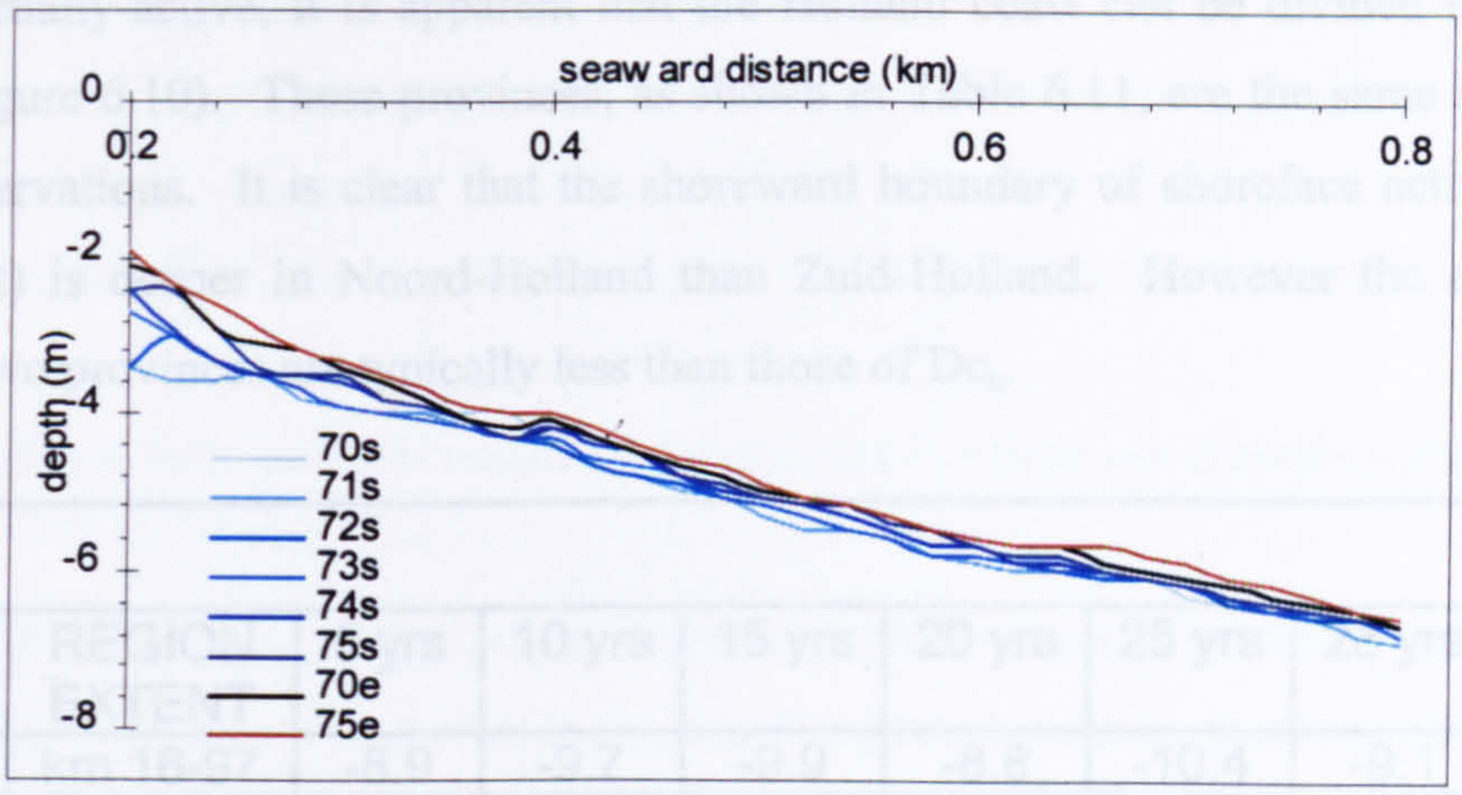


Figure 6.8. Examples of the measured profile km 77 for the years 1970 to 1975 using examples from both $JARKUS_{S+E}$. The change within the $JARKUS_E$ can be seen to be less than that of $JARKUS_S$. This indicates that the changes observed within $JARKUS_E$ cannot result from seasonal influences.

6.3) MIDDLE/LOWER SHOREFACE BEHAVIOUR : THE ACTIVE SHOREFACE?

6.3.1) INTRODUCTION

Middle/lower shoreface morphodynamic activity, first observed as a 're-opening zone', has been classified into four types. These are listed in Section 6.1 and illustrated in Figure 6.3. Spatial and temporal variations of the four types are observed mainly using the sddc fixed tail method (change criterion 0.25 m) rather than the fdc method (as the latter often proved too sensitive to depth values in the identification of change criteria (Chapter 5)). These are described in the following two sections.

6.3.2) SPATIAL BEHAVIOUR

Active shorefaces are concentrated within two main areas; km 16 to 29 and km 40 to 73. Additional profiles which exhibit activity are km 34 to 36 and km 79 to 81. Within the two main areas, fully-active profiles are located from km 24 to 29 and km 57 to 64. They are also found at km 80 to 81. The location of shoreface activity along the Holland coast is illustrated in Figure 6.9.

If one examines the shoreward boundary of activity (i.e. the 're-opening point') for those profiles which are partially-active, it is apparent that the Holland coast can be divided into two distinct provinces (Figure 6.10). These provinces, as shown in Table 6.11, are the same as those derived from Dc_s observations. It is clear that the shoreward boundary of shoreface activity (i.e. the re-opening point) is deeper in Noord-Holland than Zuid-Holland. However the depth difference between the two provinces are typically less than those of Dc_s.

REGION NAME	REGION EXTENT	5 yrs	10 yrs	15 yrs	20 yrs	25 yrs	28 yrs	32 yrs
HOLLAND	km 16-97	-8.9	-9.7	-9.9	-8.8	-10.4	-9.1	-8.9
NOORD-HOLLAND	km 16 -54	-10.5	-10.6	-11.3	-10	-10.5	-10.8	-9.8
ZUID-HOLLAND	km 57 - 97	-7.1	-9.3	-9.1	-8	-10.2	-8.4	-7.8

Table 6.11. Mean values of the re-opening point for the entire alongshore distance, Noord-Holland and Zuid-Holland using the fdc method (change criterion 0.5 m).

As the observed shoreface behaviour is dependent on both temporal and spatial scales, further details of the morphodynamic behaviour are given in the following section.

6.3.3) TEMPORAL BEHAVIOUR

Both partial and full shoreface activity is, as shown in Figure 6.9, predominately observed over the long-term (> 10 years). An alternative method of summarising the observations made concerning the shoreface evolution is as a transition matrix (Table 6.12a and b). Here the transition from each shoreface classification to each classification is given as a percentage of the entire Holland coast.

Two matrices have been calculated. The first is for km 16 to 71 in order to remove any influence from the 1965 missing data. The second is for km 16 to 97 where the assumption that, for km 72 to 97, the shoreface state of the period 25 years is as for 20 years and that of 32 years is as for 28 years is taken. The matrices shows that :

1. the dominant transition is to the same state as the previous temporal period e.g. from a fully-active state to a fully-active state;

2. the percentage of profiles which transform from a non-active state decreases with increasing temporal period i.e. the r^2 value for the relationship of profiles remaining inactive through time is equal to $-0.95_{(95\% \text{ confidence})}$;
3. the percentage of profiles transforming from an active state to either the same or different active state increases temporally; and
4. once a profile is fully-active it remains fully-active i.e. it does not change its state.

This shows that as the temporal periods increases then the percentage of profiles which are inactive decreases whilst those which are active increases. When the transition is summarised as the change to a different state regardless of temporal period, different relationships for the four classifications of profiles exhibiting shoreface activity are observed:

1. 12 % primarily remain non-active within the 32 years of observations;
2. 39 % primarily develop from the non-active to seaward partially-active shoreface. Of this 39 %, 37 % further develop into fully-active profiles;
3. 39% develop from a non-active shoreface to a shoreward partially-active shoreface. 16 % further develop into fully-active shorefaces; and
4. 10 % primarily develop from a non-active to fully-active shoreface.

It is therefore hypothesised that :

As the temporal period increases beyond 32 years, all profiles will evolve from exhibiting non-active to partially active shorefaces. Every profile will ultimately become fully active.

Although this hypothesis is supported by existing geological data, it is the timescales of change which remain unknown. These are investigated further in Chapter 8 through the projection of observed trends.

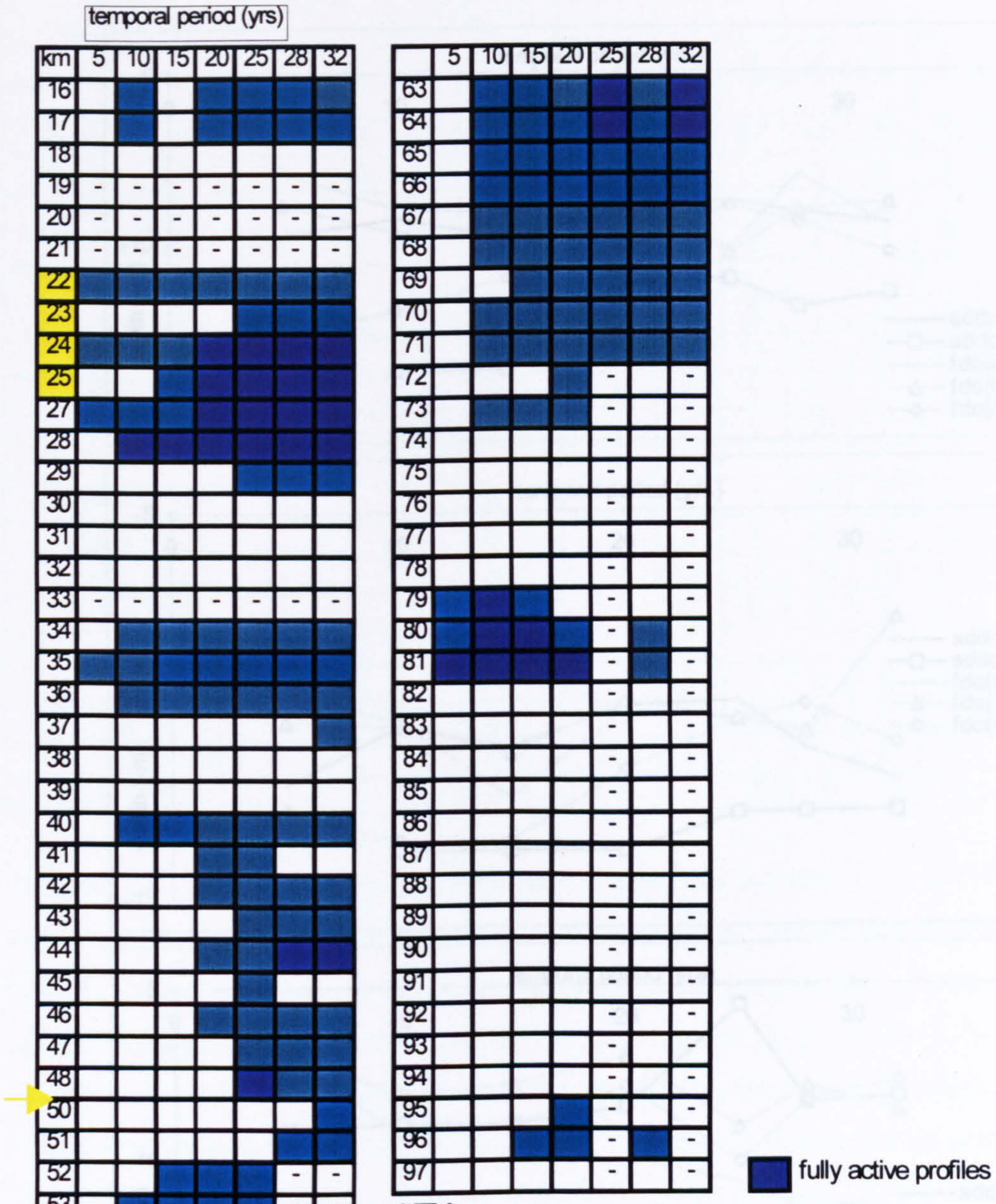


Figure 6.9. Spatial distribution of morphodynamic activity along the shoreface of the Holland coast for different temporal periods (1965 - 1997). Using the fixed tail sddc method (change criterion 0.25 m)

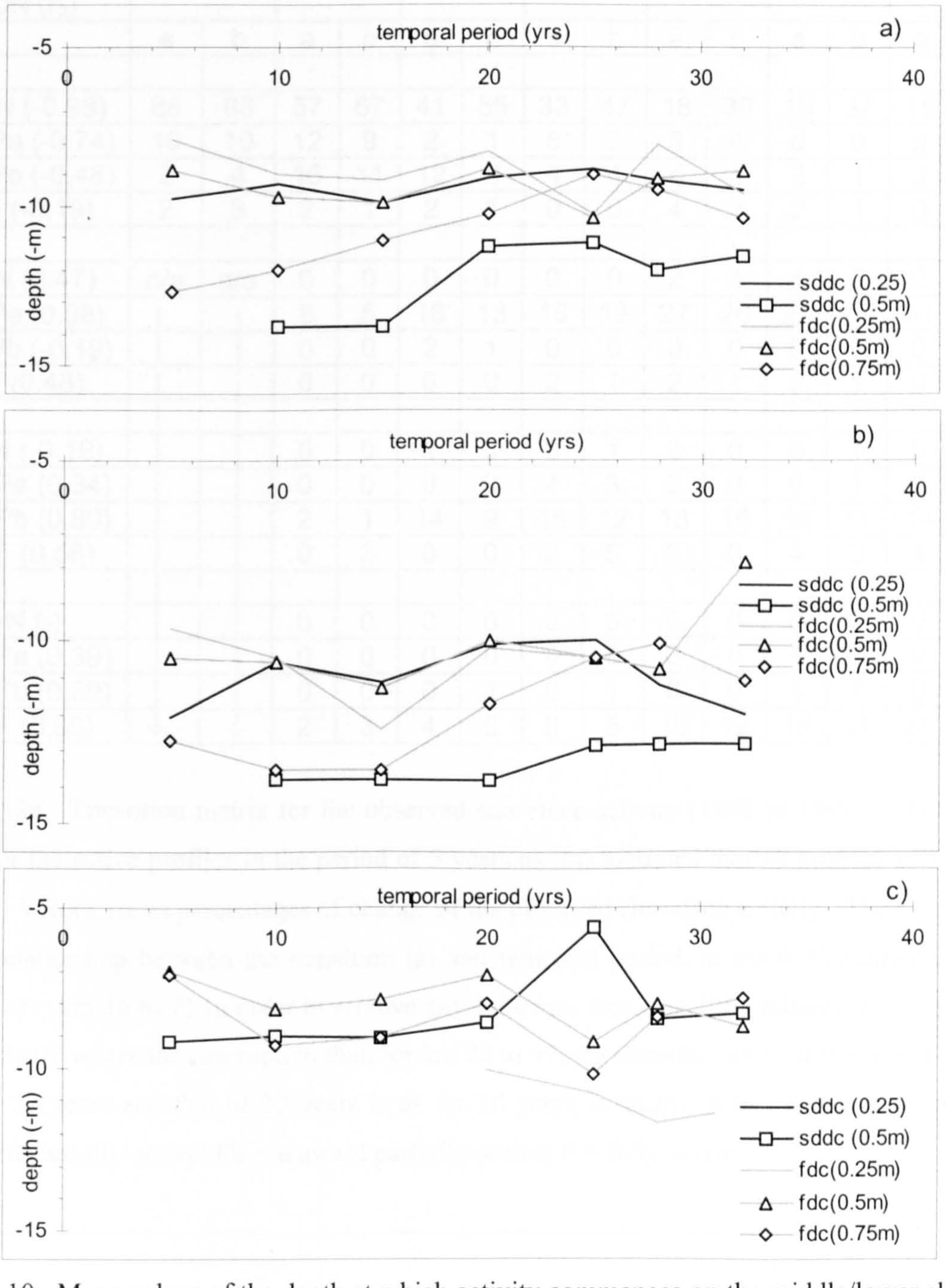


Figure 6.10. Mean values of the depth at which activity commences on the middle/lower shoreface (i.e. the 're-opening point) for each temporal period using both methods (sddc; fdc) and all criteria (0.25 m; 0.5 m; 0.75 m). Mean values are shown for : a) km 16 to 97; b) km 16 to 55 (Noord-Holland); and c) km 57 to 97 (Zuid-Holland).

TRANSI-TION (r_2)	5 yrs		10 yrs		15 yrs		20 yrs		25 yrs		28 yrs		32 yrs	
	a	b	a	b	a	b	a	b	a	b	a	b	a	b
N >N (-0.98)	88	88	57	67	41	55	33	47	18	39	16	37	16	41
>Pa (-0.74)	10	10	12	9	2	1	8	7	6	4	0	0	2	1
>Pb (-0.48)	2	4	16	11	12	9	4	4	4	3	2	1	2	1
>F (-0.19)	2	3	2	1	2	1	0	0	4	3	2	1	0	0
Pa>N (0.47)	n/a	n/a	0	0	0	0	0	0	2	1	4	5	0	0
>Pa (0.98)			8	5	18	13	18	13	27	20	27	17	31	23
>Pb (-0.19)			0	0	2	1	0	0	0	0	0	0	0	0
>F (0.48)			0	0	0	0	2	1	2	1	2	1	0	0
Pb >N (-0.19)			0	0	4	3	0	1	0	0	0	1	0	0
>Pa (0.34)			0	0	0	0	4	3	0	0	0	1	2	1
>Pb (0.80)			2	1	14	9	16	12	18	16	14	11	14	11
>F (0.58)			0	3	0	0	8	5	2	0	4	3	4	3
F>N (-)			0	0	0	0	0	0	0	0	0	0	0	0
>Pa (0.39)			0	0	0	0	0	0	0	0	4	3	0	0
>Pb (0.39)			0	0	0	1	0	1	0	0	4	7	0	0
>F (0.95)	↓	↓	2	3	4	5	6	5	16	12	16	11	24	16

Table 6.12a. Transition matrix for the observed shoreface activity (1965 to 1995). There are no values for the active profiles in the period of 5 years as it is assumed that all profiles at time 0 are inactive. Values are as percentages of change of the observed shoreface activity. The r^2 values are for the relationship between the transition (a) and temporal period, at the 95% confidence level. Column a) = km 16 to 71 in order to remove any influence from the 1965 missing data; column b) = km 16 to 97 where the assumption that, for km 72 to 97, the shoreface state of the period 25 years is as for 20 years and that of 32 years is as for 28 years is taken. Key : N = non-active; Pa = shoreward partially-active; Pb = seaward partially-active; F = fully-active.

FROM	N				Pa			
TO	N	Pa	Pb	F	N	Pa	Pb	F
Σ%	181	30	40	10	6	129	2	6
FROM	Pb				F			
TO	N	Pa	Pb	F	N	Pa	Pb	F
Σ%	4	6	78	18	0	0	4	68

Table 6.12b. Total percentage of cases taken from the transition matrix (Table 6.12a). The values represent the sum of all percentages within column (a) for each transformation over all years, excluding the 5 year temporal period. The greatest percentages is for transition to the same state. Key : N = non-active; Pa = shoreward partially-active; Pb = seaward partially-active; F = fully-active.

As stated in Section 6.2, km 72 to 97 are missing for 1965 and so observations can not be made for these profiles for the temporal periods of 25 and 32 years. This would influence final results, as demonstrated in Table 6.13. Table 6.14 therefore shows the percentage occurrence of shoreface activity through time (5 to 32 years) for km 16 to 71. The correlation coefficients for these relationships are strongly significant at the 95 % confidence level, hence showing that shoreface activity is temporally dependent :

1. $r^2 = 0.78_{(95\% \text{ confidence})}$ for the seaward-partially active shorefaces and time;
2. $r^2 = 0.93_{(95\% \text{ confidence})}$ for the shoreward-partially active shorefaces and time; and
3. $r^2 = 0.98_{(95\% \text{ confidence})}$ for the fully active shorefaces and time.

The occurrence of both shoreward and seaward partially-active shorefaces rapidly increases until the 20 year time period when the rate of increase then slows (Figure 6.11). However, the occurrence of fully-active shorefaces continually increases throughout the 32 years. This indicates that, as the temporal period increases beyond a critical point (20 years), the percentage of partially-active profiles reaches an almost constant value. The observed shoreface activity is the result of the profiles which first close on the upper shoreface (Dc_s) decreasing in occurrence whilst those profiles active across the whole shoreface continue to increase in occurrence.

TEMPORAL PERIOD (yrs)	% ALL
0	0
5	13
10	35
15	42
20	51
25	78
28	51
32	78

Table 6.13. Percentage occurrence of profiles showing shoreface activity for km 16-97. The method used here is the fixed tail sddc method (change criterion 0.25 m).

TEMPORAL PERIOD (yrs)	% P_a	% P_b	% F	% ALL
0	0	0	0	0
5	9	2	2	13
10	22	20	4	46
15	22	24	7	52
20	33	20	15	67
25	35	22	22	78
28	30	22	22	74
32	35	17	26	78

Table 6.14. Percentage occurrence of profiles showing shoreface activity for km 16 -71. The method used here is the fixed tail sddc method (criterion 0.25 m). (P_a = shoreward partial activity; P_b = seaward partial activity and closure on middle/lower shoreface; F = fully active; ALL = three types of activity combined).

The observed shoreface activity has also been represented using 100 m cross-shore 'blocks'. These blocks, coded[3] either active or inactive give a clear indication of the longshore and cross-shore distribution of shoreface activity for each temporal period. They also allow the evolution of this activity to be observed along the Holland coast. It should be noted that, in the minority of cases, blocks may alternatively be active and inactive, though it is typical for these blocks to ultimately exhibit activity over the longer time periods. Coded blocks have been plotted for Noord- and Zuid-Holland, as shown in Figure 6.12. (A more detailed figure is given in Appendix 6.2).

[3] according to the majority behaviour of the five 20 m components.

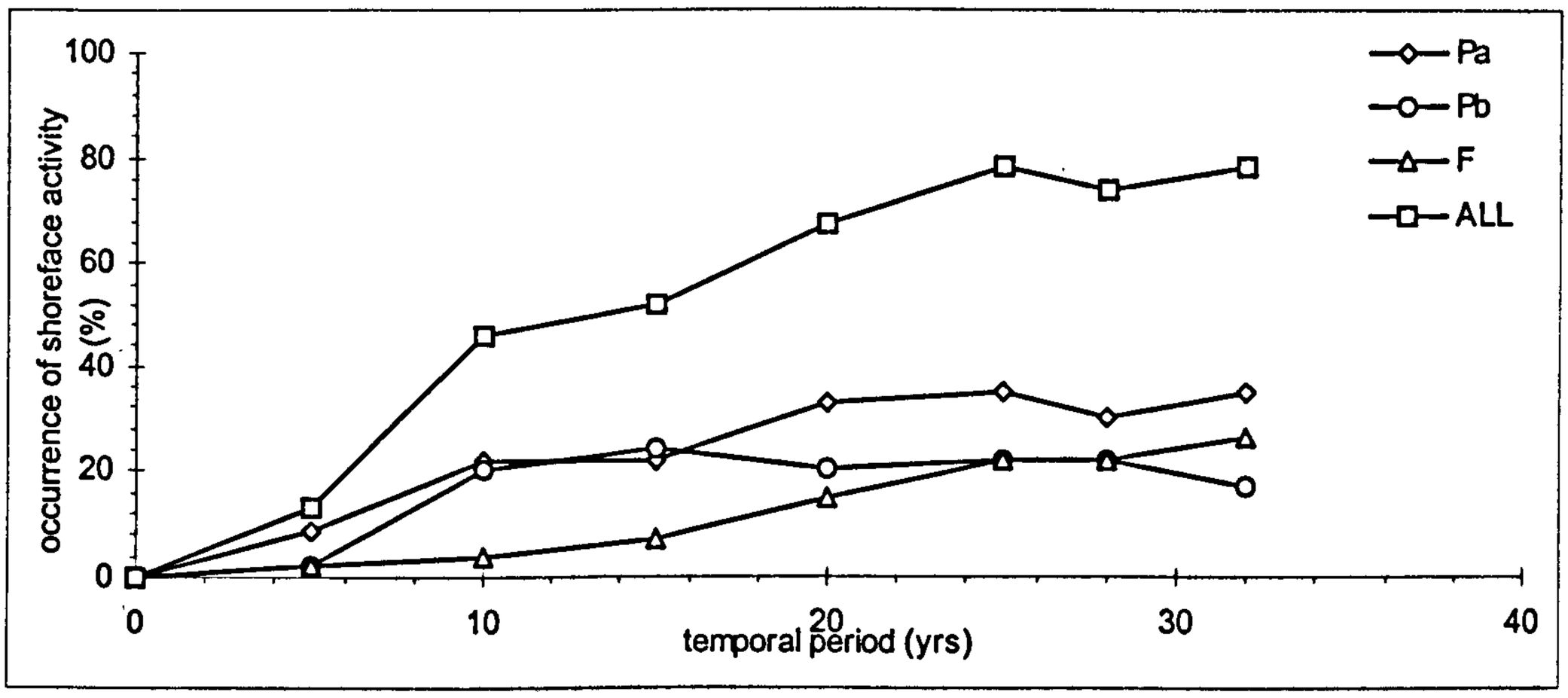


Figure 6.11. Observed relationship between the percentage occurrence of the three types of shoreface activity, for the Holland coast, and temporal period using the fixed tail sddc method (criterion 0.25 m). Pa = shoreward partial activity; Pb = seaward partial activity; F = full activity; and ALL = Pa + Pb + F.

As observed for Dc_s behaviour, the shoreface activity of Noord- and Zuid-Holland are different. These differences are now described :

1. if it is assumed that at $t = 0$, 0% of profiles exhibit shoreface activity and it is shown that, for Noord- and Zuid-Holland, at $t = 28$ years, 67% and 43% of profiles are active, respectively;
2. Noord-Holland consists of two main regions of shoreface activity within which the evolution of the shoreface activity is markedly different. Within km 16 to km 29 the evolution is significantly more variable than km 30 to km 54. This is illustrated in Figure 6.13 which shows the evolution of km 25 and km 44. It is clear that the growth of shoreface activity of km 25 is more random than that of km 44; and
3. Zuid-Holland has one main region of shoreface activity, km 57 to 73, which like km 30 to 54 has a steady temporal growth. The temporal trend of the shoreface activity from km 57 to 62 increases from 5 to 32 years. The increase is mainly in the north-east direction from the end of the harbour moles (taking northwards as shorewards). For the remaining profiles (km 63 to

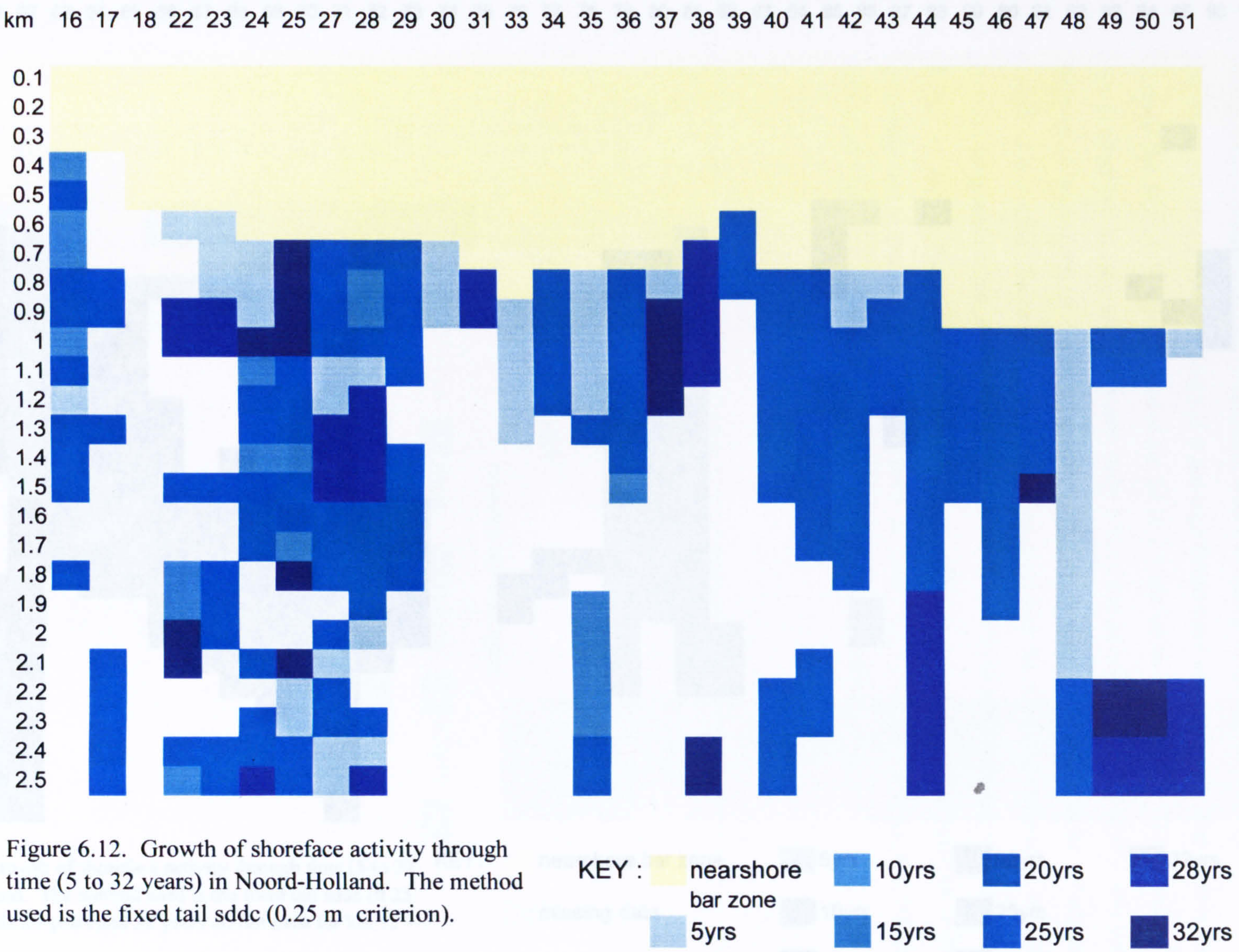


Figure 6.12. Growth of shoreface activity through time (5 to 32 years) in Noord-Holland. The method used is the fixed tail sddc (0.25 m criterion).

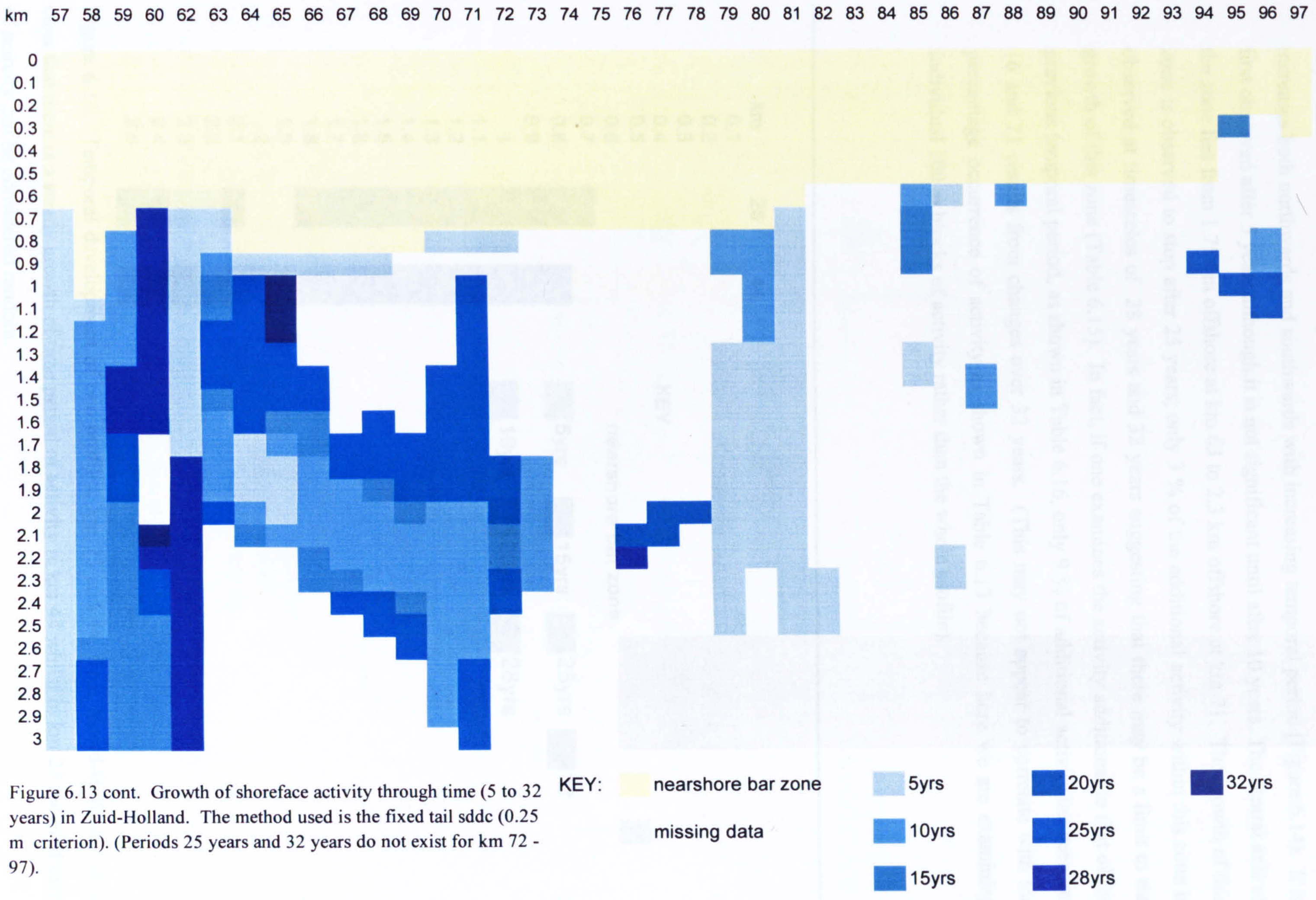


Figure 6.13 cont. Growth of shoreface activity through time (5 to 32 years) in Zuid-Holland. The method used is the fixed tail sddc (0.25 m criterion). (Periods 25 years and 32 years do not exist for km 72 - 97).

73) a zone of shoreface activity is also observed. This zone lies northwest-southeasterly and increases both northwards and southwards with increasing temporal period (Figure 6.14). It is first observed after 5 years although it is not significant until after 10 years. The central axis of the zone lies from 1.75 km offshore at km 63 to 2.3 km offshore at km 71. The growth of this zone is observed to stop after 25 years; only 3 % of the additional activity within this zone is observed at timescales of 28 years and 32 years suggesting that there may be a limit to the growth of this zone (Table 6.15). In fact, if one examines the activity additional to that of the previous temporal period, as shown in Table 6.16, only 9 % of additional activity between km 16 and 71 results from changes over 32 years. (This may not appear to correlate with the percentage occurrence of activity as shown in Table 6.13 because here we are examining individual 100 m blocks of activity rather than the whole profile).

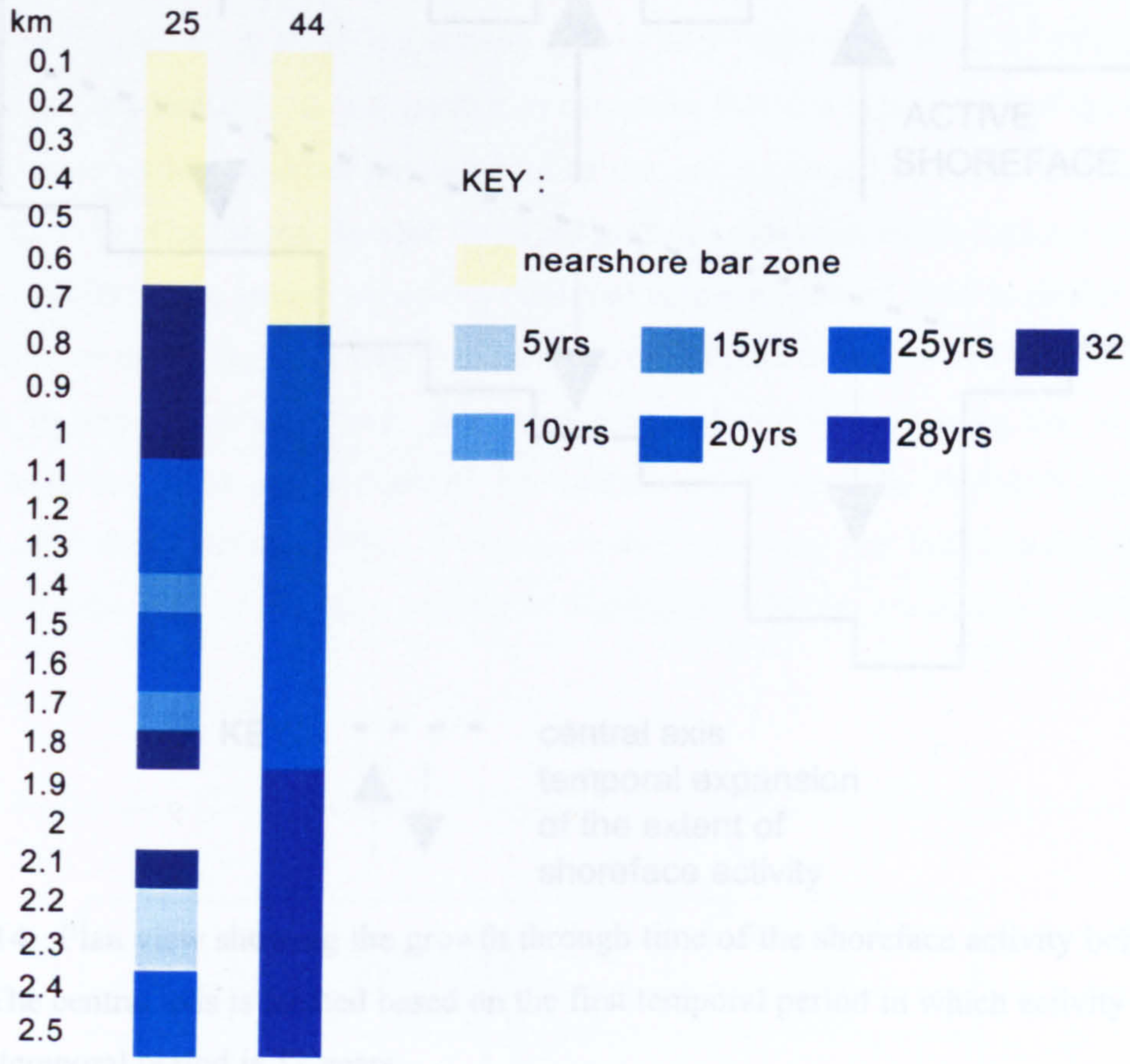


Figure 6.13. Temporal development of two profiles, km 25 and 44, from Noord-Holland. It is clear that there is a steady growth of time period of activity in km 44 whilst in km 25 the evolution of activity can be considered random.

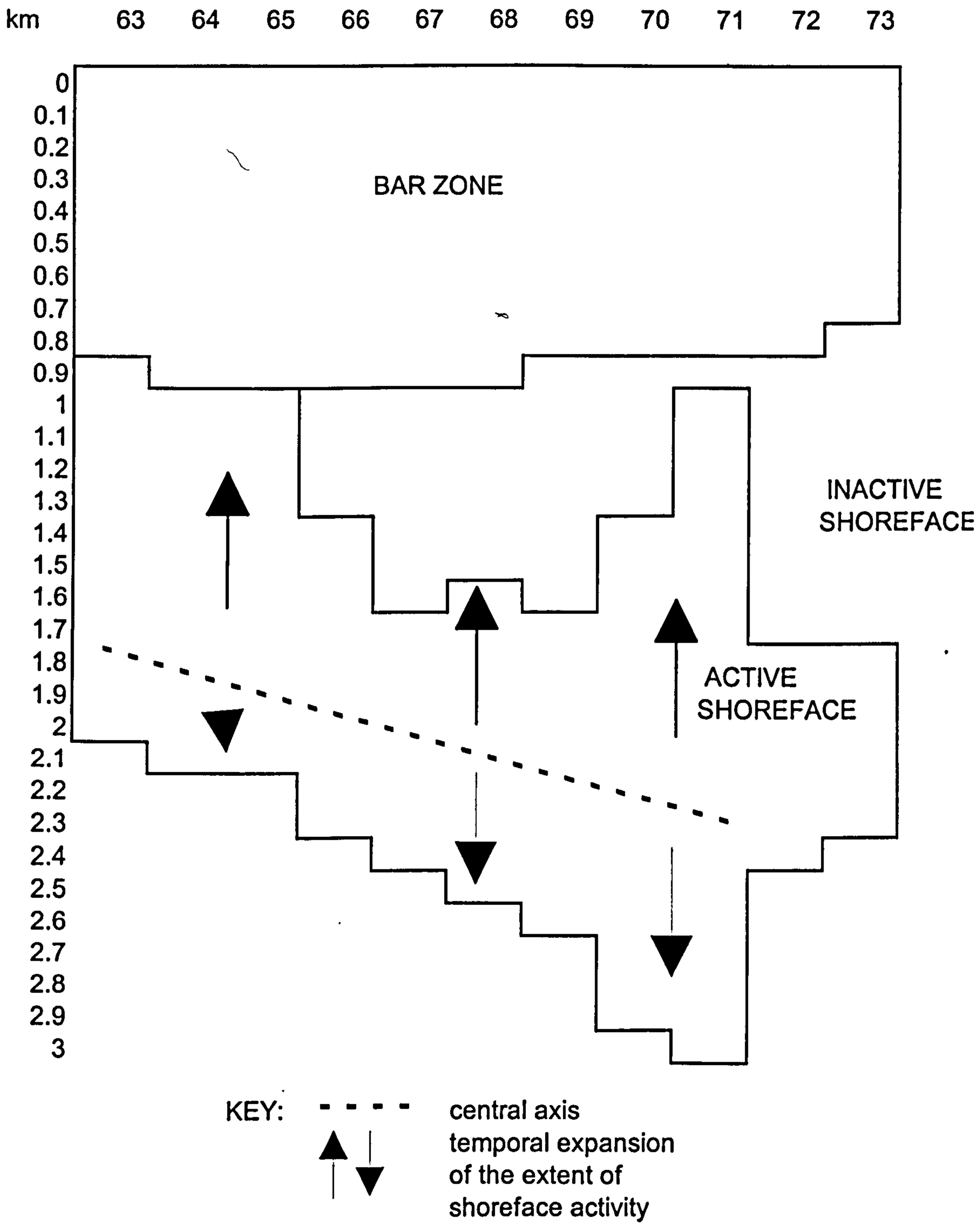


Figure 6.14. Plan view showing the growth through time of the shoreface activity between km 63 and 73. The central axis is located based on the first temporal period in which activity is observed. The final temporal period is 32 years.

TEMPORAL PERIOD (yrs)	5	10	15	20	25	28	32
ADDITIONAL ACTIVITY (%)	2	7	2.2	1.2	7	0.3	0.5

Table 6.15. The percentage of additional activity per year for each temporal period between km 63 and 73.

TEMPORAL PERIOD (yrs)	5	10	15	20	25	28	32
ADDITIONAL ACTIVITY (%)	7.2	7.2	3.8	3.4	8	7.7	2.3

Table 6.16. The percentage of additional activity per year for each temporal period between km 16 and 71.

6.3.3.1) INFLUENCE OF MISSING DATA

As observed (Figure 6.11) shoreface activity occurs on a larger percentage of profiles in Noord-Holland than Zuid-Holland. It is important to determine that this is the result of the two different morphodynamic regimes and not the influence of the data measured in 1965. In order to do this, km 57 to 71 were selected and the sddc fixed tail method (change criterion 0.25 m) used upon data from 1970 to 1997. The pattern of activity observed with and without 1965 is similar although not identical (Figure 6.15); typically less blocks are active with the exclusion of 1965. Interestingly the difference in results increases with increasing temporal period suggesting that the 1965 data becomes more important over the longer time periods i.e. bathymetric change is greater between 1965 and 1990 than 1965 and 1975. However, it does not imply that this data significantly alters the temporal behaviour of shoreface activity as highlighted with the correlation coefficients (Table 6.17).

	r^2 (95% confidence)
WITH 1965 DATA	0.98
WITHOUT 1965 DATA	0.99

Table 6.17. Correlation coefficients between percentage occurrence of shoreface activity and temporal period for two scenarios; with and without profiles 1965 data.

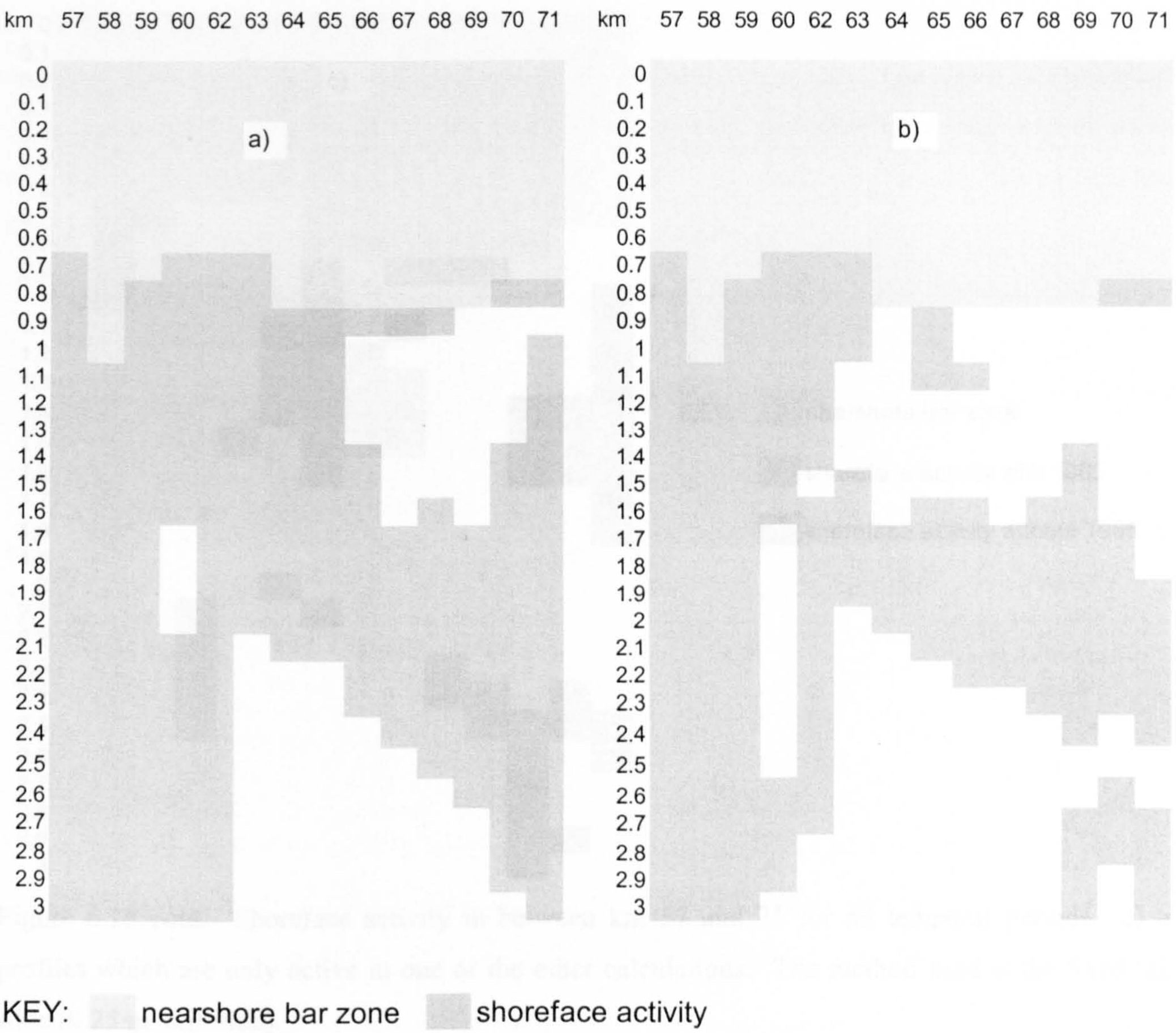


Figure 6.15. Shoreface activity in between km 57 and 71 for all temporal periods; a) = with the year 1965; b) = without the year 1965. The zone of activity in the two examples is similar. The method used is the fixed tail sddc (0.25 m criterion).

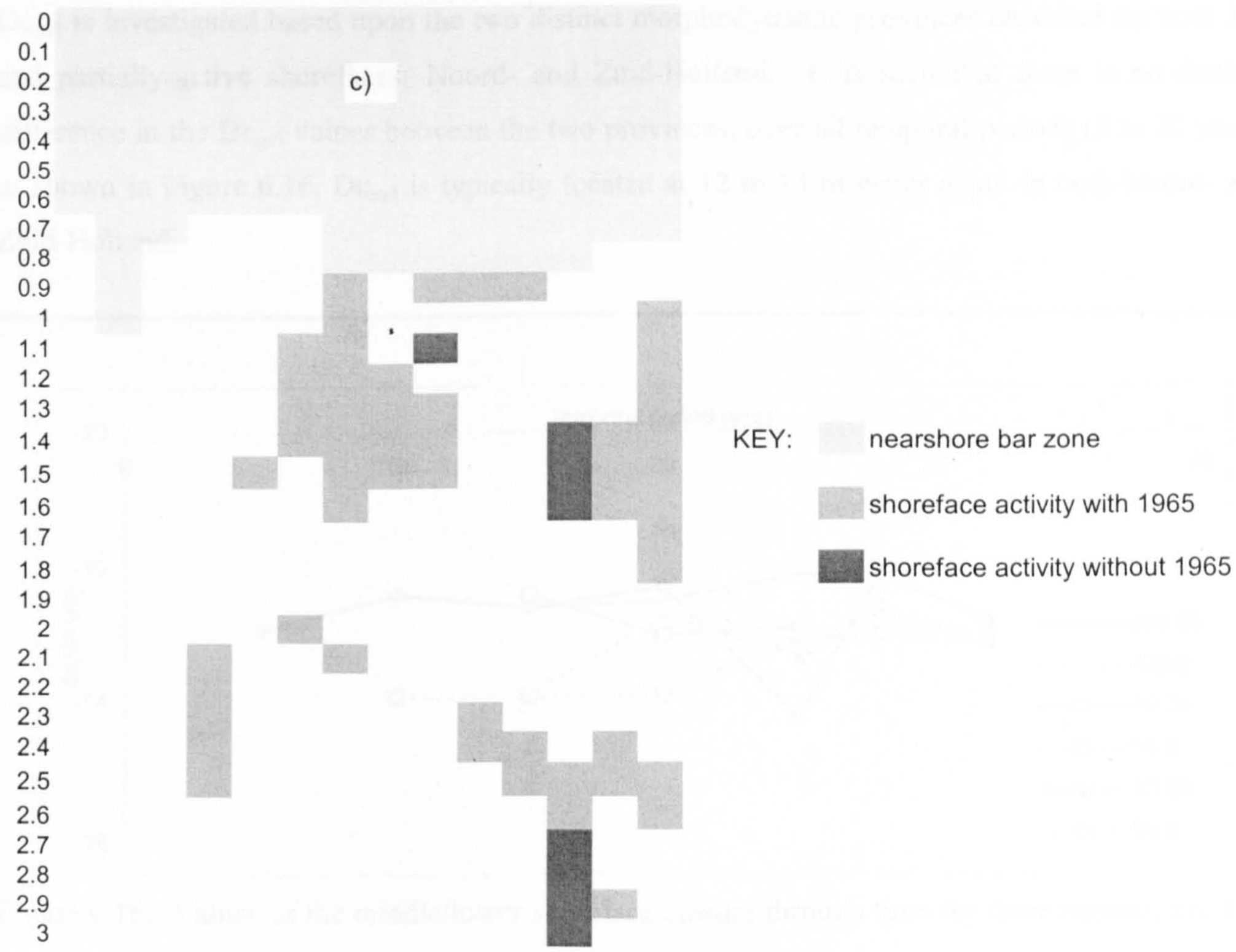


Figure 6.15 cont. Shoreface activity in between km 57 and 71 for all temporal periods. c) = profiles which are only active in one or the other calculations. The method used is the fixed tail sddc (0.25 m criterion).

6.4) SEAWARD LIMIT OF SHOREFACE ACTIVITY

6.4.1) INTRODUCTION

There exists, in some instances, a seaward boundary to the shoreface activity ($Dc_{m/l}$). When observed it is typically found on profiles classified as i) shoreward partially-active; or ii) seaward partially-active (as illustrated in Figure 6.3). Both methods (Chapter 5) are used to examine the spatial and temporal variability of $Dc_{m/l}$, as presented below.

6.4.2) SPATIAL BEHAVIOUR

$Dc_{m/l}$ is investigated based upon the two distinct morphodynamic provinces observed for both Dc_s and partially-active shorefaces; Noord- and Zuid-Holland. It is seen that there is no distinct difference in the $Dc_{m/l}$ values between the two provinces, over all temporal periods (5 to 32 years) as shown in Figure 6.16. $Dc_{m/l}$ is typically located at 12 to 13 m water depth in both Noord- and Zuid-Holland.

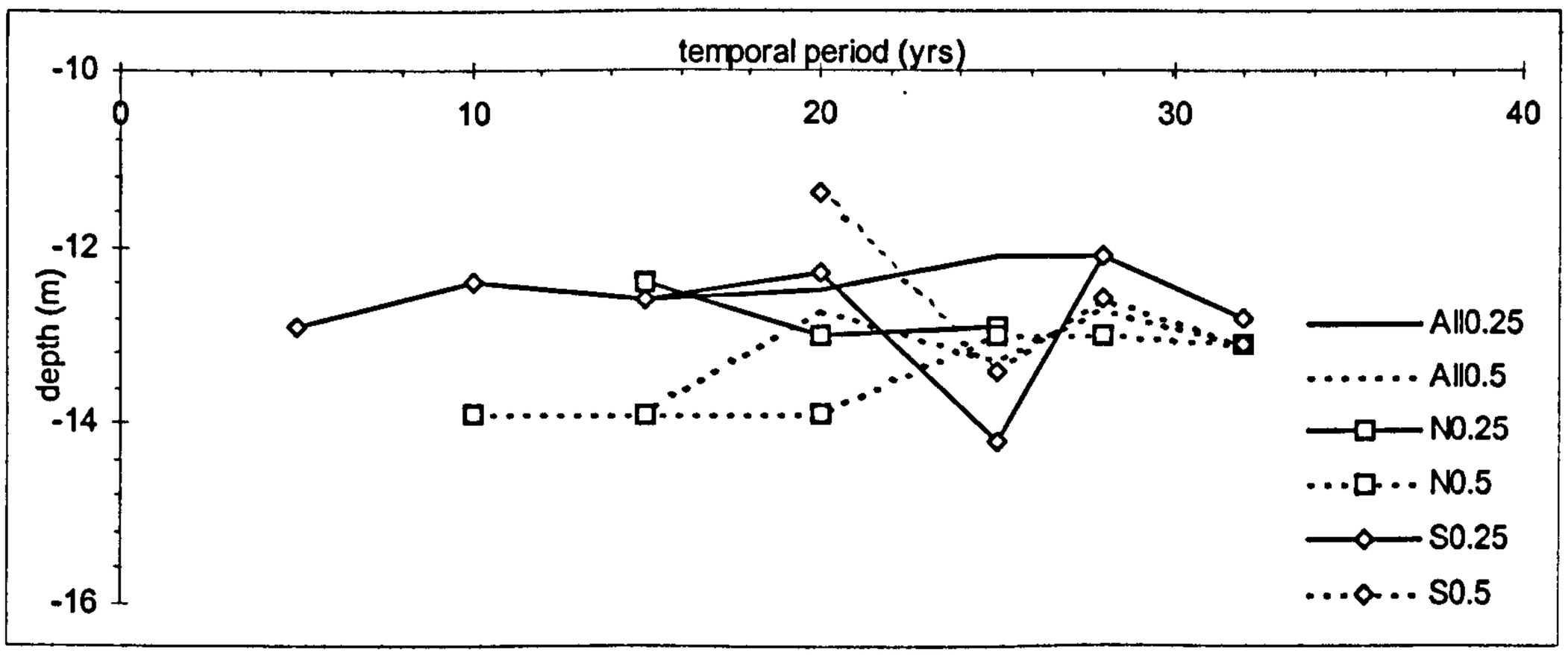


Figure 6.16. Values of the middle/lower shoreface closure through time for three regions; km 16 - 97; km 16 - 55 (Noord-Holland); and km 57 - 97 (Zuid-Holland). The fixed tail sddc method (criteria 0.25 m; 0.5 m) is used. Key : All = km 16 -97; N = km 16 -55; S = km 57 -97.

6.4.3) TEMPORAL BEHAVIOUR

The observed $Dc_{m/l}$ values do not exhibit a temporal trend for i) the Holland coast, and ii) the two provinces Noord- and Zuid-Holland. This is shown most clearly by the respective correlation coefficients, Table 6.18. The significance and weightings of the coefficients do not agree between methods or provinces.

The occurrence of $Dc_{m/l}$ is temporally dependent, as illustrated in Figure 6.17, in that when the temporal period increases, the occurrence of $Dc_{m/l}$ significantly decreases (Table 6.19). This relationship is to be expected based upon the similar ones of Dc_s and partial shoreface activity. It suggests that as the temporal period increases, the shoreface behaviour evolves from partially- to fully-active hence the $Dc_{m/l}$ is no longer observed within the data limits.

REGION	SDDC (0.25 m)	SDDC (0.5 m)	FDC (0.25 m)	FDC (0.5 m)	FDC (0.75 m)
km 16 - 97	-0.39	-0.71	-0.4	0.71	-0.4
km 16 - 55	0.78	-0.86	-0.7	-0.6	-0.3
km 57 - 97	0.11	0.7	-	0.98	-0.14

Table 6.18. Correlation coefficients (95% confidence) between the depth values of the middle/lower shoreface closure and temporal period.

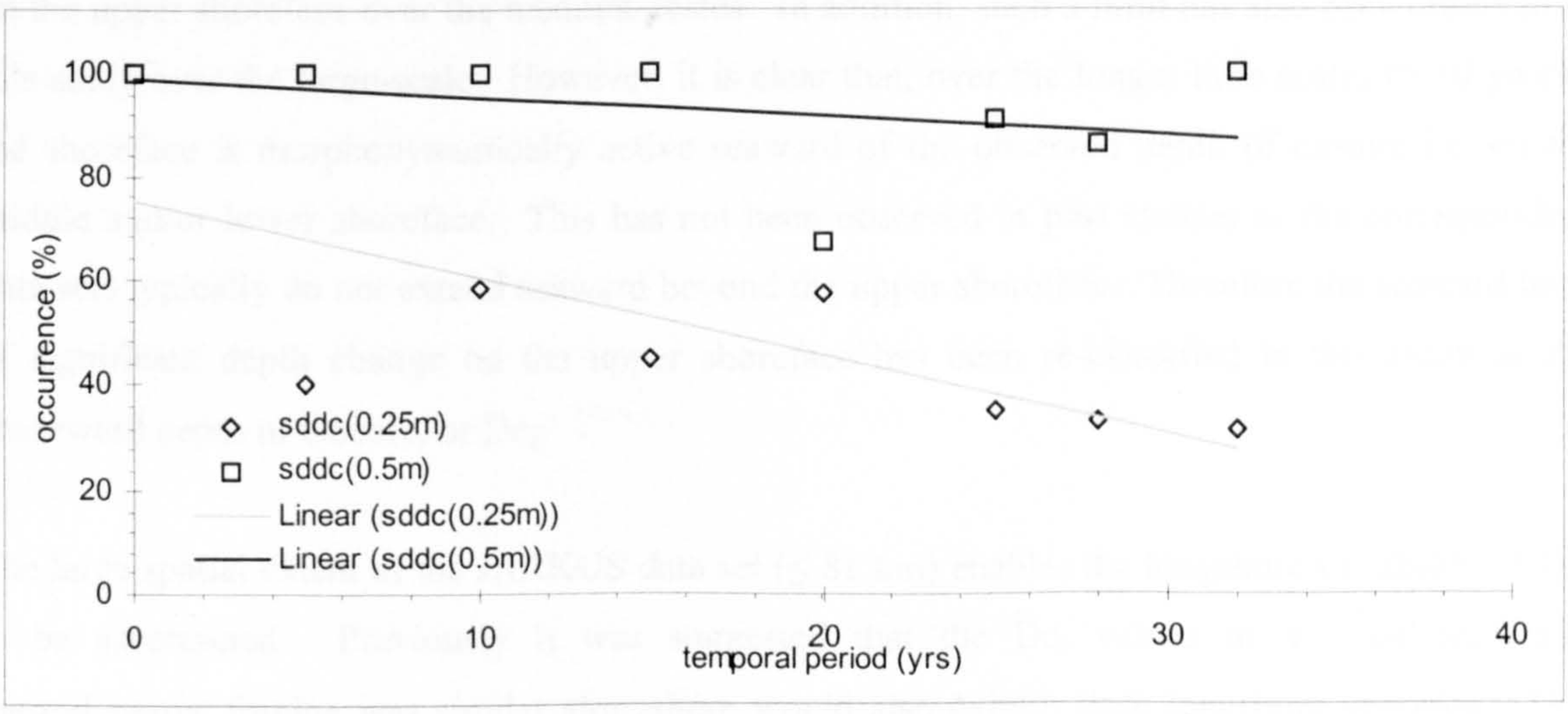


Figure 6.17. Percentage occurrence of the middle/lower shoreface closure ($Dc_{m/l}$) through time; observations and associated trendlines. The fixed tail sddc method (criteria 0.25 m; 0.5 m) is used.

	SDDC (0.25 m)	SDDC (0.5 m)	FDC (0.25 m)	FDC (0.5 m)	FDC (0.75 m)
$r^2_{(95\% \text{ confidence})}$	0.61	0.11	0.73	0.85	0.86
GRADIENT ($\%yr^{-1}$)	-1.3	-0.4	-2.8	-1.9	-1.2

Table 6.19. Correlation coefficients of the exponential trendline between the percentage occurrence of middle/lower shoreface closure and temporal period.

6.5) SUMMARY

The shoreface morphodynamic behaviour of the Holland coast is spatially- and temporally-dependent over medium- and large-scales. Previous studies which have focused upon shoreface behaviour have not observed all the behaviour shown in this research. This is fundamentally the result of data limitations; for example, the bathymetric data at Duck, N.Carolina only covers the upper shoreface of four cross-shore profiles, over the medium-term (Lee *et al*, 1995).

As has been observed in past studies (e.g. Birkemeier, 1985; Garcia *et al*, 1998; Nicholls *et al*, 1996; Rozynski *et al*, 1998), a seaward limit to significant depth change, or Dc, has been observed on the upper shoreface over the medium-scales. In addition, such a limit has also been observed in this study over the large-scale. However, it is clear that, over the longer time scales (> 10 years), the shoreface is morphodynamically active seaward of the observed depth of closure i.e. on the middle and/or lower shoreface. This has not been observed in past studies as the corresponding data sets typically do not extend seaward beyond the upper shoreface. Therefore the seaward limit of significant depth change on the upper shoreface has been re-classified in this study as the shoreward depth of closure, or Dc_s.

The large spatial extent of the JARKUS data set ($\leq$ 81 km) enables the longshore variability of Dc_s to be ascertained. Previously it was suggested that the Dc_s values of a coastline whose hydrodynamic forcing was similar alongshore would also exhibit little longshore variation. This statement is derived from the Hallermeier (1977, 1978) model which calculates closure based upon the 12 hour exceeded wave height (Eq.2.3). However it is clear from this investigation that this is not the case. Observations of Dc_s values and deviations around the mean has led to the division of the Holland coast into two provinces, even though this coast has a near-constant longshore hydrodynamic climate. Of the two provinces, Noord- and Zuid-Holland, the former has more variable, deeper Dc_s values than the latter (Table 6.1). More recent work (Marsh *et al*, 1998; Nicholls and Birkemeier, 1997; Nicholls *et al*, 1998b) which has investigated the relationship between the internal dynamics and external forcings suggest that the hydrodynamic forcing may indeed not be the only control upon Dc_s. This is examined further in Chapter 7 and 8.

The temporal dependency of closure observed over the medium-scales at other sites e.g. Duck, N.Carolina (Larson and Kraus, 1994; Nicholls *et al*, 1996; 1998a; 1998b; Nicholls and Birkemeier, 1997) is also apparent for the Dc_s along the Holland coast. Indeed this dependency extends into the large-scale; as the temporal period increases then the occurrence of Dc_s decreases such that

after 32 years 30% of profiles close on the upper shoreface. This can be compared to observations of closure in less than 8 m water depth at Duck, N.Carolina where, after 8 years only 3% of cases exhibit closure (Nicholls *et al*, 1998a). The large difference between the two sites is primarily the result of i) the JARKUS data set having forty-times more cross-shore profiles than the example from Duck, N.Carolina; and ii) the JARKUS profiles having a greater cross-shore extent than those at Duck, N.Carolina. However, the details of the temporal dependence of closure are different between previous studies and this one. Existing research concludes that as the temporal period increases then the closure value also increases, as suggested by the significant decrease in closure cases observed at Duck, N.Carolina (Table 2.8) within 8 m water depth. However this study concludes that, although the Dc_s value increases from the medium- to the large-scale (as shown by the correlation coefficients, Table 6.4) the extent of this increase is not large (as shown by gradients of the trendlines which are all < 0.1 m per annum, Table 6.5). For example the mean values of Noord- and Zuid-Holland increase by 1 m and 0.5 m, respectively. Again, this is more likely the result of differences in the data sets; if the JARKUS data set were to only extend to 8 m water depth then perhaps it could be assumed that a decrease in Dc_s cases is the result of an increase in values beyond 8 m. However, it could also be the result of the morphodynamic behaviour of the coast; the more dynamic province (Noord-Holland) shows a greater increase in Dc_s than Zuid-Holland.

As the observations of the JARKUS data set clearly indicate, the existence of the shoreward depth of closure does not mean that the remainder of the cross-shore profile is morphodynamically inactive. Indeed it is shown that, particularly over the long-term (> 10 years) the middle and lower shoreface is morphodynamically active. This observation contradicts existing studies on the depth of closure which conclude that it is not followed in the cross-shore by morphodynamic activity. However this contradiction is only true for the longer time-scales over which existing studies have assumed the behaviour to be similar to that observed over the short- and medium-scales. Middle/lower shoreface morphodynamic activity has however been observed during high energy events within short-scale point experiments e.g. Snedden *et al*, 1988 (Section 2.3.3).

The morphodynamic activity of the Holland shoreface has been classified into four types; i) an inactive shoreface; ii) a shoreward partially-active shoreface; ii) a seaward partially-active shoreface; and iv) a fully-active shoreface (Figure 6.3). Observations show the activity to be both spatially-variable and temporally-dependent.

Shoreface activity occurs to a greater extent in Noord-Holland than Zuid-Holland; after 28 years 67% and 43% of profiles are active, in the respective provinces. Noord-Holland has also been shown, through the Dc_s characteristics, to be more active than Zuid-Holland. Additionally, the shoreface activity within Noord-Holland evolves differently between km 16 to 29 and km 30 to 55. In the former province the evolution of shoreface activity is more random than in the latter province which clearly shows a pattern of cross-shore 'spreading' of activity from the middle/lower shoreface. An interesting feature of shoreface activity is also observed south of the IJmuiden harbour moles (km 55/57). Here a zone of activity exists lying northwest-southeasterly[4] which increases both northwards and southwards with increasing temporal period (Figure 6.13). The location of this zone correlates with scour holes induced by the harbour moles observed in previous studies (e.g. Roelvink *et al*, 1998). The location of the harbour moles also correlates with the longshore position of the majority of the fully active profiles; the influence of this large engineering structure upon shoreface behaviour is investigated in more detail in Chapter 7.

It is clear that, as the temporal period increases, both the occurrence and extent of shoreface activity increases such that, based on the observations, one would expect all profiles to ultimately become fully active :

As the temporal period increases beyond 32 years, all profiles will evolve from exhibiting non-active to partially active shorefaces.
Every profile will ultimately become fully active.

In conclusion therefore :

1. a limit of significant activity has been identified on the upper shoreface of the Holland coast;
2. however it is typical for further activity to be observed on the middle/lower shoreface. This has resulted in the re-classification of the 'depth of closure' to the 'shoreward depth of closure'
3. the shoreward depth of closure is both temporally-dependent and spatially variable longshore;
4. in order to adequately describe the shoreface morphodynamic behaviour, the middle/lower shoreface activity is classified as; i) a inactive shoreface; ii) a shoreward partially-active shoreface; ii) a seaward partially-active shoreface; and iv) a fully-active shoreface; and
5. the middle/lower shoreface activity is both temporally-dependent and spatially variable longshore.

[4] northwards represents shorewards

7) CAUSES AND CONTROLS UPON THE MORPHODYNAMIC BEHAVIOUR OF THE HOLLAND SHOREFACE

7.1) INTRODUCTION

Chapter 6 presented two major characteristics[1] of the morphodynamic behaviour of the Holland shoreface :

1. the shoreward depth of closure (Dc_s), located on the upper shoreface; and
2. middle/lower shoreface activity, classified into four types (Figure 6.2).

The former is more prominent over the smaller time scales and the latter over the longer time scales (> 10 years) i.e. both are temporally-dependent. Additionally both exhibit spatial variability longshore, and in the case of the middle/lower shoreface activity, also in the cross-shore.

Questions are therefore raised concerning the factors which result in the observed behaviour. This is particularly intriguing in the case of the spatial variability if one considers that, what is typically considered as the main coastal forcing - the hydrodynamics, is uniform alongshore. Hence this chapter deals with the causes and controls of the morphodynamic behaviour, as observed in Chapter 6, by concentrating upon the following research objective :

Determine the causes and controls upon the shoreface morphodynamic behaviour along the Holland coast over the medium- and large-scales

by addressing the following research questions :

What, if any, morphodynamic and hydrodynamic controls exist upon the shoreface behaviour? Do internal dynamics and external forcings play a role? What is the interaction of these over the scales investigated?

[1] there is a third morphodynamic characteristic; the middle/lower shoreface closure. However this is not always present (Chapter 6) and can be seen to be a function of the partially-active shoreface.

Do anthropogenic influences act as a control upon the morphodynamic activity? More specifically does the major engineering scheme, the IJmuiden harbour moles, induce significant morphodynamic activity? If so, what is the nature of this human influence?

The outline of this chapter is as follows. Section 7.2 and 7.3 investigate the potential causes and controls upon the shoreward depth of closure and middle/lower shoreface activity respectively. Within each section the possible influence of the IJmuiden harbour moles is also examined. The final section discusses these results in the context of the research questions posed above.

7.2) UPPER SHOREFACE BEHAVIOUR : THE SHOREWARD DEPTH OF CLOSURE

7.2.1) INTRODUCTION

The studies of Hallermeier (1977, 1978) (Chapter 2) clearly suggest that the major control upon the annual depth of closure in a wave-dominated micro-tidal environment is the wave characteristics; in particular the extreme wave height (exceeded 12 hours per annum) and the associated wave period. More recent studies have validated the time-dependent form of the model (Stive *et al*, 1992; Eq.2.6) over the short- and medium-scales and confirmed the role of extreme waves in controlling closure (e.g. Birkemeier, 1985; Nicholls *et al*, 1998b). In addition, these studies found that, with the exception of accretional periods, the Hallermeier (1977, 1978) model typically overpredicts the observed Dc. Although the hydrodynamics is the major control, the response of the short- and medium-scale closure to this forcing was found to be regulated by the morphodynamics of the nearshore bar system (Nicholls and Birkemeier, 1997; Nicholls *et al*, 1998b). It has also been suggested, based upon research on the annual timescale, that profile translation due to volume change acts as an additional control upon closure (Nicholls and Birkemeier, 1997).

The similar characteristics of depth of closure and the shoreward depth of closure suggest that the former's controls should also be investigated for the medium- and large-scale behaviour of Dc_s. This section primarily looks at the control of the primary external forcing, the hydrodynamics,

upon Dc_s and then examines the influence of the internal dynamics upon the closure response. The potential anthropogenic influence of the IJmuiden harbour moles is also investigated.

7.2.2) EXTERNAL FORCINGS : WAVE CONDITIONS

The wave climate of the Holland coast is relatively uniform in the longshore; the mean wave height from north to south changes by less than 0.2 m (Chapter 4). This simple observation suggests that, if this is the primary forcing there is an additional influence acting upon Dcs. However, the major control of the hydrodynamics must first be examined before other controls are investigated. This is done using Equation 2.6 over a 10 year temporal period. It should be noted that the use of this technique to predict closure is tested in Chapter 8 over a greater range of time periods (within the data limits), here it is purely used to determine whether the wave characteristics do indeed act as a control upon Dc_s.

Values of wave characteristics are taken from the three measuring stations applicable to this study; ELD; YM6; and MPN (Chapter 4). Data is available for the period 1979 to 1991, sufficient to calculate values of Dc_s over two 10 year periods. The calculated value of Dc_s ,which is compared with the corresponding observed value, is therefore the mean of these two periods. A correction is made to the calculated value as the Hallermeier (1977, 1978) model calculates closure relative to MLW (Nicholls *et al*, 1998a) whilst the input data is relative to NAP; 1m is therefore added to the model output. The calculated values for the three stations are assumed to vary linearly alongshore to enable more realistic comparison with the observed Dc_s[2].

The time-dependent Hallermeier (1977, 1978) model clearly provides a seaward limit to the observed Dc_s, as illustrated in Figure 7.1. In addition, the calculated values reproduce the observed longshore trend; the deepest Dc_s occurs in the northern region of Noord-Holland and decreases to its shallowest values in the southern region of Zuid-Holland (Figure 6.3). However this trend is only partly synthesised; the deviations in calculated values between north and south are not as great as with the observed values. This is quantified in Table 7.1 and indicates that, whilst the hydrodynamics act as a control upon the shoreward depth of closure, there must be an additional forcing which regulates its control.

[2] Note that the lack of wave data south of MPN means that the values for profiles km 84 to 97 are taken from the linear regression of the trend between km 57 to 83.

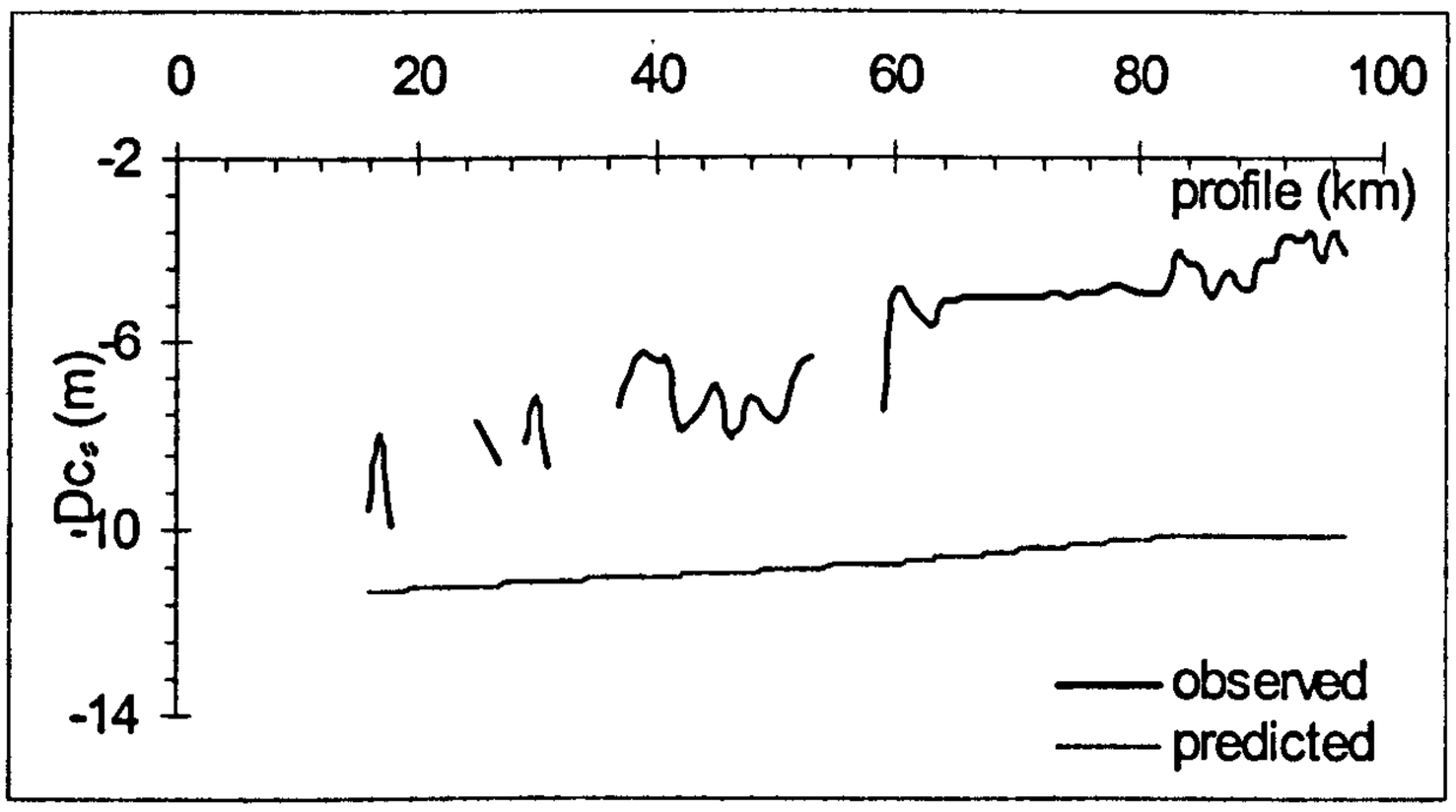


Figure 7.1. Alongshore predicted and observed values of closure for the 10 year temporal period. Predicted values are calculated using the Hallermeier (1977, 1978) model.

	SELECTED PROFILES			MEAN VALUES		
	km 17	km 97	km 17 minus 97 (m)	NOORD (km 16-54)	ZUID (km 56-97)	NOORD minus ZUID (m)
OBSERVED CLOSURE (m)	8.0	4.0	4.0	7.6	4.7	2.9
PREDICTED CLOSURE (m)	10.4	8.9	1.5	11.1	10.4	0.7
DIFFERENCE (m)	2.4	4.9	-	3.5	5.7	-

Table 7.1. Comparison of predicted and observed values of the shoreward closure from i) km 17 and km 97; and ii) Noord- and Zuid-Holland over a 10 year temporal period .

The control upon Dc_s enforced by the extreme wave height has also been investigated using modelling techniques. Here the chronology of the wave climate is examined i.e. does the order in which the extreme wave heights occur affect closure or it is only the value of the extreme wave height that is important? This work was performed using the process-based numerical model UNIBEST-TC (Chapter 5). Here the 10 year evolution of a single profile (km 81) was reproduced 10 times, each time using a different hydrodynamic time series[3]. The bathymetry of the 10 runs

[3] as stated in Chapter 5, the timeseries are based upon measurements taken from MPN and have the same statistical properties, but different sequences of wave conditions.

after the 10 years was then analysed using the sddc fixed tail (change criterion 0.25 m) method. It is clear that, from the small variation in Dc_s (Table 7.2), chronology does not play a role in the control of closure, it is, as stated in the Hallermeier (1977, 1978) model, the value of the 12 hour exceeded wave height that is important.

RUN ID	1	2	3	4	5	6	7	8	9	10	MEAN	SD
Dc_s (m)	4.9	4.8	5.0	5.0	4.9	5.0	5.2	4.8	4.9	5.0	5.0	0.1

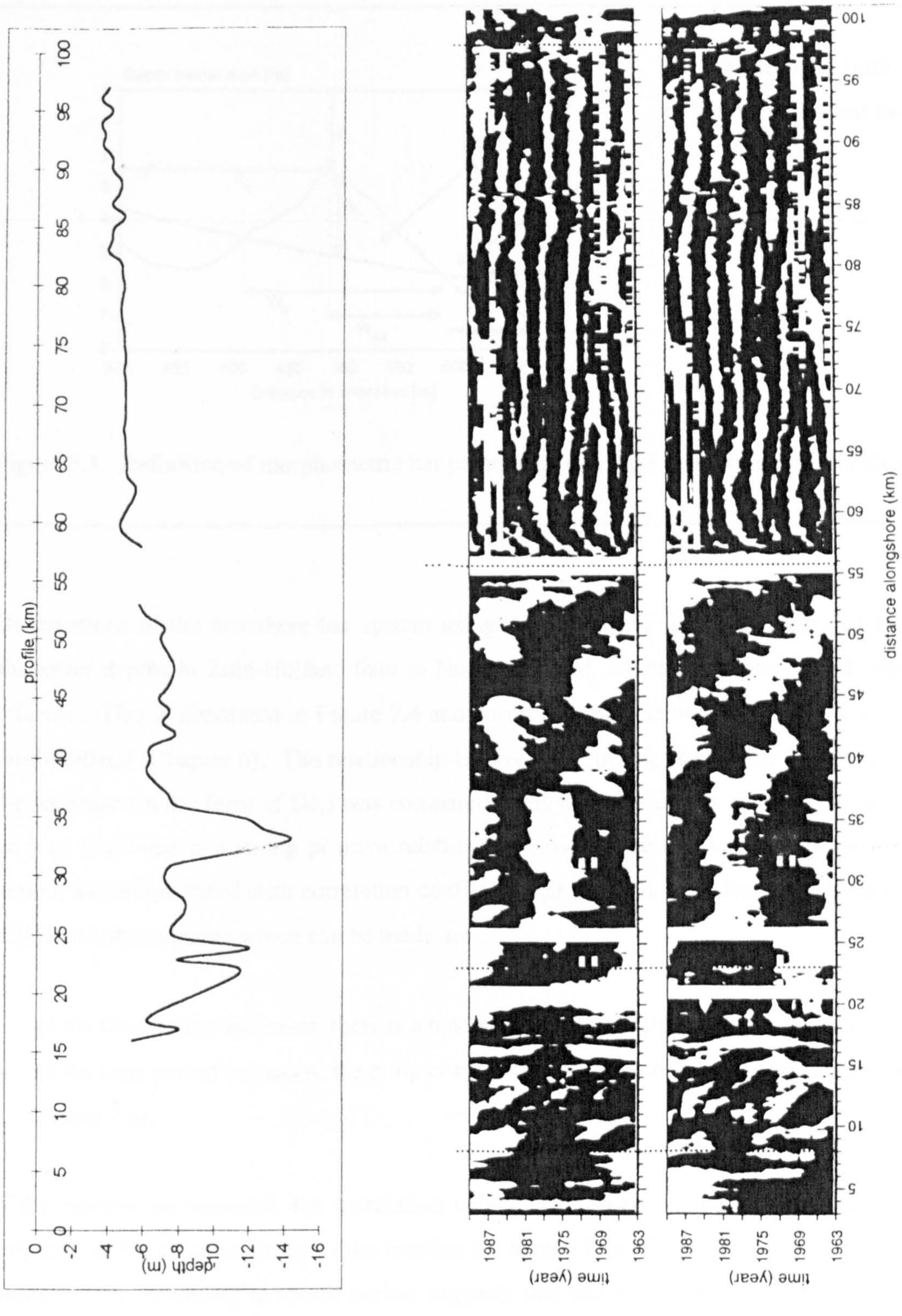
Table 7.2. Values of Dc_s over a 10 year period calculated from UNIBEST-TC output using the sddc fixed tail (change criterion 0.25 m) analysis. SD = standard deviation

7.2.3) INTERNAL DYNAMICS : MORPHODYNAMICS

The potential influence of the nearshore bar system upon the medium- and large-scale behaviour of the shoreward depth of closure is investigated here. The decadal behaviour of the bar system (e.g. Wijnberg and Terwindt, 1995), in addition to its influence upon the beach system (e.g. Short, 1992) has been the subject of recent studies (Chapter 4). It has been shown, using eigenfunction analysis of the nearshore bar system, that two longshore bar regions exist between km 16 and 97 (Wijnberg, 1995). These two bar regions are divided at km 55/56 (the IJmuiden harbour moles) therefore corresponding to km 16 to 55 and km 57 to 97. The major difference in the characteristics of these two bar regions are their offshore migration rate; 15 years and 4 years respectively (more details are given in Chapter 4). It is clear, as shown in Figure 7.2 the longshore location of these two bar regions coincides with the two Dc_s provinces identified in Chapter 6. This suggests that the nearshore bar system could act as a significant control upon Dc_s.

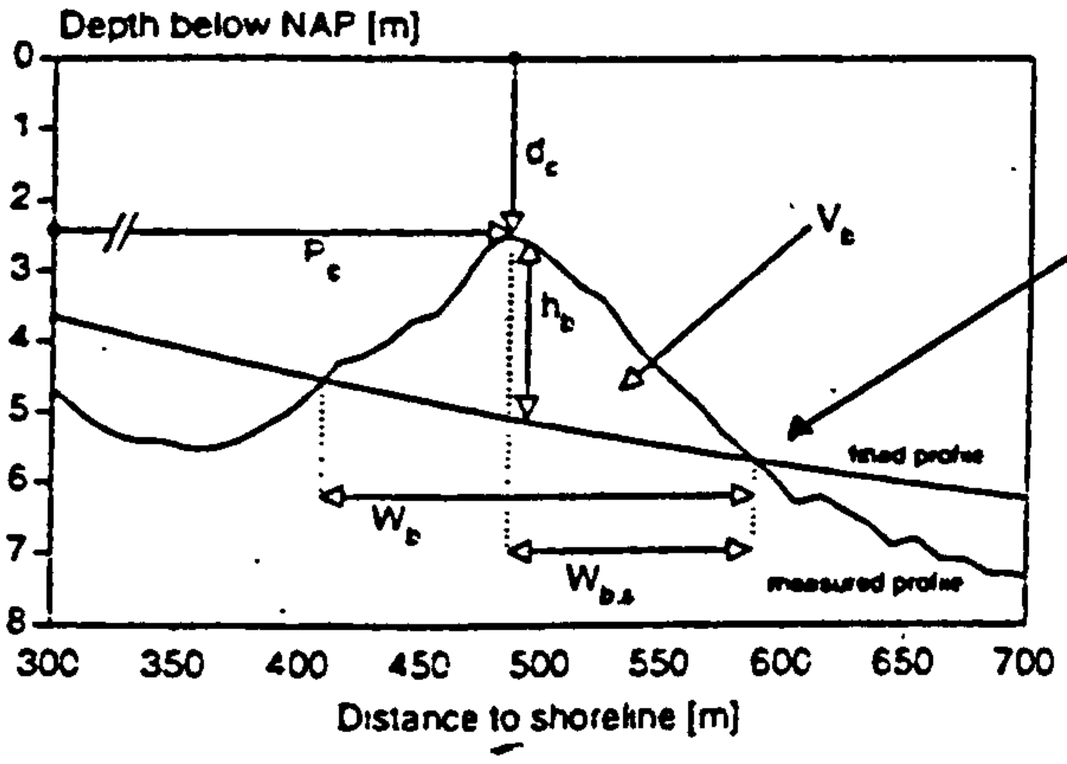
This potential influence upon Dc_s[4] is investigated using the 'seaward limit (in the cross-shore) of the nearshore bar system', or B_{SL}. The morphometric bar parameters of Ruessink and Kroon (1994), as shown in Figure 7.3, are used to identify B_{SL}. Within these parameters, the bars are classified as that part of the profile which is above the fitted profile. Therefore B_{SL} is defined as that point at which the fitted profile equals the measured one.

[4] the values of which are taken from the sddc fixed tail analysis (change criterion 0.25 m)



a) b)

Figure 7.2. Alongshore correlation between the (a) 5 year shoreward depth of closure (as defined using the fixed tail sddc method (criterion 0.25 m) and (b) bar behaviour (as defined by eigenfunction analysis; Wijnberg, 1995)



B_{SL}; the seaward limit of the nearshore bar system

Figure 7.3. Definition of morphometric bar parameters (adopted from Ruessink and Kroon, 1994).

Observations of the nearshore bar system using the $JARKUS_E$ data set reveal that B_{SL} occurs at shallower depths in Zuid-Holland than in Noord-Holland, although it does extend slightly further offshore. This is illustrated in Figure 7.4 and correlates with the observed shallower Dc_s values in Zuid-Holland (Chapter 6). The relationship between the forcing (taking the parameter of B_{SL}) and the response (in the form of Dc_s) was compared using scatter plots, as shown in Figure 7.5. It can be seen that there is a strong positive relationship between the two parameters for each temporal period, as demonstrated with correlation coefficients at the 95% confidence level; Table 7.3. Two additional observations which can be made are :

- as the time period increases, there is a tendency for the r^2 value to decrease; and
- as the time period increases, the number of deviations from the m = 1 line (or outliers) increase (Table 7.4).

If the outliers are removed, the correlation values increase (as would be expected), although the variation in the r^2 value through time remains the same (Table 7.5). The increased presence of the outliers with increasing temporal period suggests that the influence of the nearshore bar system upon Dc_s, although significant, decreases with increasing time periods.

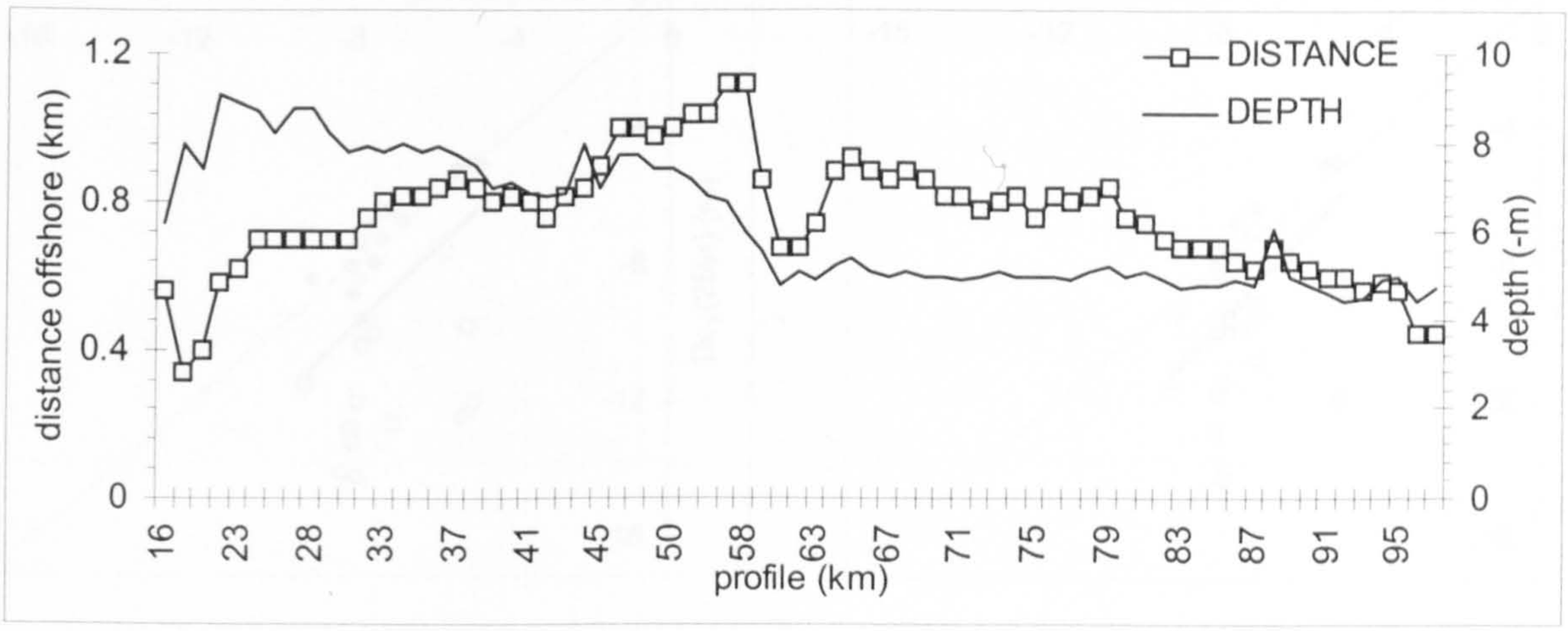
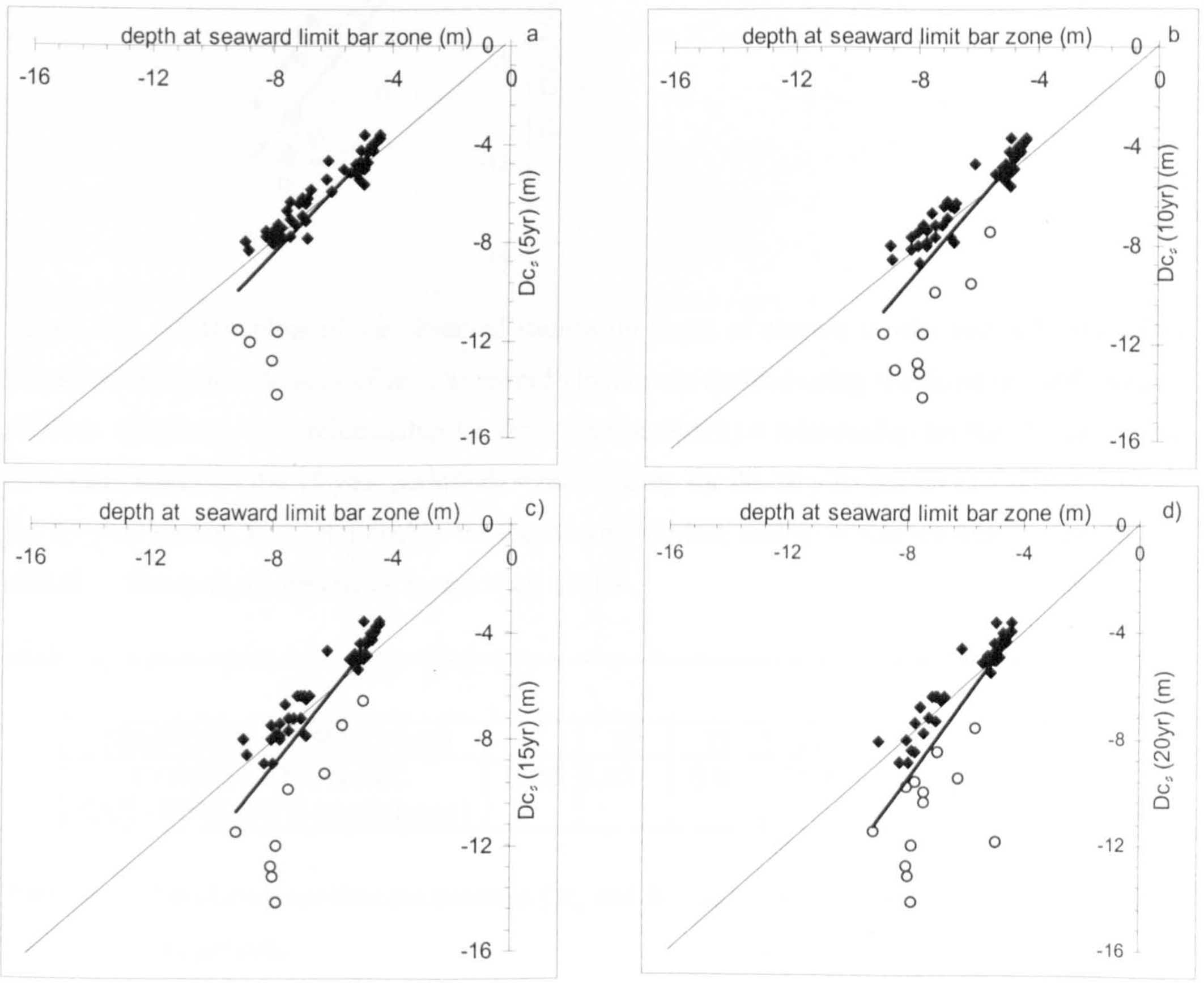
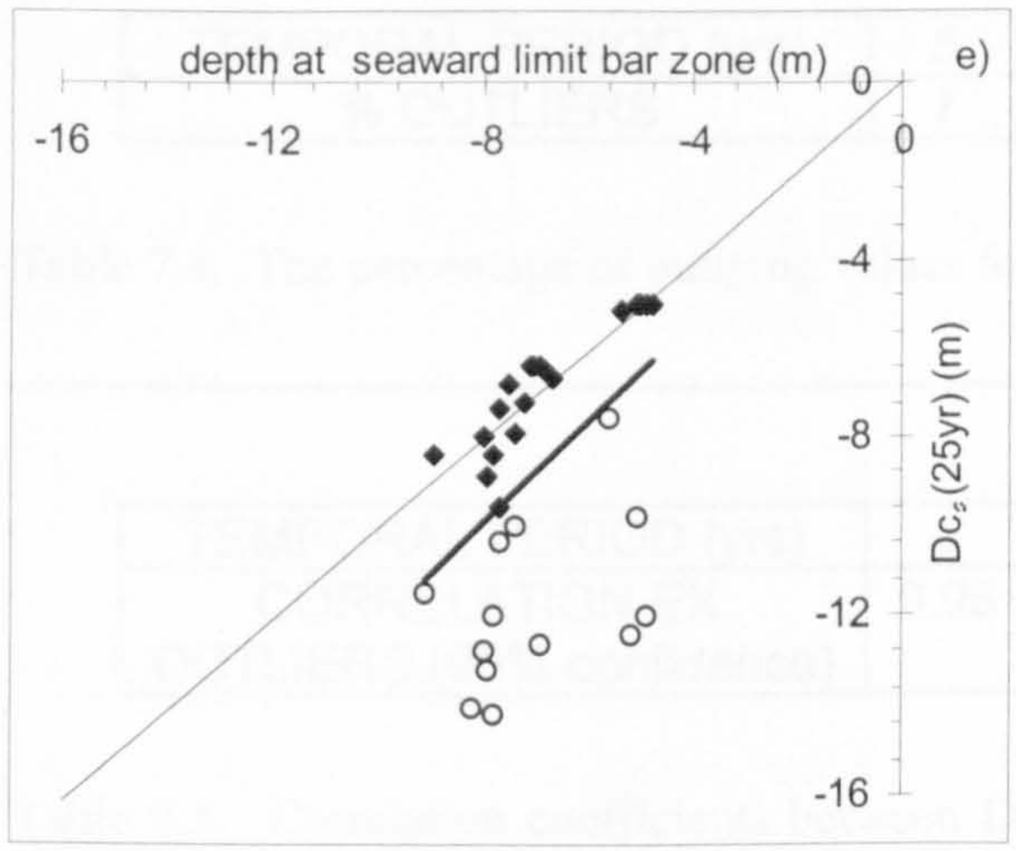
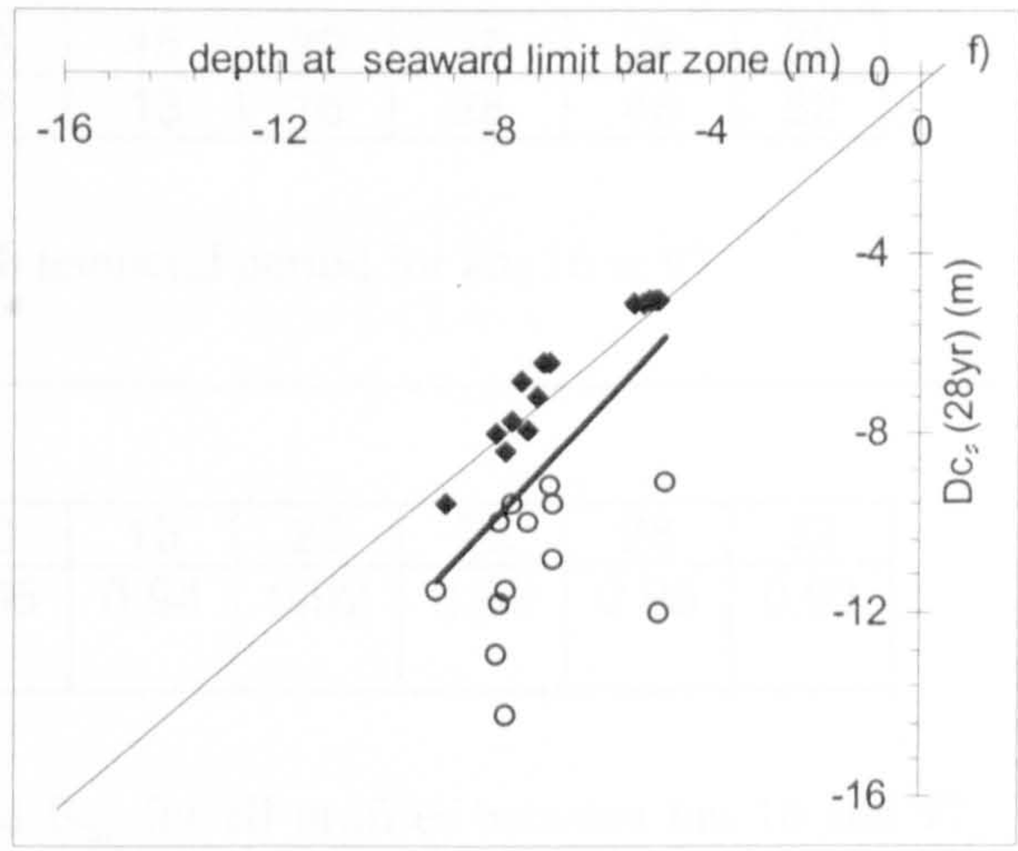


Figure 7.4. Distance offshore of the seaward limit of the nearshore bar zone and the depth at which this occurs for each profile alongshore.







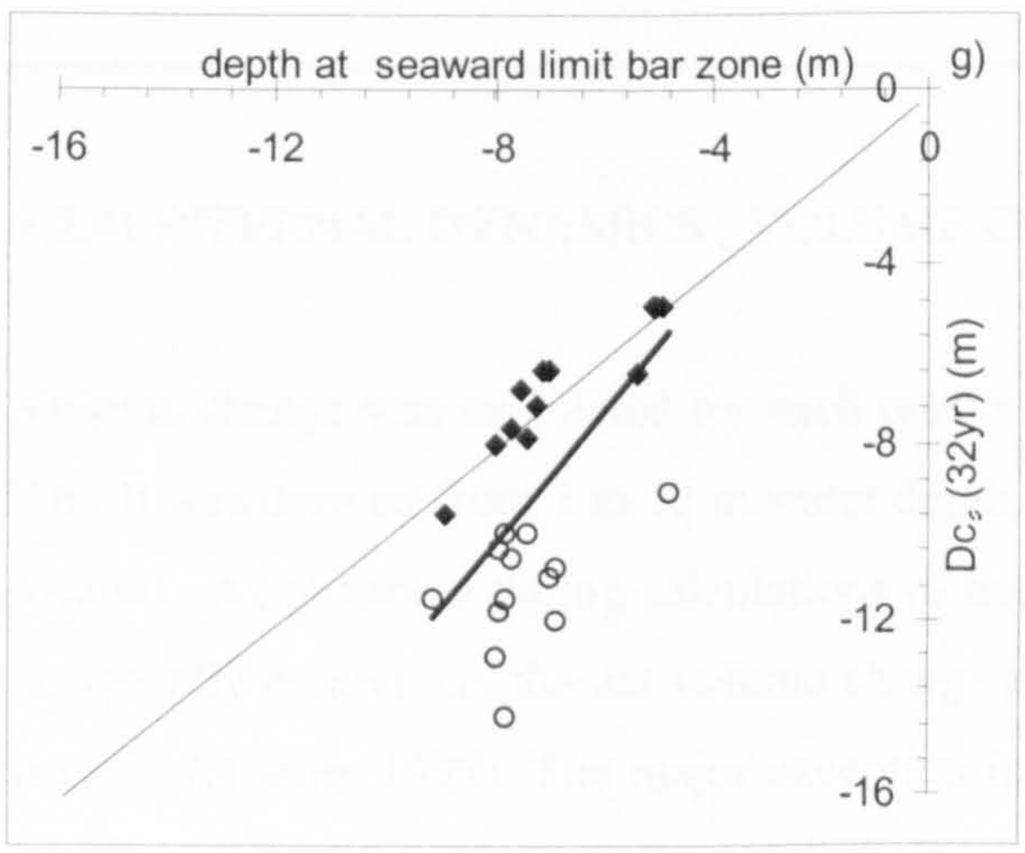


Figure 7.5. Scatter plots of the observed shoreward depth of closure vs. the seaward limit of the nearshore bar zone. Values of the shoreward closure are derived using the fixed tail sddc method (0.25 m criterion). a) = relationship for the 5 year period; b) = relationship for the 10 year period; c) = relationship for the 15 year period; d) = relationship for the 20 year period e) = relationship for the 25 year period; f) = relationship for the 28 year period; and g) = relationship for the 32 year period. . The outliers are shown by the open circles.

TEMPORAL PERIOD (yrs)	5	10	15	20	25	28	32
CORRELATION INC. OUTLIERS (95% confidence)	0.83	0.83	0.82	0.79	0.51	0.62	0.71

Table 7.3. Correlation coefficients between Dc_s and B_{SL} using all profiles between km 16 and 97 for all temporal periods.

TEMPORAL PERIOD (yrs)	5	10	15	20	25	28	32
% OUTLIERS	7	13	13	16	28	48	52

Table 7.4. The percentage of outlying values for each temporal period for km 16 to 97.

TEMPORAL PERIOD (yrs)	5	10	15	20	25	28	32
CORRELATION EX. OUTLIERS (95% confidence)	0.95	0.95	0.94	0.92	0.89	0.96	0.93

Table 7.5. Correlation coefficients between Dc_s and B_{SL} for all profiles between km 16 and 97, excluding the outliers, for all the temporal periods.

7.2.4) INTERNAL DYNAMICS : VOLUME CHANGE

Volume change was calculated for each profile over two temporal periods; 5 and 10 years (Figure 7.6. It was derived from 3 to 12 m water depth, so to include the zone in which closure is typically located. As observed during calculations of bathymetric change (Section 7.3.2), the Holland coast is typically erosive i.e. the net volume change is negative for the majority of profiles over all time periods (Hinton, 1998). The major exception is adjacent to the IJmuiden harbour moles which act as a barrier to the northwards littoral drift, resulting in sedimentation.

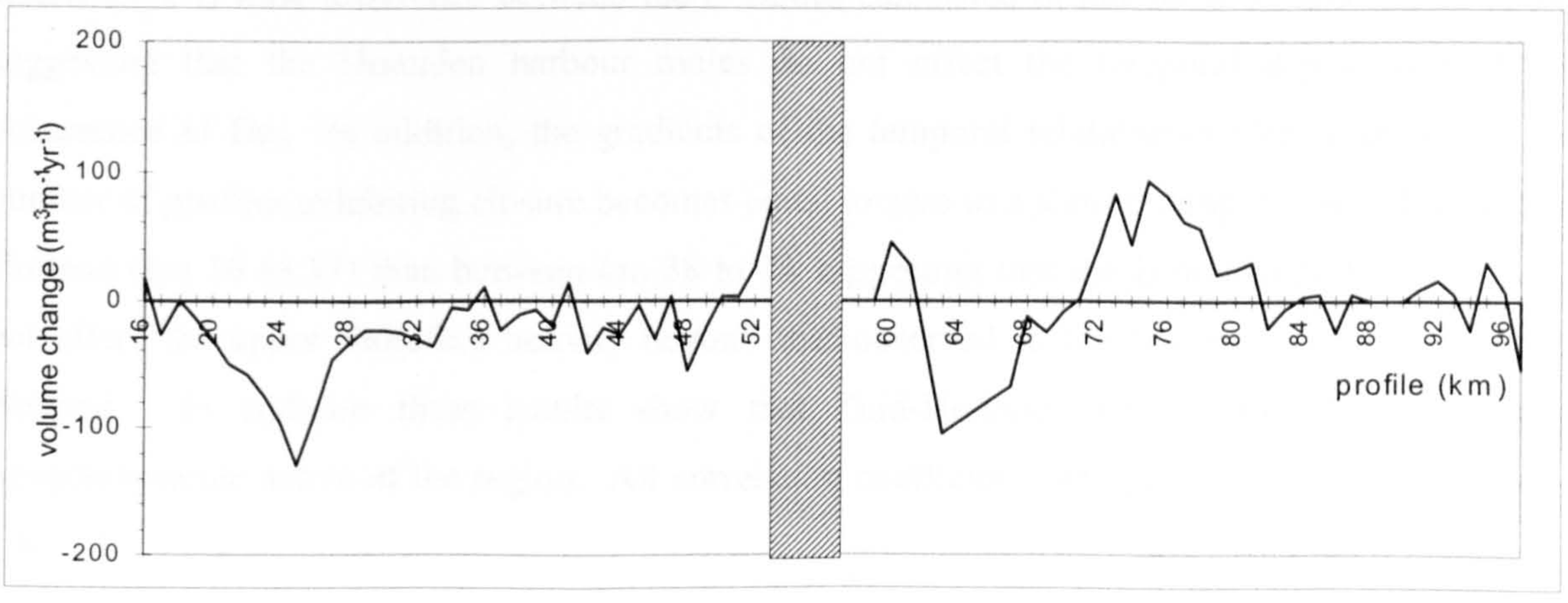


Figure 7.6. Alongshore volume changes per cross-shore profile. The lined rectangle represents the IJmuiden harbour moles.

In order to investigate this potential control, the volume change is compared with the residual closure. Residual closure is calculated through the subtraction of observed Dc_s from the corresponding calculated (using Eq.2.6) closure. Linear regression between the two variables only explains 0.11 and 0.06[5] of the variance (5 and 10 years respectively). This indicates that, on the medium- and large-scale, volume change is an extremely weak control upon closure.

7.2.5) ANTHROPOGENIC FORCINGS : THE IJMUIDEN HARBOUR MOLES (km 55/57)

The large-scale (2.5 km cross-shore; 1 km longshore) of the IJmuiden harbour moles in combination with their location and the observed boundary between the two Dc_s provinces (Chapter 6), suggests that they could have a large influence upon the coastal morphodynamic system. In order to determine whether the harbour moles do indeed have an impact upon surrounding shoreface activity a morphodynamic 'rule-of-thumb' was adopted. This rule-of-thumb is an empirical estimation based upon the idea that flow obstruction has a maximum morphological effect. It states that the influence of a structure, be it natural e.g. the Marsdiep Inlet (Figure 1.4), or anthropogenic e.g. the harbour moles, will extend to seven times its largest dimensions (Van Rijn, 1998). Therefore the length of the IJmuiden harbour moles, 2.5 km, is multiplied by the factor of seven and a distance of 18 km either side of the harbour moles highlighted. As a result, the profiles km 38 to 74 are treated separately from calculations with the profiles km 16 to 37 and km 75 to 97. The occurrence of Dc_s for each temporal period (5 to 32 years) was calculated using the sddc fixed tail method (change criteria 0.25 m).

The results obtained produce a strongly significant correlation coefficient at the 95% confidence of which there is little difference between the r^2 values calculated in km 16 to 37 and km 38 to 74, suggesting that the IJmuiden harbour moles do not affect the temporal dependence of the occurrence of Dc_s. In addition, the gradients of the temporal relationship clearly show that the number of profiles exhibiting closure becomes equal to zero in a shorter temporal period in Noord-Holland (km 16 to 37) than between km 38 to 74 suggesting that the IJmuiden harbour moles do not affect the upper shoreface activity beyond that observed in the 'natural' system of Noord-Holland. In addition these results show that Zuid-Holland (km 75 to 97) is the least morphodynamic active of the region. All correlation coefficients and gradients are given in Table 7.6.

[5] at the 95% confidence level

	NOORD-HOLLAND (km 16 - 37)	IJMUIDEN (km 38 - 74)	ZUID-HOLLAND (km 75 - 97)
CORRELATION COEFFICIENT (95% confidence)	-0.95	-0.97	-0.72
GRADIENT (%yr^{-1})	3.1	2.1	1.4

Table 7.6. Correlation coefficients and gradients between the occurrence of Dc_s and temporal period for profiles including/excluding the influence of the IJmuiden harbour moles.

7.3) MIDDLE/LOWER SHOREFACE BEHAVIOUR : THE ACTIVE SHOREFACE

7.3.1) INTRODUCTION

It is important to determine what the nature of the causes upon the middle and lower shoreface morphodynamic behaviour is. In this situation this is approached by calculating whether the activity is the result of accretional or erosional changes in the shoreface bathymetry. After this has been determined, the potential controls upon this activity can then be analysed. As no additional process-based measurements are available for use e.g. current readings around the natural terraces of Noord-Holland (Figure 4.13), the controls have to be determined through literature research (Chapter 2). In addition to the natural controls which could act upon the shoreface, the suspected anthropogenic influence of the IJmuiden harbour moles is also investigated.

7.3.2) BATHYMETRIC CHANGES : ACCRETIONAL OR EROSIONAL?

As shown in Figure 7.7 the observed shoreface behaviour has been correlated with net depth changes for the total period of measurements; 1965 to 1997 for km 16 to 71 and 1970 to 1997 for km 72 to 97. (To ensure that the net behaviour does not result from measurement error, the periods 1970 to 1997 and 1965 to 1993 are also examined for km 16 to 71, and 1975 to 1997 and 1970 to 1993 for km 72 to 97).

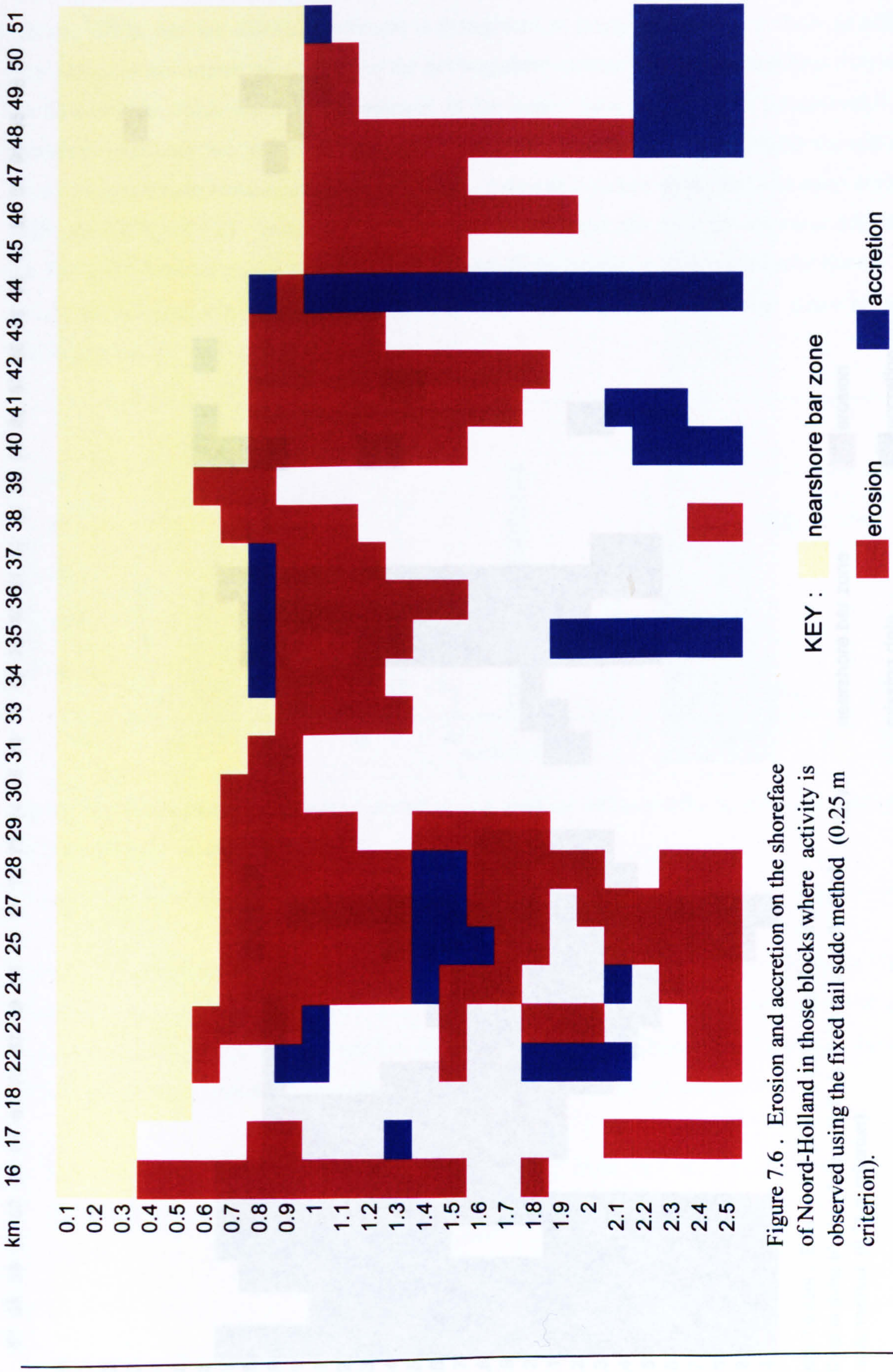


Figure 7.6 . Erosion and accretion on the shoreface of Noord-Holland in those blocks where activity is observed using the fixed tail sddc method (0.25 m criterion).

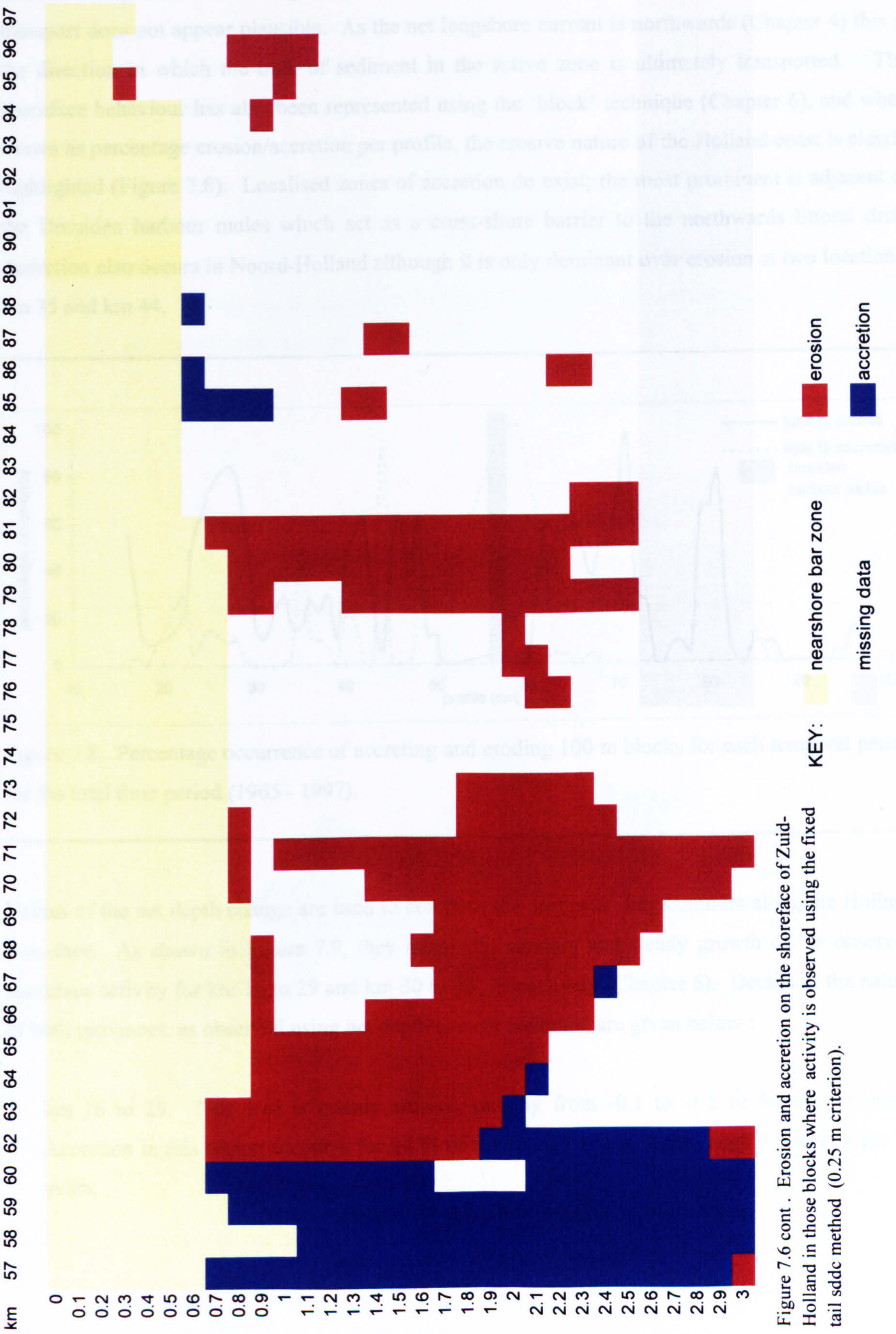


Figure 7.6 cont . Erosion and accretion on the shoreface of Zuid-Holland in those blocks where activity is observed using the fixed tail sddc method (0.25 m criterion).

The shoreface behaviour is typically erosive, as observed in existing studies (van Rijn, 1995; 1997; Hinton, 1998), and the resulting sediment is interpreted as being transported onshore as offshore transport does not appear plausible. As the net longshore current is northwards (Chapter 4) this is the direction in which the bulk of sediment in the active zone is ultimately transported. The shoreface behaviour has also been represented using the 'block' technique (Chapter 6), and when shown as percentage erosion/accretion per profile, the erosive nature of the Holland coast is clearly highlighted (Figure 7.8). Localised zones of accretion do exist; the most prominent is adjacent to the IJmuiden harbour moles which act as a cross-shore barrier to the northwards littoral drift. Accretion also occurs in Noord-Holland although it is only dominant over erosion at two locations; km 35 and km 44.

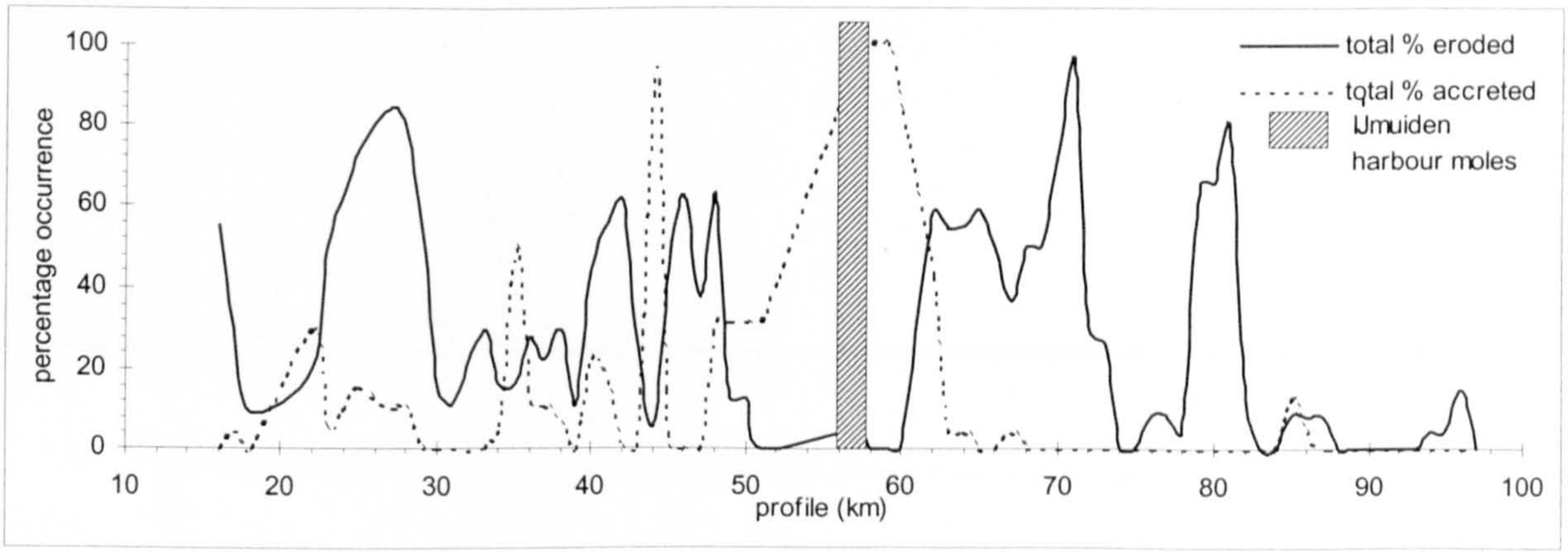


Figure 7.8. Percentage occurrence of accreting and eroding 100 m blocks for each temporal period for the total time period (1965 - 1997).

Values of the net depth change are used to compose the corresponding contours along the Holland shoreface. As shown in Figure 7.9, they mirror the random and steady growth of the observed shoreface activity for km 16 to 29 and km 30 to 73, respectively (Chapter 6). Details of the nature of both provinces, as observed using net depth change contours, are given below :

1. km 16 to 29. This area is mainly erosive, ranging from -0.1 to -1.5 m for the 32 years. Accretion in this region accounts for 14 % of the change and is in the range 0.2 to 1 m per 32 years;

2. km 30 to 51. Within this area a 'growth' of net erosion to the west[6] is observed, particularly east of km 38 to 40 (Table 7.7). As is most apparent in between km 46 and 51, this behaviour is concentrated towards the shoreward boundary of the profile (< 1.5 km offshore);
3. km 57 to 62. Net accretion is observed, ranging from 0.1 m to 5.1 m for the 32 year period. The greatest accretion is observed at the shoreward limit of those profiles closest to the IJmuiden harbour moles e.g. 5.1 m accretion per 32 years occurs at 0.7 km offshore at km 57.
4. km 63 to 73. Here erosion follows the temporal growth of activity northwards and southwards from a northwesterly-southeasterly axis offshore (Figure 6.12); the greatest erosion is observed in the centre of the zone and decreases northwards and southwards; and
5. km 79 to 81. The net depth change for this area is relatively constant (x = -0.2 m; sd = $\pm$0.1 m). The greatest erosion is located 1.8 to 2.1 km offshore.

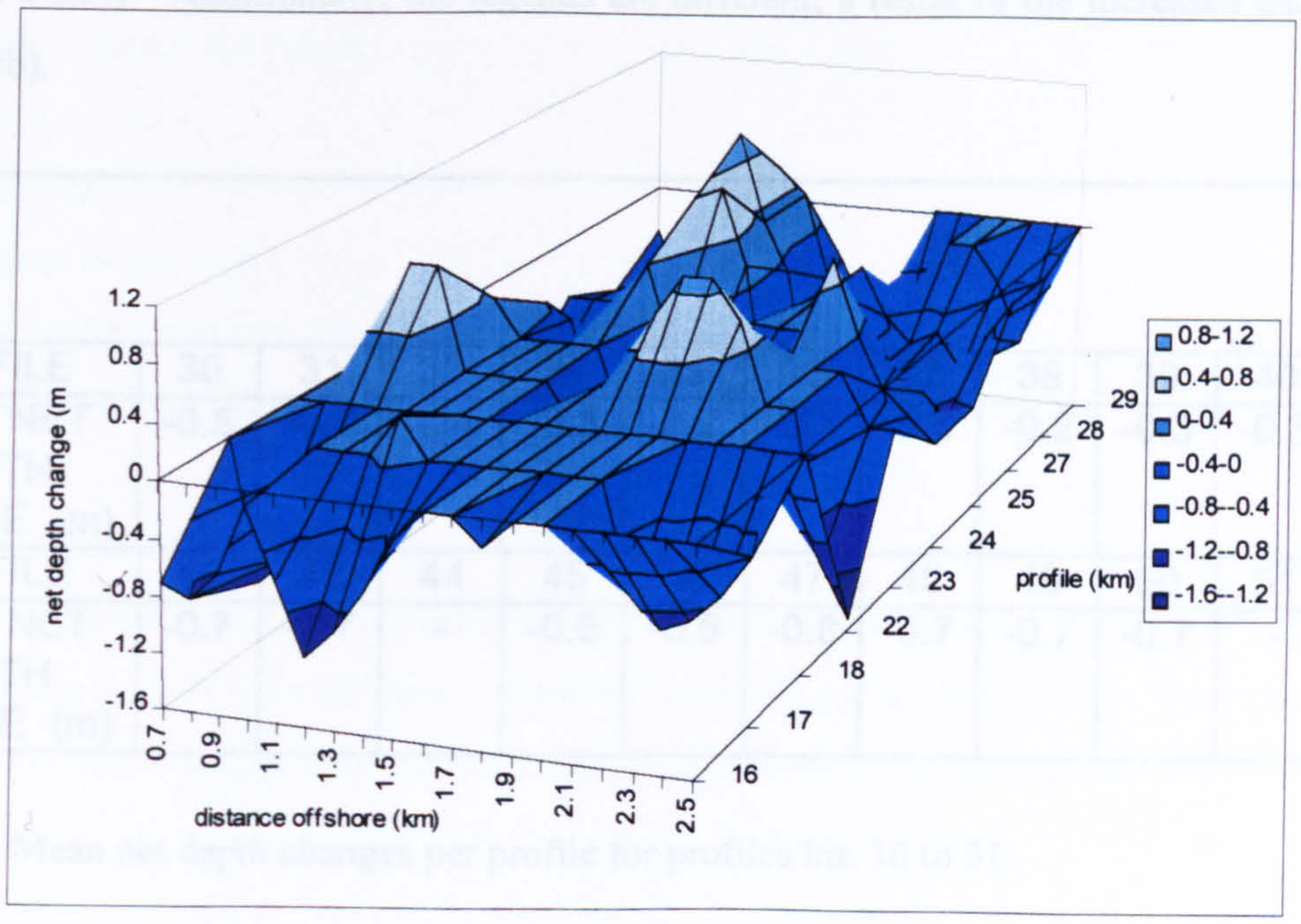


Figure 7.9a. Contours of net depth change for each profile in the region km 16 to 29. It is clear that there is no distinct pattern of erosion/accretion.

[6] here shorewards is northwards

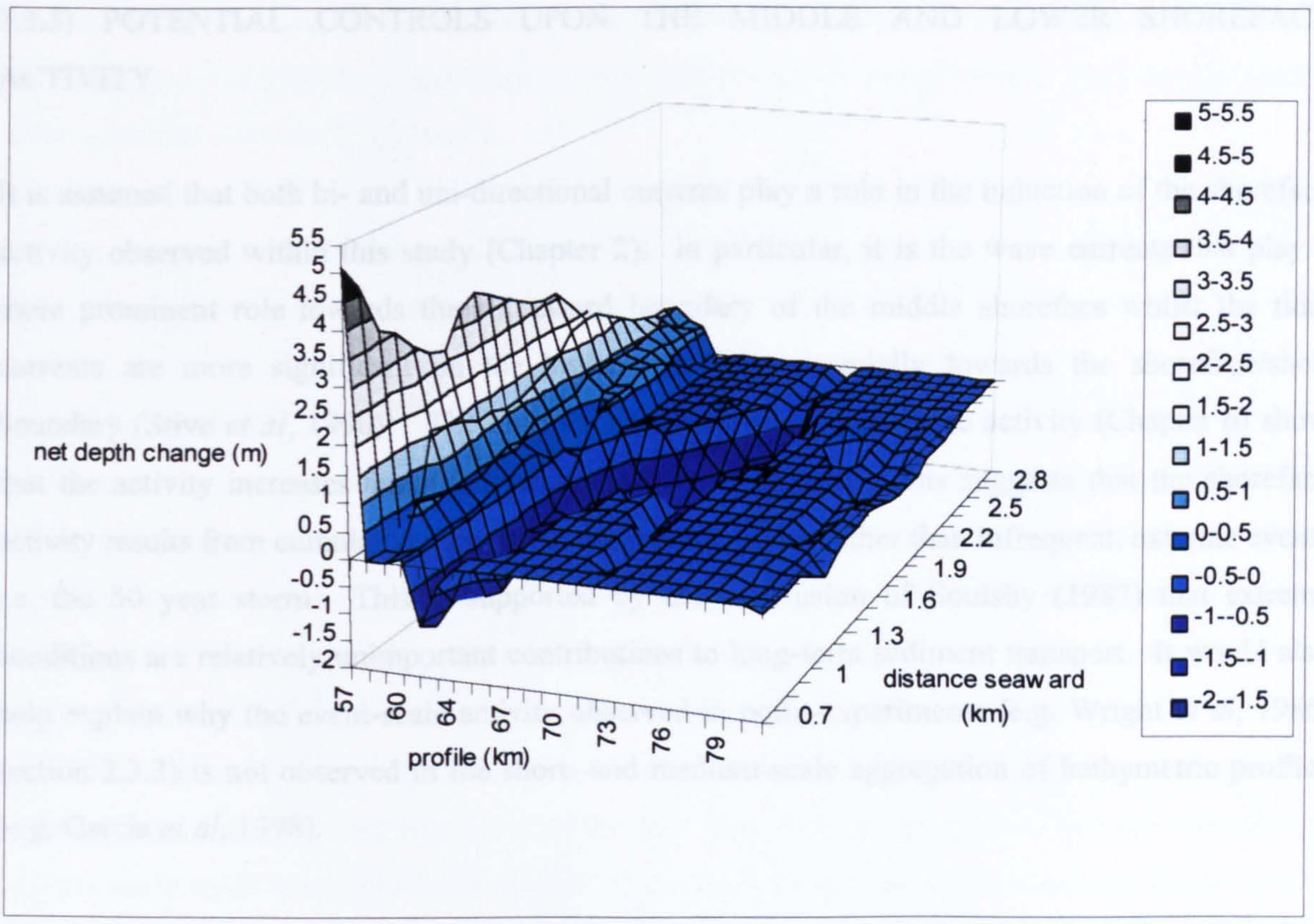


Figure 7.9b. Contours of net depth change in the region km 57 to 81 for the total period (1965 - 1997). Note that the orientation of Figure 7.9a) and b) are different, allowing the scour hole of b) to be seen clearly. Additionally, the legends are different, a result of the increased data points in Figure 7.9b).

PROFILE	30	31	33	34	35	36	37	38	39	40	41
MEAN NET DEPTH CHANGE (m)	-0.5	-0.7	-0.4	-0.3	-0.2	-0.5	-0.5	-0.2	-0.3	-0.3	-0.4
PROFILE	42	43	44	45	46	47	48	49	50	51	
MEAN NET DEPTH CHANGE (m)	-0.7	-0.7	-	-0.6	-0.6	-0.8	-0.7	-0.7	-0.7	-	

Table 7.7. Mean net depth changes per profile for profiles km 30 to 51.

7.3.3) POTENTIAL CONTROLS UPON THE MIDDLE AND LOWER SHOREFACE ACTIVITY

It is assumed that both bi- and uni-directional currents play a role in the induction of the shoreface activity observed within this study (Chapter 2). In particular, it is the wave currents that play a more prominent role towards the shoreward boundary of the middle shoreface whilst the tidal currents are more significant on the lower shoreface, especially towards the shoreface/shelf boundary (Stive *et al*, 1990). The observations made of the shoreface activity (Chapter 6) show that the activity increases temporally at an almost steady rate. This suggests that the shoreface activity results from cumulative effects i.e. the regular storm, rather than infrequent, extreme events i.e. the 50 year storm. This is supported by the conclusion of Soulsby (1987) that extreme conditions are relatively unimportant contributions to long-term sediment transport. It would also help explain why the event-scale activity observed in point-experiments (e.g. Wright *et al*, 1986; section 2.3.3) is not observed in the short- and medium-scale aggregation of bathymetric profiles (e.g. Garcia *et al*, 1998).

This section investigates potential influences additional to wave- and current-activity. They take the form of both natural and anthropogenic controls and are listed below :

1. shoreface-connected ridges;
2. offshore terraces;
3. offshore bars;
4. shoreface bathymetry;
5. Hondsbossche and Pettermer seawall; and
6. IJmuiden harbour moles.

Another potential control upon the shoreface activity could be argued to be sand wave migration. However, these are not found in water depths less than 14 m off the Holland coast (Van Alphen and Damoiseaux, 1989). In addition, a residual current of greater than 0.5 ms^{-1} is required for their migration (Stride, 1963) and the residual current off the Holland coast is only 0.1 ms^{-1} (Van Rijn, 1997).

The longshore location of the proposed controls are shown alongside those profiles which are observed to exhibit active shorefaces in Figure 7.10. It is apparent that there is no obvious relation

between the location of the potential controls and shoreface activity, although it is suggested that the highly variable growth of shoreface activity between km 16 and 29 results from the interaction of the potential controls 2, 3, 4 and 5.

The control that each of the six features of the Holland coast could have upon the shoreface behaviour, inducing activity are now discussed :

7.3.3.1) SHOREFACE-CONNECTED RIDGES

As discussed in Chapter 4, the shoreface-connected ridges are located within the central Holland coast and are mapped at depths of 14 to 15 m (typically the shelf-shoreface boundary). If one examines the geomorphological map of the Holland coast (Appendix 4.1) it is possible to see that the shoreward boundary of the ridges are very abrupt and not to be expected in a natural system. Indeed, 3-dimensional bathymetric plots taken from the $JARKUS_E$ data set (Figure 7.11) clearly show the ridges extending further onshore than suggested by this map. The ridges are associated with the large-scale i.e. they interact with the shoreface over the long-term, and are estimated to migrate northwards along the Holland coast at a rate of 1 myr^{-1} based on relatively limited short-term process measurements and modelling (Van de Meene, 1984). This coincides with the timescale over which the observed shoreface activity becomes significant (Chapter 6). At the locations where the shoreface-connected ridges interact with the middle to lower shoreface they might therefore cause bathymetric activity over the large-scale, although this remains speculative.

7.3.3.2) OFFSHORE TERRACES

Two offshore terraces are located in Noord-Holland, at approximately km 15. As shown in the bathymetric plot of Figure 7.12 they are prominent features of the shoreface in this province for example from its shallowest point the shallower terrace extends southwards by 6 km, deepening by 8.5 m. There is no known literature on the evolution and erosion of the terraces, or current patterns around them; existing studies suggest that they are composed of erosion-resistant sediment (Bakker *et al*, 1998; Chapter 4). This suggests that they act as an 'interruption' to 'normal' current patterns. The combination of steep flanks (this would enhance any gravitational effects) and increased current flow could result in long-term changes in the local bathymetry. The author however, feels that before the terraces can be related to the observed shoreface activity at this location with confidence, further research needs to be performed on what appears to be a relatively unknown morphological feature of the Holland coast.

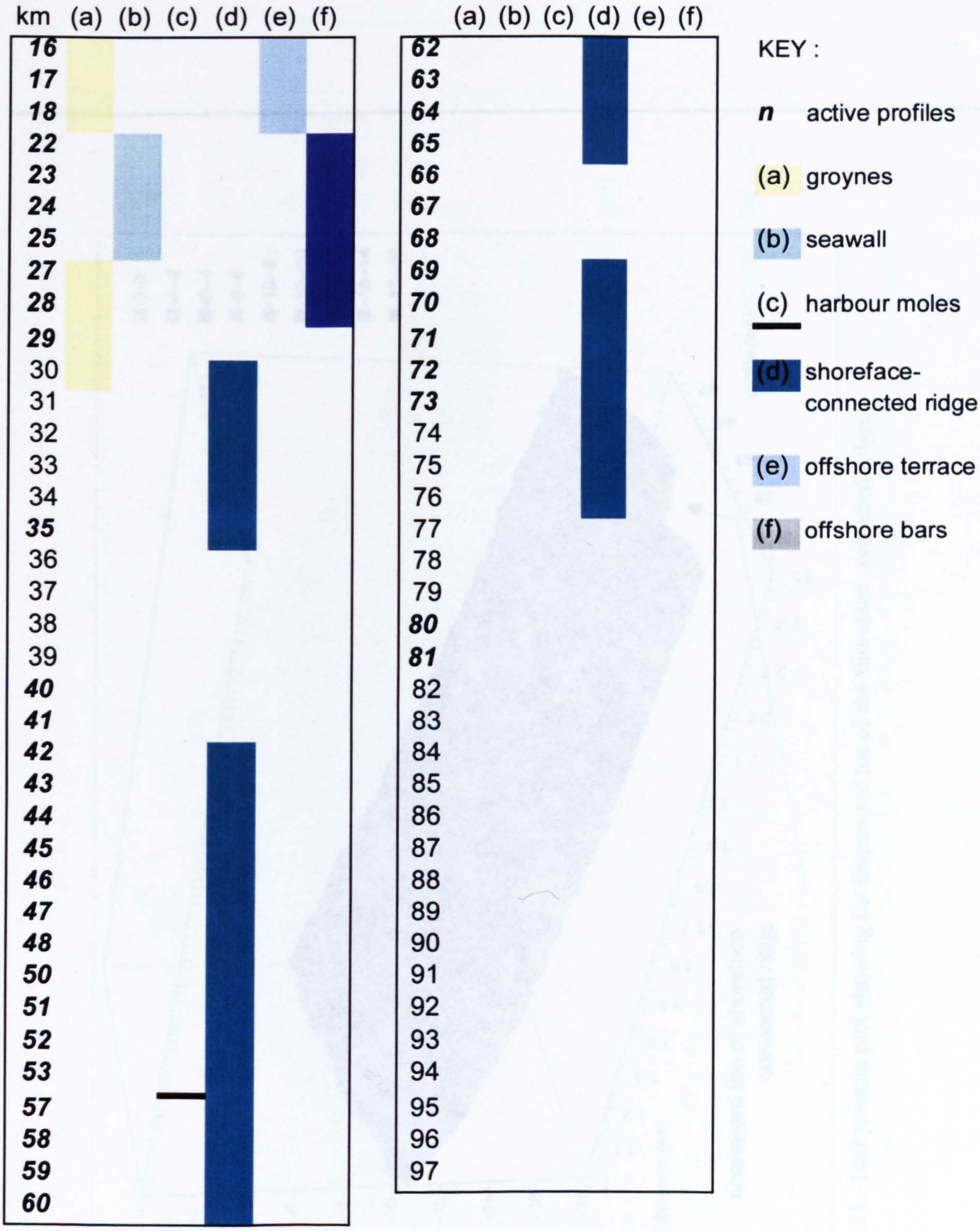


Figure 7.10. The alongshore location of possible influences upon the shoreface activity. (The shoreface-connected ridges are extended onshore from their position as shown on the geomorphological map of Van Alphen and Damoiseaux, 1988).

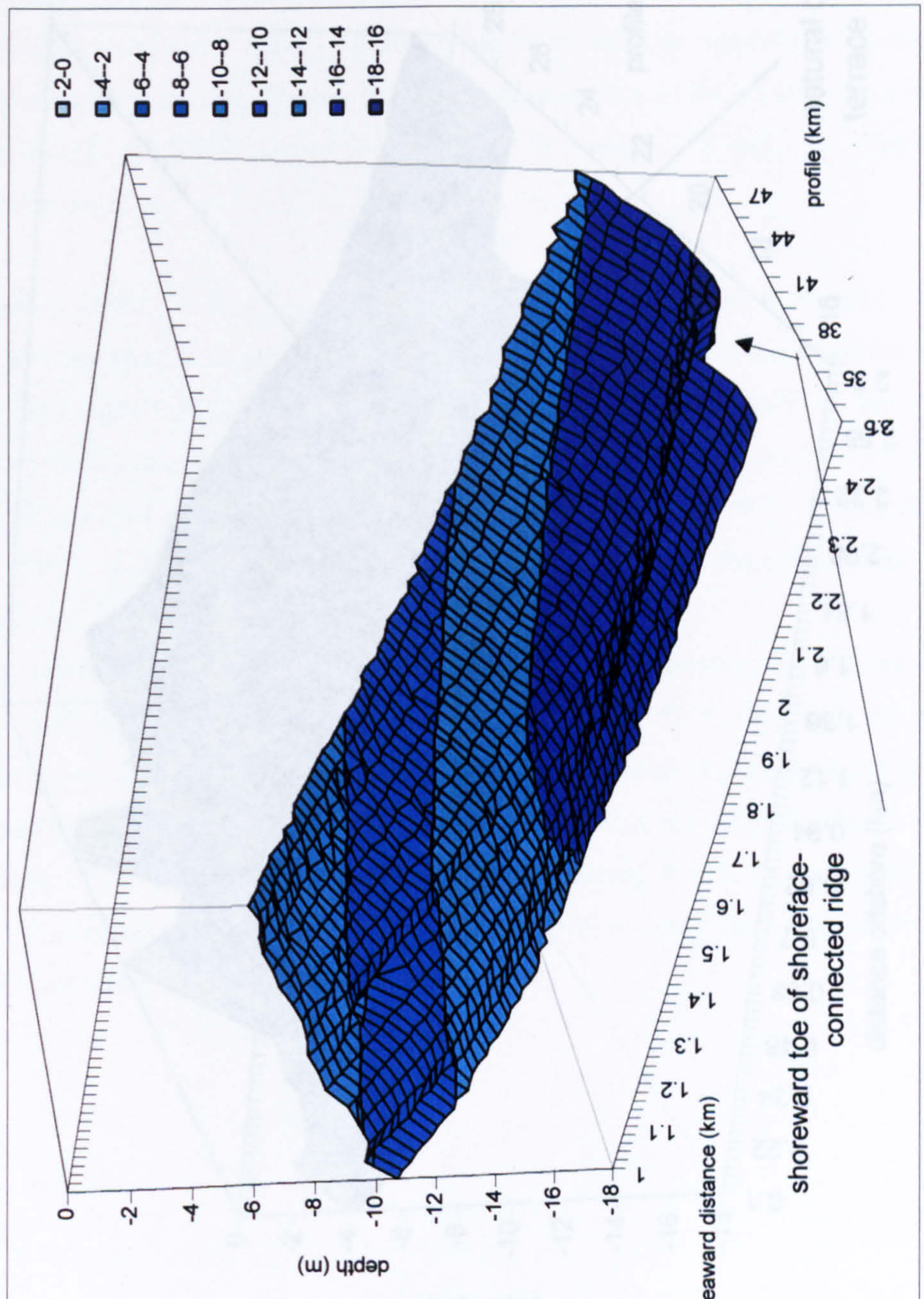


Figure 7.11. Bathymetric plot showing the shoreward toe of the shoreface-connected ridges.

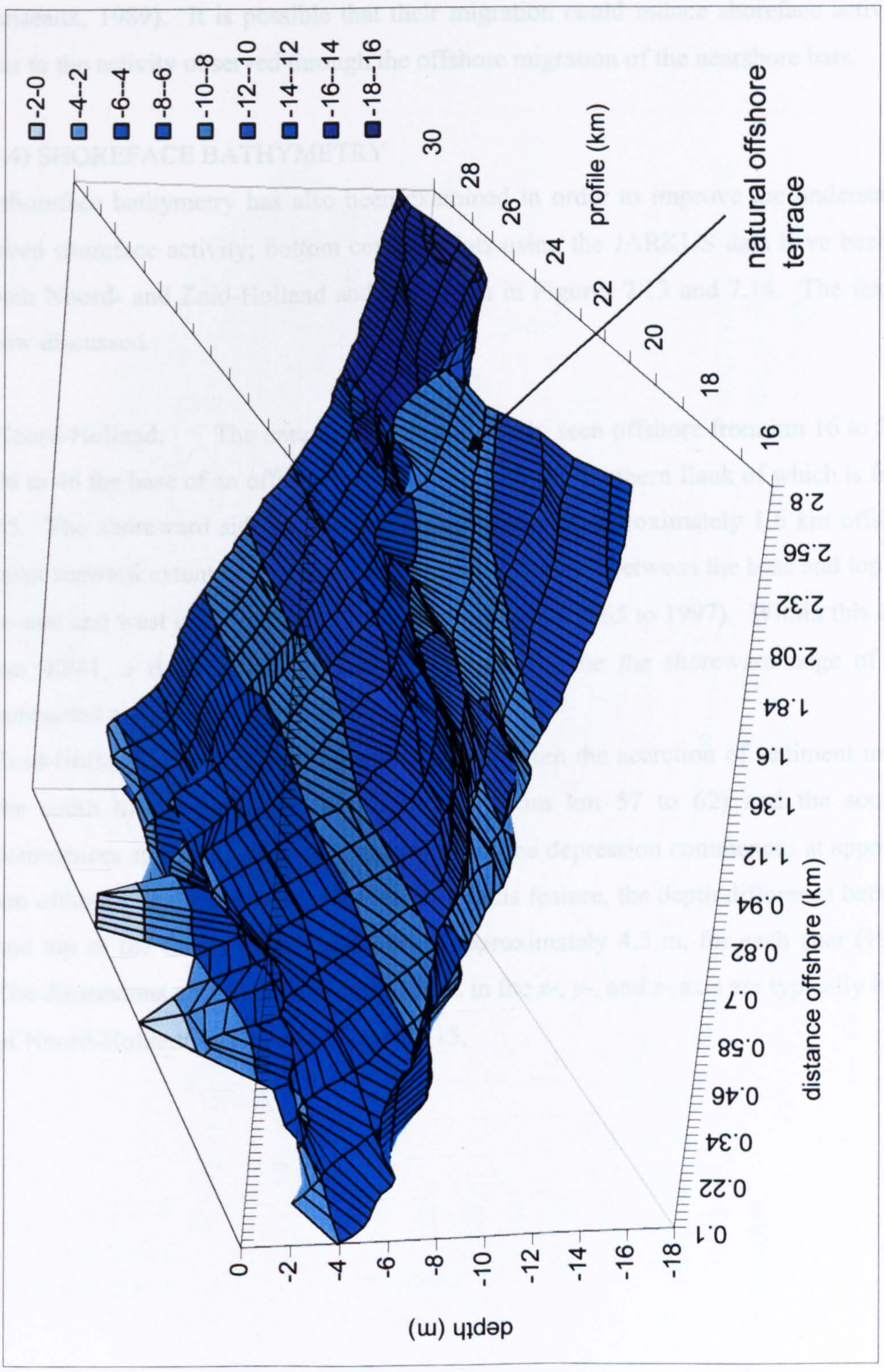


Figure 7.12. Bathymetry of the Holland coast from km 16 to 30 clearly showing the natural terrace from km 16 to 22. (Data taken from 1970).

7.3.3.3) OFFSHORE BARS

These features have been observed between km 20 and 28 in water depths ranging from 10 m to 20 m. The bars are up to several kilometres long and are typically 3 to 6 m high (Van Alphen and Damoiseaux, 1989). It is possible that their migration could induce shoreface activity, which is similar to the activity observed through the offshore migration of the nearshore bars.

7.3.3.4) SHOREFACE BATHYMETRY

The shoreface bathymetry has also been examined in order to improve the understanding of the observed shoreface activity; bottom contour plots using the JARKUS data have been constructed for both Noord- and Zuid-Holland and are shown in Figures 7.13 and 7.14. The features of both are now discussed :

1. Noord-Holland. The natural terraces are clearly seen offshore from km 16 to 25. From km 26 to 46 the base of an offshore depression exists, the southern flank of which is from km 47 to 55. The shoreward side of this depression begins at approximately 1.6 km offshore. At the most seaward extent of this feature, the depth difference between the base and top of the flanks to east and west is approximately 8 m, for each year (1965 to 1997). Within this depression, at km 40/41, a ridge is observed and is assumed to be the shoreward edge of a shoreface-connected ridge; and
2. Zuid-Holland. The northwards flank is formed from the accretion of sediment immediately to the south of the IJmuiden harbour moles (from km 57 to 62) and the southward flank commences at km 72. The shoreward flank of the depression commences at approximately 1.7 km offshore. At the most seaward extent of this feature, the depth difference between the base and top of the flanks to east and west is approximately 4.5 m, for each year (1965 to 1997). The dimensions of the southern depression, in the *x*-, *y*-, and *z*- axis are typically less than those of Noord-Holland, as shown in Figure 7.15.

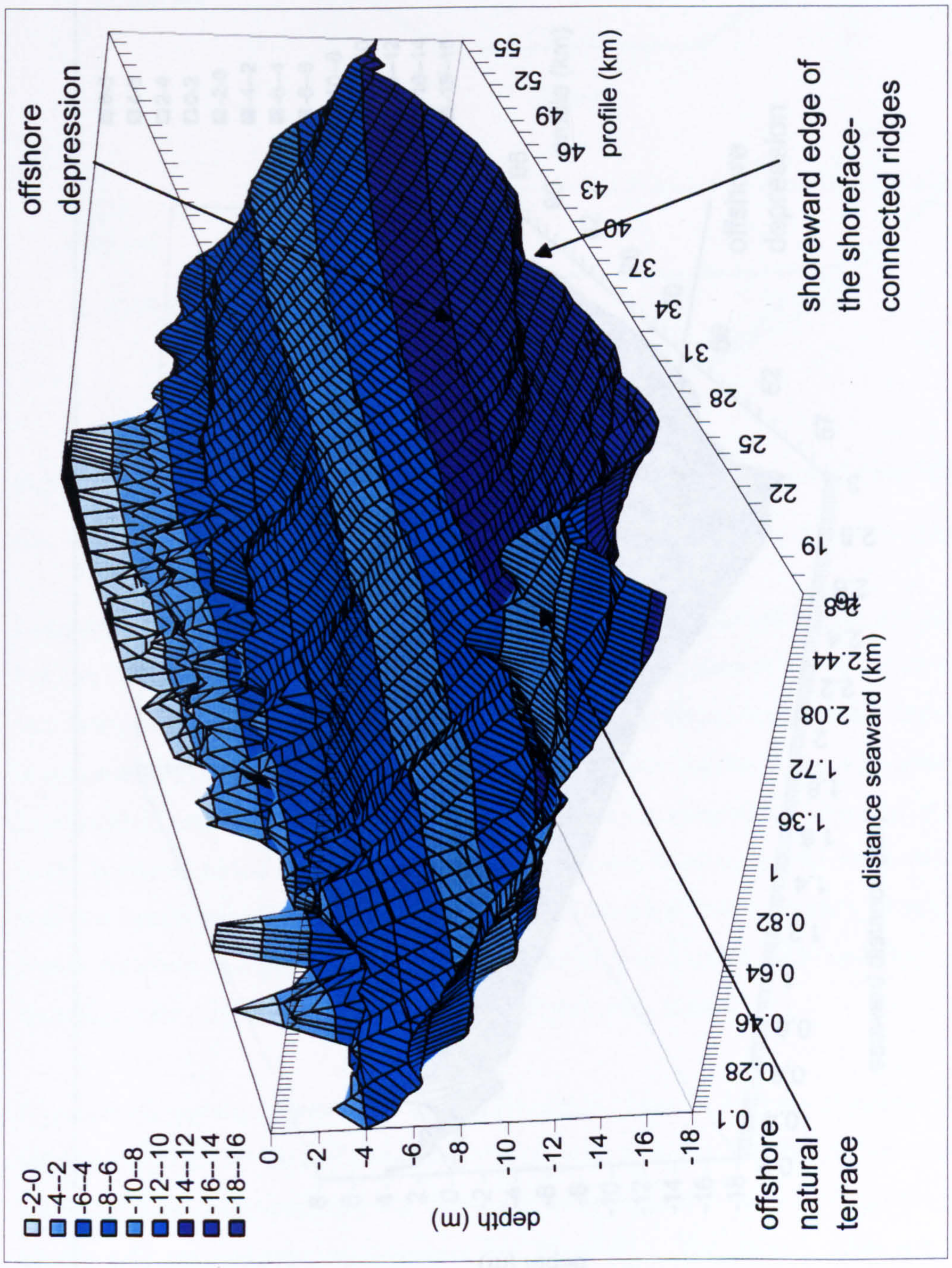


Figure 7.13. Bathymetry of Noord-Holland with the major features highlighted. (Data from 1970).

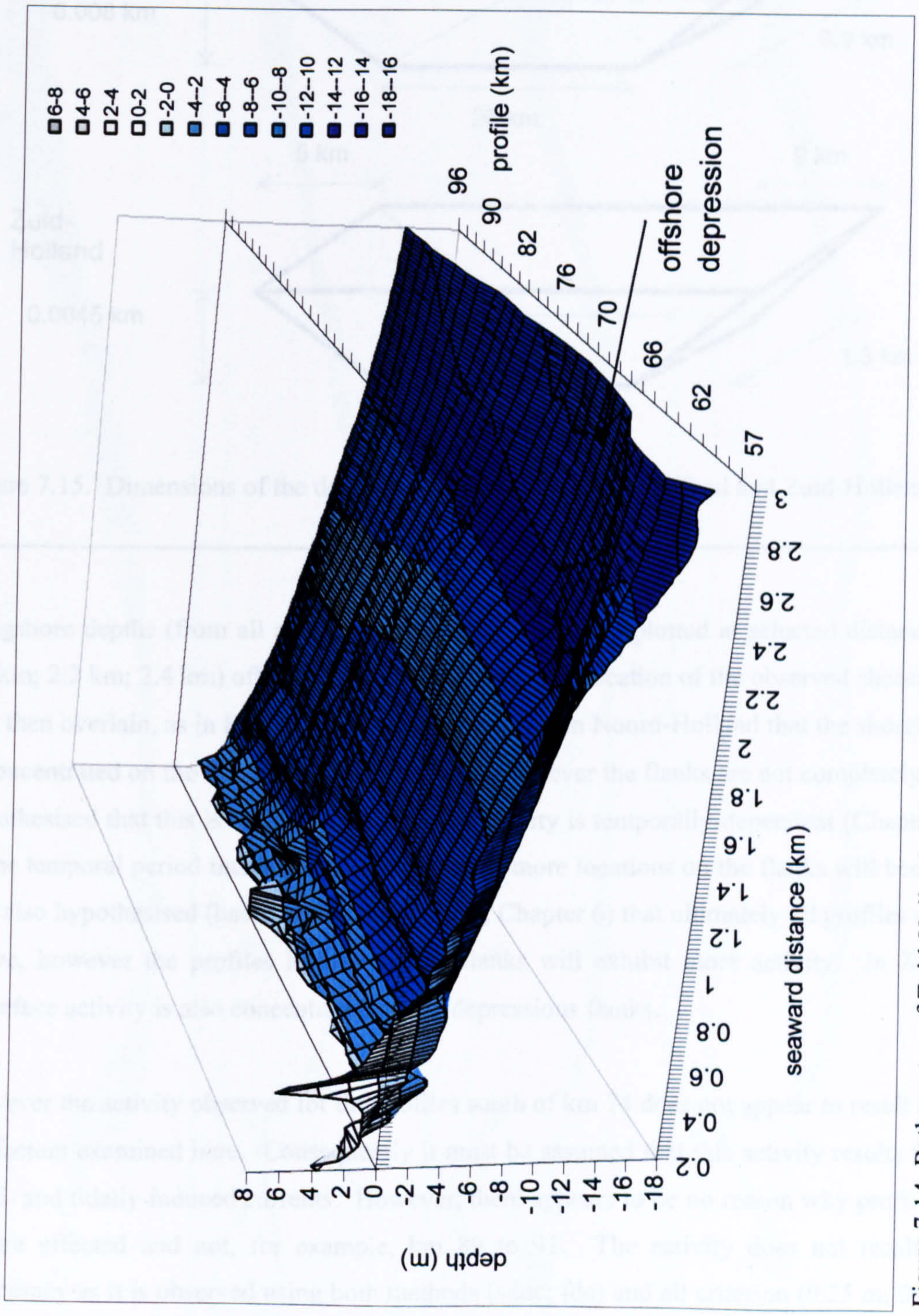


Figure 7.14. Bathymetry of Zuid-Holland with features highlighted. (Data from 1997).

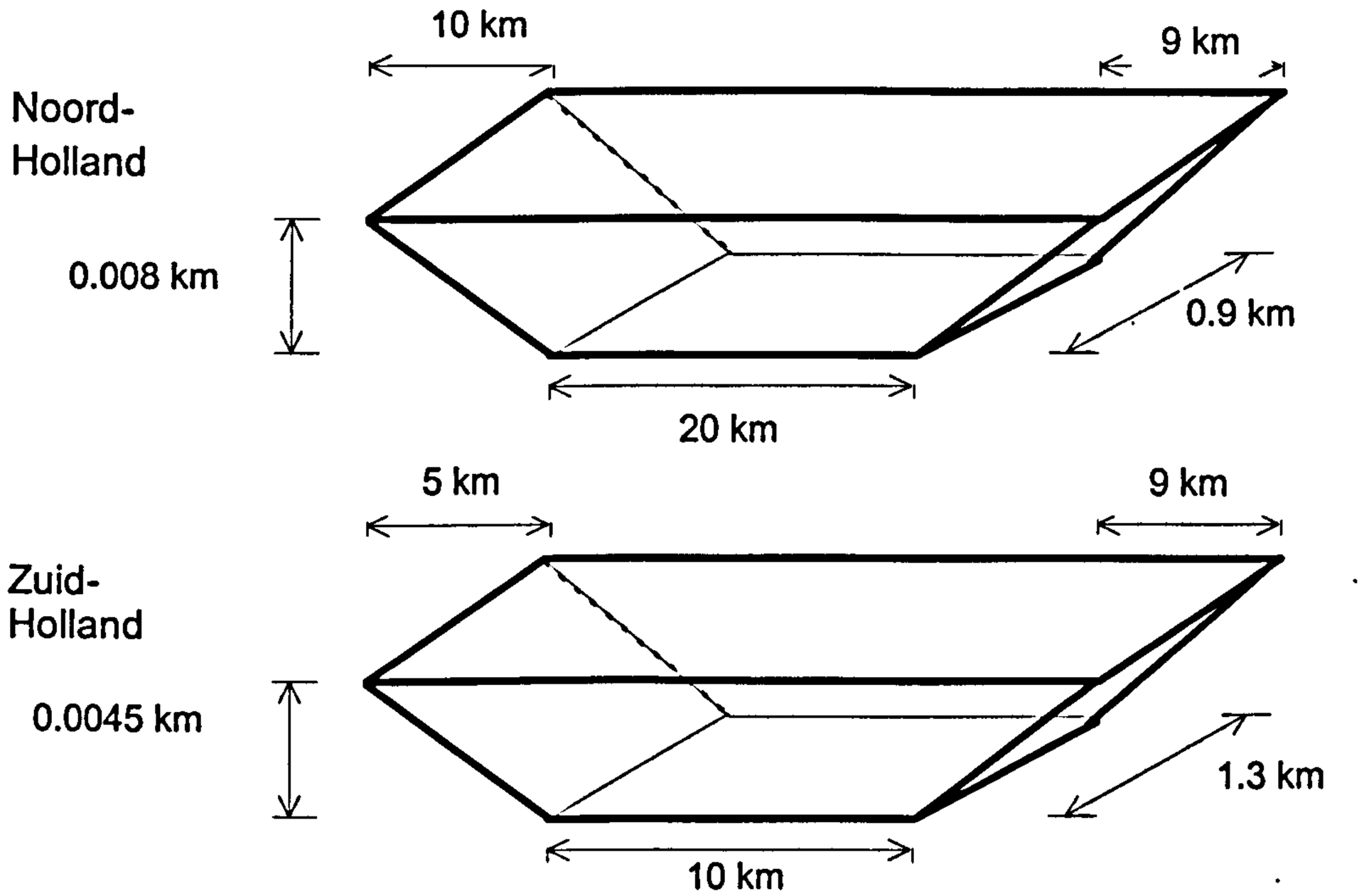


Figure 7.15. Dimensions of the depressions located in Noord-Holland and Zuid-Holland.

Longshore depths (from all available years) have also been plotted at selected distances (1.4 km; 1.8 km; 2.2 km; 2.4 km) offshore in both provinces. The location of the observed shoreface activity was then overlain, as in Figure 7.16. It is apparent within Noord-Holland that the shoreface activity is concentrated on the flanks of the depressions. However the flanks are not completely active; it is hypothesised that this is because the shoreface activity is temporally-dependant (Chapter 6) and so as the temporal period increases beyond 32 years, more locations on the flanks will become active. It is also hypothesised (based upon observations; Chapter 6) that ultimately all profiles will become active, however the profiles located on the flanks will exhibit more activity. In Zuid-Holland shoreface activity is also concentrated on the depressions flanks.

However the activity observed for the profiles south of km 74 does not appear to result from any of the factors examined here. Consequently it must be assumed that this activity results from wave-, wind- and tidally-induced currents. However, there appears to be no reason why profiles km 79 to 81 are affected and not, for example, km 89 to 91. The activity does not result from data inaccuracy as it is observed using both methods (sddc; fdc) and all criterion (0.25 m; 0.5 m; 0.75m which respectively corresponds to a 66 %; 95 % and 99.5 % confidence that real change has occurred).

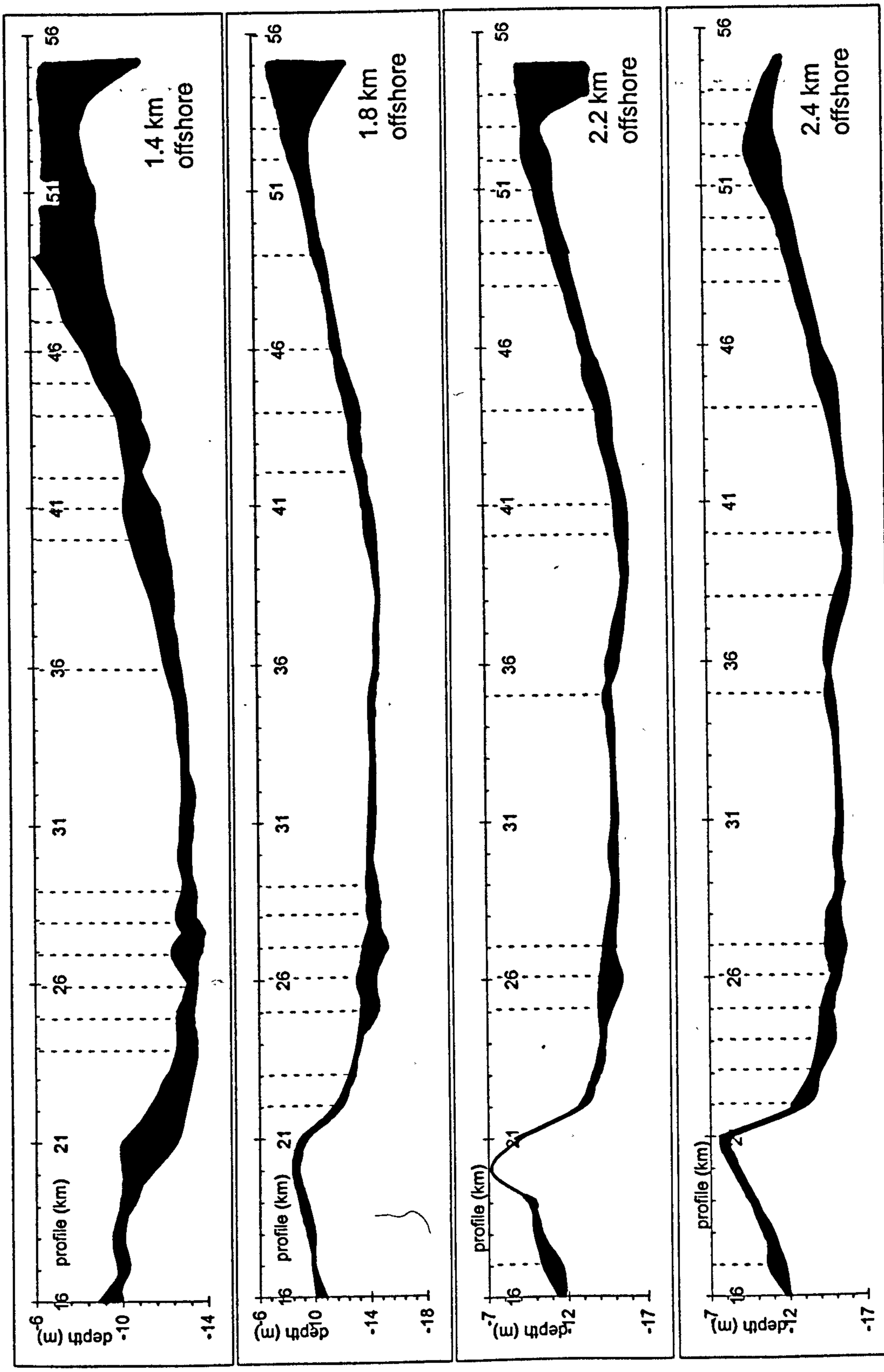


Figure 7.16. Alongshore contours vs. locations of shoreface activity within Noord-Holland for the total period (1965 - 1997). The dashed lines show the active profiles at the appropiate depth. (Note that sddc and fdc analysis has not been performed on profiles 19 to 21 as a result of missing data for certain years).

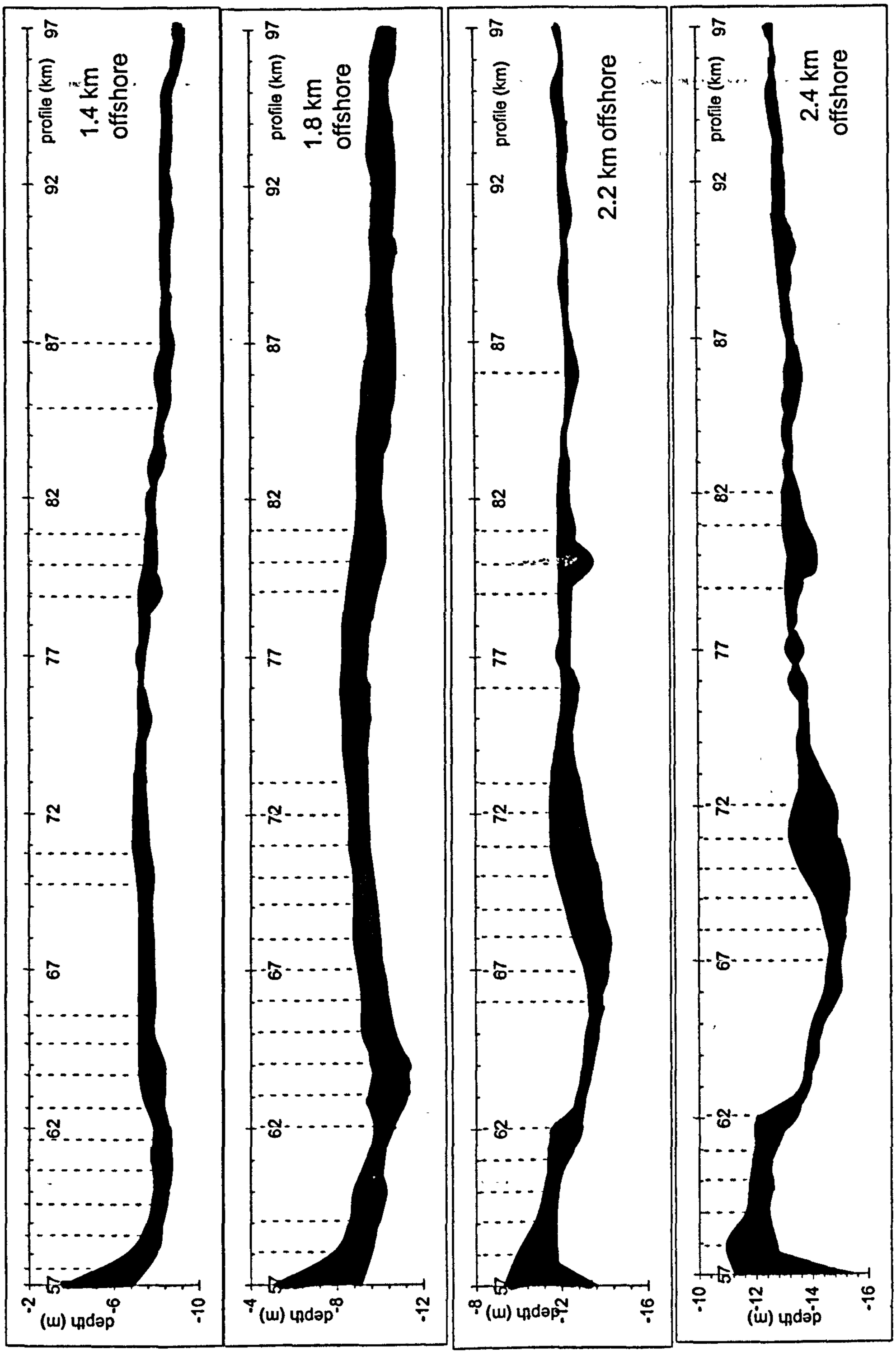


Figure 7.16cont.. Alongshore contours vs. locations of shoreface activity within Zuid-Holland for the total period (1965 - 1997). The dashed lines show the active profiles at the appropiate depth.

7.3.3.5) HONDSBOSSCHE AND PETTERMER SEAWALL

The Hondsbossche and Pettermer seawall (km 20 to 26) acts as an anthropogenic headland, protruding seaward from the present coastline. The profiles seaward of the seawall are steep, in particular the profiles immediately to the north of the seawall are the steepest along the Holland coast 1:0.02 (Chapter 4). This is probably due to shoreface erosion resulting in landward translation of the middle/lower shoreface but no landward profile translation in the nearshore due to the fixed boundary of the seawall. Alongshore gradients have been associated with shoreface activity (see following paragraph) and it is suggested this association can also be made here in the cross-shore. Bathymetric plots of the region (Figure 7.17) immediately north and seaward of the seawall show steep gradients in both the longshore (km 16 to 19; 1:0.002) and cross-shore (km 19; 1:0.02). It can be expected that sediment iniation readily occurs due to wave- and tidal-currents in addition to the enhanced gravitational effects enforced by the Hondsbossche and Pettermer seawall.

7.3.3.6) IJMUIDEN HARBOUR MOLES

There is a concentration of observed shoreface activity adjacent to the IJmuiden harbour moles (Figure 6.10). So, in order to see if the IJmuiden harbour moles do, as expected, exert the largest influence upon the shoreface behaviour, the occurrence of the three types of shoreface activity with time has been calculated for all profiles excluding km 38 to 74 (see section 7.2.5). Correlation coefficients were then calculated between the two variables[7] at the 95% confidence level. As with the investigation including profiles km 38 to 74, the relation between temporal period and occurrence of shoreface activity, as a combination of the three types, is strong and positively correlated. However, if each of the three classifications are examined as a function of time, a different evolution arises to that which exists for all profiles (km 16 to 97). This is clearly shown using all correlation coefficients, as in Table 7.8.

The correlation coefficients, calculated without profiles km 38 to 74, indicate that the number of profiles exhibiting shoreface activity increases through time. However this is the result of an increase in both the shoreward and seaward partially-active profiles rather than in the fully-active profiles. Additionally, those profiles exhibiting shoreward partial-activity do not significantly increase with time and instead the occurrence remains at a relatively constant value. This would suggest that seaward partially-active profiles are more characteristic of the shoreface behaviour of the Holland coast. Therefore the effect of the IJmuiden harbour moles is to induce shoreface activity across the entire cross-shore distance of a profile at temporal periods shorter than under

[7] occurrence of shoreface activity; temporal period

natural forcings. So if this anthropogenic influence were not present upon the Holland coast, partially-active profiles would be predominant and evolve to fully active profiles at temporal periods greater than 32 years.

The nature of the IJmuiden harbour moles control upon the shoreface activity is also supported by results from the examination of their influence upon the middle/lower shoreface closure ($Dc_{m/l}$).

Correlation coefficients calculated without profiles km 38 to 74 (section 7.2.4) show that the occurrence of $Dc_{m/l}$ decreases as a function of time. Note that the r^2 value calculated using analysis based on the change criterion 0.5 m is not as significant as with the 0.25 m criterion; the larger criterion has a greater change margin i.e. the percentage of profiles exhibiting seaward closure remains at a more constant value through time (Table 7.9). This suggests that the form of the influence of the IJmuiden harbour moles is to induce activity across the whole shoreface rather than the evolution of partial activity to full activity (where partial activity represents both shoreward and seaward partial activity).

	WITH IJMUIDEN INFLUENCE				WITHOUT IJMUIDEN INFLUENCE			
	P_a	P_b	F	ALL	P_a	P_b	F	ALL
CORRELATION COEFFICIENT (95% confidence)	0.93	0.72	0.98	0.95	0.61	0.91	0.93	0.96

Table 7.8. Correlation coefficients between percentage occurrence and temporal period (5 to 32 years). The method used here is the fixed tail sddc method (criterion 0.25 m). (P_a = shoreward partial activity; P_b = seaward partial activity and closure on middle/lower shoreface; F = fully active; ALL = three types of activity combined).

	WITH IJMUIDEN INFLUENCE		WITHOUT IJMUIDEN INFLUENCE	
	0.25 m	0.5 m	0.25 m	0.5 m
r^2 (95 % confidence)	-0.75	-0.35	-0.87	-0.4

Table 7.9. Correlation coefficients between percentage occurrence of the seaward limit of shoreface activity and temporal period for two scenarios; with and without profiles directly affected by the IJmuiden harbour moles.

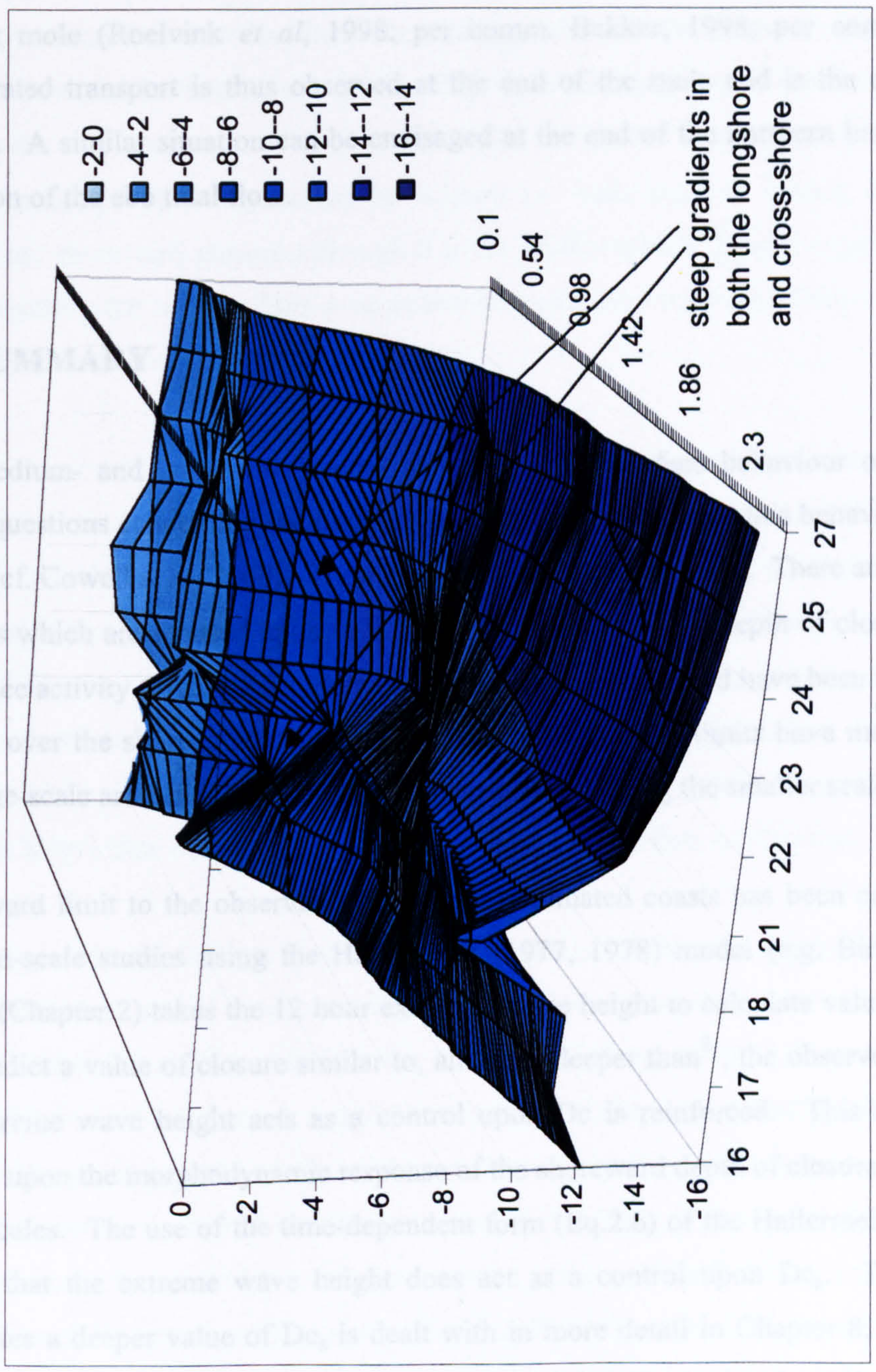


Figure 7.17. Bathymetry from km 16 to 27 clearly showing the steep alongshore and cross-shore gradients adjacent to the Hondsbossche and Pettermer seawall. (Data taken from 1970).

The effect of the IJmuiden harbour moles upon the adjacent shoreface is significant and the 'mechanism' behind the induction of activity can be equated to the influence of the harbour moles upon the local tidal currents. Process-based modelling, based upon the morphodynamic development of this area (Roelvink *et al*, 1998), has been used to reproduce the altered tidal currents; the northwards directed longshore current is halted and diverted seawards by the southern harbour mole (Roelvink *et al*, 1998; per comm. Bakker, 1998; per comm. van Rijn, 1998). Accelerated transport is thus observed at the end of the mole and is the cause of the sediment erosion. A similar situation can be envisaged at the end of the northern harbour mole due to the diversion of the ebb tidal flow.

7.4) SUMMARY

The medium- and large-scale spatial and temporal shoreface behaviour observed in Chapter 6 raised questions concerning the forcing conditions which relate to this behaviour over the specified scales (cf. Cowell *et al*, 2000). These questions are addressed here. There are two morphodynamic features which are focused upon in this chapter; the shoreward depth of closure and middle/lower shoreface activity (Figure 6.2). Some of the controls investigated have been recognised in previous studies over the short-, and sometimes, medium-scales; data limits have meant that controls over the large-scale are derived from assumptions made regarding the smaller scale behaviour.

A seaward limit to the observed Dc of wave-dominated coasts has been calculated in short- and medium-scale studies using the Hallermeier (1977, 1978) model (e.g. Birkemeier, 1985). This model (Chapter 2) takes the 12 hour exceeded wave height to calculate values of closure, and as it can predict a value of closure similar to, although deeper than[8] , the observed closure the fact that the extreme wave height acts as a control upon Dc is reinforced. This study investigates this control upon the morphodynamic response of the shoreward depth of closure over the medium- and large-scales. The use of the time-dependent form (Eq.2.6) of the Hallermeier (1977, 1978) model shows that the extreme wave height does act as a control upon Dc_s. The observation that it calculates a deeper value of Dc_s is dealt with in more detail in Chapter 8. In addition, it is also shown that it is the value of this wave height which is important and not its location in a sequence of wave heights i.e. chronology does not play a role in the control of the shoreward depth of closure.

[8] except during accretional events (Nicholls *et al*, 1998a)

Although a typical 0.2 m variation in wave height from Noord- to Zuid-Holland does result in a Dc_s variation of 1.5 m (km 17 to km 97; Table 7.1), it does not explain why there are two distinct provinces of Dc_s (Figure 6.3) within Holland. An identical division of the coast is seen using the morphodynamics of the nearshore bar region (Figure 7.2; Wijnberg, 1995). This suggests that internal dynamics, taking the form of the nearshore bars, play a role in the control of the shoreward closure. Indeed, it is seen that there is a strong, positive relation between Dc_s and B_{SL} (the seaward limit of the nearshore bar region) (Figure 7.5). It is therefore concluded that over the medium- and large-scales the response of Dc_s to the control of the wave forcing is 'regulated' by the morphodynamics of the nearshore bar system i.e. both external forcing and internal dynamics control the shoreward closure although it is the former which i) has the greater control; and ii) is constrained by the latter. This is in agreement with existing work (Chapter 2) which states that, over the short- and medium-scales, :

> "*the response to the wave forcing is constrained by the internal dynamics of the morphological system*" (Nicholls *et al*, 1998b)

However, it is also apparent that the interaction of these controls is dependent upon the temporal period. Figure 7.5 shows that as the temporal period increases from 5 to 32 years, so the percentage of outliers[9] increases from 7% to 52%. This suggests that the influence of the bar system is less significant over the longer time periods (the increased role of the hydrodynamics over the longer time periods can not be investigated due to data limitations).

It was hypothesised that the IJmuiden harbour moles would play a role in the occurrence of Dc_s due to its i) large spatial extent and ii) position relative to the boundary between the two provinces of Dc_s (Chapter 6) and the nearshore bar system (Wijnberg, 1995). It was surprising therefore to find that it had little influence upon the occurrence of Dc_s; correlation coefficients$_{(95\% \text{ confidence level})}$ between temporal period and occurrence of Dc_s are significant when the profiles 'affected' by the harbour moles are both included and excluded (Table 7.6). It is suggested that this is the result of many of the profiles which are 'affected' by the harbour moles[10] falling under the classification of seaward partially-active or fully-active (Figure 6.7) and so do not exhibit a shoreward closure.

[9] as identified by significant variation from the m = 1 line
[10] according to the 'rule of thumb' of Van Rijn (1998)

There is little information available about the causes and controls which act upon the morphodynamic behaviour of the shoreface. Of the information that does exist, it is typically for the short-term (e.g. Niedoroda *et al,* 1985; Brink, 1987; Wright, 1995) and usually provides information concerning the characteristic sediment transport recorded during event-scale experiments (e.g. Snedden *et al*, 1988). As already stated in this chapter, there are no measurements available of the behaviour of the Holland shoreface, hence the controls upon the observed behaviour are determined through literature reviews.

The activity observed on the Holland shoreface results from erosive processes. This was determined from net depth change calculations and agrees with existing sediment budget studies (de Ruig, 1989; Knoester, 1990; van Vessem and Stolk, 1990; de Ruig and Louisse, 1991; van Rijn, 1995; 1997; Hinton, 1999). The contours of net depth change (Figure 7.9) mirror the observed growth of shoreface activity in Noord- and Zuid-Holland, in addition (as one would expect) the greatest activity is correlated with the greatest quantity of erosion. The shoreface erosion is controlled by regular events whose cumulative effects result in the shoreface activity steadily increasing through time; irregular, extreme events do not appear to influence the observed shoreface activity (cf. Soulsby, 1987). It also appears that bathymetric gradient plays an important role. Slopes of greatest cross-shore and longshore gradient correlate with locations of the shoreface activity (Figure 7.16) and so it is suggested that these locations are more susceptible to sediment erosion by currents[11]. (The entrained sediment is ultimately transported onshore by the dominant cross-shore currents).

It is not possible to produce conclusions about the controls upon the middle and lower shoreface activity due to a lack of measurements (e.g. current measurements in the proximity of the natural terraces). However, it has been possible within this study to quantitatively determine the influence of the IJmuiden harbour moles upon the activity and so draw conclusions. Using the van Rijn (1998) rule of thumb it has been possible to determine the evolution of the Holland shoreface without the influence of the harbour moles. It is clearly seen that this large-scale engineering structure has a significant impact upon the morphodynamic activity along this coast. Correlation coefficients$_{(95\% \text{ confidence level}}$ for the temporal dependence of the three types of active shoreface are strongly significant both with and without the profiles affected by the harbour moles (Table 7.8). However differences do exist between the two scenarios which led to the conclusion that the IJmuiden harbour moles act to induce morphodynamic activity along entire cross-shore profiles at

[11] wave currents towards the shoreward boundary and tidal currents towards the seaward boundary

time periods less than under natural forcings. This conclusion is also drawn when the same investigation is undertaken for the middle/lower shoreface closure (Table 7.9).

In conclusion therefore :

1. the shoreward depth of closure is under the control of external forcings, as the 12-hour exceeded wave height, and internal dynamics, as the morphodynamics of the nearshore bar system. The effect of the former is constrained by the latter and is more significant over the longer time periods;
2. the active middle and lower shorefaces are typically erosive and it is hypothesised to be under the influence of a number of factors, the most evident being regular events interacting with local increases and decreases in the slope gradients;
3. the IJmuiden harbour moles have a significant impact upon the middle/lower shoreface activity, causing it to become fully active at shorter time scales than in a natural system; and
4. more research, in the form of instrument deployment e.g. current meters, needs to be undertaken before the controls upon the shoreface activity can be confidently identified and completely understood.

8) PREDICTIONS OF THE SHORT-, MEDIUM- AND LONG-TERM BEHAVIOUR OF THE HOLLAND SHOREFACE

8.1) INTRODUCTION

This study is unique as it has allowed the observation of morphodynamic behaviour of a wave-dominated shoreface along 81 km of shoreline to 15 to 16 m depths over 32 years. There are few coastlines for which observations, such as that presented here are available. In the absence of such data, predictive techniques and models, are often relied upon to provide the necessary information. Yet if there is insufficient knowledge relating to large-scale behaviour, how can one confidently predict the appropriate behaviour? A consequence of minimal levels of data and information is insufficient calibration of the proposed techniques. It is therefore the purpose of this chapter to test existing predictive methods of coastal behaviour. In concurrence with the topic of this research, emphasis is placed upon the large-scale shoreface behaviour, although the short- and medium-scales are also examined. Additionally, projections are made beyond the JARKUS data limits (32 years) based upon observations from this study to allow an insight into the timescales of shoreface evolution over the very-long-term, including the impacts of human interference upon this evolution. Although most of these projections can not be calibrated they will provide useful information concerning the potential nature of very-long-term trends; deviations between the trends and model outputs should alert the user to possible errors within the model[1]. The research objectives three and four are focused upon (section 1.3) :

Evaluate the ability of existing models to predict shoreface morphodynamic behaviour

Examine how the shoreface behaviour may evolve beyond the data limit

This is done by addressing the following research questions :

Can the medium- and large-scale depth of closure be predicted using the time-dependent analytical Hallermeier (1977, 1978) model (Chapter 2), which has already been vigorously tested on

[1] this is a very real concern in present research as many of the existing coastal models are designed for the short- to medium-term. Use over the long-term could result in the inherent errors, which are insignificant over the smaller scales, becoming important over the long-term (see Chapter 5 and section 8.2.3).

the small-to medium-scale for micro-tidal, wave-dominated coasts? What are the limitations, if any, of this model?

Can a process-based model (UNIBEST-TC; Chapter 5) designed for the short-term evolution of a cross-shore profile be used to identify depth of closure over this and larger scales? What are the limitations of upscaling a short-term model in this way? In addition, can this model accurately reproduce the observed behaviour over the entire shoreface?

Can projections of the observed behaviour be made beyond the data limit? Are the resultant timescales consistent with the results of existing models? What are the limitations of such methods? Are the assumptions made appropriate?

It is the characteristics of the shoreward depth of closure and shoreface activity, as previously observed (Chapter 6), which are used in this chapter for predictive purposes. Section 8.2 i) tests an analytical model used to predict the depth of closure and adopted here for the shoreward depth of closure; and ii) investigates the potential use of a process-based model, which is more commonly used for the evolution of cross-shore profiles over the short-scale. The third section (8.3) projects the observed behavioural trends of both Dc_s and three classifications of shoreface activity (the partially- and fully-active classifications; Chapter 6). The final section discusses the results obtained in the previous sections in the context of the research questions.

8.2) EVALUATION OF EXISTING MODELS

8.2.1) INTRODUCTION

It has been shown (Birkemeier, 1985; Nicholls *et al*, 1998b; Marsh *et al*, 1998) that the analytical Hallermeier (1977, 1978) model calculates a seaward limit to the observed short- and medium-term depth of closure for all wave-dominated situations, except those of rapidly accreting or eroding profiles (Table 2.7). Chapter 7 clearly shows that this model is important in the prediction of closure as it takes as its input the extreme wave conditions; the primary control upon Dc_s. It is therefore imperative that its abilities are tested over all relevant scales, especially those over which

many coastal management schemes are being designed for; the large-scale. Hence this section primarily tests the ability of Eq.2.6 to predict Dc_s over the large-scale.

The Hallermeier (1977, 1978) model was designed to calculate Dc, therefore it should, as existing work suggests, be able to predict reasonably accurate values of Dc_s (when compared to the observed). However, models also exist whose prime function is not the calculation of Dc_s but whose output could be used to determine this parameter. One such example is the process-based numerical UNIBEST-TC model (Bosboom *et al*, 1997; Chapter 5). This model was fundamentally designed to predict the short- and medium-term evolution of single cross-shore profiles; comparison between its output and corresponding field data revealed that it is capable of fulfilling this aim (cf. Roelvink and Broker, 1993). This was encouraging and so the abilities of UNIBEST-TC to correctly predict the shoreface characteristics identified in Chapter 6 were tested here.

8.2.2) THE ANALYTICAL MODEL : HALLERMEIER (1977, 1978)

The approach used in Chapter 7 (Section 7.2.2) is adopted here, as illustrated in Figure 8.1. The only difference is the calculation of an additional two temporal periods; 1 and 5 years.

Hence, both $JARKUS_{s \text{ and } E}$ are used for comparative purposes; in the case of the 1 year period, comparisons have been made using observed values taken from the nine selected profiles used in Chapter 6. The results are presented in the following order; firstly the spatial variation of the calculations are addressed and then the temporal variation within the three time periods is given.

8.2.2.1) SPATIAL VARIATION

The calculated Dc_s values are deeper in Noord-Holland than Zuid-Holland for all three temporal periods as shown in Table 8.1 which gives the mean $Dc_{s1,\ 5,\ 10\ years}$[2] for each wave station. The spatial variation calculated by Eq.2.6 agrees with observations (Chapter 6; Figure 6.3). However, as already remarked (Chapter 7), the calculated values do not exhibit as strong a longshore trend as the observed values; the difference between Noord- and Zuid-Holland is smaller than one would expect based on observations (Figure 8.2; Table 8.2). A result of the 'underestimation' of the longshore difference in closure, has resulted in the overprediction of observed values being much larger in Zuid-Holland than Noord-Holland.

[2] Dc_{st} = the Dc_s value over *t* years

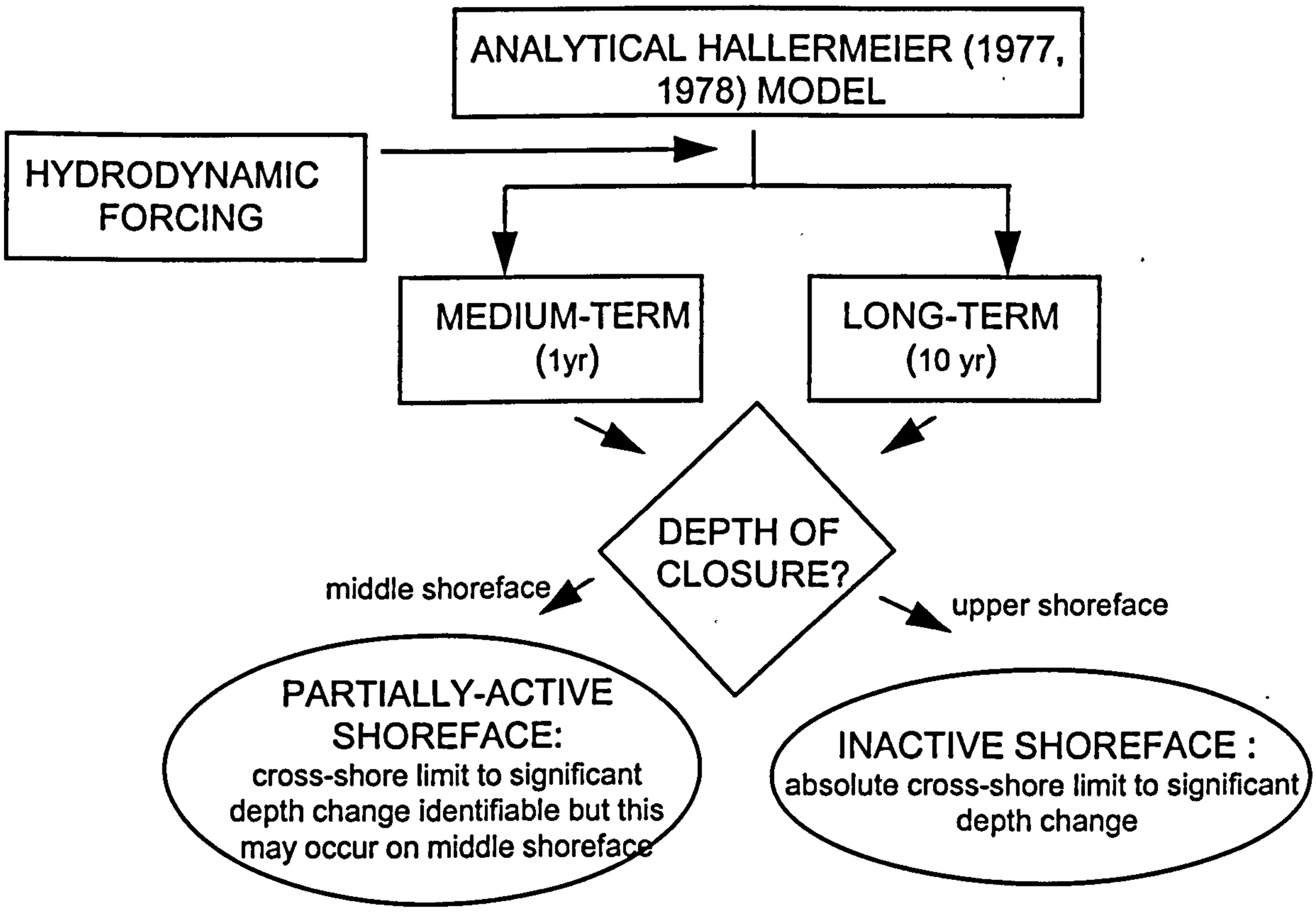


Figure 8.1. Flow diagram showing the model-orientated approach of the analytical Hallermeier (1977, 1978) model over medium- and large-scales. Hydrodynamic data from the Holland coast was used as the model input. The calculated values revealed a seaward limit to the significant depth change either a) on the upper shoreface, or b) on the middle shoreface. Hence profiles were calculated to be either a) inactive, or b) partially-active.

STATION	ELD			YM6			MPN		
	1 yrs	5 yrs	10 yrs	1 yrs	5 yrs	10 yrs	1 yrs	5 yrs	10 yrs
MEAN CLOSURE (m)	10.1	11.5	11.9	9.6	10.9	10.9	8.6	9.8	10.2
SD (m)	1.5	0.4	0.6	0.7	0.9	0.5	0.9	0.6	0.7

Table 8.1. The mean and standard deviation (sd) of the calculated values for closure at each of the three stations. Each mean value represents the average of all possible calculations e.g. Dc_{s5yrs} = $((Dc_{s1979\text{-}1983}) + (Dc_{s1980\text{-}1984}) + (Dc_{s1981\text{-}1985}) + (Dc_{s1982\text{-}1986}) + (Dc_{s1983\text{-}1987}) + (Dc_{s1984\text{-}1988}) + (Dc_{s1985\text{-}1989}) + (Dc_{s1986\text{-}1990}) + (Dc_{s1987\text{-}1991}) / 9)$.

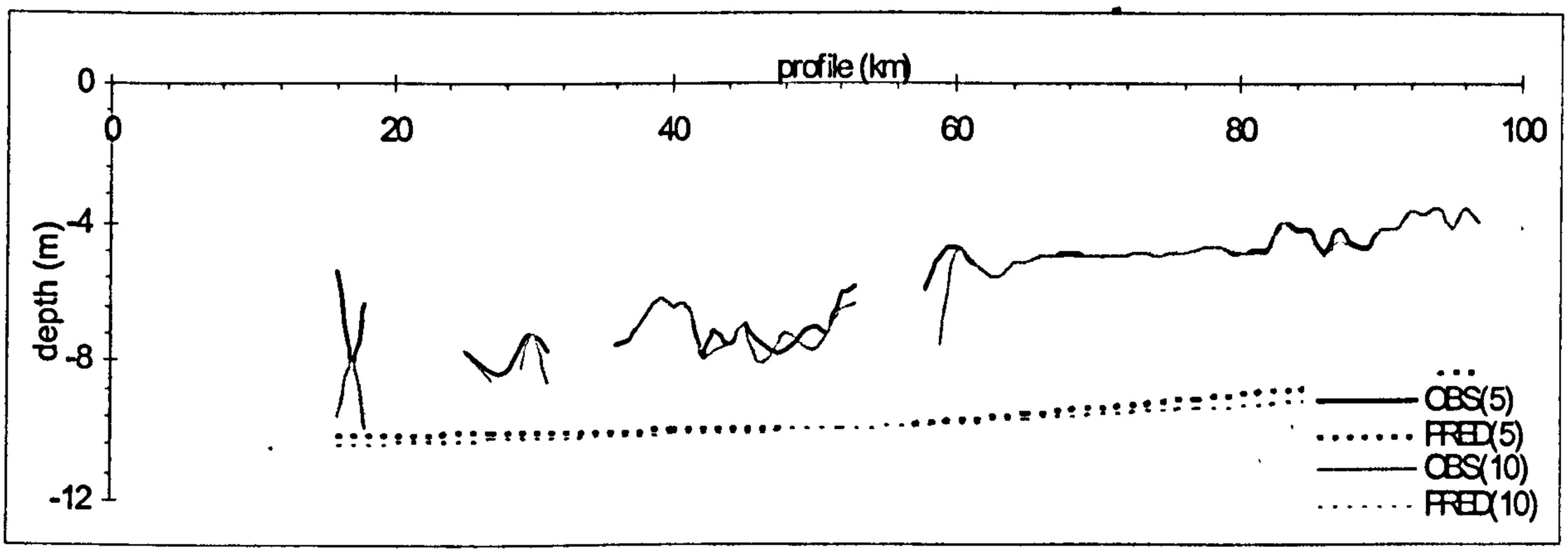


Figure 8.2. The observed and calculated values of Dc_s over 5 and 10 years for the entire Holland coast. Calculated values are taken from the Hallermeier (1977, 1978) model. It is clear that, in all cases, the Hallermeier (1977, 1978) model provides a seaward limit to the observed closure.

	km 17			km 97			RANGE km 17 to 97 (m)		
	1 yrs	5 yrs	10 yrs	1 yrs	5 yrs	10 yrs	1 yrs	5 yrs	10 yrs
OBSERVED CLOSURE (m)	7.5	8.0	8.0	3.2	4.0	4.0	3.3	4.0	4.0
PREDICTED CLOSURE (m)	8.8	10.1	10.4	7.2	8.3	8.9	1.6	1.8	1.5

Table 8.2. Comparison of calculated and observed values of the shoreward closure from km 17 and 97 over 1, 5 and 10 years. It can be seen that the difference in observed values from north to south is greater than that calculated using the time-dependent Hallermeier (1977, 1978) model.

8.2.2.2) TEMPORAL VARIATION

For all three temporal periods, Eq.2.6 overpredicts the observed closure i.e. it provides a seaward limit. In more detail :

- all annual observed values from the nine selected profiles are less than the corresponding calculated values by a minimum of 1.3 m and a maximum of 4.0 m (Table 8.3);
- Eq.2.6 overpredicts the 5-yearly observed Dc_s values for all longshore profiles (Figure 8.3a) by a range of 2.1 m to 4.3 m; and

- the 10-yearly observed Dc_s values are overpredicted by Eq.2.6 along the entire Holland coast (Figure 8.3b) by a minimum of 2.4 m and maximum of 4.9 m.

PROFILE (km)	17	27	37	47	57	67	77	87	97
OBSERVED Dc_s (m)	7.5	6	5.5	6.2	4.6	4.8	*n/c*	4.3	3.2
PREDICTED Dc_s (m)	8.8	8.7	8.7	8.6	8.6	8.2	7.8	7.5	7.2

Table 8.3. Comparison between the annual observed and calculated values for the nine selected profiles along the Holland coast. *n/c* = no closure.

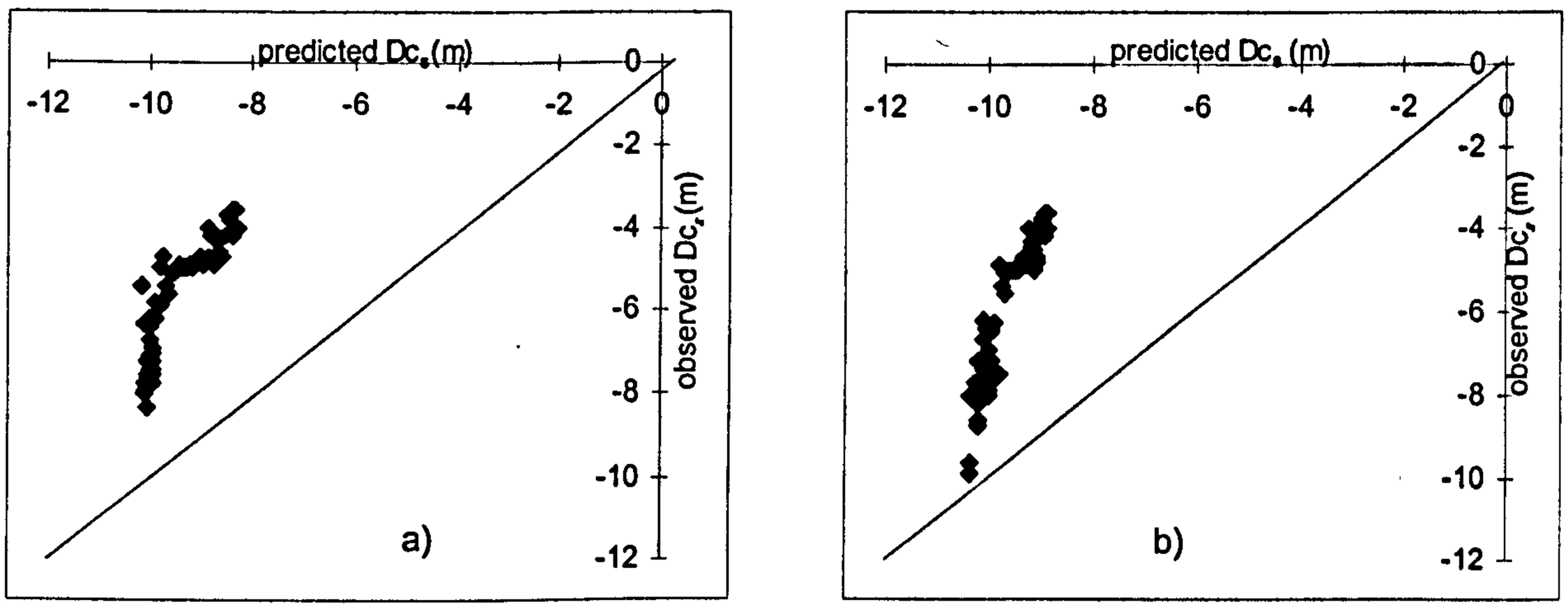


Figure 8.3. Comparison between the observed and predicted values of the shoreward depth of closure. Calculated values are derived using the Hallermeier (1977, 1978) model. The overprediction of the observed closure is clear for both temporal periods; a) = 5 years; b) = 10 years.

It is also observed that the temporal growth of the calculated values is greater than that shown by the observed values, as illustrated using the example of km 17 in Table 8.4.

	km 17			DIFFERENCE between yrs (m)	
	1 yrs	5 yrs	10 yrs	1:5 yrs	5:10 yrs
OBSERVED CLOSURE (m)	7.5	8.0	8.0	0.5	0
PREDICTED CLOSURE (m)	8.8	10.1	10.4	1.3	0.3

Table 8.4. The overprediction of the temporal growth of closure over the 10 years is shown using the example of km 17. Note that this observation is applicable to all longshore profiles.

The final observation which can be made is that the temporal increase of closure is not predicted to occur at a steady rate i.e. it is non-linear. This result is not surprising as there are few factors which increase linearly with time, for example wave heights do not increase from 1 m over 1 year to 10 m over 10 years. Indeed the greatest increase is observed over the shorter time periods (Table 8.5; Figure 8.4) and is supported by observations of closure which conclude that the temporal relationship of Dc_s is logarithmic (Section 6.2.3). This suggests that collection of reliable hydrodynamic data beyond 1 year[3] will not be of any gain in the calculation of closure as the calculated values will remain similar to the value of the previous period (Table 8.4); this is seen with YM6 where an increase in temporal period from 5 to 10 years does not correspond with an increase in Dc_s. However, this does assume that the statistics of the hydrodynamic climate will not significantly change beyond this critical period.

	CHANGE IN PREDICTED VALUES (m)	
STATION	1 : 5 yrs	5 : 10 yrs
ELD	1.4	0.5
YM6	1.3	0
MPN	1.3	0.4

Table 8.5. Changes in the predicted value of closure between temporal periods for each wave station.

[3] note that in order to obtain one years worth of reliable hydrodynamic data it may be necessary to collect 10 years worth and then calculate the mean in order to remove any variability. If this is not done then there is the risk that the annual period of data used represents a year which is unusually calm/stormy.

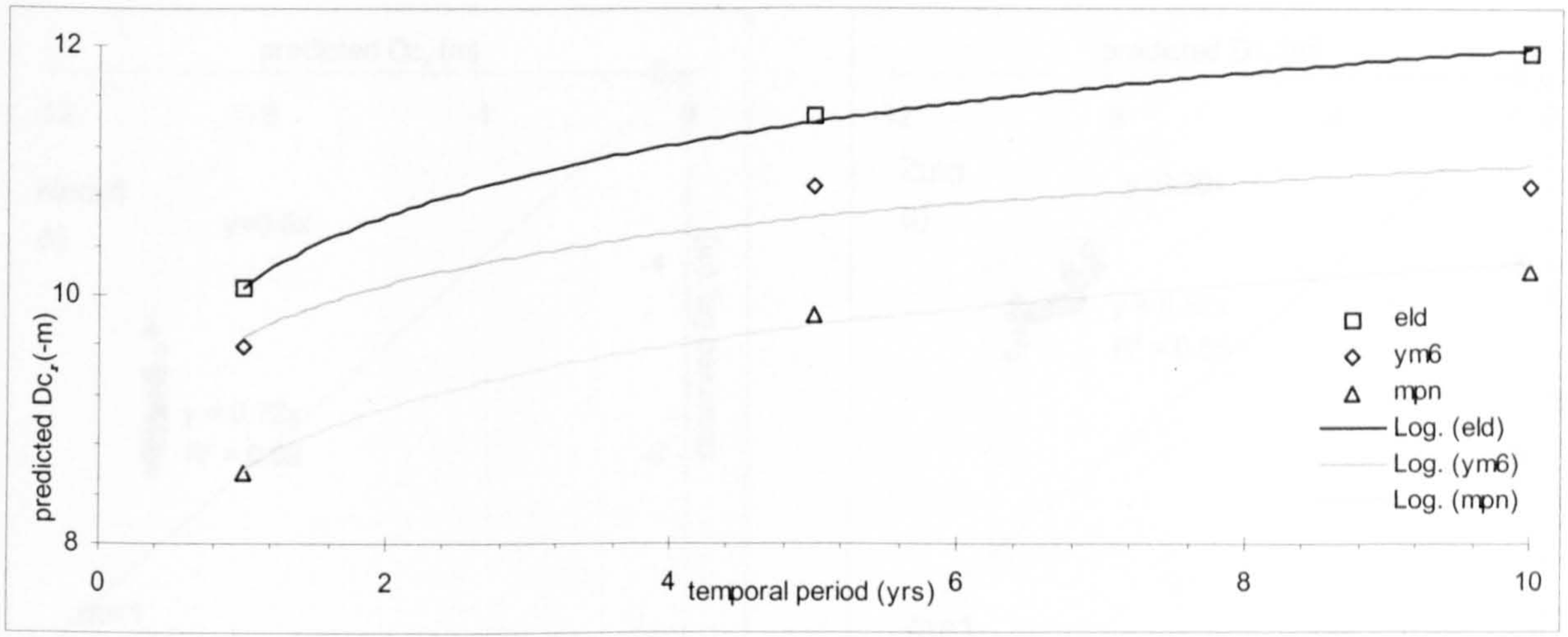


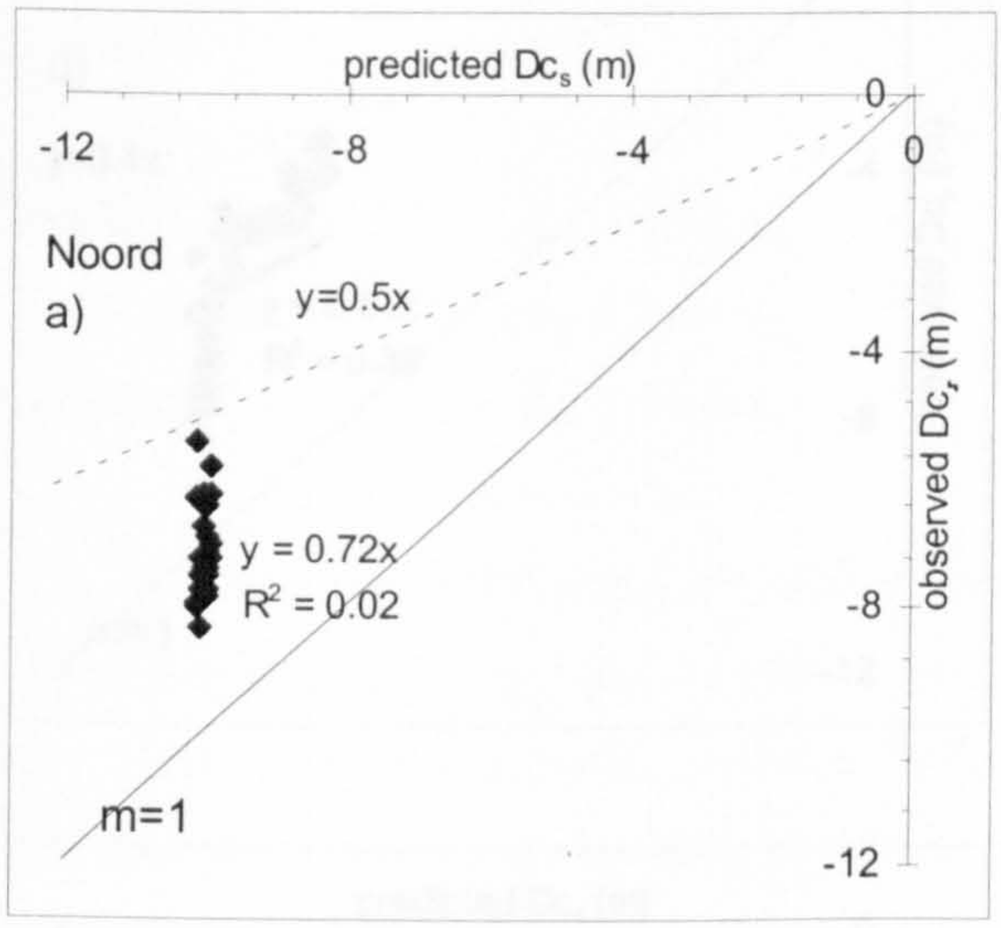
Figure 8.4. Predicted values of the shoreward depth of closure for various temporal periods. The line of best fit is shown here which takes a logarithmic trend. It can be seen that the increase from 1 to 5 years is greater than that from 5 to 10 years. Predictions are made using the time-dependent Hallermeier (1977, 1978) model.

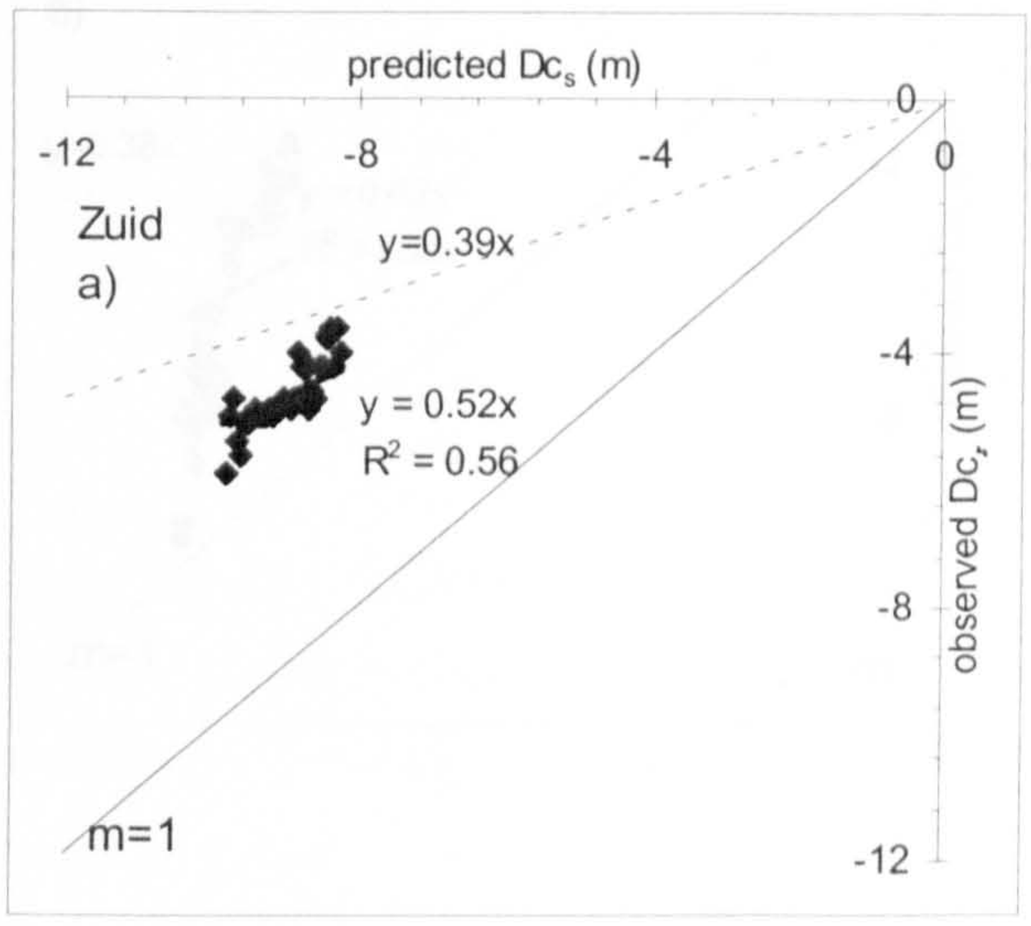
8.2.2.3) COMPARISON BETWEEN THE OBSERVED AND PREDICTED CLOSURE

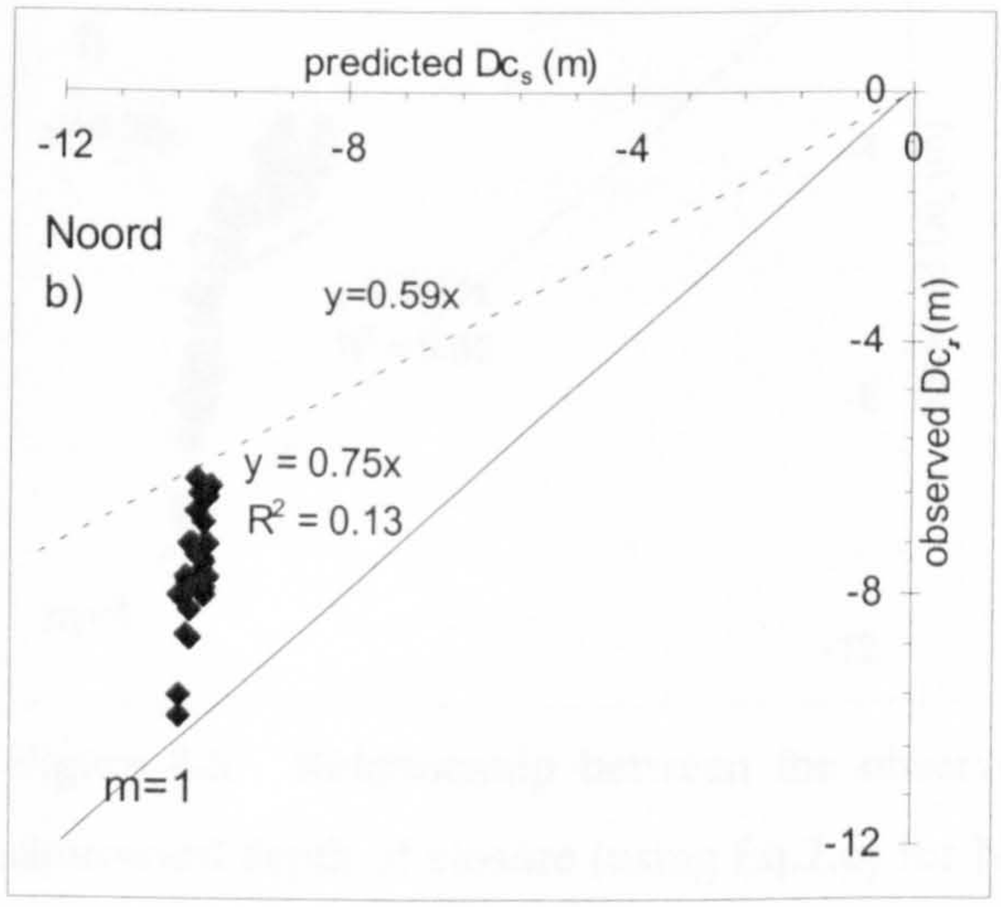
The difference between the observed Dc_s (m), as calculated using the sddc fixed tail (change criterion 0.25 m) analysis, and that predicted using the Hallermeier model can be used as an indication of how much of the predicted change actually occurs on the Holland coast. This is done by taking a best-fit approach between the two variables where a value of zero for the predicted is equal to zero for the observed (Figure 8.5). The empirical formulae are given below (Eq.8.1 to 8.6) for the two provinces and the entire Holland coast for two temporal periods; 5 and 10 years :

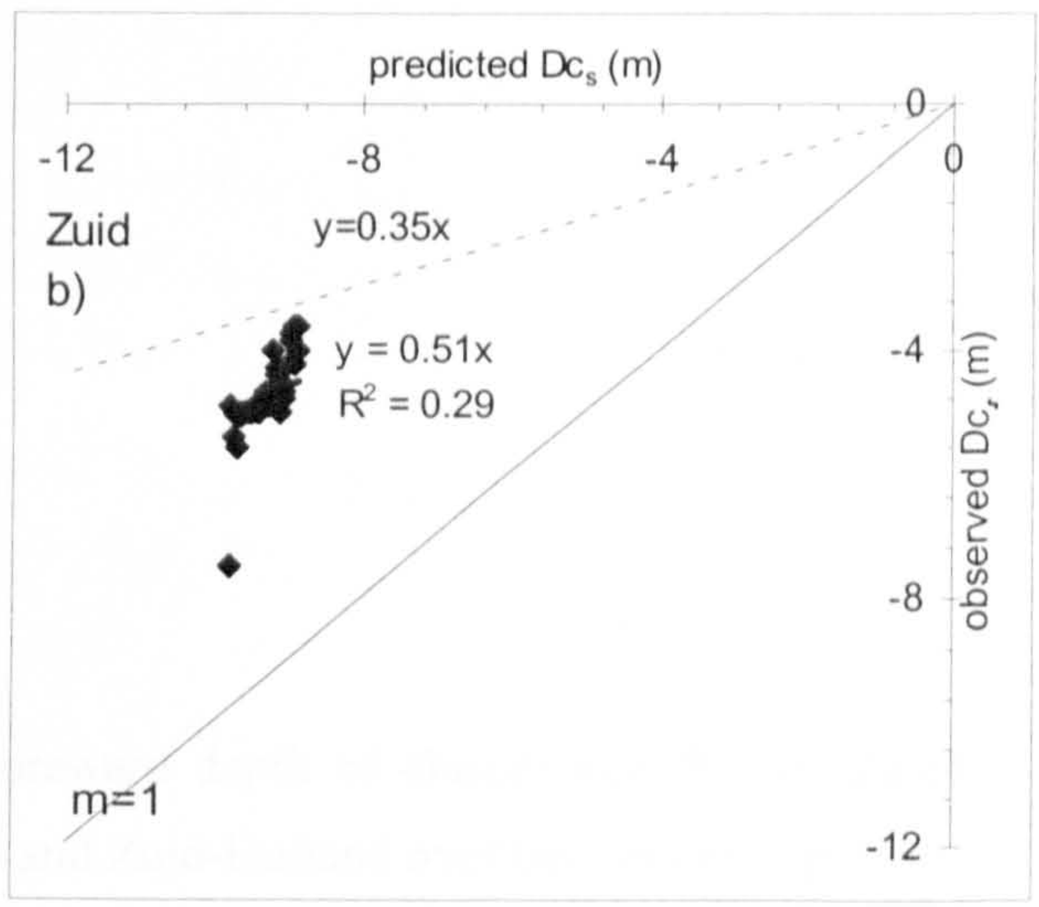
Noord-Holland	5 years	$d_{Tl} = 0.72 d_{el}$	($r^2 = 0.02$)	(Eq.8.1)
	10 years	$d_{Tl} = 0.75\ d_{el}$	($r^2 = 0.13$)	(Eq.8.2)
Zuid-Holland	5 years	$d_{Tl} = 0.52\ d_{el}$	($r^2 = 0.56$)	(Eq.8.3)
	10 years	$d_{Tl} = 0.51\ d_{el}$	($r^2 = 0.29$)	(Eq.8.4)
Holland	5 years	$d_{Tl} = 0.61\ d_{el}$	($r^2 = 0.39$)	(Eq.8.5)
	10 years	$d_{Tl} = 0.62\ d_{el}$	($r^2 = 0.29$)	(Eq.8.6)

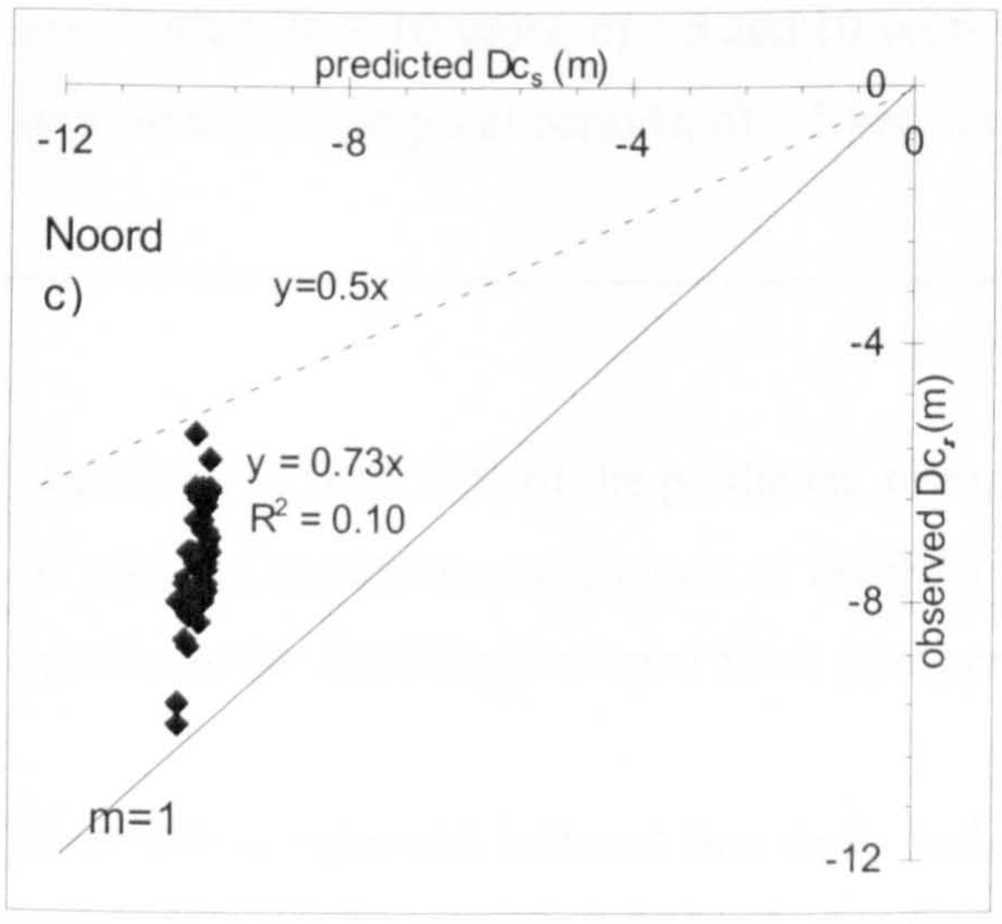
(Here d_{Tl} = observed shoreward closure; d_{el} = predicted shoreward closure using Eq. 2.6)

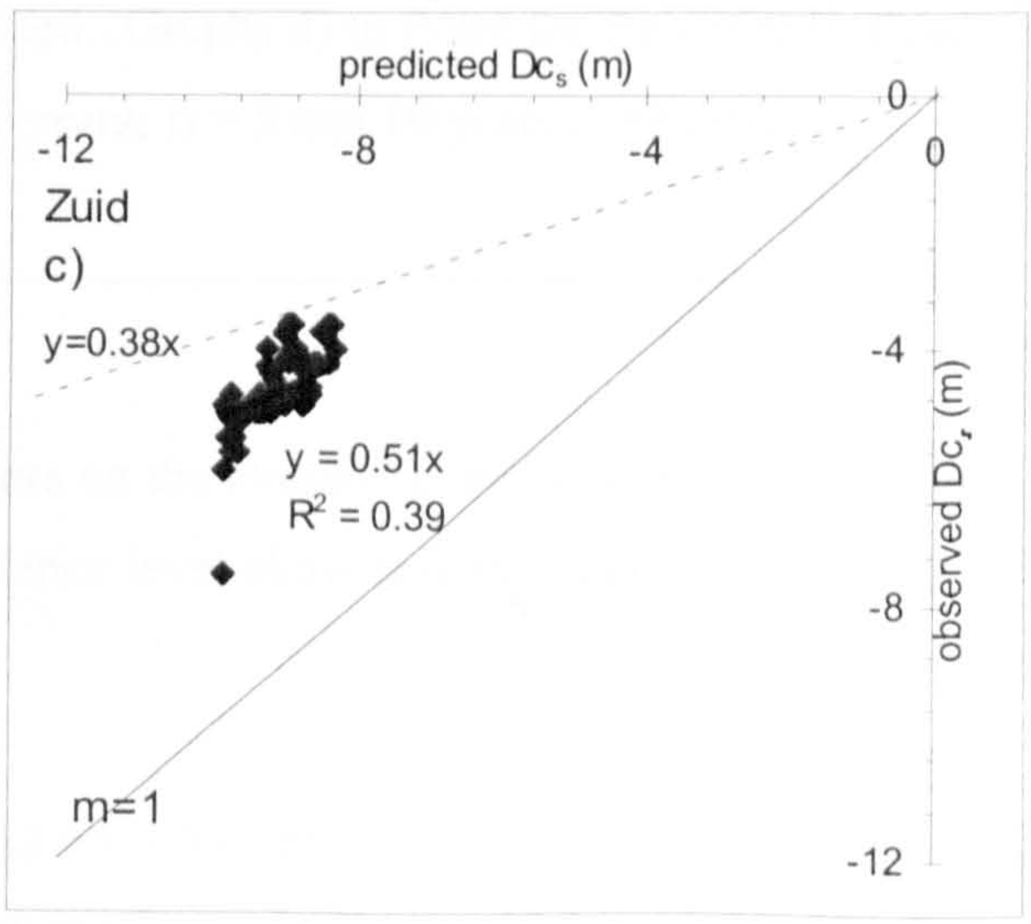

predicted Dc$_s$ (m)
-12
-8
-4
0
Noord
a)
y=0.5x
y = 0.72x
R^2 = 0.02
observed Dc$_s$ (m)
m=1

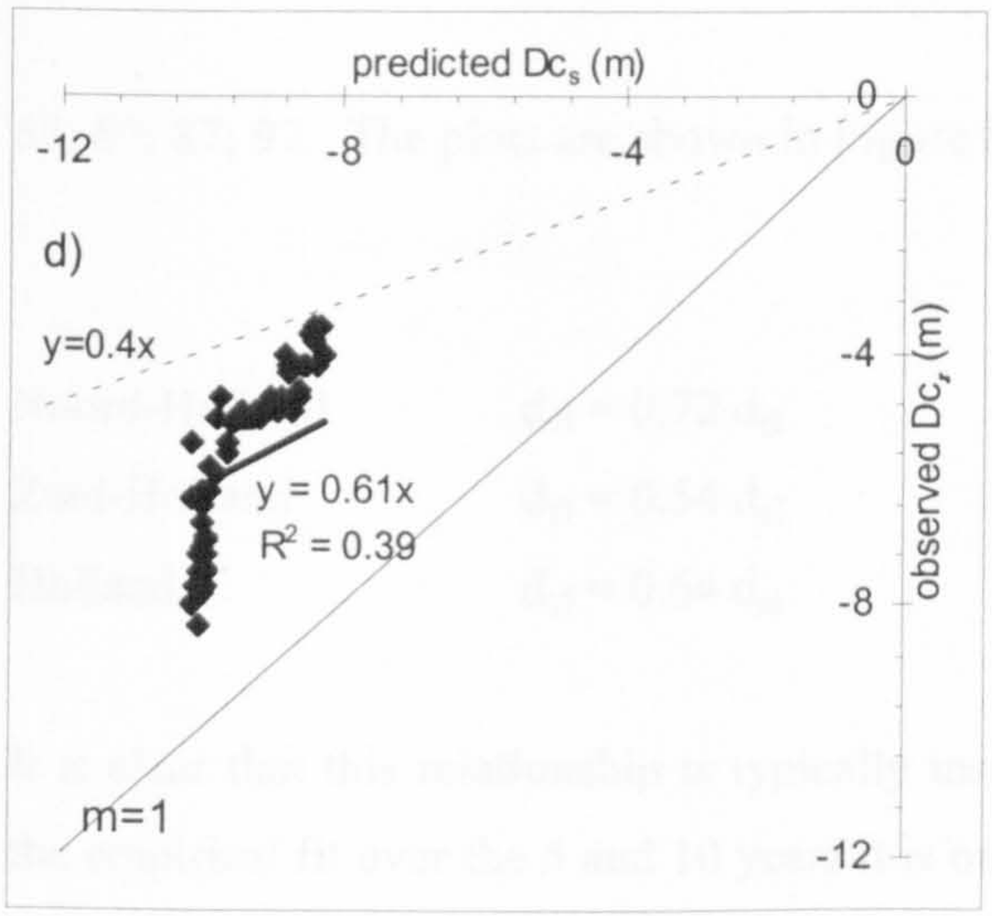

predicted Dc$_s$ (m)
-12
-8
-4
0
Zuid
a)
y=0.39x
y = 0.52x
R^2 = 0.56
observed Dc$_s$ (m)
m=1

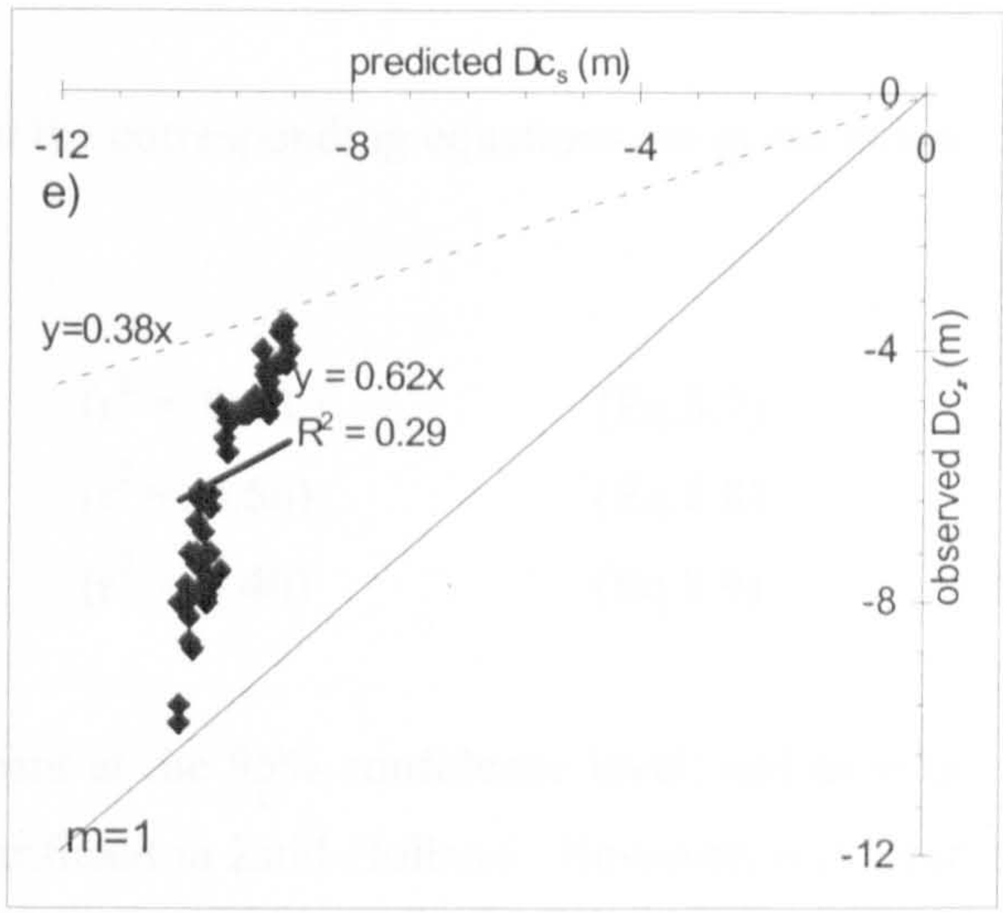

predicted Dc$_s$ (m)
-12
-8
-4
0
Noord
b)
y=0.59x
y = 0.75x
R^2 = 0.13
observed Dc$_s$ (m)
m=1


predicted Dc$_s$ (m)
-12
-8
-4
0
Zuid
b)
y=0.35x
y = 0.51x
R^2 = 0.29
observed Dc$_s$ (m)
m=1


predicted Dc$_s$ (m)
-12
-8
-4
0
Noord
c)
y=0.5x
y = 0.73x
R^2 = 0.10
observed Dc$_s$ (m)
m=1


predicted Dc$_s$ (m)
-12
-8
-4
0
Zuid
c)
y=0.38x
y = 0.51x
R^2 = 0.39
observed Dc$_s$ (m)
m=1





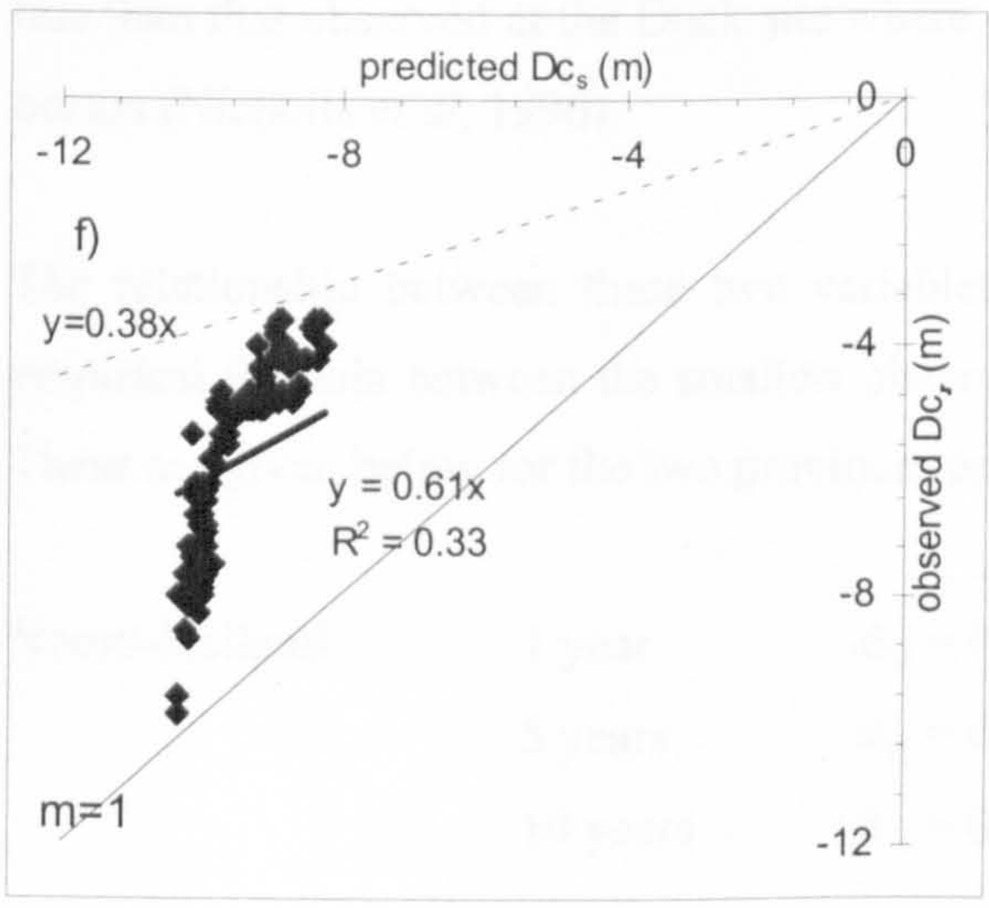


Figure 8.5. Relationship between the observed shoreward depth of closure and the calculated shoreward depth of closure (using Eq.2.6) for Noord- and Zuid-Holland over two temporal periods; a) = 5 years; b) = 10 years; c) = 5 and 10 years combined. Graphs d) to f) are for the entire Holland coast over two temporal periods; d) = 5 years; e) = 10 years; f) = 5 and 10 years combined.

Therefore, 51% to 75% of the predicted change occurs on the Holland coast over the periods 5 to 10 years. Correlation coefficients at the 95% confidence level show that this relationship is only significant for Zuid-Holland over the 5 year period.

To enable comparison between this study and existing ones, the approach adopted above has also been used over the annual scale for the ten profiles previously used (Chapter 6); km 17; 27; 37; 47;

57; 67; 87; 97. The plots are shown in Figure 8.6 and the corresponding equations are given below :

Noord-Holland	$d_{Tl} = 0.72\ d_{el}$	($r^2 = 0.08$)	(Eq.8.7)
Zuid-Holland	$d_{Tl} = 0.54\ d_{el}$	($r^2 = 0.56$)	(Eq.8.8)
Holland	$d_{Tl} = 0.64\ d_{el}$	($r^2 = 0.40$)	(Eq.8.9)

It is clear that this relationship is typically insignificant at the 95% confidence level; and as with the empirical fit over the 5 and 10 years it is only significant in Zuid-Holland. However, it is clear that 54% to 72% of the change predicted by the Hallermeier model occurs in this examples; this is less than that observed at the Duck site where over the annual period, 76% of the change predicted occurs (Nicholls *et al*, 1996).

The relationship between these two variables (d_{Tl}; d_{el}) can also be assessed by calculating the empirical formula between the smallest observed Dc_s value and the predicted values (Figure 8.6). These are given below for the two provinces and the entire Holland coast for all temporal periods :

Noord-Holland	1 year	$d_{Tl} = 0.60\ d_{el}$	(Eq.8.10)
	5 years	$d_{Tl} = 0.50\ d_{el}$	(Eq.8.11)
	10 years	$d_{Tl} = 0.59 d_l$	(Eq.8.12)
Zuid-Holland	1 year	$d_{Tl} = 0.40\ d_{el}$	(Eq.8.13)
	5 years	$d_{Tl} = 0.39\ d_{el}$	(Eq.8.14)
	10 years	$d_{Tl} = 0.35\ d_{el}$	(Eq.8.15)
Holland	1 year	$d_{Tl} = 0.40\ d_{el}$	(Eq.8.16)
	5 years	$d_{Tl} = 0.40\ d_{el}$	(Eq.8.17)
	10 years	$d_{Tl} = 0.38\ d_{el}$	(Eq.8.18)

Therefore the minimum values of observed closure represent 35% to 60% of the predicted change within the Holland coast.

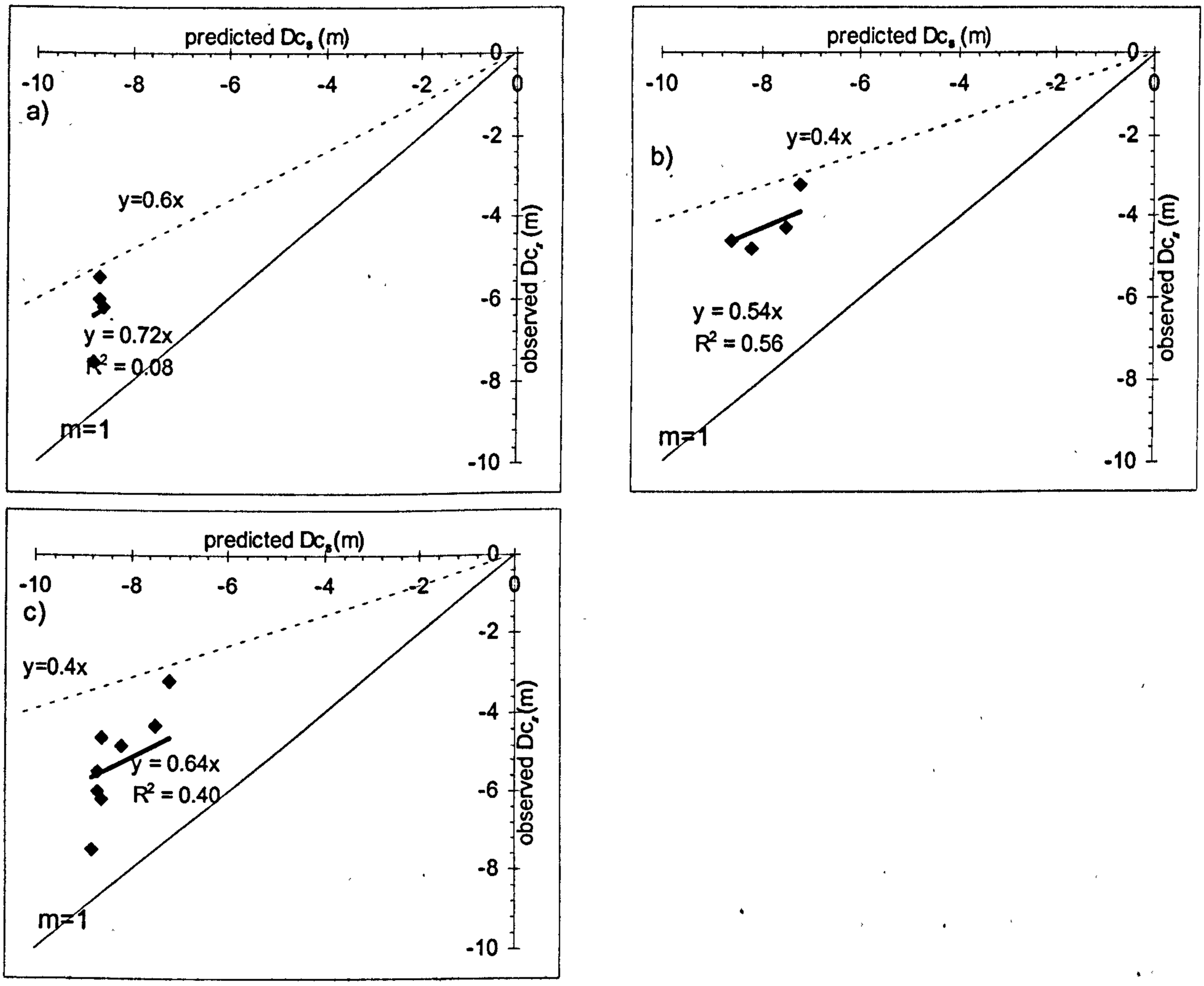


Figure 8.6. Relationship between the observed shoreward depth of closure and the calculated shoreward depth of closure (using Eq.2.6) over the annual temporal period for a) = Noord-Holland; b) = Zuid-Holland; c) = the entire Holland coast.

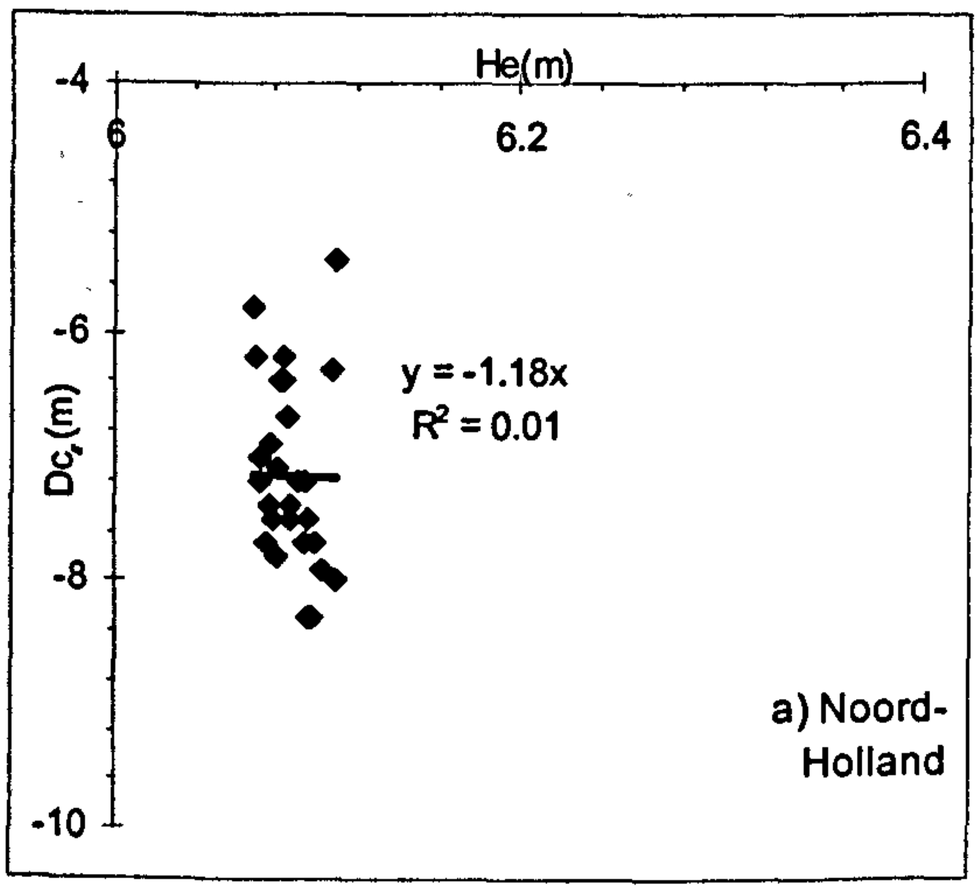
The over-prediction of closure by Eq.2.6 has led to the derivation of an empirical formula for the calculation of Dc_s. Rather than using the Hallermeier model as a basis and altering the constants, as done by Birkemeier (1985) (see Eq.2.4), this empirical formula examines the relationship between the 12 hour-exceeded wave height and the observed Dc_s. The wave height represents the mean wave height for the appropriate temporal period for each profile and Dc_s is taken from the sddc fixed tail (change criterion 0.25 m) analysis. It was performed for the Holland coast and the two provinces (Noord- and Zuid-Holland) for two temporal periods (5 and 10 years). The relationship is more significant at the 95% confidence level for Zuid-Holland, perhaps a

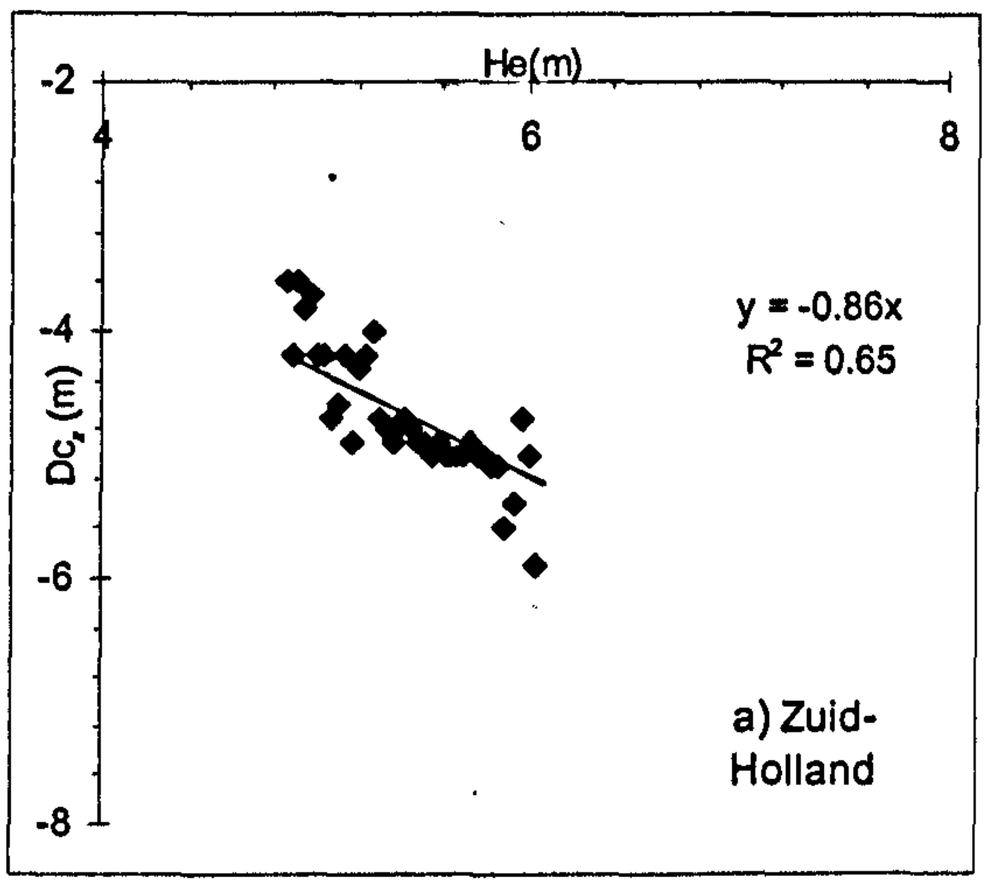
consequence of the small variability in Dc_s values and increased morphodynamic activity in Noord-Holland. When data was taken from the entire Holland coast two populations exist, correlating to the two provinces. Additionally, the two temporal periods compose two distinct populations within Noord-Holland; the result of differences in the 12-hour exceeded wave height rather than the closure values. These points are illustrated in Figure 8.7. The empirical formula which could be used to predict closure along the Holland coast (and within its two provinces), over the long-term, takes the assumption that when the 12-hour exceeded wave height is equal to zero, Dc_s is also equal to zero. The formula are given below for the combination of the 5 and 10 year temporal periods:

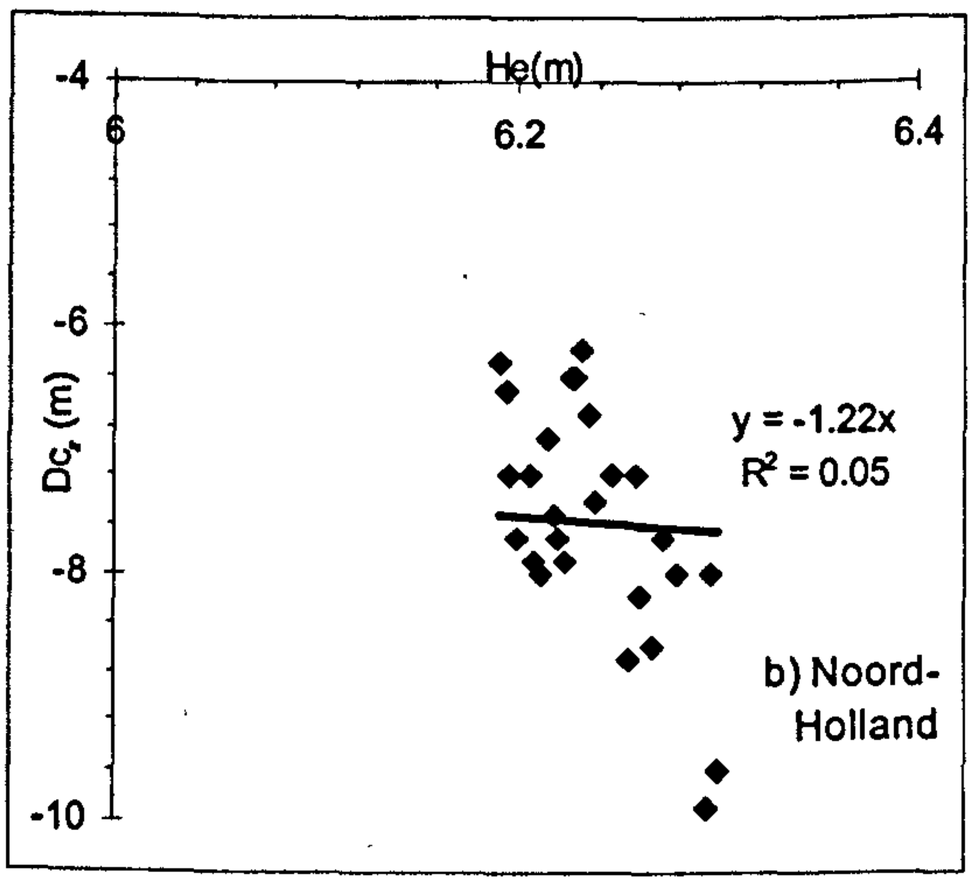
Noord-Holland.	$d_{Tl} = -1.20H_e$	($r^2 = 0.07$)	(Eq.8.19)
Zuid-Holland.	$d_{Tl} = -0.85H_e$	($r^2 = 0.52$)	(Eq.8.20)
Holland.	$d_{Tl} = -1.01H_e$	($r^2 = 0.39$)	(Eq.8.21)

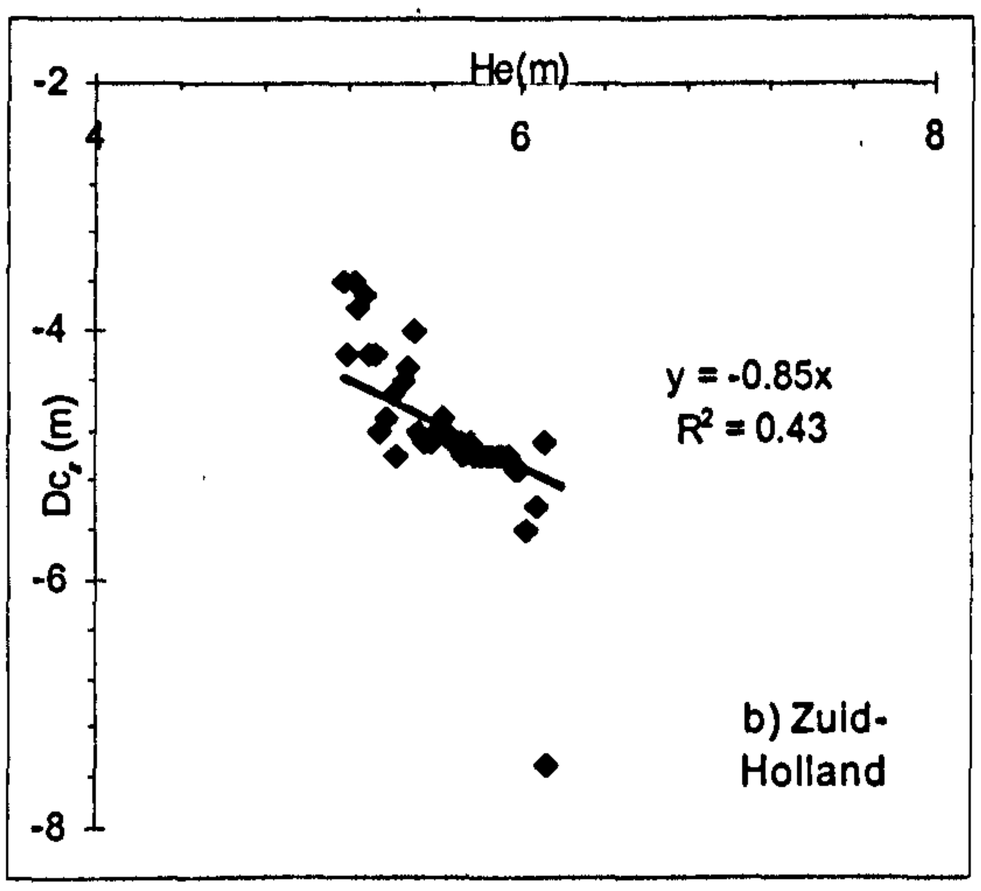
(Here H_e represents the 12-hour exceeded wave height as used in Eq. 2.6).

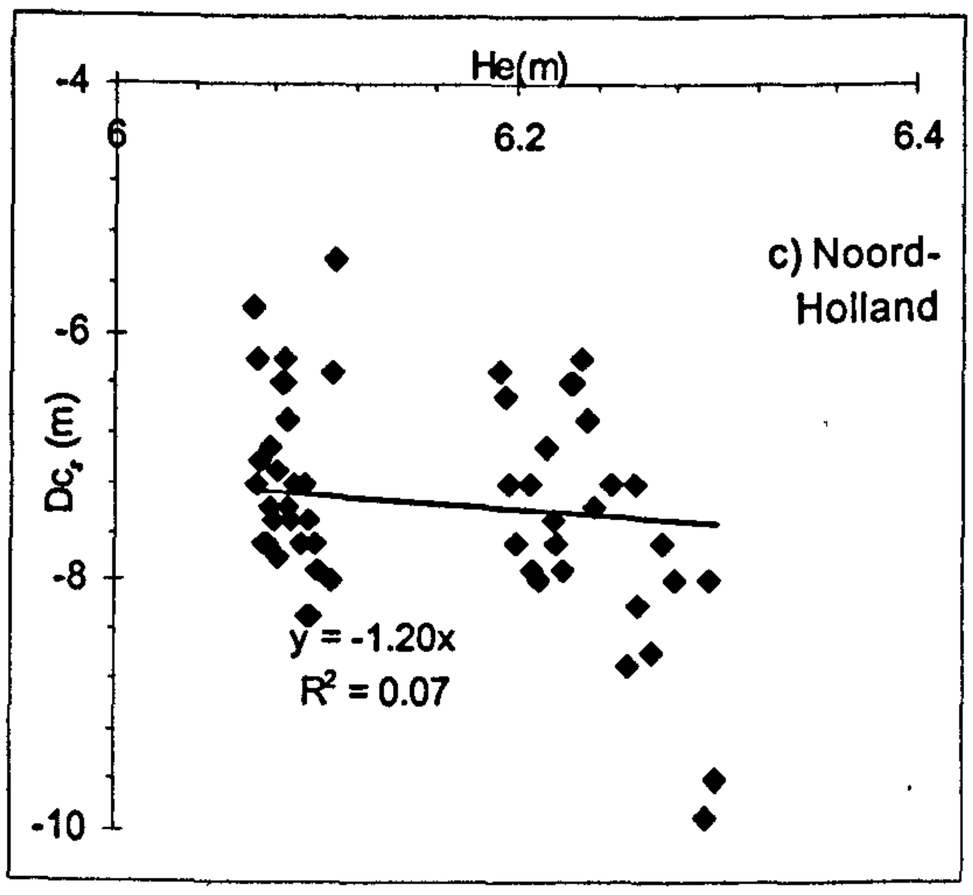
Although it has been possible to derive a simple empirical formula between the 12-hour exceeded wave height and shoreward depth of closure, it only explains less than 55% of the relationship (see respective r^2 values). This is due to the strong signature of the nearshore bar system as a control upon Dc_s, particularly in Noord-Holland ($r^2 = 0.07$) where it becomes apparent that there is a need for a more detailed understanding of the acting processes. It is therefore recommended that the Hallermeier (1977, 1978) model is used in closure calculations, especially on shorefaces other than Holland, as it will always produce a seaward limit to the actual closure; the underprediction of closure is more likely to have negative impacts within for example sediment budget calculations, than the overprediction. However, the empirical formula derived above should provide a robust value of the shoreward depth of closure when applied to the Holland coast.

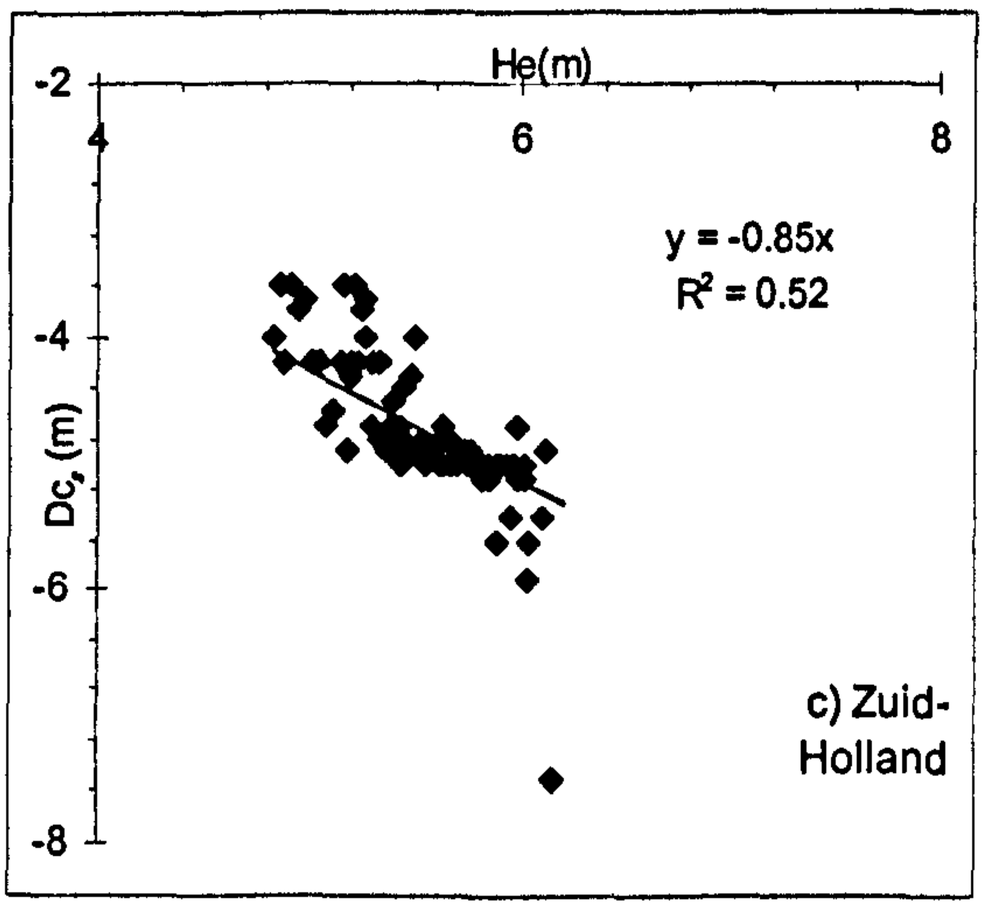

He(m)
-4
6
6.2
6.4
-6
-8
-10
Dc, (m)
y = -1.18x
R² = 0.01
a) Noord-Holland


He(m)
-2
4
6
8
-4
-6
-8
Dc, (m)
y = -0.86x
R² = 0.65
a) Zuid-Holland


He(m)
-4
6
6.2
6.4
-6
-8
-10
Dc, (m)
y = -1.22x
R² = 0.05
b) Noord-Holland


He(m)
-2
4
6
8
-4
-6
-8
Dc, (m)
y = -0.85x
R² = 0.43
b) Zuid-Holland


He(m)
-4
6
6.2
6.4
-6
-8
-10
Dc, (m)
y = -1.20x
R² = 0.07
c) Noord-Holland


He(m)
-2
4
6
8
-4
-6
-8
Dc, (m)
y = -0.85x
R² = 0.52
c) Zuid-Holland

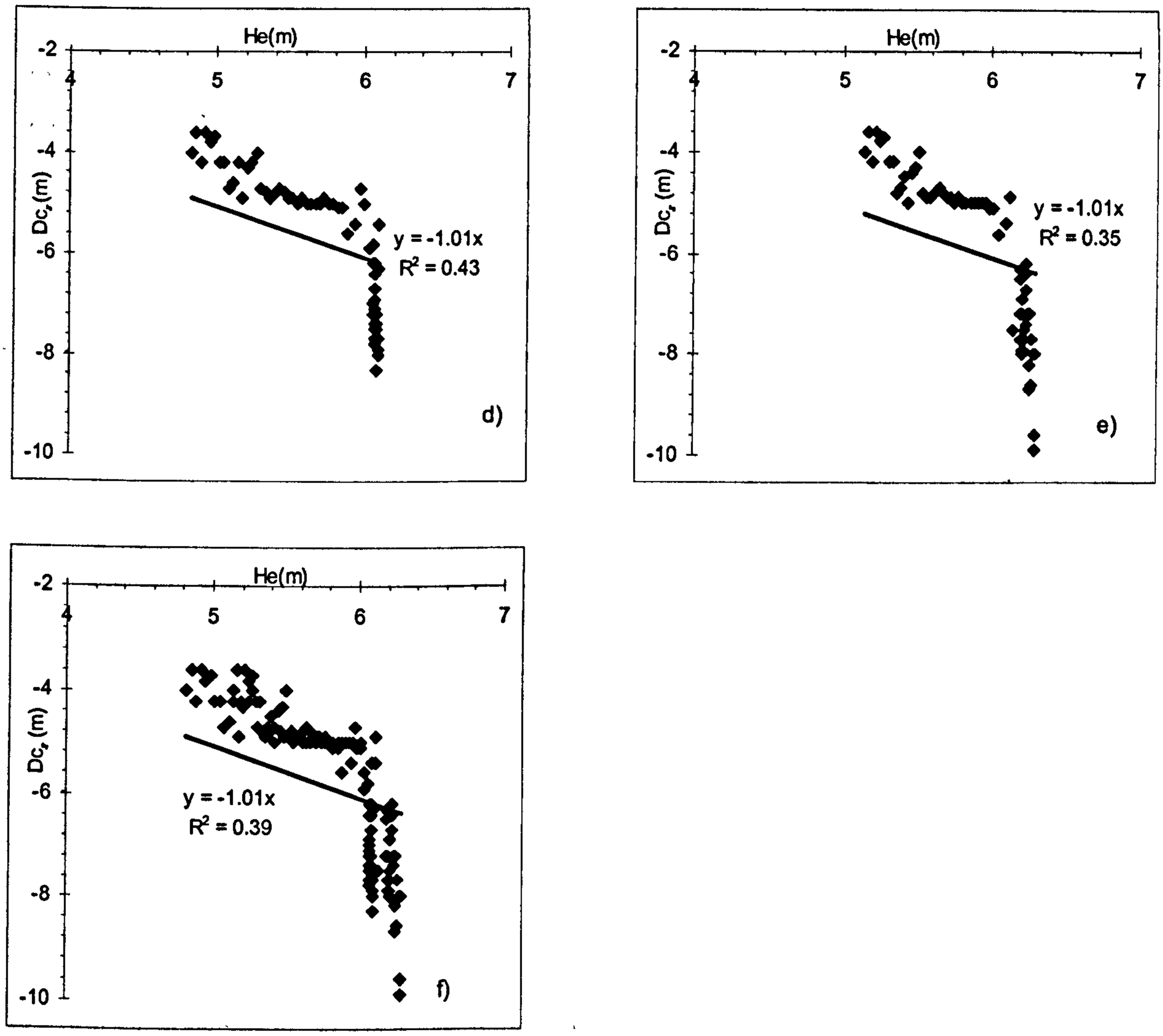


Figure 8.7. Relationship between the observed shoreward depth of closure and the 12-hour exceeded wave height for Noord- and Zuid-Holland over two temporal periods; a) = 5 years; b) = 10 years; c) = 5 and 10 years combined. Figures d) to f) are for the entire Holland coast; d) = 5 years; e) = 10 years; f) = 5 and 10 years combined. Note that the intercept of the axis are not set at zero; the small range of the x-axis means that this is not an option.

8.2.3) THE PROCESS-BASED MODEL : UNIBEST-TC

As stated in the introduction to this section, UNIBEST-TC does not specifically calculate the location of shoreface activity/inactivity. However, it is possible to analysis the model's bathymetric output in order to identify this behaviour. Therefore the model input, output and parameters were set as summarised in Table 8.6. The bathymetric output, selected from the twelve

temporal periods, was analysed using the sddc fixed tail method (change criterion 0.25 m^4). (The approach adopted is shown in Figure 8.8). Comparisons were then made between the observed (using $JARKUS_{S+E}$) and calculated values. For comparative purposes, the calculated values of closure were rounded up to the nearest metre; the fact that this model is not specifically designed to predict Dc_s makes it more interesting to see if it is applicable to this task.

CATEGORY	DETAIL
HYDRODYNAMIC INPUT	wave height, wave period, incidence angle, storm surge level
MORPHODYNAMIC INPUT	km 81 (-14.9 m to +5 m)
TIME STEP	1 day
TYPE OUTPUT	bathymetry
NUMBER OF RUNS	10
RUN LENGTH	10 years
TEMPORAL PERIODS ANALYSED	1 month, 0.5 yr, 1 yr, 1.5 yr, 2 yr, 2.5 yr, 3 yr, 3.5 yr, 4 yr, 5 yr, 7.5 yr, 10 yr

Table 8.6. Summary of the input, settings and output of UNIBEST-TC as used in this study. Further details are given in Chapter 5.

Preliminary comparison between the bathymetric output and $JARKUS_E$ clearly showed that UNIBEST-TC was unable to correctly predict the middle to lower shoreface evolution (Figure 5.8). Therefore this technique was only tested for its ability to predict Dc_s. However, models are increasingly being designed to include the shoreface. Due to the limitations imposed by process-based models, these tend to be behaviour-orientated (Chapter 2) and are used to describe both the shoreface and shelf behaviour over the very-large-scale (decades to millennia). One example of a behaviour-orientated model is the Advection-Diffusion Model (ADM) of Niedoroda *et al*, 1995.

[4] although it could be argued that the output from UNIBEST-TC does not contain measurement error and should be analysed using a self-selecting tail, a fixed tail change criterion of 0.25 m is used here. This is because not only i) does the input profile contain this error but also ii) all the field data contains this error and so comparison between observed and calculated values would not be 100% correct if it were ignored; when performing comparisons, as many variables as possible must be kept the same between the data sets.

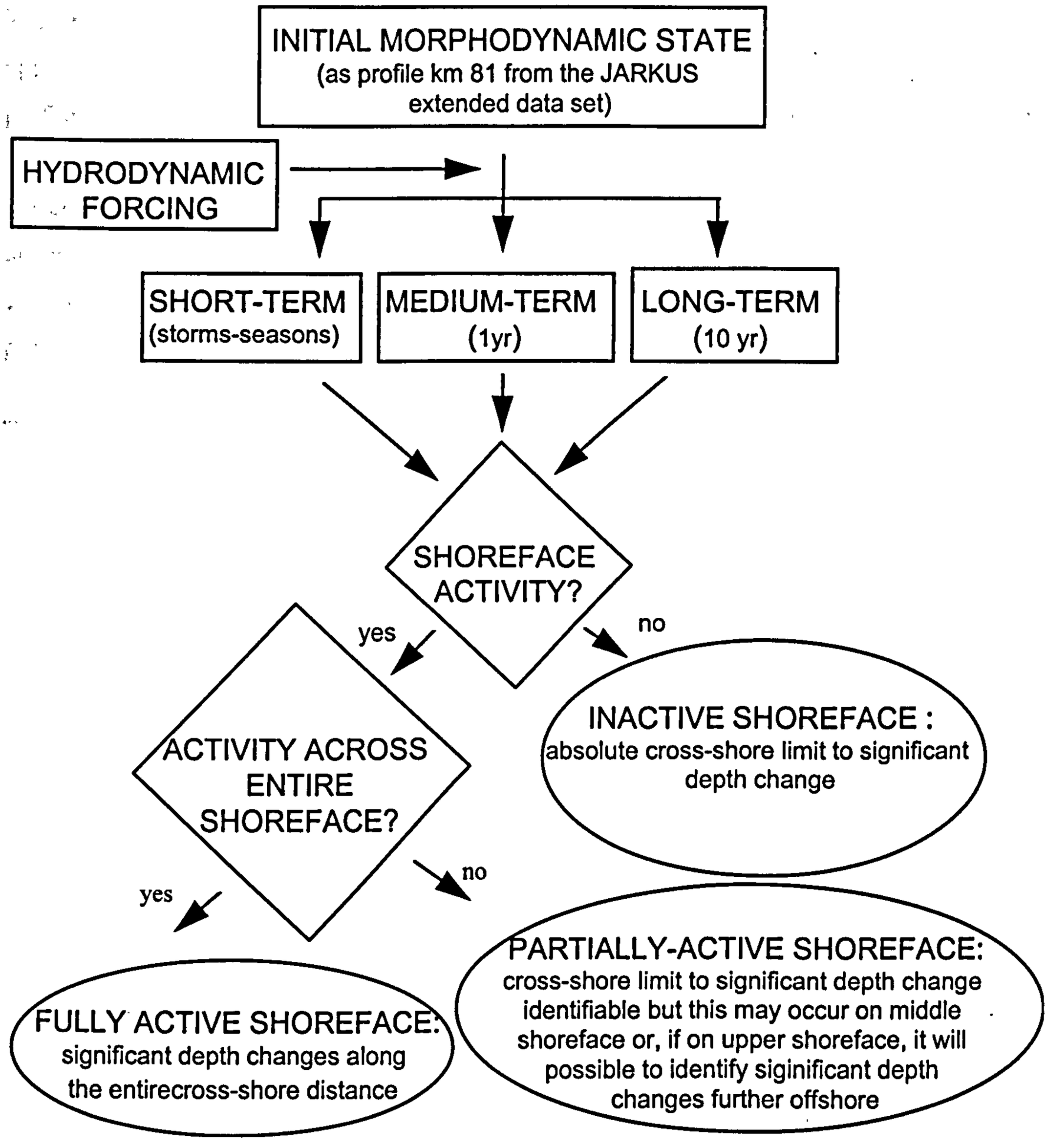


Figure 8.8. Flow diagram showing the model-orientated approach using the process-based UNIBEST-TC model over all scales within the Large Scale Coastal Evolution concept of Stive *et al* (1990). Model runs using a single cross-shore profile and hydrodynamic forcing over the different scales produced different profile evolution's. These were analysed for a) a seaward limit of significant depth change and b) significant shoreface activity (according to the depth change criterion selected).

8.2.3.1) OBSERVATIONS OF THE MODEL OUTPUT

The results from the model runs show that significant bathymetric changes do not occur on the upper shoreface over periods less than 1 year, even in the nearshore bar zone. In addition, only one profile exhibits closure over the annual timescale; all other profiles are inactive across the cross-shore. This is the result of the sddc values of the upper shoreface being less than the selected fixed tail change criterion (0.25 m), as shown in Figure 8.9. Therefore the calculated profiles do not undergo short-scale significant depth changes on the upper shoreface, according to the change criterion used. However, the shoreward depth of closures can be identified in all the runs for time periods equal to and greater than 1.5 years.

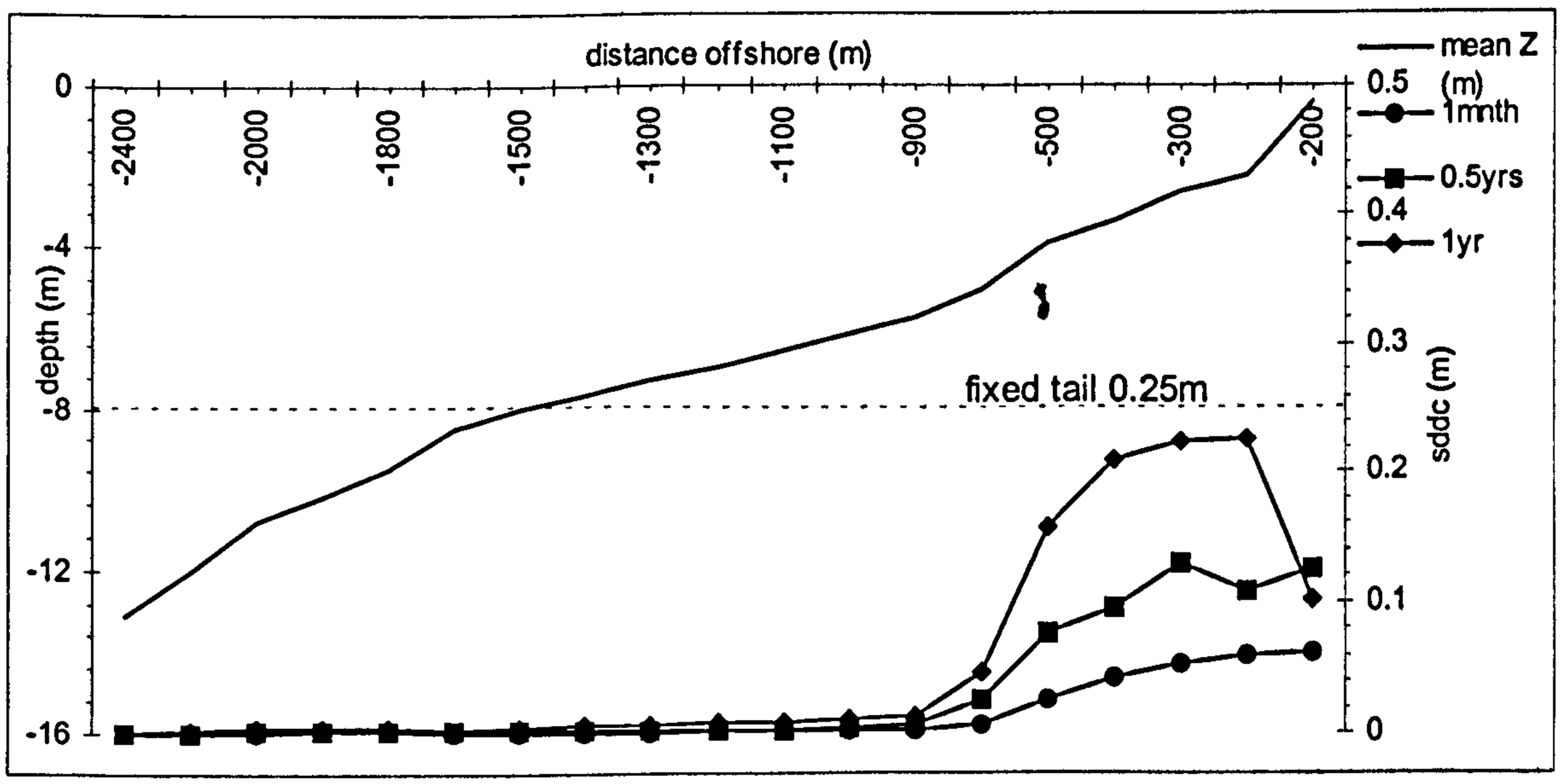


Figure 8.9. Sddc plots of the output of run 1 of UNIBEST-TC for three temporal periods; 1 month; 0.5 years; 1 year. It can be seen that for each of these the sddc values are less than the fixed tail criterion 0.25 m.

Dc_s is predicted to increase with increasing temporal period, as shown in Table 8.7. Using values rounded to 1 decimal place, the predicted increase over the total period is 1.5 m, this is five times greater than the corresponding increase in observed values for km 81; 0.3 m.

TEMPORAL PERIOD (yrs)	MEAN Dc_s (m)	SD Dc_s (m)
1	3.5	0
1.5	3.9	0.3
2	4	0.2
2.5	4.4	0.1
3	4.5	0.1
3.5	4.3	0.2
4	4.3	0.3
5	4.9	0.2
7.5	5	0.1
10	5	0.1

Table 8.7. Mean Dc_s values derived from the bathymetric output of UNIBEST-TC over a maximum temporal period of 10 years. Fixed tail sddc analysis (change criterion 0.25 m) has been used. (SD = standard deviation of all values around the mean)

8.2.3.2) COMPARISON BETWEEN OBSERVED AND CALCULATED VALUES OF CLOSURE

Agreement is very good between the calculated and the corresponding observed values for each temporal period, with the exception of the 2 year period (Figure 8.10). In addition, when the calculated values of the half-yearly intervals are compared with the observed values of annual intervals, a continuation of the existing trends is observed (Table 8.8). These results give confidence in the numerical model.

The greatest temporal increase in the calculated Dc_s is seen in the first five years, after which the increase slows dramatically (Table 8.9). Therefore, as with the observed values for km 81, the temporal dependence of the calculated values is best described using a logarithmic trendline (Figure 8.11), for which the associated correlation coefficient is $0.90_{(95\% \text{ confidence})}$. This also agrees with the trendlines observed for Dc_s characteristics derived from both data sets ($JARKUS_{S+E}$), as described in Section 6.2.

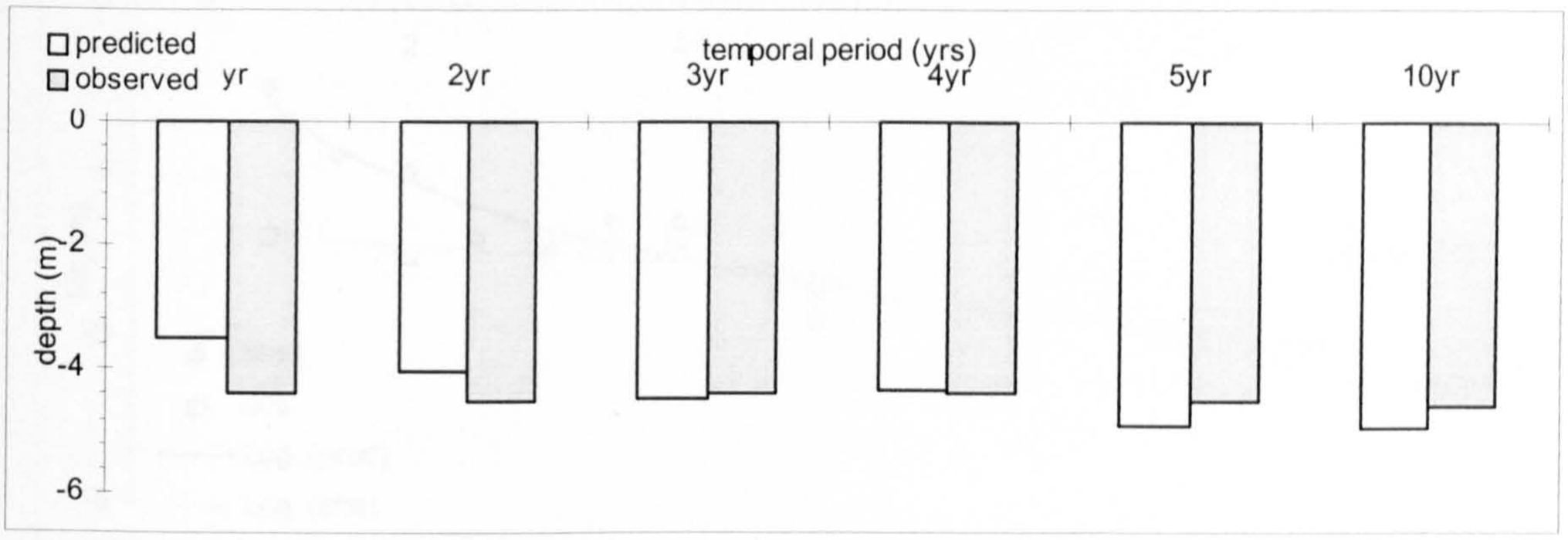


Figure 8.10. Predicted versus observed values of the shoreward depth of closure for all temporal periods. Predicted values are derived from sddc analysis of UNIBEST-TC output. It is seen that in all cases, with the exception of the 2 year, the Dc_s values agree.

TIME (yrs)	1	1.5	2	2.5	3	3.5	4
OBSERVED CLOSURE (m)	4	-	5	-	4	-	4
PREDICTED CLOSURE (m)	-	4	-	4	-	4	-

Table 8.8. Selected values of the shoreward closure showing that the half-yearly values do agree with the trend of the yearly observed values. (Values have been rounded up to the nearest metre).

TEMPORAL INCREASE (yrs)	1:5	5:10
CHANGE IN CALCULATED VALUE (m)	1.4	0.1

Table 8.9. Changes in the calculated Dc_s value between temporal periods

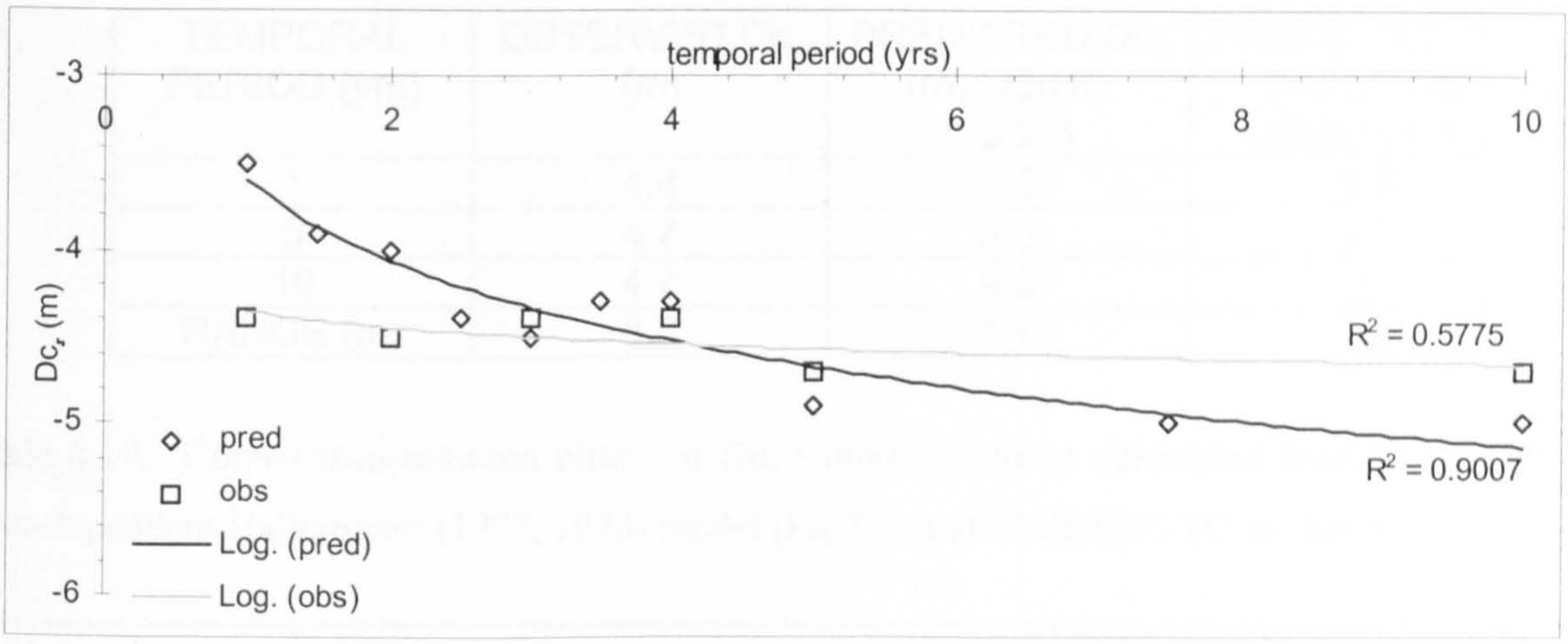


Figure 8.11. The temporal dependence of observed and calculated closure values for km 81 shown using a logarithmic trendline. Calculated values are derived using the process-based UNIBEST-TC model. Both are best fitted with this trendline, although that of UNIBEST-TC is more significant at the 95% confidence level.

8.2.4) COMPARISON BETWEEN THE HALLERMEIER (1977, 1978) AND UNIBEST-TC MODELS

The predicted temporal behaviour of Dc_s using UNIBEST-TC is similar to that observed using the time-dependent Hallermeier (1977, 1978) model; the temporal increase between the two is 1.5 m and 1.7 m respectively. In addition the greatest increase in Dc_s is calculated to occur in the first five years (Table 8.4 and 8.8) i.e. both methods predict the Dc_s temporal behaviour to be logarithmic[5], as suggested by Nicholls *et al* (1996) (Figure 8.4 and 8.11). However it is UNIBEST-TC which has proven to predict the more realistic values when compared to the observed; Eq.2.6 calculates values which are, on average, 4.1 m greater than the observed. These points are quantified in Table 8.10 and illustrated in Figure 8.12. Therefore UNIBEST-TC shows promise as the more sophisticated method of predicting the shoreward depth of closure than the Hallermeier (1977, 1978) model. However, before this method is applied elsewhere, a more rigorous testing procedure should be enforced.

[5] the testing of all possible non-linear trendlines revealed that the logarithmic had the best fit to the data

TEMPORAL PERIOD (yrs)	OBSERVED Dc_s (m)	PREDICTED Dc_s (m) USING EQ.2.6	PREDICTED Dc_s (m) USING UNIBEST-TC
1	4.4	7.6	3.5
5	4.7	8.9	4.9
10	4.7	9.3	5
RANGE (m)	0.3	1.7	1.5

Table 8.10. Comparison between observed Dc_s values and those calculated from the use of the time-dependent Hallermeier (1977, 1978) model (Eq.2.6) and UNIBEST-TC for km 81.

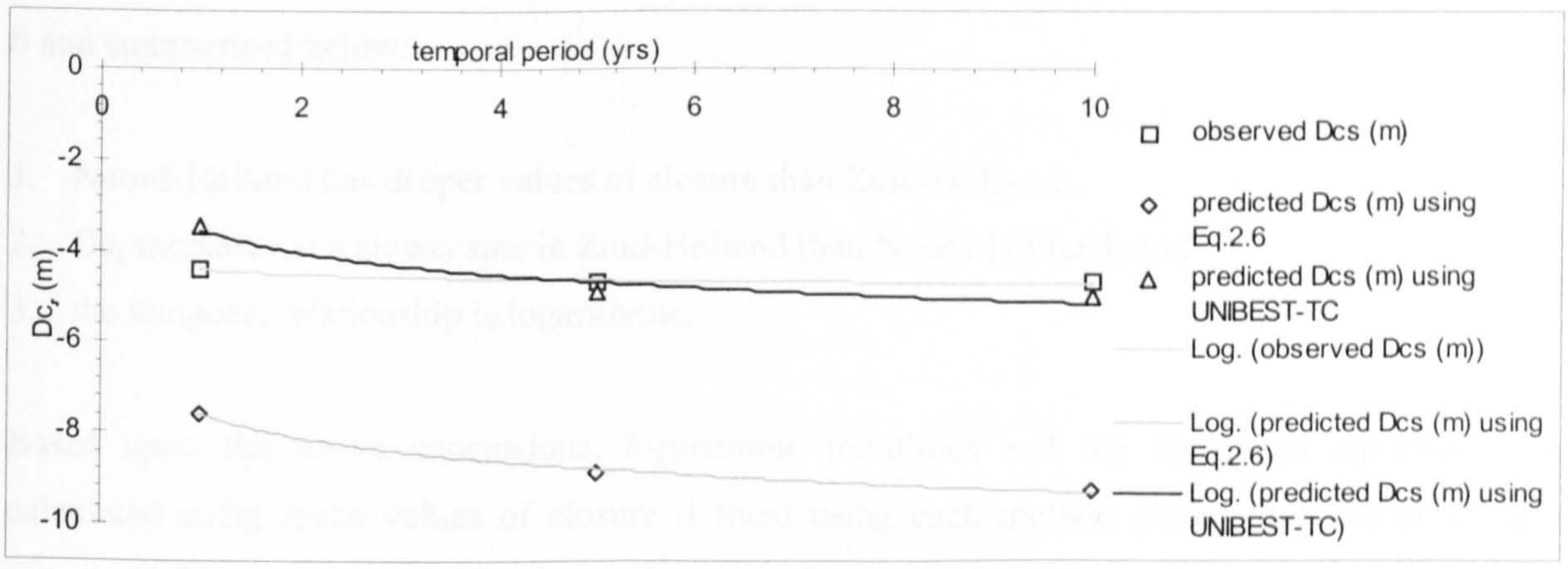


Figure 8.12. Comparison between the calculated and observed values of closure. Values are calculated using the Hallermeier (1977, 1978) and UNIBEST-TC models. Both models mimic the observed logarithmic increase in closure values, although it is the latter which calculates values similar to the observed.

8.3) EVOLUTION OF SHOREFACE BEHAVIOUR BEYOND THE DATA LIMITS

8.3.1) INTRODUCTION

Observations of shoreface morphodynamic behaviour have been made over the medium- and large-scales up to the limit of the data (32 years) (Chapter 6). It would however be useful to have insight, which is currently lacking, into the shoreface evolution over timescales up to a minimum of 100 years, a period relevant to many coastal management decisions. It will also provide useful

information for model development over this period. The morphodynamic JARKUS data set is unique as it provides the opportunity to explore the long-term evolution of the shoreface, so filling the gap between the process-knowledge of, for example, Wright *et al* (1996) and the geological scale knowledge of, for example, Stive and De Vriend (1995). Therefore projections are made based upon the trends[6] of the shoreward depth of closure and shoreface activity, as previously observed. The assumption taken and potential violations are given in Chapter 5.

8.3.2) THE SHOREWARD DEPTH OF CLOSURE

8.3.2.1) CHARACTERISTICS

The conclusions which have been made concerning the Dc_s characteristics are taken from Chapter 6 and summarised below:

1. Noord-Holland has deeper values of closure than Zuid-Holland;
2. Dc_s increases at a slower rate in Zuid-Holland than Noord-Holland; and
3. the temporal relationship is logarithmic.

Based upon the above conclusions, logarithmic trendlines and the associated equation were calculated using mean values of closure derived using each method (sddc; fdc) and all change criteria (0.25 m; 0.5 m; 0.75 m), as shown in Figure 8.13. The projected values were then calculated every 10 years for a maximum temporal period of 100 years. This was performed for the Holland coast and the two provinces (Noord- and Zuid-Holland). All projected trends are shown in Figure 8.14.

It is clear that the lower limit, or deepest values, of Dc_s are given by the fixed tail sddc method (change criterion 0.25 m) whilst the upper limit is given by the same method, but the change criterion of 0.5 m. All values calculated using the observations derived using the fdc analysis are therefore typically found within these limits. It is projected that the greatest Dc_s values exhibit the largest temporal increase and vice versa, however the increase through time is not large (Table 8.11). The minimum and maximum values calculated for each province through the extrapolation of observed results are shown in Figure 8.15. Though the projected values are widely spread in the cross-shore, particularly in the more morphodynamically active province of Noord-Holland, the upper and lower limits provide a useful guideline for the shoreward depth of closure up to 100

[6] trends take the form of both characteristics and occurrence of the behaviour

years. However projections of the fully-active profiles (as discussed in section 8.3.3) mean that the predicted Dc_s values beyond the 80 year period should only be used for illustrative purposes. The limits every 10 years are given in Table 8.11.

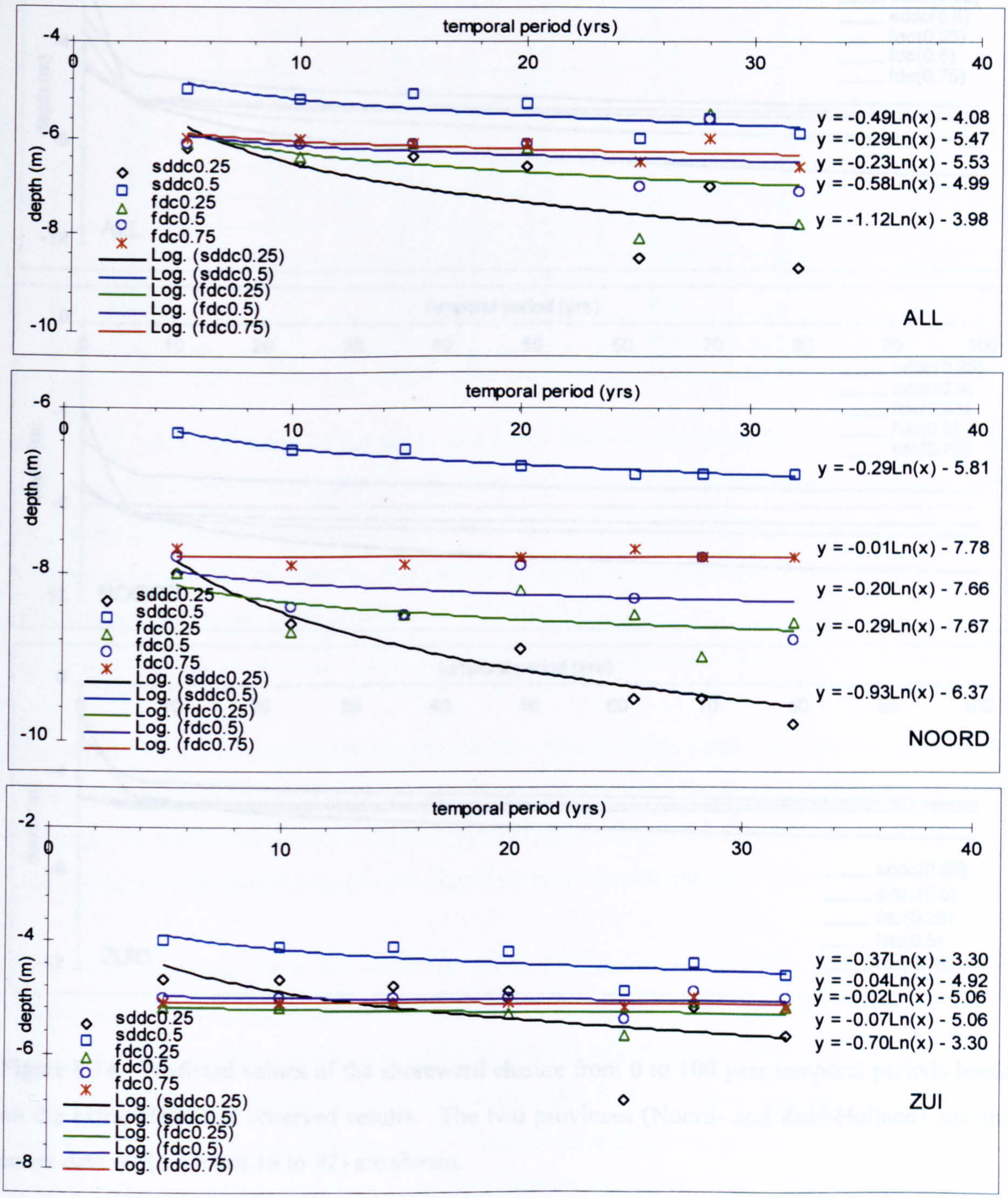


Figure 8.13. Logarithmic behaviour of the temporal dependence of the depth of closure and associated equations. The two provinces (Noord- and Zuid-Holland) and the entire data set (ALL = km 16 to 97) are shown.

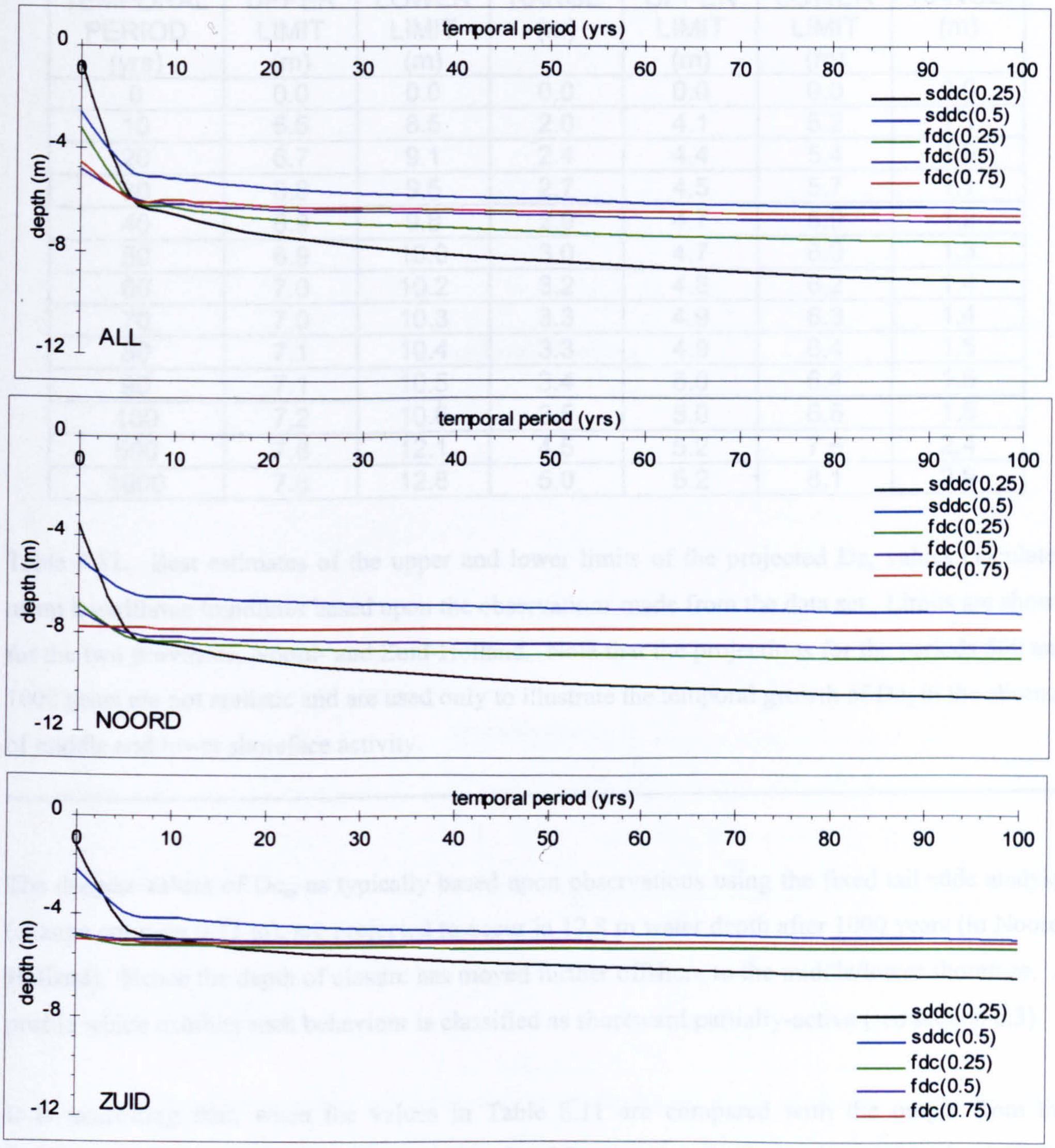


Figure 8.14. Predicted values of the shoreward closure from 0 to 100 year temporal periods based on the extrapolation of observed results. The two provinces (Noord- and Zuid-Holland) and the entire data set (All = km 16 to 97) are shown.

	NOORD-HOLLAND			ZUID-HOLLAND		
TEMPORAL PERIOD (yrs)	UPPER LIMIT (m)	LOWER LIMIT (m)	RANGE (m)	UPPER LIMIT (m)	LOWER LIMIT (m)	RANGE (m)
0	0.0	0.0	0.0	0.0	0.0	0.0
10	6.5	8.5	2.0	4.1	5.2	1.1
20	6.7	9.1	2.4	4.4	5.4	1.0
30	6.8	9.5	2.7	4.5	5.7	1.1
40	6.9	9.8	2.9	4.7	5.9	1.2
50	6.9	10.0	3.0	4.7	6.0	1.3
60	7.0	10.2	3.2	4.8	6.2	1.4
70	7.0	10.3	3.3	4.9	6.3	1.4
80	7.1	10.4	3.3	4.9	6.4	1.5
90	7.1	10.5	3.4	5.0	6.4	1.5
100	7.2	10.6	3.5	5.0	6.5	1.5
500	7.6	12.1	4.5	5.2	7.6	2.4
1000	7.8	12.8	5.0	5.2	8.1	2.9

Table 8.11. Best estimates of the upper and lower limits of the projected Dc_s values calculated using logarithmic trendlines based upon the observations made from the data set. Limits are shown for the two provinces, Noord- and Zuid-Holland. Note that the projections for the periods 500 and 1000 years are not realistic and are used only to illustrate the temporal growth of Dc_s in the absence of middle and lower shoreface activity.

The deepest values of Dc_s, as typically based upon observations using the fixed tail sddc analysis (change criterion 0.25 m), are projected to occur in 12.8 m water depth after 1000 years (in Noord-Holland). Hence the depth of closure has moved further offshore to the middle/lower shoreface. A profile which exhibits such behaviour is classified as shoreward partially-active (see section 6.3).

It is interesting that, when the values in Table 8.11 are compared with the output from the Hallermeier (1977, 1978) model, it is only after 20 years that the lower limit of projections for Noord-Holland exceed the model output for the same region over the annual period (taken from the mean of all profiles in Noord-Holland, as given in Table 8.3). If this is repeated for Zuid-Holland, it is only after 1000 years that the Eq.2.6 output exceeds the projection. This is a significant observation as it implies that there is no great advantage to using the Hallermeier (1977, 1978) model over periods greater than a year in both a morphodynamically inactive (as Zuid-Holland) and active (as Noord-Holland) coastal regions.

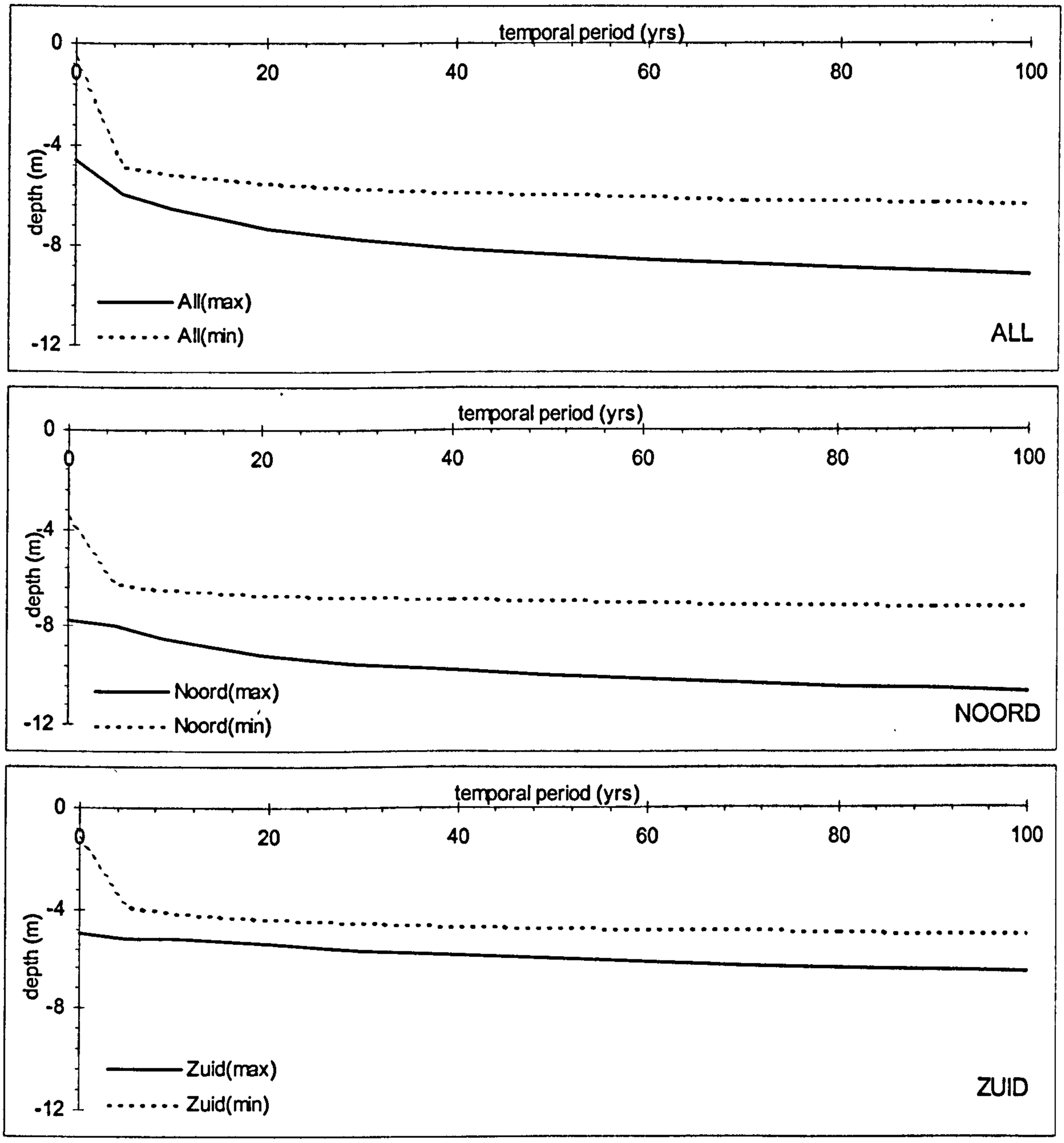


Figure 8.15. The maximum and minimum values of shoreward depth of closure taken from both methods and all criteria. The two provinces (Noord- and Zuid-Holland) and the entire data set (ALL = km 16 to 97)are shown. It can be seen that the greatest range of values is seen over the short-scales. The range also increases continually from the 10 year to 100 year period. Predicted values are smallest in Zuid-Holland and largest in Noord-Holland.

8.3.2.2) NUMBER OF PROFILES SHOWING SHOREWARD CLOSURE

The conclusions which have been made concerning the temporal dependence of Dc_s , as discussed in Chapter 6, are summarised below:

1. as the temporal period increases the percentage of profiles exhibiting Dc_s decreases; and
2. the relationship is best represented using a exponential trendline.

Exponential regression and the associated equation were derived using the percentage of profiles exhibiting closure for each method (sddc; fdc) and all change criteria (0.25 m; 0.5 m; 0.75 m), as shown in Figure 8.16. The equation was used to calculate the percentage of profiles displaying Dc_s every 10 years, for a maximum temporal period of 100 years. Due to the missing data of 1965 from km 72 to 97, this was performed for all profiles between km 16 and 71. All the projections are shown in Figure 8.17.

It is shown that there is a wide range of projected values of those profiles which show Dc_s through time; unlike that of the Dc_s values, the upper limit is given using the observations of the sddc fixed tail analysis (change criterion 0.5 m) and the lower limit using the fdc method (change criterion 0.25 m). The temporal occurrence of Dc_s will be of interest to the coastal manager though what is perhaps of particular interest is the time period at which the percentage occurrence becomes equal to fifty, twenty-five and zero; it is typical that the mean profile within a region is used as an indication of its shoreface behaviour although in reality there will be variation within the region. The use of these percentages will provide an index of the shoreface evolution within the Holland coast. At the latter point no profile along this wave-dominated coastline exhibits a shoreward closure i.e. profiles are either shoreward-partially active or fully-active. The critical periods calculated here, between km 16 and 71, are given in Table 8.12.

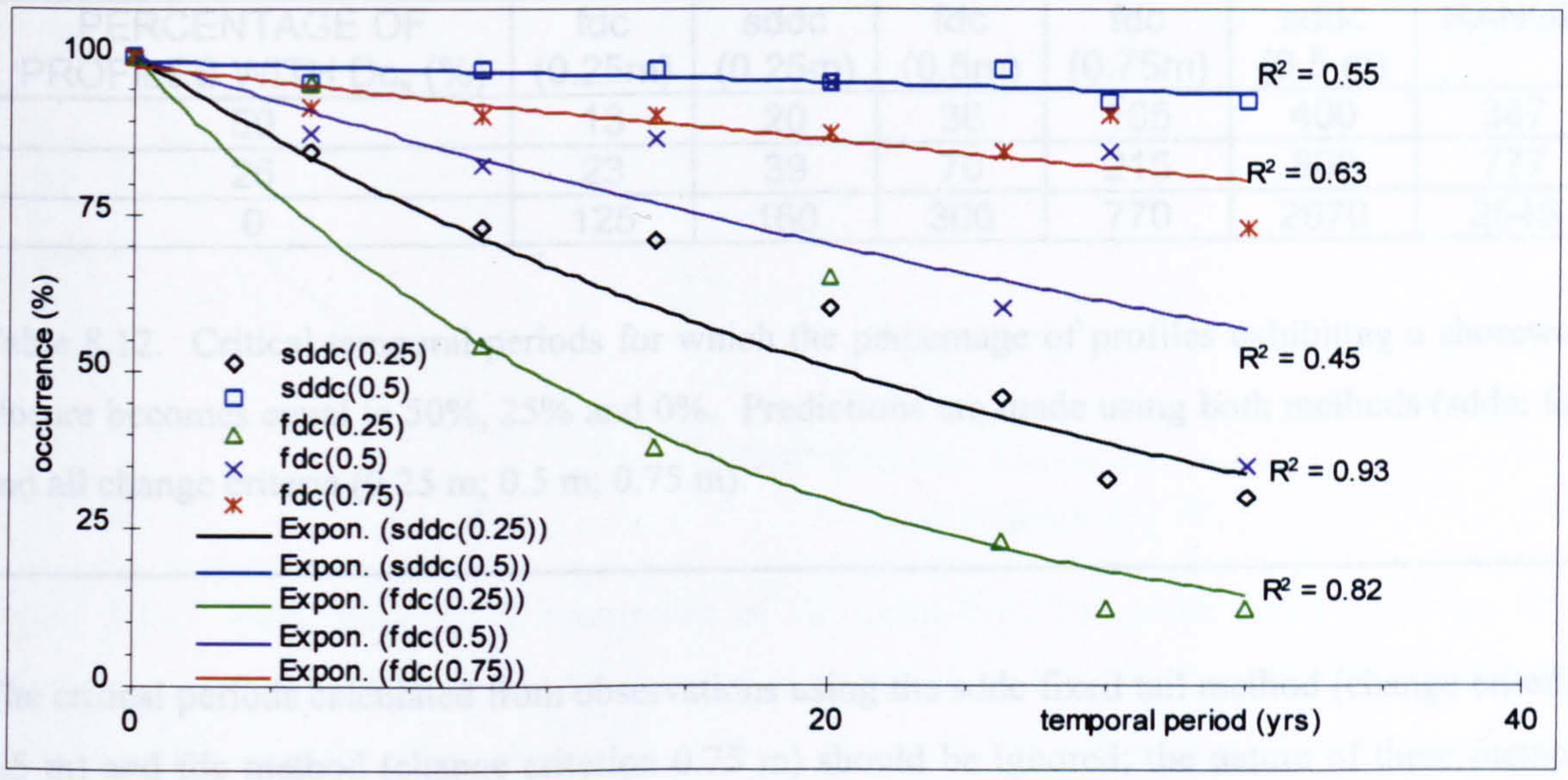


Figure 8.16. Exponential trendlines as used in the projection of the observed occurrence of Dc_s. All methods (sddc; fdc) and criteria (0.25 m; 0.5 m; 0.75 m) are shown .

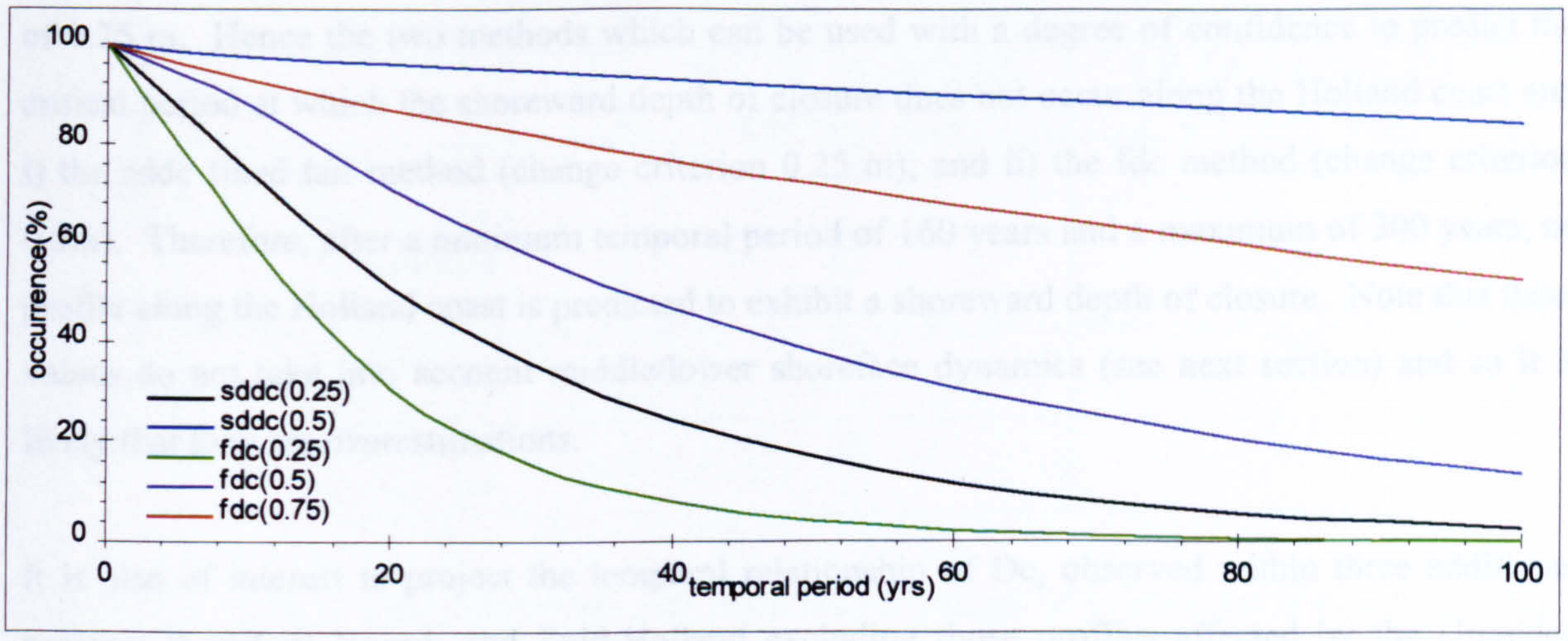


Figure 8.17. Predicted values of the occurrence of shoreward closure from 0 to 100 year temporal periods based on the extrapolation of observed results, for km 16 to 71. There is a wide range of temporal periods for when the occurrence will equal zero; 125 (fdc; 0.25 m) to 2670 (sddc; 0.5 m) years. It is suggested that the trends projected using the sddc (0.25 m) and fdc (0.5 m) are used as the other combinations of method and change criteria prove to be too sensitive (see text).

PERCENTAGE OF PROFILES WITH Dc_s (%)	fdc (0.25m)	sddc (0.25m)	fdc (0.5m)	fdc (0.75m)	sddc (0.5 m)	RANGE
50	13	20	36	105	400	387
25	23	39	70	215	800	777
0	125	160	300	770	2670	2545

Table 8.12. Critical temporal periods for which the percentage of profiles exhibiting a shoreward closure becomes equal to 50%, 25% and 0%. Predictions are made using both methods (sddc; fdc) and all change criteria (0.25 m; 0.5 m; 0.75 m).

The critical periods calculated from observations using the sddc fixed tail method (change criterion 0.5 m) and fdc method (change criterion 0.75 m) should be ignored; the nature of these methods combined with the large criteria allow large margins of change so that the observed occurrence of Dc_s does not change greatly between 5 and 32 years (Figure 6.6). Similarly, the critical period calculated using the observed periods of the fdc method (criterion 0.25 m) should also be ignored. This is because the method has proved to be too sensitive when using the smaller change criterion of 0.25 m. Hence the two methods which can be used with a degree of confidence to predict the critical period at which the shoreward depth of closure does not occur along the Holland coast are; i) the sddc fixed tail method (change criterion 0.25 m); and ii) the fdc method (change criterion 0.5m). Therefore, after a minimum temporal period of 160 years and a maximum of 300 years, no profile along the Holland coast is predicted to exhibit a shoreward depth of closure. Note that these values do not take into account middle/lower shoreface dynamics (see next section) and so it is likely that they are overestimations.

It is also of interest to project the temporal relationship of Dc_s observed within three additional regions; i) and ii) Noord- and Zuid-Holland excluding those profiles affected by the IJmuiden harbour moles; and iii) those profiles affected by the moles. Note that due to missing data of 1965 from km 72 to 97 the calculation of Zuid-Holland excluded temporal periods 25 and 32 years. The projections, using non-linear relationships, are shown in Figure 8.18, whilst the critical temporal period for which the percentage of profiles exhibiting closure are equal to zero are given in Table 8.13.

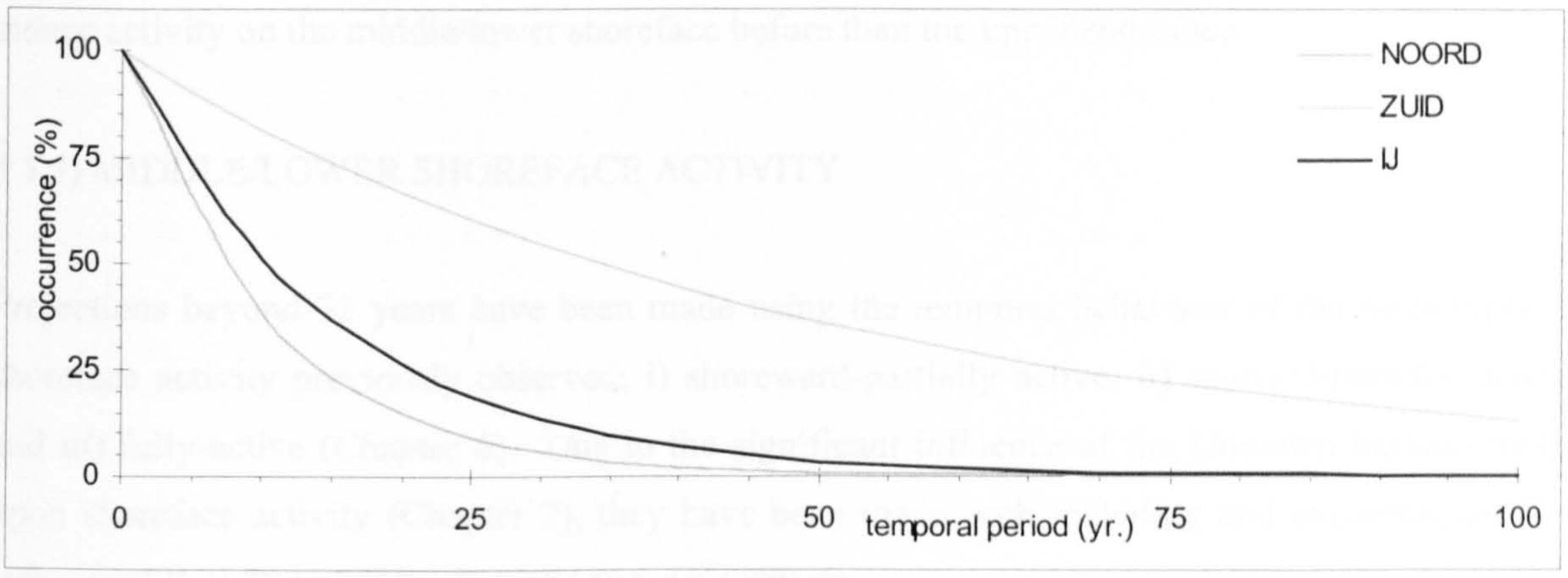


Figure 8.18. Projections of the occurrence of Dc_s from 0 to 100 years based upon non-linear relationships. The projections are for three regions chosen to identify the effect of the IJmuiden harbour moles upon Dc_s. The three regions are i) Noord-Holland (km 16 to 37); ii) Zuid-Holland (km 74 to 97); and iii) IJmuiden (km 38 to 73). Projections are based upon observations made with the sddc fixed tail method (0.25 m criterion).

REGION	CRITICAL TEMPORAL PERIOD (yrs) WHEN :	
	25% OF PROFILES EXHIBIT Dc_s	0% OF PROFILES EXHIBIT Dc_s
NOORD-HOLLAND (km 16 - 37)	15	60
IJMUIDEN (km 38 - 74)	21	80
ZUID-HOLLAND (km 75 - 97)	68	260
HOLLAND* (km 16 - 97)	39	160

Table 8.13. Critical temporal periods for which the percentage of profiles exhibiting a shoreward depth of closure is equal to 25% and 0% for four different regions. All results are derived using the sddc fixed tail (change criterion 0.25 m). (* = taken from Table 8.12).

It is clear that Noord-Holland is the most morphodynamically active region as it is here that the percentage of profiles exhibiting closure becomes equal to zero in the shortest time. These results also support the observation that Zuid-Holland is the most morphodynamically inactive region; it takes 260 years for no profile to exhibit Dcs. The critical time period for the profiles affected by the IJmuiden harbour moles is slightly longer than in Noord-Holland, supporting previous results

which state that the harbour moles do i) not influence the shoreward depth of closure; and ii) induce activity on the middle/lower shoreface before than the upper shoreface.

8.3.3) MIDDLE/LOWER SHOREFACE ACTIVITY

Projections beyond 32 years have been made using the temporal behaviour of the three types of shoreface activity previously observed; i) shoreward-partially active; ii) seaward-partially active; and iii) fully-active (Chapter 6). Due to the significant influence of the IJmuiden harbour moles upon shoreface activity (Chapter 7), they have been made both including and excluding profiles influenced (km 38 to 74) by the anthropogenic structure.

8.3.3.1) ANALYSIS USING ALL PROFILES

The conclusions which have been made from observations of the temporal behaviour of all profiles along the Holland coast, as taken from Chapter 6, are summarised below:

1. as the temporal period increases, the occurrence of partially active profiles (both shoreward and seaward) increases until a critical temporal period is reached when the occurrence reaches an almost constant value;
2. the number of fully active profiles are observed to continually increase with increasing temporal period.

The relationship is equally well represented using linear and non-linear trendlines, as shown in Figure 8.19, although the latter fit is slightly better, the difference in appropriate r^2 values is typically of the order of 0.01. For predictive purposes the non-linear trendlines and corresponding equations were used as the linear trendlines suggest that the partially-active shorefaces will continue to increase and observations (Chapter 6) show that this is not the case. Projected values of occurrence were then calculated every 10 years, for a maximum temporal period of 100 years using the non-linear equation.

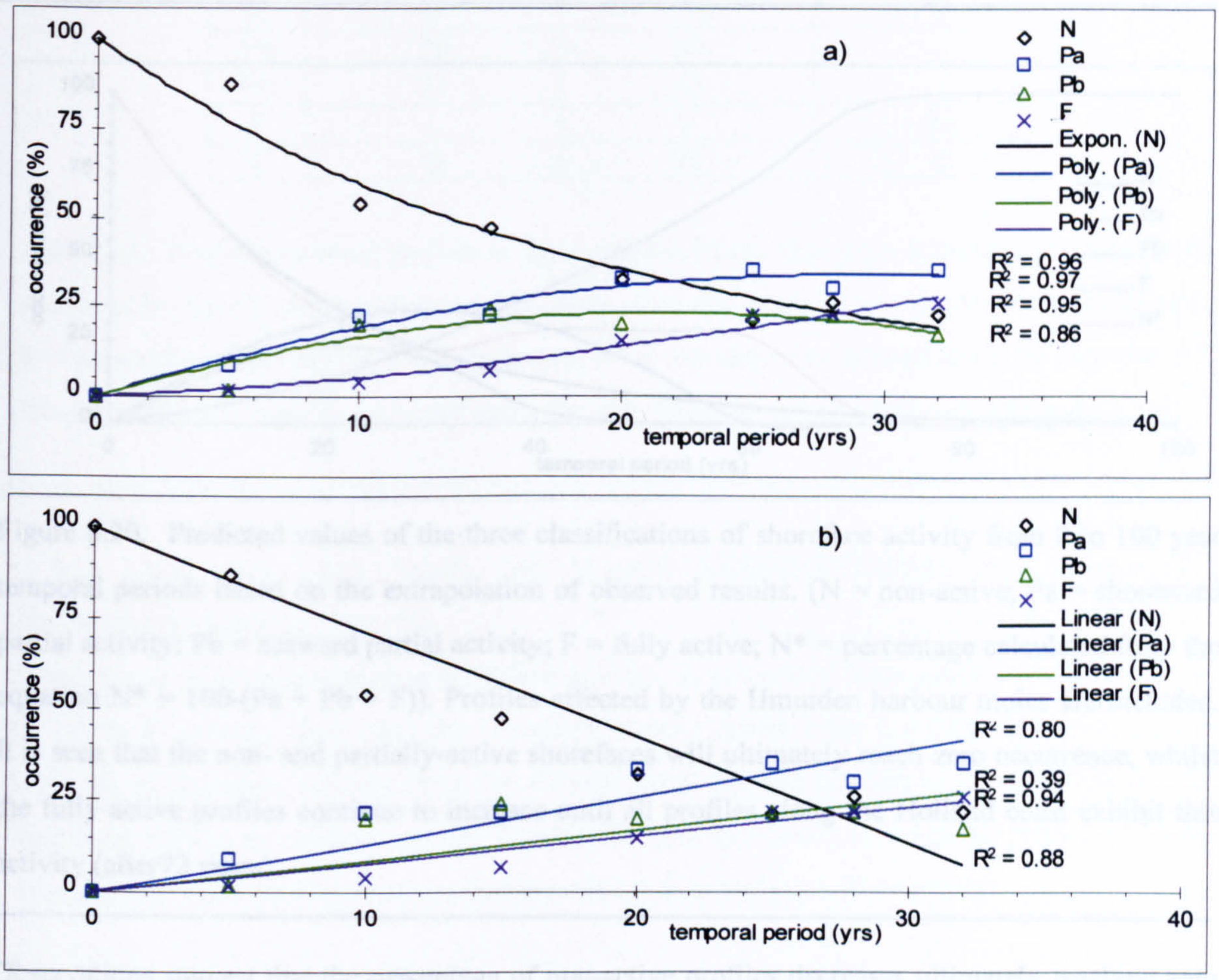


Figure 8.19. The temporal dependence of the classifications of shoreface activity taken from observations and the corresponding trendline. a) shows non-linear trendlines (order 2). b) shows linear trendlines. The R^2 values represent the correlation between the two variables according to the trendline.

As can be seen in Figure 8.20, those profiles exhibiting partially active shorefaces ultimately becomes zero whilst that of the fully active profiles reaches 100%. This agrees with the hypothesis based upon the original observations that :

As the temporal period increases, all profiles will evolve from exhibiting non-active to partially-active shorefaces. The profiles will then ultimately become fully active.

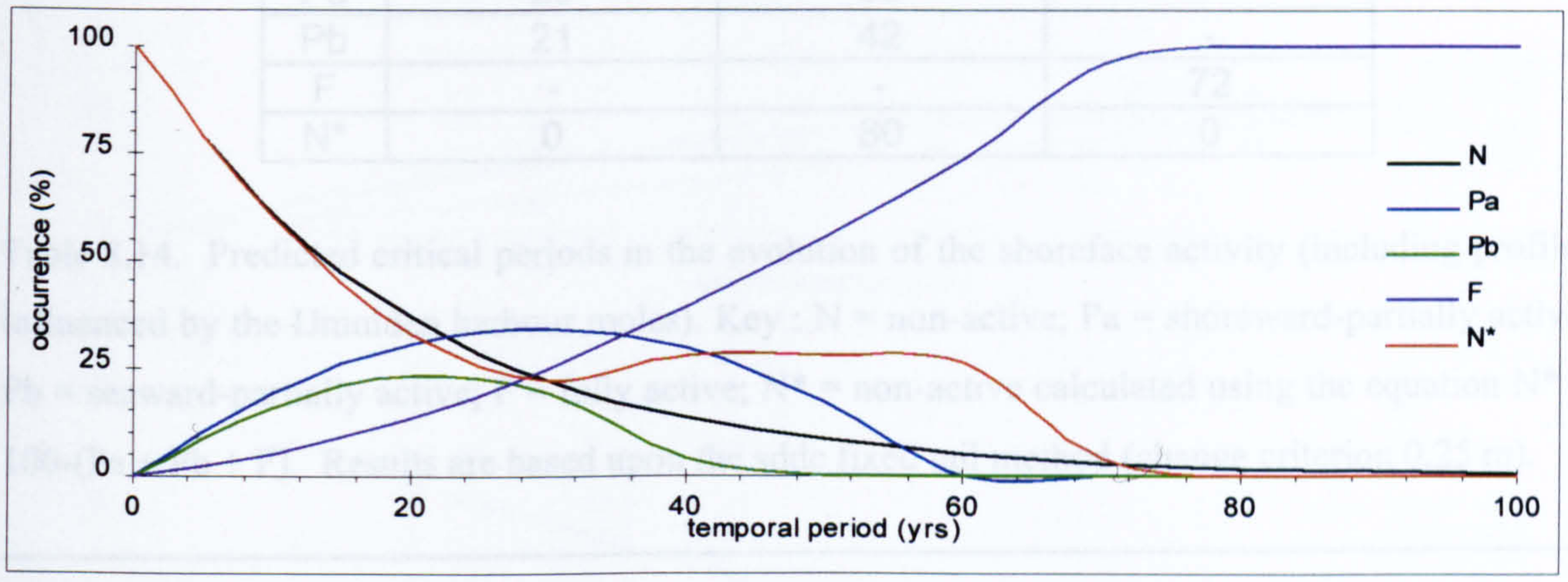


Figure 8.20. Predicted values of the three classifications of shoreface activity from 0 to 100 year temporal periods based on the extrapolation of observed results. (N = non-active; Pa = shoreward partial activity; Pb = seaward partial activity; F = fully active; N* = percentage calculated from the equation N* = 100-(Pa + Pb + F)). Profiles affected by the IJmuiden harbour moles are included. It is seen that the non- and partially-active shorefaces will ultimately reach zero occurrence, whilst the fully active profiles continue to increase until all profiles along the Holland coast exhibit this activity (after72 years).

Observations suggest that the percentage of non-active profiles decreases ultimately reaching zero (see Figure 6.6). Projections have been made of this classification using two methods, the first using exponential trendlines and the second was based upon the results from projections of the other three classifications. It can be seen that the critical periods are similar for both methods, giving further confidence in the results. The maximum number of shoreward-partially active profiles is projected to be reached after a temporal period of 29 years whilst it is reached after 21 years by the seaward-partially active profiles. The occurrence of the partially active profiles then decreases, becoming equal to zero after 59 and 42 years, respectively. The temporal increase in fully active profiles continues until the entire Holland shoreface is active after 72 years. However, this increase is not steady; after the number of partially-active profiles reaches a maximum, an acceleration in the increase in fully active profiles is observed. The critical periods in the evolution of the Holland shoreface are given in Table 8.14.

	CRITICAL PERIOD (yrs) WHEN :		
	MAXIMUM OCCURRENCE	ZERO OCCURRENCE	OCCURRENCE = 100%
N	0	110	0
Pa	29	59	-
Pb	21	42	-
F	-	-	72
N*	0	80	0

Table 8.14. Predicted critical periods in the evolution of the shoreface activity (including profiles influenced by the IJmuiden harbour moles). Key : N = non-active; Pa = shoreward-partially active; Pb = seaward-partially active; F = fully active; N* = non-active calculated using the equation N* = 100-(Pa + Pb + F). Results are based upon the sddc fixed tail method (change criterion 0.25 m).

8.3.3.2) ANALYSIS EXCLUDING THE MAJOR ANTHROPOGENIC INFLUENCE (THE IJMUIDEN HARBOUR MOLES)

Observations of the occurrence of shoreface activity, as calculated from profiles km 16 to 37, and km 75 to 97, clearly show that the IJmuiden harbour moles have a strong influence upon the evolution of shoreface activity along the Holland coast causing profiles to become fully active at rates faster than in an unforced system (Chapter 7). The hypothesis stated in the previous section is therefore still valid but it is expected that the critical time periods will be greater.

As with previous predictions, non-linear and linear trendlines both well represent the observed temporal relationship (Figure 8.21). However, it is clear that the former relationship does provide the better fit of the two. Projected values of occurrence were calculated every 10 years, for a maximum temporal period of 100 years using the non-linear equation. However, the temporal period was subsequently extended beyond the 100 years as initial calculations showed that the critical periods were greater than this selected upper limit.

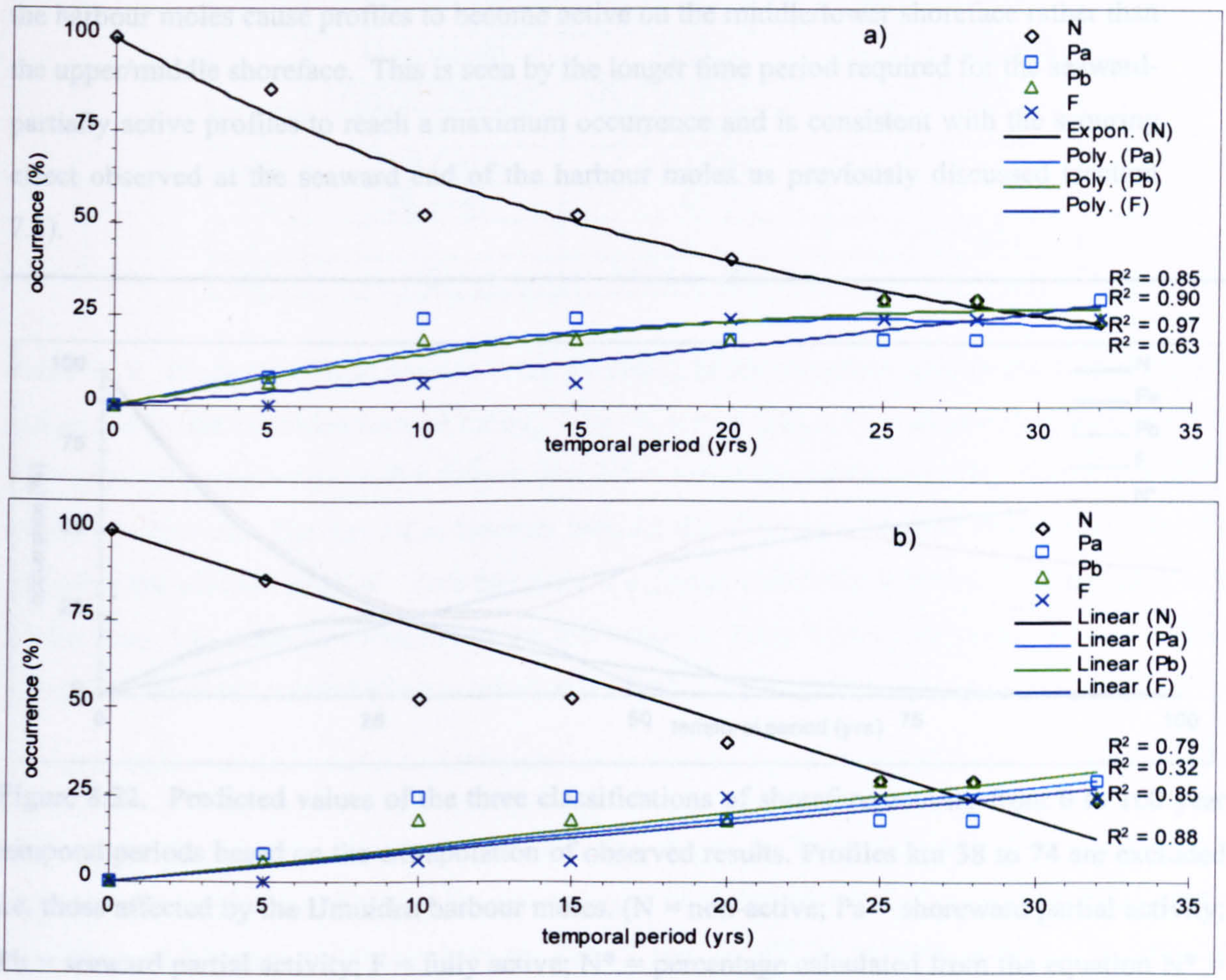


Figure 8.21. The temporal dependence of the classifications of shoreface activity taken from observations and the corresponding trendline. Profiles influenced by the IJmuiden harbour moles are removed. a) shows non-linear trendlines; b) shows linear trendlines. The R2 values represent the correlation between the two variables according to the trendline. It is clear that the non-linear trendlines provide the best fit.

As can be seen in Figure 8.22, the behaviour of the non, partially and fully active shorefaces mimic that observed when profiles km 38 to 74 are included; the non-active profiles decrease to zero, the partially active shorefaces increase until a maximum occurrence is reached after which it then decreases, ultimately reaching zero whilst the fully active profiles continually increase. *However*, there is one important difference between the two projections; the length of time taken for the classifications to reach their critical periods. These periods for profiles excluding km 38 to 74 are shown in Table 8.15. It also becomes apparent that the IJmuiden harbour moles do not effect the shoreward-partially active shorefaces to the same extent that they do the seaward-partially active

ones; it is therefore suggested that besides the quicker induction to the fully active shoreface, the harbour moles cause profiles to become active on the middle/lower shoreface rather than the upper/middle shoreface. This is seen by the longer time period required for the seaward-partially active profiles to reach a maximum occurrence and is consistent with the scouring effect observed at the seaward end of the harbour moles as previously discussed (section 7.3).

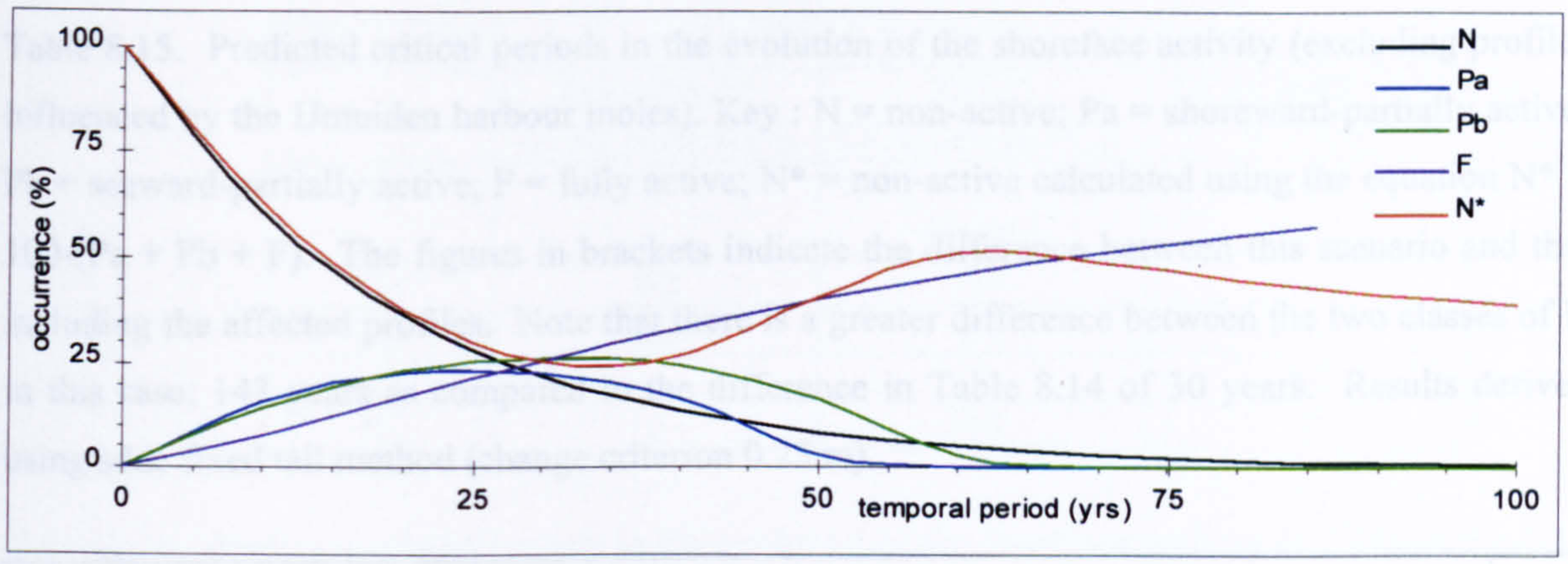


Figure 8.22. Predicted values of the three classifications of shoreface activity from 0 to 100 year temporal periods based on the extrapolation of observed results. Profiles km 38 to 74 are excluded i.e. those affected by the IJmuiden harbour moles. (N = non-active; Pa = shoreward partial activity; Pb = seaward partial activity; F = fully active; N* = percentage calculated from the equation N* = 100-(Pa + Pb + F)). When compared to the projections made including km 38 to 74, one can see that the lengths of time taken to reach the critical points for each classification are typically longer (Table 8.14).

This procedure was also repeated for the separate evolution of three regions as observations (Chapter 6; Figure 6.8) show that these provinces have different morphodynamical behaviour; the three regions are; i) km 16 to 37 (Noord-Holland); ii) km 38 to 74 (profiles affected by the harbour moles); and iii) km 75 to 97 (Zuid-Holland; note that due to missing data of 1965 from km 72 to 97 the calculation for this region excluded temporal periods 25 and 32 years). It is expected that whilst all profiles will ultimately become fully active, Noord-Holland will exhibit this behaviour first.

	CRITICAL PERIOD (yrs) WHEN :		
	MAXIMUM OCCURRENCE	ZERO OCCURRENCE	OCCURRENCE = 100%
N	0	27 (-83)	0
Pa	20 (-9)	41 (-18)	-
Pb	25 (+4)	42	-
F	-	-	170 (+98)
N*	0	170 (+90)	0

Table 8.15. Predicted critical periods in the evolution of the shoreface activity (excluding profiles influenced by the IJmuiden harbour moles). Key : N = non-active; Pa = shoreward-partially active; Pb = seaward-partially active; F = fully active; N* = non-active calculated using the equation N* = 100-(Pa + Pb + F). The figures in brackets indicate the difference between this scenario and that including the affected profiles. Note that there is a greater difference between the two classes of N in this case; 143 years as compared to the difference in Table 8.14 of 30 years. Results derived using sddc fixed tail method (change criterion 0.25 m).

The results (based upon non-linear equations (as shown in Table 8.16 and Figure 8.23)) only supports part of this hypothesis. For the example of Noord-Holland, it is projected that after a maximum of 63 years no profile between km 16 and 37 will be partially-active. The temporal behaviour of the fully-active profiles within the 32 years is well represented using linear, logarithmic and polynomial equations. However, it is the former that best describes the observed behaviour; all profiles will become fully active within a time period similar to that already calculated; 100 years. With the polynominal form the occurrence of these profiles ultimately becomes zero, whilst with the logarithmic all profiles are fully active after 4500 years. It is suggested that this is a consequence of the sampling population limits; spatially it is 17 profiles and temporally 32 years. However, when considering Zuid-Holland, there is no temporal trend of the shoreface classifications and so the projections for this region are discounted. This indicates that the timescale in Zuid-Holland is much slower than in Noord-Holland. The results for km 38 to 74 show that the IJmuiden harbour moles act to induce activity across the entire profile at smaller temporal periods that in the 'natural' system; 52 years (km 38 to 74) versus 100 years (km 16 to 37).

NOORD	CRITICAL PERIOD (yrs) WHEN :		
	MAXIMUM OCCURRENCE	ZERO OCCURRENCE	OCCURRENCE = 100%
N	0	130	0
Pa	30	55	-
Pb	30	55	-
F	-	0	100
N*	0	100	0

IJMUIDEN	CRITICAL PERIOD (yrs) WHEN :		
	MAXIMUM OCCURRENCE	ZERO OCCURRENCE	OCCURRENCE = 100%
N	0	84 (<10% after 40 yrs)	0
Pa	50	104	-
Pb	20	37	-
F	-	0	52
N*	0	40	0

Table 8.16. Predicted critical periods in the evolution of the shoreface activity of i) Noord-Holland (excluding profiles influenced by the IJmuiden harbour moles); and ii) those profiles affected by the harbour moles (km 38 to 74). Key : N = non-active; Pa = shoreward-partially active; Pb = seaward-partially active; F = fully active; N* = non-active calculated using the equation N* = 100-(Pa + Pb + F). Results derived using sddc fixed tail method (change criterion 0.25 m).

The integration of Table 8.15 and 8.16 show that there is some disagreement between the projections. For example 100% of profiles are fully-active after approximately i) 170 years for the entire Holland coast; and ii)100 to 4500 years for Noord-Holland. However, there is also agreement as shown in the critical time periods for the non- and partially-active shorefaces between Noord-Holland and the entire Holland coast. It is suggested that the limited integration results from the strong temporal signature observed in Noord-Holland.

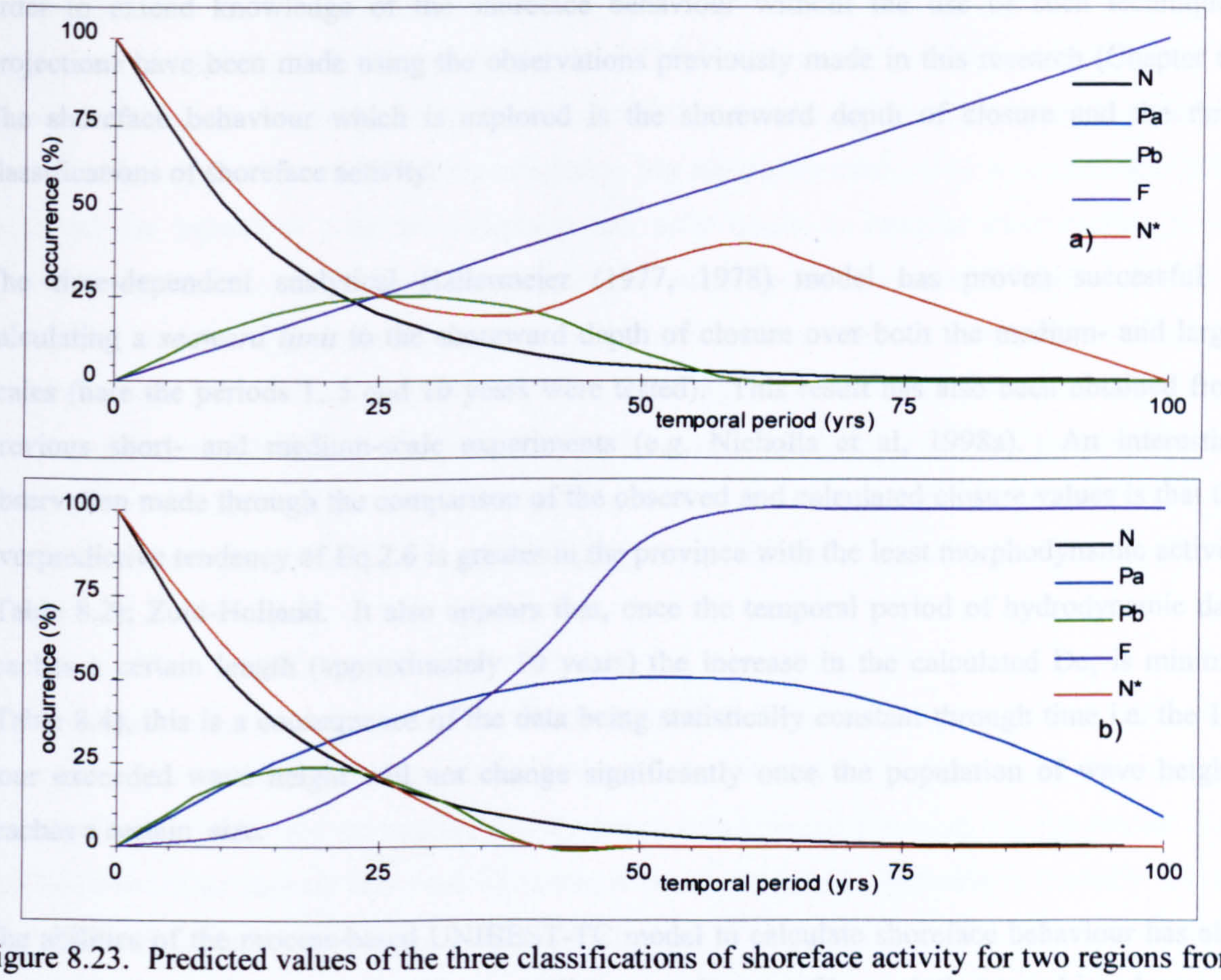


Figure 8.23. Predicted values of the three classifications of shoreface activity for two regions from 0 to 100 year temporal periods based on the extrapolation of observed results. The two regions are a) Noord-Holland (km 16 to 37); and b) IJmuiden (km 38 to 73). (N = non-active; Pa = shoreward partial activity; Pb = seaward partial activity; F = fully active; N* = percentage calculated from the equation N* = 100-(Pa + Pb + F)). When compared to the projections made including km 38 to 74, one can see that the lengths of time taken to reach the critical points for each classification are typically longer (Table 8.14).

8.4) SUMMARY

There are few existing studies which have, as has this one, been able to observe medium- and large-scale shoreface behaviour. So for those coastlines that have insufficient data, predictive techniques are relied upon to determine the morphodynamic behaviour. Existing models have been tested here to determine not only their accuracy at predicting the behaviour but also their

limitations. It is shown that these methods are only useful over a certain temporal period, so in order to extend knowledge of the shoreface behaviour without the use of such techniques, projections have been made using the observations previously made in this research (Chapter 6). The shoreface behaviour which is explored is the shoreward depth of closure and the three classifications of shoreface activity.

The time-dependent analytical Hallermeier (1977, 1978) model has proven successful in calculating a *seaward limit* to the shoreward depth of closure over both the medium- and large-scales (here the periods 1, 5 and 10 years were tested). This result has also been obtained from previous short- and medium-scale experiments (e.g. Nicholls et al, 1998a). An interesting observation made through the comparison of the observed and calculated closure values is that the overpredictive tendency of Eq.2.6 is greater in the province with the least morphodynamic activity (Table 8.2); Zuid-Holland. It also appears that, once the temporal period of hydrodynamic data reaches a certain length (approximately 10 years) the increase in the calculated Dc_s is minimal (Table 8.4), this is a consequence of the data being statistically constant through time i.e. the 12-hour exceeded wave height will not change significantly once the population of wave heights reaches a certain size.

The abilities of the process-based UNIBEST-TC model to calculate shoreface behaviour has also been tested here. It has proven able to predict cross-shore profile evolution to a high degree of accuracy on the short- and medium-scales (Szmytkiewicz *et al*, 1997). However, the bathymetric output from the model clearly showed that it is unable to correctly calculate the evolution of the middle and lower shoreface (Figure 5.7) and so was only used to predict the shoreward depth of closure. The results obtained suggest that UNIBEST-TC can be used with confidence to predict Dc_s over the short- and medium-timescales, for coastlines which have relatively little morphodynamic activity. Although it has not been tested for coastlines which are highly morphodynamically active, results from existing studies suggest that it also has potential here, for example Roelvink and Broker (1993) found that UNIBEST-TC accurately re-created the evolution of cross-shore profiles at Terschelling, The Netherlands. This location has a high level of morphodynamic activity as highlighted by the morphological nearshore bar cycle of 12 years (Ruessink, 1998) (3 years less than the same cycle in Noord-Holland). However, although the predicted and observed closure values over the 10 year period agree (Figure 8.8), scepticism does exist concerning the overall accuracy of the final bathymetry of the predicted profile; the final cross-shore profile does not exhibit bars. Therefore, although UNIBEST-TC does have the ability

to mimic the offshore degeneration and nearshore growth of bars on the short- and medium-term, it appears that this ability, especially in the form of the latter characteristic, does not exist on the long-term (Figure 8.21). It is concluded that UNIBEST-TC should only be used to predict the shoreward depth of closure on the short- and medium-scales; Dc_s is a morphodynamic parameter shown to be under the control of the nearshore bar morphodynamics and discrepancies in the predicted bar behaviour over the long-term can only result in inherent discrepancies in the predicted depth of closure. Indeed the programmers of the model have warned against the use of this model over the large-scale as it does contain inherent errors which, although insignificant on the time-scales[7] for which it was designed, do become larger and more significant over these larger scales (per. comm. Walstra, 1998). It is therefore surprising that i) the predicted Dc_s over the long-term agrees with the corresponding observed Dc_s, and ii) the temporal trend of the observed and calculated values shows such good agreement, as seen with the correlation coefficients (Figure 8.9).

The projections of observed trends of the shoreward depth of closure and partially and fully active shorefaces give an informative view of the future development of the Holland coast. Though such a method is limited by the assumption that the future behaviour of the coast will not deviate from that observed over periods less than 32 years, it is one of the few techniques available for the determination of the very-large-scale coastal behaviour. The results from the projections should, however only be used as an indication of future shoreface behaviour as it is clear that in some instances the time periods for the different classifications do not correlate (e.g. Table 8.15). It is important that the fact that 'after time *t* all profiles will become fully active' is applied to all large-scale shoreface studies. The critical time *t* is shown, through the comparison of results i) with and without km 38 to 74, and ii) Noord- and Zuid-Holland, to be a function of the forcings and so morphodynamic behaviour of the shoreface.

Extrapolation beyond the 32 year data limit has confirmed the hypotheses made from the observations of the JARKUS data set (Chapter 6). Closure values increase slowly with time period (Figure 8.13; Table 8.11) such that, after 100 years, the deepest values (10.6 m) in Noord-Holland indicate that the profile would have evolved into a shoreward-partially active shoreface, if there was no middle/lower shoreface activity. It is also suggested that after a minimum time period of 160 years and a maximum period of 300 years the entire Holland shoreface will become fully active on every profile (Figure 8.15). Although if the evolution of the provinces are

[7] the short- and medium-scales

examined the important temporal periods are 60, 80 and 260 years (Noord-Holland, IJmuiden, and Zuid-Holland respectively). These temporal periods agree with the results of modelling studies which indicate that the shoreface becomes fully active over 10 to 100 years (Figure 2.11; Nicholls *et al*, 1998c). It is also clear that the harbour moles force the shoreface to become fully active at time periods less than in an unforced situation; 100 years (km 16 to 37) versus 50 years (km 38 to 74). In all examples the shoreward- and seaward-partially active shorefaces never reach 100%, instead reaching a maximum occurrence within the range 20 and 50 years (Table 8.14, 8.15 and 8.16).

In conclusion therefore :

1. the Hallermeier (1977, 1978) model calculates a seaward limit to the shoreward depth of closure of a wave-dominated coastline, over the medium- and large-scales;
2. UNIBEST-TC is only able to correctly predict the evolution of the upper shoreface over the short- and medium-scales. Values of the shoreward closure can be calculated using this model over the said scales; and
3. the extrapolation technique is a useful tool in determining future coastal behaviour if its limitations are taken into consideration. It shows that i) all profiles along the Holland coast will evolve from exhibiting a shoreward closure to becoming fully active within the time period 160 to 300 years; ii) the IJmuiden harbour moles cause the profiles to become fully active at significantly smaller time periods than in an unforced situation, approximately 70 years; and iii) the morphodynamic behaviour of Zuid-Holland occurs at much longer timescales than Noord-Holland.

9) DISCUSSION

9.1) INTRODUCTION

It can be argued that the shoreface is the most important part of the coastal system, for this region acts as the buffer zone between the land and sea environments and is a potential sediment source or sink (Cowell *et al*, 2000). Although many of the feedback relationships which act upon the shoreface are understood over the short- and, sometimes, medium-scales (100 m and storms-seasons; 1 km and years, respectively), there is still "*little information available on depth change along the profile and its time variation*" (Larson and Kraus, 1994). Hence there is a growing need for knowledge over the large-scale (10 km and decades); this is primarily a result of an increase in i) the strategic perspective within coastal zone management of long-term modelling; and ii) the requirement for information concerning long-term predictability methods (and so predictability limits). It is this knowledge gap that this study, through the adoption of a data-orientated approach, has focused upon.

The main aim of this research was to determine the spatial- and temporal-characteristics of shoreface morphodynamic behaviour over all scales, paying particular attention to changes over timescales longer than 10 years. It was the availability of the large-scale Dutch data set $JARKUS_{S+E}$ which allowed this to be fulfilled. Indeed this study led to the observation of numerous shoreface morphodynamic characteristics (as discussed in following sections), the majority of which were previously unobserved or poorly described :

1. the *shoreward closure* (Dc_s). ;
2. the *re-opening point* (Ro) and associated *re-opening zone*; and
3. the *middle/lower shoreface closure* ($D_{cm/l}$).

The identification of the re-opening zone led to further classification of the shoreface activity :

1. an *inactive shoreface*;
2. a *shoreward partially-active shoreface*;
3. a *seaward partially-active shoreface*; and
4. a *fully-active shoreface.*

The objective of this chapter is to discuss the results obtained in this study and compare them with existing work (which is typically available for similar shoreface characteristics but over the smaller scales) and through integration with key debates e.g. the validity of long-term models.

9.2) OBSERVATIONS OF MEDIUM- AND LARGE-SCALE SHOREFACE BEHAVIOUR

The coastal environment can be divided into regions of distinct morphodynamic characteristics e.g. the tidal inlet and dune system. The morphodynamic region which is studied here, the shoreface, extends from the outer limit of the breaker bars to the nearly horizontal continental slope. The different coastal regions have been traditionally viewed as separate sections within the coastal environment. However, recent work based upon long-term modelling efforts (e.g. Cowell *et al*, 2000) has shown that there exists a coupling between these sections which is dependent upon the scale of interest. This has been done through the development of the 'coastal tract concept' in which boundary conditions and internal dynamics are defined for low-order (long-term) coastal behaviour. An example of the coupling is shown through the response to forcing which results in the fast (short-scale) exchange of sediment within the beach-surf zone and a slow (large-scale) exchange within the surf zone-inner shelf system (Wright *et al*, 1985). In reality these sections must not be considered separately. However, for ease of description and discussion this chapter principally treats the two main shoreface zones (the upper shoreface and middle/lower shoreface) independently of each other. Latter sections take an integrated view, discussing the forcings and responses of the shoreface as a function of scale.

9.2.1) CHARACTERISTICS OF THE CROSS-SHORE PROFILE

The Holland coast is composed of different nearshore morphodynamic provinces, as revealed through observations of the seaward limit to significant depth change (this study) and the near-shore bar system (e.g. Wijnberg and Terwindt, 1995). The main provinces are termed Noord- and Zuid-Holland and correspond to the profile range km 16 to 54 and km 57 to 97, respectively. Although the same distinctive cross-shore features (Dc_s; Ro) are displayed in both provinces, differences in their associated characteristics and temporal-behaviour have resulted in the identification of these regions. This section will discuss the cross-shore properties found within a typical profile along the Holland coast, as observed within this study. Details concerning the

differences (both temporally and spatially) observed alongshore are dealt with in the following section.

The sddc analysis of the large-scale JARKUS data set has revealed the presence of three major morphodynamic features of the Holland shoreface, all of which are particular to certain time scales (Figure 6.2). The application of these features to other, global, shorefaces is discussed in section 9.5.

9.2.1.1) THE *SHOREWARD DEPTH OF CLOSURE* (Dc_s).

This feature's properties are equivalent to those of the depth of closure (e.g. Nicholls *et al*, 1996) in that it represents a 'cross-shore limit to *significant* depth change' (according to the change criterion chosen). However, in this instance, the data limits are such that it can be seen that the shoreward closure is often (typically over the larger-scales) followed in the cross-shore by further shoreface activity. It is suggested that the traditionally termed 'depth of closure' (Dc) should be re-classified as the 'shoreward depth of closure'(Dc_s); data limitations in the cross-shore over the medium- and large-scales (e.g. at Duck, N.Carolina) have meant that depth of closure represents a definite cross-shore boundary to morphodynamic activity. However, if it were possible to extend these data sets it is highly probable that significant morphodynamic activity would be observed seaward of Dc; this is presently being investigated at Duck, N. Carolina (cf. Beaver *et al*, 1999).

Dc_s is strongly spatially- and temporally-dependent over the time-scales investigated here (5 to 32 years), agreeing with observations made in previous studies which studied the short-scale dependence of Dc through time and space. It is these spatial and temporal signatures which have lead to the longshore division of the Holland coast into morphodynamically similar provinces, as discussed in section 9.2.2. In addition the logarithmic behaviour (Figure 8.17) of the Dc_s occurrence[1] is such that projections show that no profile will exhibit Dc_s after the 160 years (using the sddc fixed tail change criterion 0.25 m) and 300 years (using the fdc change criterion 0. 5 m).

9.2.1.2) THE *RE-OPENING POINT* (Ro) AND ASSOCIATED *RE-OPENING ZONE*

It has historically been assumed that the shoreward closure was the seaward limit to morphodynamic activity. However, significant profile changes have been observed in this study seaward of Dc_s over time periods typically greater, or equal, to 10 years[2]. Middle/lower shoreface activity has only previously been observed during high-energy events (Vincent *et al*, 1983; Wright

[1] as seen in short-scale studies e.g. Nicholls *et al* (1996).
[2] a few profiles do exhibit this behaviour over smaller temporal periods e.g. km 24 (Figure 6.9).

et al, 1986; Snedden *et al*, 1988; Wright, 1983) although other geological and modelling approaches have suggested that these changes take place on the large-scale (Niedoroda *et al*, 1985; Stive *et al*, 1990; Roelvink and Stive, 1990; Cowell *et al*, 1995; Stive and De Vriend, 1995). The observations made within this thesis show that this activity results from slow, steady cumulative processes i.e. regular storms rather than fast, infrequent causes i.e. extreme events. It is suggested that the observed bathymetric changes are caused by the wave-induced processes which result from regular storms; the most significant process of which has been shown to be wave asymmetry (Roelvink and Stive, 1990; Stive *et al*, 1990). The nature of this change indicates that the shoreface is steadily evolving to a new form. The evolution of the shoreface to this 'new form' will be a continuing process as the boundary conditions (e.g. sea-level) and forcings (e.g. hydrodynamic climate) are also continually changing (cf. Hoozemans, 1990).

The cross-shore location where significant profile changes (according to the change criterion selected) commence has been termed the re-opening point and the seaward cross-shore region of activity the re-opening zone. This activity is typically restricted to the middle and/or lower shoreface and has not been observed in past studies due to their spatial and temporal data limitations. Observations made within this investigation have led to the development of a classification of the shoreface activity, based upon the concept of re-opening (Figure 6.2) as listed below:

1. an *inactive shoreface*. No morphodynamic activity is observed seaward of Dc_s. This behaviour is typical of i) time periods less than 10 years; and ii) morphodynamically inactive regions e.g. km 89 to 93;
2. a *shoreward partially-active shoreface*. The shoreface is active until the middle/lower shoreface i.e. there is no closure on the upper shoreface;
3. a *seaward partially-active shoreface*. The shoreface exhibits a shoreward closure and then re-opens further seaward. The profile may exhibit closure towards its seaward limit; and
4. a *fully-active shoreface*. Morphodynamic activity occurs across the entire shoreface to the data limits i.e. the profile does not exhibit a shoreward closure. This activity is typical of the longer time periods e.g. 32 years.

The occurrence of the four different shoreface classifications are both temporally- and spatially-dependent, as discussed in subsequent sections. It is suggested that the latter three shoreface types are typically found over the longer temporal periods where strong forcings act (both natural and

anthropogenic) upon the morphodynamics, an example of an anthropogenic forcing is the IJmuiden harbour moles which cause the tidal currents to accelerate (Roelvink *et al*, 1998).

Additionally, as previously stated, it is the non-active shoreface which is typical of the shorter time periods and the fully-active shorefaces of the longer time periods; as the time scale increases then a profile will evolve from an inactive to a partially-active and ultimately to a fully-active shoreface. This is particularly apparent in Noord-Holland, whilst in Zuid-Holland morphodynamic time periods mean that it is not as obvious. The hypothesis that ultimately all profiles along the Holland coast will be fully active has been used by extrapolation of observed trends where possible[3].

The extrapolation was carried out for the three types of shoreface activity, both including and excluding those profiles which have been estimated (using the van Rijn 'rule of thumb'; Chapter 7) to be influenced by the IJmuiden harbour moles; km 38 to 74. (The latter scenario is discussed in the following section). It is shown that all profiles on the 'natural' Noord-Holland shoreface are predicted to become fully active after a minimum of 100 years (Table 8.16).

9.2.1.3) THE *MIDDLE/LOWER SHOREFACE CLOSURE* ($Dc_{m/l}$)

This feature marks the seaward limit to the middle/lower shoreface activity and so will not be observed on those profiles which have a fully-active shoreface. $Dc_{m/l}$ is not always observed along a seaward partially-active profile; it is suggested that this is due to data limitations and if the cross-shore measurements were to be extended further seaward a closure would be observed (according to the change criterion selected). (Note that this feature is not discussed further as it is an integral part of the shoreward- and seaward-partially active shorefaces).

9.2.2) CHARACTERISTICS OF THE CROSS-SHORE PROFILE WITHIN THE TWO PROVINCES

The cross-shore features discussed above (Dc_s; Ro; $Dc_{m/l}$) are for a typical profile within km 16 to 97. If one were to divide the coast into the two main provinces Noord- and Zuid-Holland, then variations in the average profile become apparent, resulting from differences in the temporal development of the two provinces. (Note: this has been completed for all profiles excluding those influenced by the IJmuiden harbour moles as the morphodynamic activity of these profiles (km 38

[3] the morphodynamic inactivity of Zuid-Holland mean that this method will not produce viable results

to 74) has been shown to be accelerated by the moles). Characteristic features of profiles within the two provinces as a function of time are now discussed :

9.2.2.1) NOORD-HOLLAND

This province exhibits a higher degree of morphodynamic activity when compared to that of Zuid-Holland (Figure 6.3), this is most apparent on the upper shoreface (see section 9.2.2). The direct consequence of this is that, with the exception of 4 profiles, km 16 to 37 exhibits some form of activity over the time period investigated. Indeed over the longer temporal periods (32 years), 53% of the Noord-Holland profiles are partially-active and 24% are fully active (this has evolved from 18% (partially-active) and 6% (fully active) over the 5 year period). As a result of the dominant features which have been observed throughout the time period of investigation, two profiles should be used to represent this province over a period of 32 years. These profiles therefore characterise all the information gained from the observations made within this study :

- temporal periods from 5 to 20 years. The typical profile only exhibits a shoreward depth of closure; the remainder of the profile is inactive (Figure 9.1a); and
- temporal periods from 25 to 30 years. The characteristic profile is partially-active (Figure 9.1b). However, no distinction can be made between the two forms of this activity (shoreward and seaward) and so the fact that the middle/lower shoreface is active should be taken as representative.

Extrapolation of the observed trends suggests that over temporal periods greater than 100 years, the typical profile for Noord-Holland will be fully-active (Figure 9.1c).

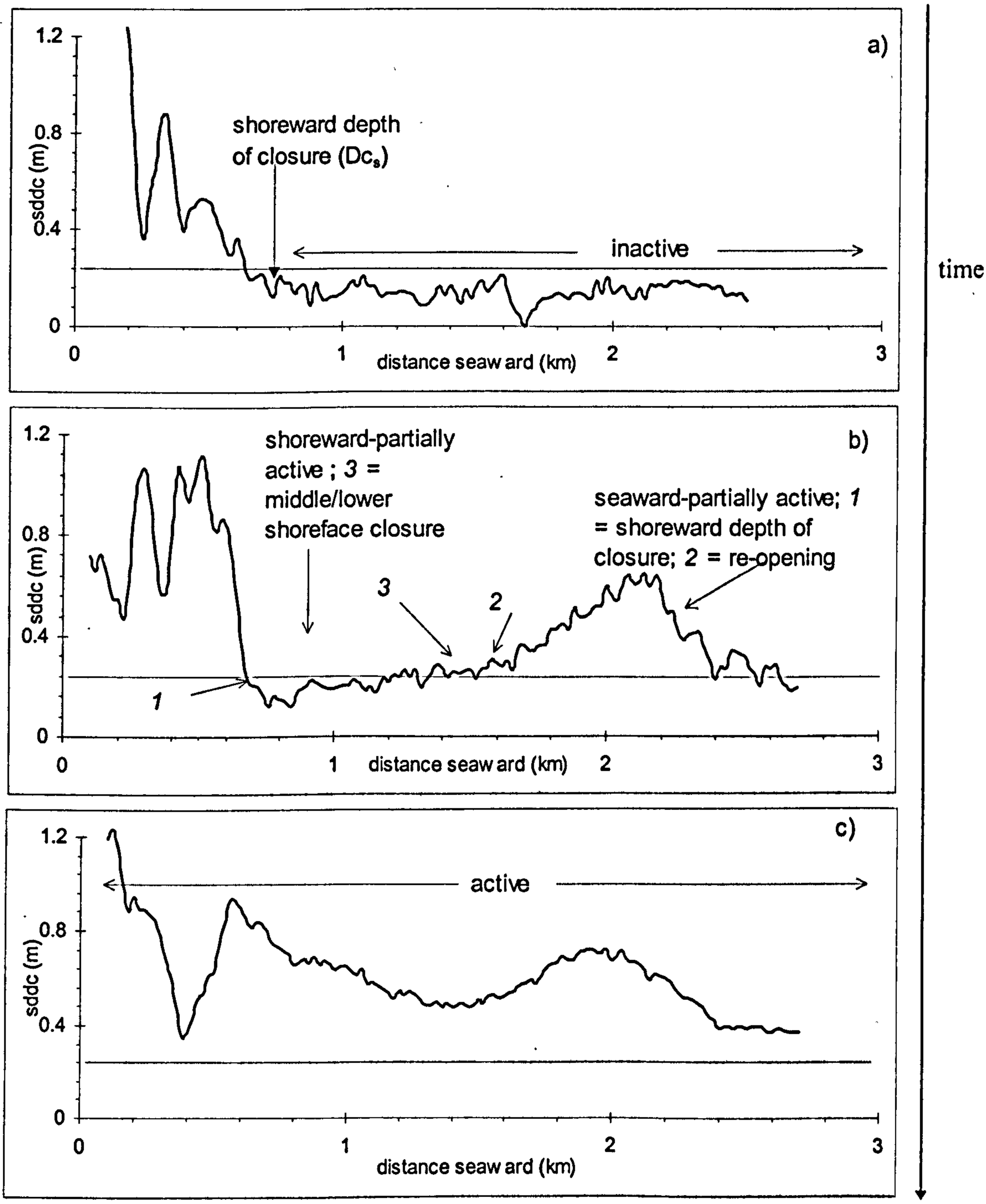


Figure 9.1. Characteristic profiles of Noord-Holland demonstrating the cross-shore features observed and inferred over different time scales using the sddc change criterion 0.25 m. a) = temporal period < 20 years; b) = temporal period > 25 - 30 years; c) = temporal period > 100 years.

9.2.2.2) ZUID-HOLLAND

Although shoreface activity has been observed for the profiles km 57 to 73, they are strongly influenced by the harbour moles and so they have been discounted in the determination of a representative profile. The result is that there is a dominance of morphodynamic inactivity (Figure 6.9) within this province from 5 to 28[4] years; at the largest temporal period 87% of profiles have inactive shorefaces. Therefore one representative profile can be used for this province over the entire period:

- temporal period 5 to 30 years. The characteristic profile is non-active; it only features a shoreward depth of closure, there is no morphodynamic activity seaward of it (Figure 9.2a).

Observed trends of behaviour within Noord-Holland and along the entire Holland coast suggest that ultimately the typical profile will become fully-active. However, due to the less significant morphodynamic activity in Zuid-Holland, timescales of activity cannot be extrapolated for this province based upon the JARKUS data set. It is suggested however, that over a 100 year period the characteristic profile will be partially-active whilst over larger time periods profiles within Zuid-Holland would be best represented using a fully-active profile (Figure 9.2b and 9.2c, respectively) i.e. the time scale of Zuid-Holland is much longer than that of Noord-Holland. This example can be used to encourage the continued collection of the JARKUS data set; an underestimation of future shoreface activity (as a result of data limitations) could lead to errors in sediment budgets.

9.2.3) SHOREFACE BEHAVIOUR ALONG LARGE COASTAL STRETCHES

Differences in the morphodynamic behaviour along the Holland shoreface have resulted in the identification of provinces of similar alongshore characteristics. These coastal sections are distinguished using the behaviour of two morphodynamic features; the shoreward depth of closure and middle/lower shoreface activity. It should be noted that the boundaries of the regions identified using these two different properties may not correlate as the former is located on the upper shoreface and the latter on the middle and lower. This section aims to discuss the coastal stretches identified using the two behavioural traits along with the controls which act upon them.

[4] note that the largest temporal period is 28 years due to missing data for the profiles km 72 to 97 for the year 1965.

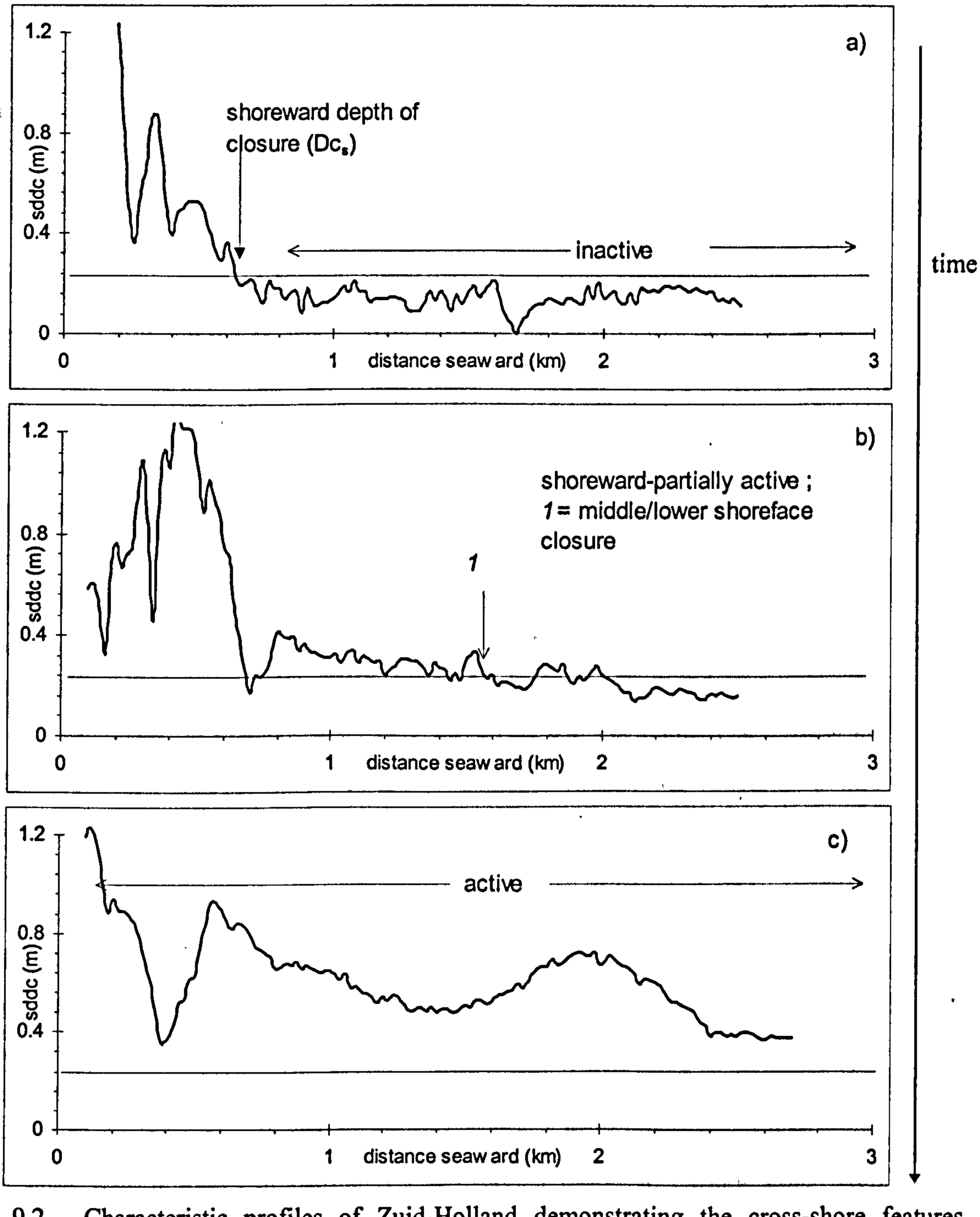


Figure 9.2. Characteristic profiles of Zuid-Holland demonstrating the cross-shore features observed and inferred over different time scales using the sddc change criterion 0.25 m. a) = temporal period 30 - 100 years; b) = temporal period > 100 years; c) = temporal period > 1000 years.

9.2.3.1) UPPER SHOREFACE CHARACTERISTICS : THE SHOREWARD DEPTH OF CLOSURE WITHIN THE TWO OBSERVED PROVINCES

The combination of depth values (taken from each of the temporal periods investigated) and variation of these values around the mean has led to the identification of two main provinces of Dc_s along the Holland coast. These provinces are clearly very different and are discussed below :

Noord-Holland (km 16 to 54).

This province is characterised by the variable, deeper values of closure; the mean value[5] over a 20 year period is 7.3 m and the associated standard deviation is 0.83 m. In addition, the shoreward closure disappears on many of the profiles due to the presence of morphodynamic activity on the upper/middle shoreface; this feature is absent from 47% of profiles over the 20 year period. It is possible to further divide Noord-Holland into two sub-provinces. This is done at approximately km 35/36 where to the north, although the observed Dc_s values do not differ from the profiles to the south, there are few occurrences of a shoreward closure. For example over the 10 year period only 31% of profiles between km 16 and 35/36 exhibit Dc_s, whilst, for this same period, between km 35/36 and 54 a shoreward depth of closure is present on all the profiles.

As has been observed in previous work over the short- and medium-scales (Larson and Kraus, 1994; Nicholls *et al*, 1996; 1998a; 1998b; Nicholls and Birkemeier, 1997), both the value and occurrence of Dc_s is temporally-dependent. However, although there is an increase in Dc_s from the 5 to 32 years, it is not as large[6], or as significant[7], as the previous work suggests (over this period Dc_s is observed to increase by a maximum of 1 m[8]). For example, work performed at Terschelling, The Netherlands showed that for an un-nourished cross-shore profile, Dc increased by approximately 2 m over a 20 year period (Marsh *et al*, 1998). The limited increase in Dc_s along the Holland coast as compared to that in existing studies does not result from the latter making no distinction between depth of closure and shoreward depth of closure[9]. This could be used if profiles which closed on the middle/lower shoreface were still classified as exhibiting a shoreward closure rather than a shoreward partially active shoreface and so closure would significantly increase with time. Nevertheless, the exponential increase of closure through time is strongly significant; the r^2 value using the sddc change criterion 0.25 m is $0.98_{(95\% \text{ significance})}$ for this

---

[5] using the sddc fixed tail criterion 0.25 m.

[6] gradients of the temporal relationship of Dc_s values range from 0m (fdc change criterion 0.75 m) to -0.04m (fdc change criterion 0.5 m)

[7] the range of correlation coefficients for this relationship is 0.1 (fdc change criterion 0.75 m) to 0.96 (sddc change criterion 0. 5 m).

[8] using the fdc change criterion 0.5 m.

[9] the former was defined based upon profiles which typically extended no deeper than 8 m.

province. This result concurs with previous work; when compared to work on the upper shoreface at Duck, N. Carolina, only 3% of profiles exhibit closure after 8 years (Nicholls *et al*, 1998a).

Zuid-Holland (km 57 - 97).

Constant, shallow values of closure are observed in Zuid-Holland; the mean value[10] of Dc_s over a 20 year period is 4.7 m and the corresponding standard deviation value 0.46 m. However, unlike Noord-Holland, there is a distinct absence of morphodynamic activity on the middle and lower shoreface and so, as previously stated, Dc_s is a characteristics feature of a cross-shore profile for the total period of investigation; after 20 years, only 10% of profiles do not exhibit a shoreward depth of closure.

The observed temporal dependence of Dc_s values is less significant in Zuid-Holland than in Noord-Holland and is in greater contradiction with conclusions made in previous work; for example the mean value for this province increases by 0.1 m[7] over the period of investigation. An additional point which should be addressed here is that of the change criterion selected. The criteria used within this study relative to the sddc fixed tail and fdc method are 0.25 m, 0.5 m and 0.75 m and it has been noted that as the criterion increases in magnitude so does the margin of change. A consequence of this is that when using the larger change criterion, the zone of activity is typically restricted to the seaward boundary of the bar zone and is constant through time i.e. Dc_s is relatively constant in time, both in value and occurrence along the Holland coast. This observations could also be used as the reason why there is such a difference in the results between this and previous studies. For example the smallest change criterion used within this thesis is 0.25 m whilst the criterion used in previous studies is typically smaller; 6 cm at Duck, N.Carolina (Nicholls *et al*, 1998a) and Lubiatowo, Poland (Rozynski *et al* (1998). Therefore a greater change in both value and occurrence could be expected in the studies at Duck and Lubiatowo.

The temporal decrease in the percentage of profiles exhibiting a shoreward closure is also both exponential and strongly significant; the r^2 value using the sddc change criterion 0.25 m is $0.95_{(95\%\ \text{significance})}$. The main difference in this relationship between the two provinces is not its degree of significance but rather the actual percentages of occurrence; Dc_s is a more characteristic feature of the shoreface in Zuid-Holland over all time periods, occurring on 87% of profiles after 28 years.

[10] using the sddc fixed tail criterion 0.25 m.

9.2.3.2) UPPER SHOREFACE CHARACTERISTICS : CONTROLS ACTING UPON THE SHOREWARD DEPTH OF CLOSURE

The division of the Holland coast into these provinces is surprising if one considers that the major coastal forcing[11], the hydrodynamics, is relatively constant alongshore; deviations in wave height from north to south are typically of the order of 0.2 m (Figure 4.7). Indeed, the frequently used method of calculating closure, the Hallermeier (1977, 1978) model, takes as its basis the 12-hour exceeded wave height (per annum) and the associated wave period (Eq.2.3). This model was shown (Chapter 8) to support the conclusions of previous, smaller-scale studies that the hydrodynamics do indeed act as a control upon closure.

So, although the hydrodynamics act as a control upon Dc_s (the overprediction by Eq.2.6 is not large enough to reject it) there must be additional factors influencing the morphodynamic response. This leads to a question, which although derived for the nearshore bar region of the Holland coast, can be adapted for this study :

> *"Are the different bar regions the result of different outcomes of an inherently non-deterministic system, or the results of different environmental conditions?"* (De Vriend, 1998b).

When adapted for this study, the question posed is :

> *"Are the distinct provinces of the shoreward closure the result of the internal dynamics of the system, or the result of external forcing?"*

The external forcing is the hydrodynamics, which are constant alongshore, although resulting differences in the internal dynamics can give quite different responses.

Factors which have been suggested in previous studies, and have also been investigated here, are; i) bar morphodynamics (e.g. Marsh *et al*, 1998); and ii) volume change (cf. Capobianco *et al*, 1997; Nicholls and Birkemeier, 1997). An identical division of the Holland coast into two provinces to that based upon Dc_s is observed using the nearshore bar morphodynamics (Wijnberg, 1995), suggesting that the control of the internal dynamics is more likely to take the form of the

[11] if there is no force acting upon a body (in this instance the morphodynamic environment) then there will be no change of motion of the body (i.e. the morphodynamics remain constant); Newton's First Law of Motion (Pond and Pickard, 1983).

nearshore bar system than volume changes. Indeed, correlation's between residual Dc_s values[12] and volume changes over 5 and 10 years are weakly significant and this factor is discarded as an important control (Chapter 7). However, it should be taken into consideration that the Holland coast is highly erosive (Figure 7.8) (de Ruig, 1989; Knoester, 1990; van Vessem and Stolk, 1990; de Ruig and Louisse, 1991; van Rijn, 1995; 1997; Hinton, 1999) and it is possible that volume change could influence Dc_s along coasts which have a different nature e.g. those that are accretive or have variable trends.

This study confirms the hypothesis that the nearshore bar system along the Holland coast has an effect upon the Dc_s behaviour. The bars undergo a morphological cycle which is composed of their generation, offshore migration and degeneration/disappearance (Chapter 4). This morphodynamic cycle repeats at different intervals in the two provinces (15 years in Noord-Holland and 4 years in Zuid-Holland) and is such that the degeneration of the outer bar, which in turn controls the behaviour of the inner bars (Wijnberg, 1995; Hinton and Aarninkhof, 1998), occurs at a greater depth in Noord-Holland than in Zuid-Holland. The suppression of the offshore migration of the bar system at Terschelling, The Netherlands by nourishment (Marsh *et al*, 1998) lends further support to this conclusion; in this region Dc_s was located at shallower depths than in the un-nourished region.

The longshore pattern of the outer bar degeneration agrees with the large-scale spatial pattern observed with Dc_s that the deeper values are located in the northern province. The factors which control the degeneration of the outer bar are four-fold, the most important has been shown to be bar volume (Wijnberg, 1995); the sediment volume of the bar in Noord-Holland is approximately twice that of Zuid-Holland (500 m^3m^{-1} and 250 m^3m^{-1}, respectively). The remaining factors are suggested to be i) the efficiency/intensity of the degeneration process; ii) the frequency occurrence of the degeneration process; and iii) the frequency occurrence/efficiency conditions. The control of the nearshore bar system was further confirmed through comparison between Dc_s and B_{SL} (the seaward limit of the nearshore bar region) for which the correlation coefficients[13] ranged from $0.89_{(95\% \text{ significance})}$ to $0.96_{(95\% \text{ significance})}$ (Figure 7.5). However, the importance of this control is seen to decrease with increasing temporal period (Table 7.4). This result agrees with previous work performed on the Holland coast :

[12] residual Dc_s = calculated (using Hallermeier (1977, 1978) - observed
[13] excluding outlying values which are identified by significant variation from the m = 1 line

> "*the behaviour of the upper shoreface is often dominated by the seaward migration of the longshore bars*" (Van Alphen and Damoiseaux, 1989).

Hence Dc_s is under the control of both external forcing (the hydrodynamics) and internal dynamics (the nearshore bar system), and this is in agreement with previous short- and medium-scale work :

> "*the response to the wave forcing is constrained by the internal dynamics of the morphological system, in the form of the nearshore bar system*" (after Nicholls *et al*, 1998b)

It is therefore a combination of the fairly uniform i) temporal behaviour of the nearshore bar system[14] in the cross-shore; and ii) hydrodynamic climate through time which results in the fairly insignificant temporal increase of Dc_s values. An additional observation is that B_{SL} remains relatively constant through time rarely exceeding, for example, 8 m in Noord-Holland. It should be noted that this could be a result of the method which removes the seasonal change in the morphodynamics, for example the effects of high-energy events are not observed. It can therefore be concluded that for the medium- and large-scales, as with the short-scale, the shoreward depth of closure can be expected to increase with increasing temporal period but the range of the increase is a factor of the particular morphodynamic and hydrodynamic conditions of a coast. The strong relation between Dc_s and B_{SL} also suggests that the latter could be used as a predictive tool to determine the position of Dc_s, particularly over the shorter timescales when it has been shown to enforce stronger control. In this instance, bathymetric data would be required but it would also mean that there is no necessity for hydrodynamic data (which is used for input to the Hallermeier (1977, 1978) model) or a great deal of analysis using bathymetric data.

An additional external forcing which should be considered is that of the anthropogenic IJmuiden harbour moles which primarily interact with the other previously mentioned external forcing; the hydrodynamics (Figure 9.3). This interaction takes the form of the moles interrupting the 'natural' northwards longshore currents and diverting the current seaward. This in turn results in the acceleration of the tidal currents, inducing significant sediment erosion (per comm. Bakker, 1998; per comm. van Rijn, 1998; Roelvink *et al*, 1998). What is surprising is that this large-scale man-made feature does not appear to have any impact upon the temporal occurrence of Dc_s. The r^2

[14] as controlled by the degeneration position of the outer bar

values excluding and including those profiles affected by the moles (km 38 to 74) are strongly significant; the value based upon observations using the sddc fixed tail analysis (change criterion 0.25 m) is $-0.99_{(95\% \text{ significance})}$ for both cases.

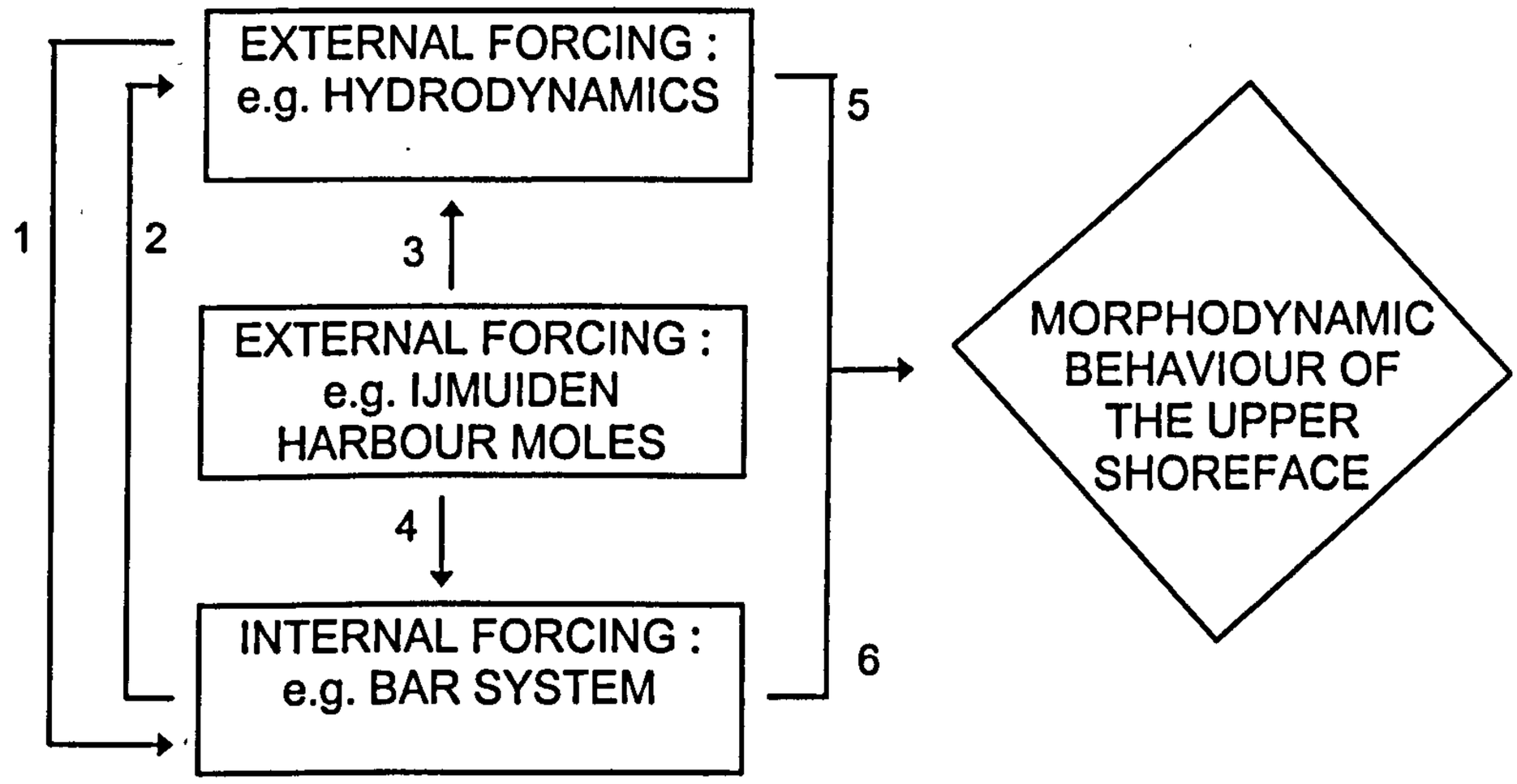


Figure 9.3. Conceptualism of the forcings which act upon the upper shoreface of the Holland coast. The significance of these is dependent upon the time scale.

9.2.3.3) MIDDLE/LOWER SHOREFACE CHARACTERISTICS : 'RE-OPENING'

Re-opening is the term used to loosely describe the shoreface activity seaward of Dc_s which is further divided into non-, partially- and fully-active shorefaces. This activity is shown to result from erosive processes which dominate the Holland coast (localised areas of accretion are observed such as immediately adjacent to the IJmuiden harbour moles) (Figure 7.8), so agreeing with past sediment budget studies (e.g. van Rijn, 1995). Although general identification of this activity led to the identification of the same two large-scale coastal provinces as that of Dc_s, a more detailed examination suggests a further categorisation of the Holland coast, as discussed below.

Noord- and Zuid-Holland are identified by the extent of shoreface activity which occurs within them, and this can be highlighted by discounting those profiles effected by the IJmuiden harbour moles (km 38 to 74; Chapter 8). In the former province a greater percentage of profiles are active, indeed, as already stated (section 9.2.1) the characteristic profile for this province over all temporal scales features shoreface activity whilst the representative profile for Zuid-Holland over the same scales has the property of the shoreward depth of closure (Figure 9.1 and 9.2, respectively). The evolution of the mean shoreface activity within each region is shown in Figure 9.4. here it can be seen that Noord-Holland evolves from a non-active to partially-active shoreface at longer time periods that those profiles affected by the IJmuiden harbour moles. In addition the profiles in Zuid-Holland remain inactive over the 32 years.

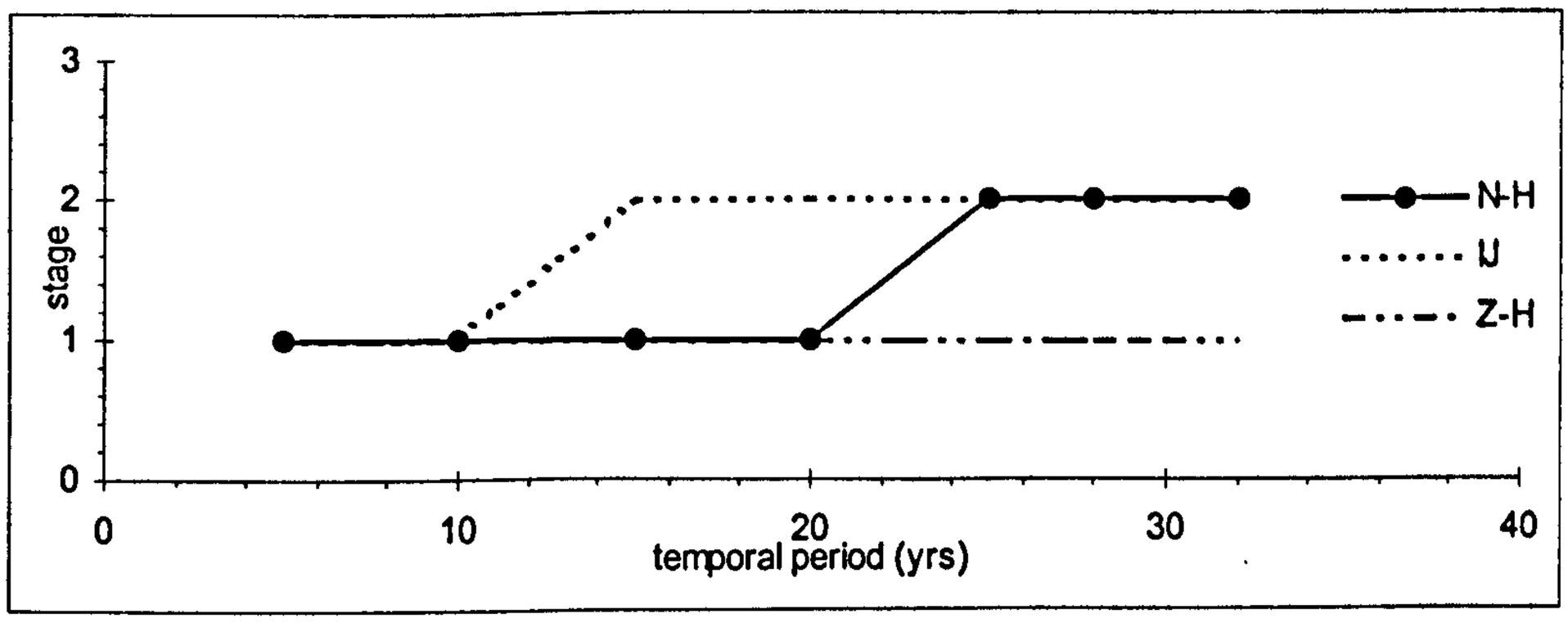


Figure 9.4. The evolution of the mean profile as observed in three regions of the Holland coast from the perspective of the shoreface activity. The three regions are Noord-Holland (km 16 to 37); ii) IJmuiden (km 38 to 73); iii) Zuid-Holland (km 74 to 97). Stage 1= non-active; 2 = partial-activity; 3 = fully-active.

The more detailed division of the Holland coast results in four large-scale stretches, within which three small-scale regions can also be identified. As shown in Figure 9.5, the stretches are composed of profiles which are either primarily active (km 16 to 29 and km 40 to 73) or inactive (km 30 to 40 and km 74 to 97). It is interesting to note that the observation that this coast can be divided into two morphodynamic regions (as identified by shoreface behaviour in water depths less than 8 m) is not observed here, reinforcing the importance of bathymetric measurements which extend to (at a minimum) the lower shoreface The regions of shoreface activity are now taken in turn and discussed in terms of their temporal behaviour and the potential controls on them.

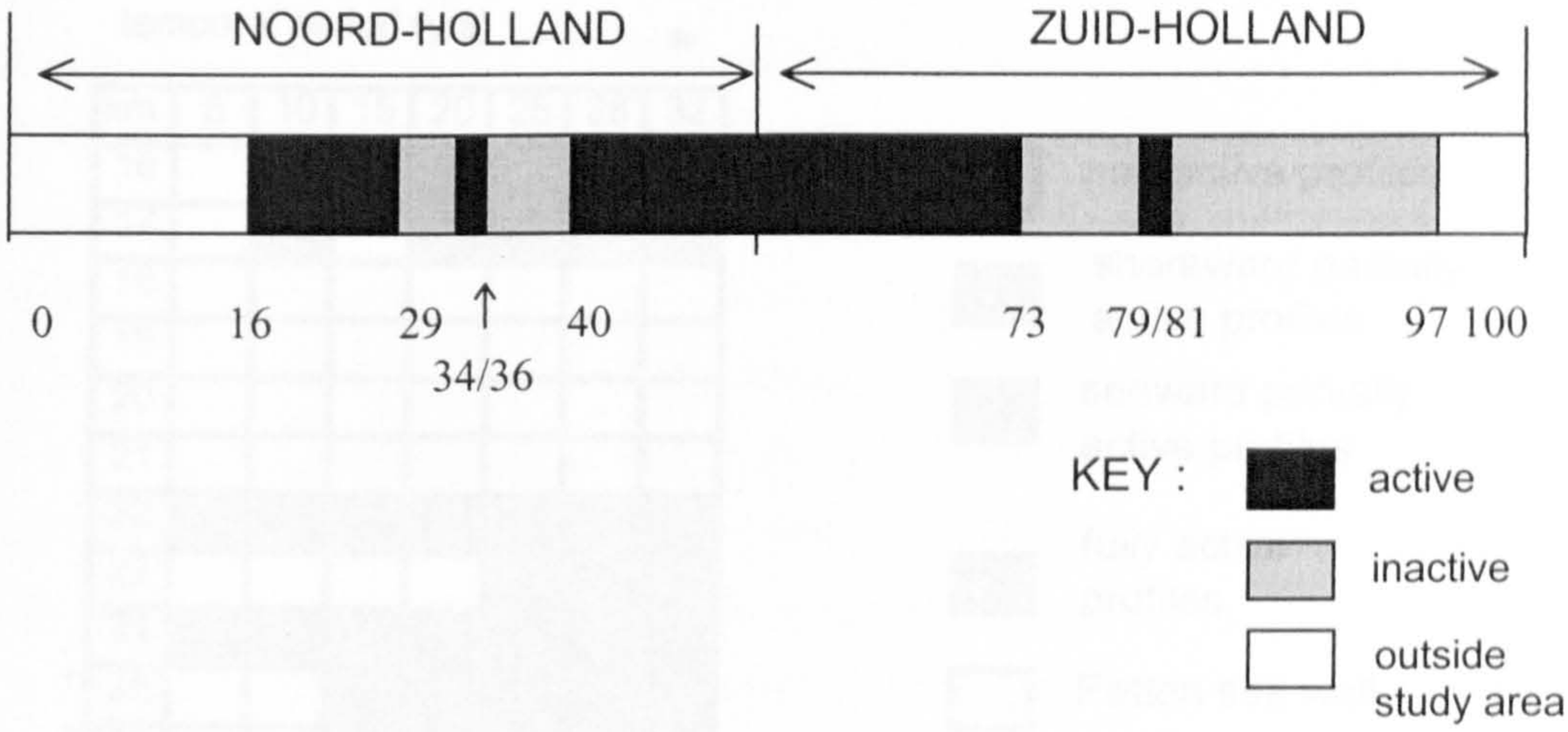


Figure 9.5. Categorisation of the Holland coast into large-scale stretches as a function of the middle/lower shoreface behaviour.

Km 16 to 29 (within Noord-Holland).

This region is composed of 30% of partially-active profiles after 5 years which evolves to 50% of partially-active and 40% of fully-active profiles after the 32 years (Figure 9.6). The observed activity primarily manifests itself through the erosion (as 86% of the change) of the shoreface; ranging from -0.1 to -1.5m for the total period. It is within this region that one can clearly see the evolution from the non-active to partially-active and finally to fully-active shorefaces, although it does not show a patterned (or steady) temporal growth in the activity. For example km 25 (which undergoes the three stage evolution within the 32 years) has a temporal increase in shoreface activity in both the shoreward and seaward directions (Table 9.1).

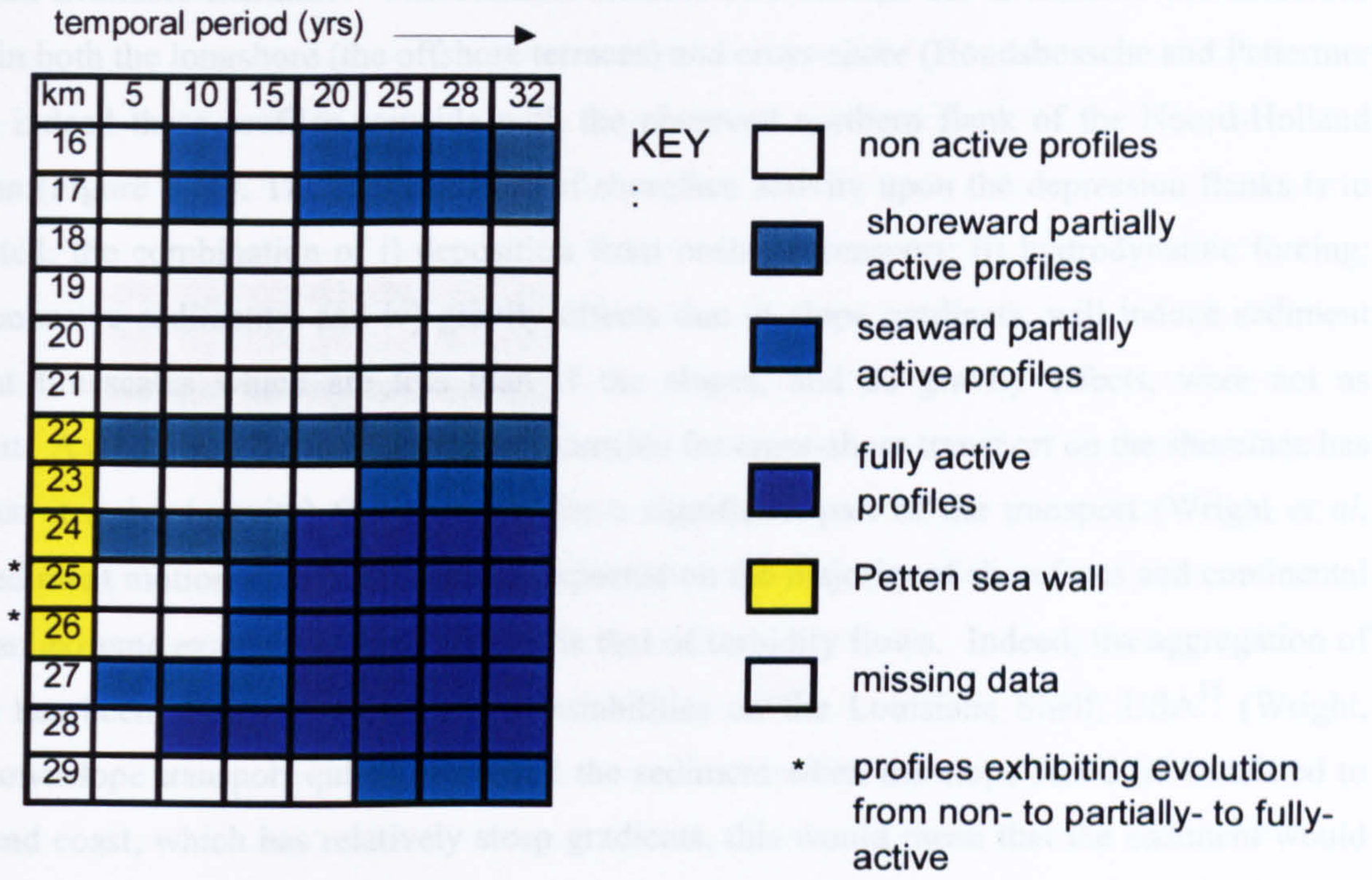


Figure 9.6. Spatial distribution of morphodynamic activity along the shoreface of km 16 to 29 (Noord-Holland) for different temporal periods (1965 - 1997). Using the fixed tail sddc method (change criterion 0.25m).

TEMPORAL PERIOD (yr.)	5	10	15	20	25	28	32
ADDITIONAL SHOREFACE ACTIVITY (km)	0.7, 0.8, 0.9	1.2, 1.6	1.1	1.7, 2.1, 2.3, 2.4	1.3, 1.5	2.5	1

Table 9.1. Temporal growth of shoreface activity for km 25, showing the 'random' growth of the behaviour.

It is suggested, through geographical association, that the observed growth of activity is the result of the combination of the offshore terraces (approximately km 15), Hondsbossche and Pettermer seawall (km 20 to 26) and shoreface bathymetry. Although there are no available current

measurements for these areas, deductions have been made concerning the nature of the their effects based upon available literature. The offshore terraces and seawall act to increase the shoreface gradient in both the longshore (the offshore terraces) and cross-shore (Hondsbossche and Pettermer seawall), indeed these profiles coincide with the observed northern flank of the Noord-Holland depression (Figure 7.16). The concentration of shoreface activity upon the depression flanks is to be expected; the combination of i) deposition from onshore transport; ii) hydrodynamic forcing; iii) non-cohesive sediments; and iv) gravity effects due to slope gradients, will induce sediment motion at timescales which are less than if the slopes, and so gravity effects, were not as significant. A study into the mechanisms responsible for cross-shore transport on the shoreface has shown that it is iv) (gravity) that accounts for a significant part of the transport (Wright *et al*, 1996). Sediment motion such as this can be expected on the majority of shorefaces and continental shelves, an extreme example of such activity is that of turbidity flows. Indeed, the aggregation of sediment has been shown to create slope instabilities on the Louisiana Shelf, USA[15] (Wright, 1995). Downslope transport quickly removed the sediment when the slope failed (if translated to the Holland coast, which has relatively steep gradients, this would mean that the sediment would travel either in the longshore or offshore direction, if in the latter the dominant cross-shore transport would initiate net transport in the onshore direction (Roelvink *et al*, 1990). (Such effects are likely on all the depression flanks in both Noord- and Zuid-Holland and will not be mentioned further).

Km 34 to 36 (within Noord-Holland).

This smaller-scale zone of activity becomes apparent after the 5 year temporal period, however throughout the 32 years the activity remains either shoreward-partially active or seaward-partially-active. The only coastal feature which exists upon these profiles is the shoreward foot of the shoreface connected ridges, however this only extends to, at the most shoreward point, the middle/lower shoreface boundary (Figure 7.11) and so can not explain why the majority of profiles over all temporal period are shoreward-partially active (100% over 10 years and 67% over 32 years). However, it could explain why km 35 is a seaward-partially active profile after the 15 year period; the ridges have been shown to interact with the shoreface over the long-term (Van de Meene, 1984) via the northwards longshore migration and interruptions to near-bed current flow. There does not appear to be any explanation for the remainder of this active zone (i.e. why the majority of profiles are partially-active) with the exception of the cumulative effects of the hydrodynamic forcing upon the shoreface.

[15] which although a delteric coast highlights the fact that such environmental factors should be considered.

Km 40 to 73 (within Noord- and Zuid-Holland).

This active zone covers that area which has been calculated, using the van Rijn 'rule of thumb' to be under the influence of the IJmuiden harbour moles; km 38 to 74. The size and occurrence of the shoreface activity within this region is shown to be temporally-dependent (Figure 6.2), indicating that it results from cumulative effects (such as regular storms) rather than infrequent, extreme events. The harbour moles are shown to induce the shoreface activity at rates faster than in a natural system so that[16], it is after 72 years rather than 170 years that the entire Holland shoreface will be fully active (Figure 8.20 and 8.23). The cause of this activity is therefore attributed to the disturbance that the moles place upon the 'natural' current system. This is seen most clearly immediately adjacent to the southern arm where detailed measurements show that a large scour hole has developed near the end of this arm. Process-based morphodynamic modelling has been used to simulate the growth of the scour hole over a 5 year period. It has shown that the tidal currents have the dominant effect upon the development of the scour hole, although wave-induced processes and two-dimensional turbulence also play a role. The northwards directed longshore current is halted and diverted seawards by the southern harbour mole (Roelvink *et al*, 1999; per comm. Bakker, 1998; per comm. Van Rijn, 1998). This results in accelerated transport at the end of the mole causing the scour hole (Roelvink *et al*, 1998). The shoreface activity observed in this study, though not located at the seaward extremity of the southern mole, does correlate with the shoreward boundary of the scour hole, as measured over the 5 year period investigated by Roelvink *et al* (1998). It is therefore suggested that the temporal development of this particular zone of shoreface activity is the result of cumulative effects of the altered tidal currents which act to increase the area and depth of erosion through time.

Km 79 to 81.

This small region of shoreface activity is surprising in two respects; the first is that it is located in amongst 21 profiles which remain inactive over the 32 years; and the second is that all three profiles are observed to become fully active after the 10 year period. This would suggest that the bathymetric measurements are incorrect, however, the nature of the analysis techniques (sddc; fdc) used (Chapter 5) ensure that errors are removed. In addition the selected change criterion (0.25 m; 0.5 m; and 0.75 m) relate to a 66%, 95% and 99.5% confidence that a real bathymetric change has occurred. These results need to be investigated further as they may have relevance to the upper

[16] taking the assumption that the large-scale coastal behaviour over temporal periods greater than the 32 years will not deviate from the trends observed over periods less than, or equal to, the 32 years.

shoreface experiments which are carried out at this location as a result of the ARGUS camera installation (Aarninkhof and van Noort, 1998).

9.2.4) IMPLICATIONS OF FUTURE CHANGES TO THE HOLLAND COAST

Uniformity, "*the state in which everything is homogeneous*", is one of the many key debates within coastal research and management. The debate is composed of what is essentially two schools of thought, the first is of the opinion that variability within forcings e.g. wave height, is a real phenomenon which could influence the long-term behavioural trend of the forcing such that, in the extreme, there is no long-term trend (cf. Lamb, 1985). The second school of though takes the stance that long-term variability is not significant, merely acting as noise within the long-term behaviour (cf. Hoozemans, 1990). It is also one of the reasons why difficulties arise with long-term modelling efforts; if boundary conditions/forcings to the coastal system change through time how can the system be modelled, particularly if the nature of the change and the effects are poorly understood? This problem is especially difficult due to the non-linearity of the coastal system. The problem of uniformity takes its guise in many forms e.g. storminess, and these are now discussed in relation to their influence upon the observations and predictions made within this study upon the Holland shoreface. They will also hold relevance to shorefaces in general for which the understanding on the long-term is a matter of key importance. It is suggested that the forms discussed below are important to the shoreface behaviour over different timescales; sea-level is more important over the long-term whilst storminess has significance over the short- and medium-terms.

9.2.4.1) SEA-LEVEL RISE

Louisse and Kirk (1990) show that rising sea-levels are a serious threat to the low-lying Dutch coastline, especially those areas which are liable to subsidence (e.g. Helmer *et al*, 1996; Bergh and Nijkamp, 1998). For example present data shows that there is a global rise of 0.18 m per century (Warrick and Oerlemans, 1992) whilst scenarios for the Holland coast show a i) present rise of 0.20 m per century; ii) expected rise of 0.60 m per century; and iii) pessimistic rise of 0.85 m per century (Louisse and Kirk, 1990).

Although the work carried out in this thesis does not account for this external forcing[17], the consequences upon the shoreface and implications to the results are now discussed. Shoreface

[17] for example the projections made based upon long-term observations take the assumption that the large-scale coastal behaviour over temporal periods greater than the 32 years will not deviate from the trends observed over periods less than, or equal to, the 32 years.

responses to rising sea-level are shown to take two forms; the first is the landward translation of the upper beach which results in accretion in the offshore profile as described by the Bruun Rule (Bruun, 1962) whilst the second response is that of Dean (1990) which states that shoreline retreat may not occur if the beach profile has excess sand relative to the equilibrium profile. The former was confirmed from observations made of 25 profiles over a 7 year period at The Great Lakes (Hands, 1983), although it was shown that a lag-time in the profile response to the rise in sea-level exists, whilst ideas from both have been combined in a conceptual model describing the large-scale evolution of the Dutch coast (Stive *et al*, 1990). Here both landward and seaward profile translations are suggested for the central and northern Holland coast respectively; this behaviour has been observed within this study. Figure 9.7 illustrates the profile response to rising sea-level according to the ideas introduced above. Long-term modelling using the ADM also shows that there are different responses to rising sea-level along the cross-shore profile; the shelf profile is flattened by decreasing the shoreface slope and increasing the shelf slope, relative to the static sea-level profile (Niedoroda *et al*, 1995). The consequence upon the shoreward depth of closure of an empirical profile using the ADM is the deepening of Dc_s, such that after 10 000 years the entire shoreface is active (Nicholls *et al*, 1998c). The different long-term predictions of the ADM and Hallermeier (1977, 1978) model[18] is a consequence of the former taking as its basis advection-diffusion processes not breaking waves; it has been shown in this study that annual calculations from the latter model can be used as a seaward limit to Dc_s over the long-term (100 years). It is suggested that if the rate of sea-level rise were increased beyond that used in the study of Nicholls *et al* (1998c)[19] then the Dc_s would deepen at a faster rate and must be accommodated by sediment budgets (although it has been shown in this study that Dc_s does not move offshore as rapidly as the middle/lower shoreface activity moves onshore).

It is also expected that if the rate of sea-level changes beyond that observed at present for the Holland coast then the projections of shoreface activity would become less representative. This is because an increase in the rate of sea-level rise would result in increased shoreface activity and so shorter critical time periods for those profiles exhibiting i) no activity to reach 0%; ii) partial-activity to reach a maximum and ultimately 0; and iii) full-activity to reach 100%. The opposite could be expected if the rate slowed i.e. critical time periods would decrease. However, based upon present consensus the likelihood of this latter scenario is slim, although the aggregation of a number of data sets shows that, due to noise within the data, it cannot be concluded that there is an increase in the rate of sea-level rise (Dean, 1990).

[18] the former predicts a more rapid seaward growth of Dc_s

[19] 0.125 m per century

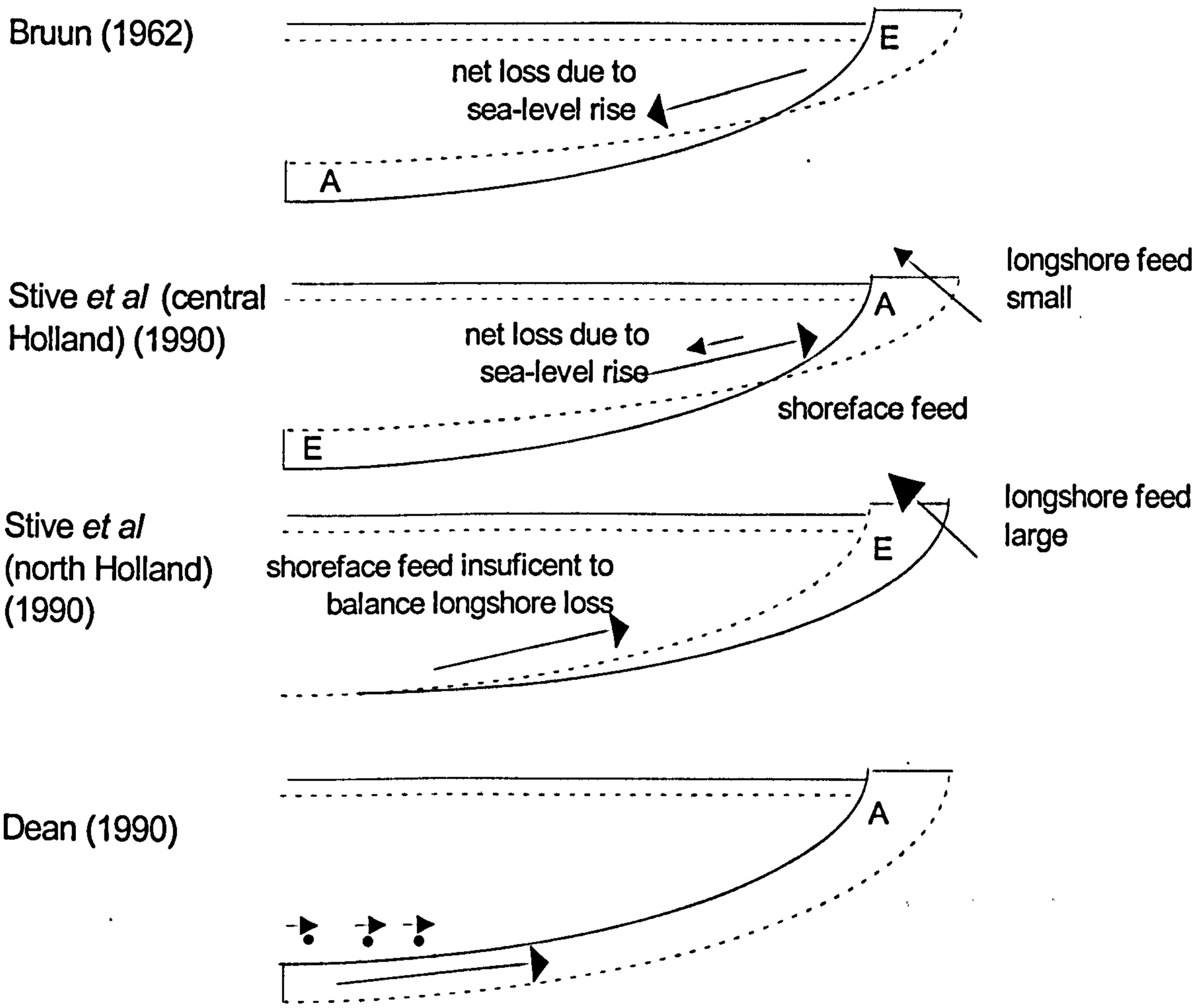


Figure 9.7. Profile response to rising sea-level according to the ideas of Bruun (1962), Stive et al (1990) and Dean (1990). The dashed line represents the state of sea-level and bathymetry before the sea-level rise. The arrows represent the direct of dominant sediment transport. A= accretion; E= erosion.

9.2.4.2) STORMINESS

As introduced in Chapter 2, storminess is another forcing which has the potential to vary through time, it could also be used as an indication of the variation within the hydrodynamic climate.

The hydrodynamic climate of the North Sea over the latter half of this century has been shown to be increasing in magnitude (Carter and Draper, 1988) as a consequence of increasing wind velocity (Hoozemans, 1990). This is supported by data from two wave stations in the north-east

Atlantic which show an increase in the median wave height by 11% and 27% over the 10 year period of operation (Carter and Draper, 1988). However, the increase over recent years is comparable to the hydrodynamic intensity at the beginning of this century (WASA, 1998). Studies also show disagreement concerning the variability of the climate between years; "*the North Sea .... is liable to bigger variation of its climate than have hitherio been appreciated*" (Lamb, 1985) versus "*the distribution is not becoming broader or narrower but is shifting as a whole to smaller or larger values*" (WASA, 1998). Annual variation has been previously noted e.g. the largest change in significant wave height at Seven Stones Light Vessel, Lands End, UK, between 1960 and 1990 was recorded from 1971/1972 to 1972/1973 where a drop of 17% occurred (Carter and Draper, 1988). A large variation could potentially not only 'disguise' the long-term trend but also potentially influence coastal morphodynamic behaviour.

The effect of this, and the increasing long-term trend upon the shoreface, are now discussed. It has been shown that some control upon the shoreward depth of closure is enforced by the 12-hour extreme wave height. So, taking the long-term trend, an increasing energetic hydrodynamic climate will logically result in an increase in Dc_s. Similarly, an annually varying wave climate will result in Dc_s changing over this same (annual) scale. However it is unlikely that this variation will be apparent in the long-term as Dc_s represents the end point of a series of forcings; it is expected that variability in the forcing will not leave a signature in the long-term Dc_s. This is especially true if the calculation of the shoreward closure over *t* years is dealt with as in this study; for example the Dc_s of a 10 year period represents the mean value of the Dc_s calculated for the periods 1965 to 1975, 1970 to 1980, 1975 to 1985 and 1980 to 1990. In calculating Dc_s in this way any variation is reduced.

Shoreface activity is shown to result from steady cumulative forcing effects i.e. as a consequence of regular events rather than infrequent extreme storms with a frequency less than 1 year. Therefore any variability within the hydrodynamic climate could alter the time period over which these effects become significant, iniating shoreface activity. Although it is observed that shoreface activity is only significant over temporal periods greater than 10 years, variability in the forcing could change this to longer temporal periods if there were insufficient regular storms. As with Dc_s, the calculation of shoreface bathymetric changes over *t* years can be determined without the influence of variation by taking a mean value from *x* sets of the *t* years[20].

[20] $Dc_{s10\ years} = ((Dc_{s1965}\ to\ Dc_{s\ 1975}) + (Dc_{s1970}\ to\ Dc_{s1980}) + (Dc_{s1975}\ to\ Dc_{s\ 1985}) + (Dc_{s1980}\ to\ Dc_{s1990}))/4$

9.2.4.3) CHANGES IN COASTAL MANAGEMENT STRATEGIES

Within the period of investigation, the Holland coast has been continually managed in order to prevent losses resulting from erosion and hence maintain the dunes to stop flooding. For although the middle and lower shoreface act as a source of sediment (e.g. Walstra *et al*, 1998), there is still a deficit of sand on the beach, active zone and upper shoreface (e.g. van Rijn, 1995) as a result of losses due to the northwards littoral drift and aeolian processes. As public concern increases and the economics become more viable, coastal management is increasingly taking the form of beach nourishment schemes. Indeed, between 1965 and 1997 there have been 27 such projects along the Holland coast. (Note that the hard engineering schemes of the Hondsbossche and Pettemer seawall and adjacent groyne fields were installed prior to 1965). Observations made within this study do not suggest that the location of the beach nourishment schemes have influenced either the characteristics of the shoreward depth of closure or the occurrence/growth of shoreface activity. This is in contradiction to the findings of the work of Marsh *et al* (1998) which shows that the depth of closure is shallower in the nourished area than in the un-nourished area of Terschelling, The Netherlands. The difference between the two studies could be a consequence of the location of the nourishment fill; at Terschelling the fill occurred in the trough between the outer and middle bars whilst along the Holland coast nourishment typically occurred on the beach.

During 1990 the coastal defence strategy of Holland took a different approach; all subsequent management efforts were to have the ultimate aim of maintaining the shoreline at its 1990 position (De Ruig, 1998). This ambitious strategy is resulting in the intensification of coastal protection projects. It is anticipated that the effect of this upon shoreface activity will be to decrease the erosive tendencies. However the strategy only enforces the maintenance of the shoreline position. If nourishment is increased on the beach, active zone and even upper shoreface it will result in shoreface steepening; sea-level rise in the central Holland coast is shown (Stive *et al*, 1990) to result in the seaward translation of the cross-shore profile, so the erosion of the middle and lower shoreface coupled with decrease in the erosion of other more shoreward zones will result in increased shoreface steepening. Nourishment on the middle and lower shoreface could potentially reduce this process as the foreign sediment will be transported onshore in favour of the deeper (buried) indigenous material. It is however suggested by this author that the 1990 coastal defence strategy will soon have to be reviewed as the quantity of sand required for nourishment schemes will become extremely large and expensive; it may be that a large percentage of this money could be spent on the research and installation of other schemes e.g. the 'give and take' strategy suggested by Helmer *et al* (1996) in which certain sections of the dunes are removed and lagoons

built behind the gap designed for the purpose of flooding. This scheme is currently being tested at km 31.

If this strategy continues indefinitely then, as a result of the increased rate of shoreface steepening, one could expect the profiles to become partially- and, ultimately, fully-active over shorter time periods than projected within this study. This is attributable to the steepening increasing longshore and cross-shore gradients, a factor shown to potentially act as a control upon shoreface activity.

9.3) TIMESCALES OF SHOREFACE RESPONSE

Regardless of the environmental conditions (cf. Wright *et al*, 1985) the three shoreface sections (upper; middle; lower) are generally assumed to respond to forcings over different timescales i.e. shoreface response is temporally dependent. For example a substantial assumption of the Panel model (Stive and De Vriend, 1995) is that the upper shoreface responds on a much smaller timescale (e.g. the event-scale) than the lower shoreface (e.g. the large-scale). Indeed, analysis of a 6.5 year time series of hydrodynamic and bathymetric data led to the conclusion that :

> *"the fast response .... of beach and surf zone change .... whilst the slower responses .... the inner shelf"* (Wright *et al*, 1985)

In this instance the fast response took the form of sediment exchange between the surf zone and beach, and the slower response exchange between the surf zone and inner shelf.

The results from this thesis also support the assumption stated above. Observations based upon 32 years worth of bathymetric data show that both the partial- and fully-active shorefaces are predominately observed over the long-term i.e. greater than 10 years.

Hence, over the short temporal periods shoreface activity is only observed on the upper shoreface i.e. it is only in this cross-shore zone that fast responses to the forcing will be observed. As the temporal period increases to the large-scale, the forcing is such that a morphodynamic response can now be observed on the middle, and eventually the lower, shoreface i.e. the response times of these shoreface zones are slow so that signatures will only be observed over the large-scale. Long-term continual bathymetric measurements also enable the nature of these responses to be observed

i.e. do the responses result in the sudden or steady change in bathymetry? Along the Holland coast it is the latter form which characterises the bathymetric change and so it is concluded that these changes result from slow, steady cumulative processes (probably common storms) rather than from fast, sudden infrequent causes. This form of response is similar to the observation made during modelling efforts that "*the response at any one time is dependent on the forcing conditions that have occurred over some preceding period of time*" (Kriebel and Dean, 1993). These conclusions lend further support to the point that the shoreface will not react as one unit to a forcing over a particular time period. It has important implications to modellers, researchers and coastal managers who may have previously assumed otherwise, for example when modelling the shoreface response to severe storms it is necessary only to include the beach and upper shoreface as the remainder of the shoreface will not show response over the event-scale (cf. Kriebel and Dean, 1993). However, if modelling the response to storms over the large-scale, the middle and lower shoreface will need to be included to interact at different periods than that of the beach and upper shoreface.

This conclusion could have significance for the shoreward depth of closure for an increase in temporal period will therefore result in an increase in sediment exchange between the upper and lower shoreface (Wright *et al*, 1985; Stive and De Vriend, 1995). This suggests, as highlighted by Nicholls *et al* (1998a) that closure will be a response to forcing other than the 12-hour exceeded wave height (as calculated by Hallermeier (1977)) and the nearshore bar system (which is shown in this study to have a greater significance over the smaller time periods). However, as already stated it is the cross-shore growth of the middle/lower shoreface activity that results in profiles becoming fully active rather than the seaward growth of the shoreward depth of closure so the increase in sediment exchange is more likely to effect that critical time period at which the profiles begin to become partially- and ultimately, fully active.

9.4) SCALE RELATIONSHIPS IN THE MORPHODYNAMIC SYSTEM

This study shows that the morphodynamic behaviour of the shoreface is spatially- and temporally-dependent and can therefore be linked to the 'primary-scale relationship' of De Vriend (1991) (Chapter 2) which states that :

"a process of a certain scale will be in dynamic interaction with coastal behaviour within a certain scale"

Based on this concept and related ideas the 'coastal tract cascade' concept has been developed (Cowell *et al*, 2000) which "*discriminates between cause and effect on the basis of scale*" :

> "this concept *formalises concepts for separating coastal processes and behaviour into a hierarchy on the basis of scale ..... providing a systematic basis for distinguishing, for any level .... , those processes that must be included as internal variables in modelling coastal change, from those that constitute boundary conditions and ..... those regarded as unimportant 'noise'..."*

The coastal tract cascade concept has been applied to the Holland coast by considering the entire shoreface (upper to lower) as a whole system, for each of the scales investigated. The categorisation of the causes and effects which occur upon the Holland shoreface can be adopted for other shorefaces with similar characteristics e.g. wave-dominated, erosive, onshore sediment transport. Hence they should prove useful to researchers and managers in solving global coastal problems over the medium- and large-scales. As previously stated, the processes and controls which act on the medium-scales act as boundary conditions for those on the large-scale and noise on the short-scale (De Vriend, 1991), this idea is repeated for the short- (but not in this study) and large-scale.

It has been found that, on the basis of scale, two coastal tracts can be used to describe the observed behaviour of the entire Holland shoreface (km 16 to 97). If one divides the Holland coast into the two provinces identified on the basis of similar morphodynamic behaviour[21] (Noord- and Zuid-Holland), these two tracts are also viable, but for different scales. For example the shoreface of Zuid-Holland is observed to be morphodynamically inactive over the scales investigated (medium- to large-scale) and so the forcings which are only applicable to the medium-scale behaviour of the entire Holland shoreface should be used for the large-scale behaviour of Zuid-Holland. It is therefore observed that as the temporal period increases, the processes controlling the shoreface behaviour evolve. The composition and development of the two tracts are now discussed.

Figure 9.8 and 9.9 conceptualises the relationship between the causes and effects by classifying the causes into three categories, as investigated within this study; internal dynamics; external dynamics; and anthropogenic forcings (which could also be classified as an external forcing).

[21] excluding those profiles forced by the IJmuiden harbour moles

Figure 9.8 illustrates the processes which are important on the Holland shoreface over the smaller time periods (≤ 5 years). Observations made within this study clearly show that it is only the upper shoreface which is active over these scales; "*the upper shoreface responds to forcings over the smaller timescales*" (Stive and De Vriend, 1995). Therefore the significant processes are only given for this zone and, based upon the results from this thesis, take the form of :

1. internal dynamics; nearshore bar system; and
2. external forcings; hydrodynamic climate and IJmuiden harbour moles.

The interaction between points 1 and 2 above are given with the figure. As previously stated the division of the Holland coast, when excluding profiles km 38 to 74, results in the two provinces Noord- and Zuid-Holland. The processes given in Figure 9.8 are applicable for the smaller time periods in Noord-Holland and also the longer time periods (< 30 years) in Zuid-Holland. Obviously the external forcing of the IJmuiden harbour moles is removed due to the exclusion in this instance of those profiles influenced by them.

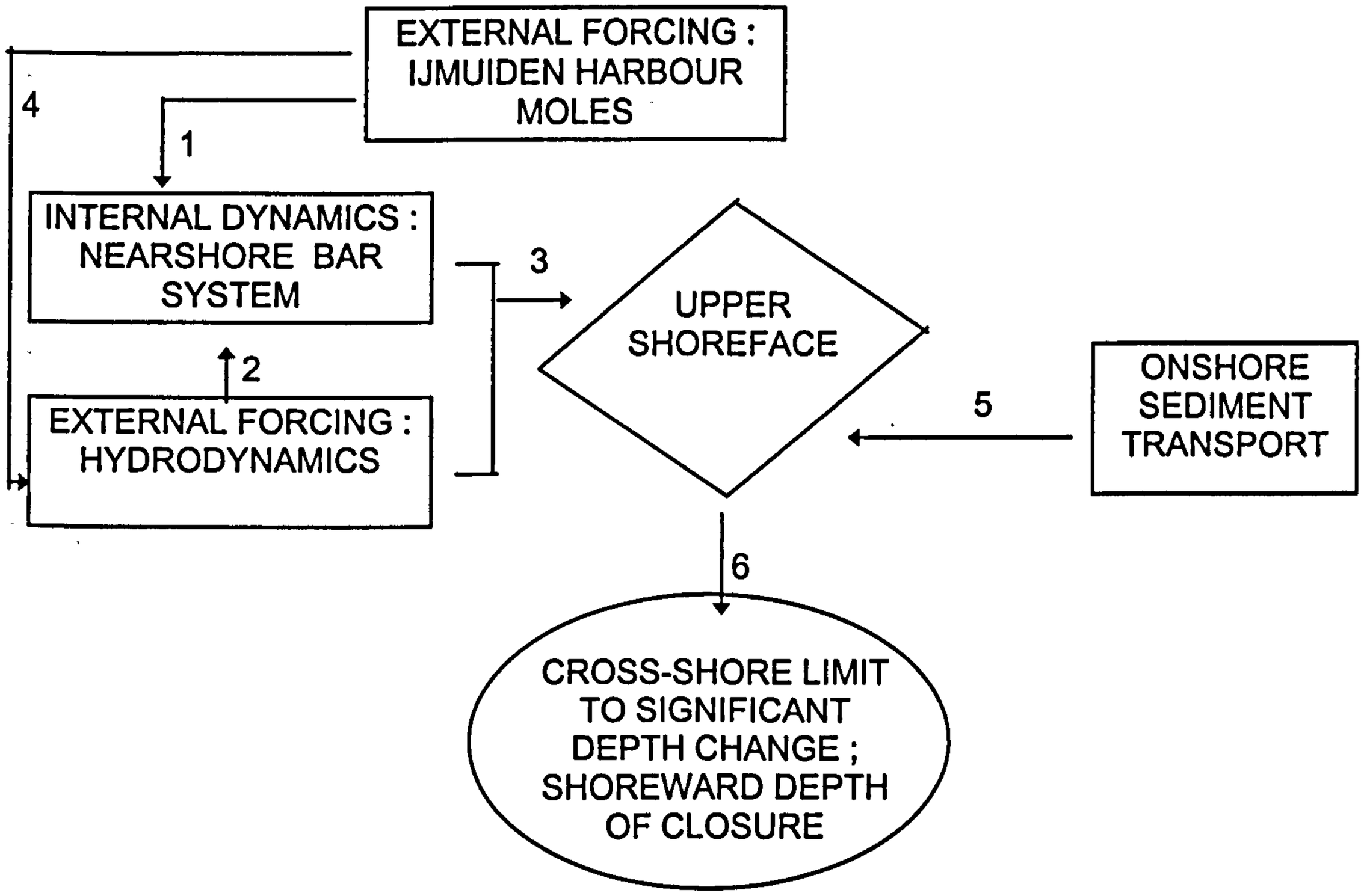
Figure 9.9 illustrates the significant processes acting upon the Holland shoreface over the long-term (≥ 10 years). It is over these scales that the effects of forcings are observed on the middle and lower shoreface in the form of bathymetric changes; the lower shoreface responds on a much larger timescale than the upper shoreface (Stive and De Vriend, 1995). Therefore processes which control the shoreface behaviour over these scales are ones which act upon all shoreface zones (upper; middle; lower). However, the same process does not necessarily act upon all the zones, for example the control enforced by the nearshore bar system, though less significant than over the smaller time scales, only results in upper shoreface behaviour. This is because it is the seaward limit of the bar zone which controls shoreface activity and it is typically found in water depths of 8 m or less i.e. the seaward boundary of the upper shoreface. In addition, although shoreface activity increases with increasing time period, this does not result from the seaward growth of shoreface activity from the upper shoreface but rather the slow, steady cross-shore growth of the middle/lower shoreface activity. Therefore different processes must be acting upon the upper and middle/lower shoreface. Of those processes identified, there are some which are more speculative than others, particularly on the middle/lower shoreface. This is because, although all the forcings have been investigated, it is only those on the upper shoreface which have been investigated based upon data rather than literature (see Chapter 7). The significant processes which act over the longer time periods are therefore :

1. upper shoreface : internal dynamics; nearshore bar system;
2. upper shoreface : external forcings; hydrodynamic climate and IJmuiden harbour moles;
3. middle/lower shoreface : internal dynamics; e.g. bathymetry; and
4. middle/lower shoreface : external forcings; e.g. hydrodynamic climate and IJmuiden harbour moles.

The interaction between the four forcings are given with the figure. If divided into the provinces of Noord- and Zuid-Holland, this figure would only be viable for the former province over the same time scale. It is suggested that it would become applicable to Zuid-Holland over periods greater than and equal to 100 years. Again, the external forcing of the IJmuiden harbour moles would be removed due to the exclusion in this instance of those profiles influenced by them.

The results of this investigation are such that they are able to help in the extension of predictability limits by answering the majority of the questions posed in Chapter 2 :

1. the interaction between the different forcings is relatively unknown, although it has been suggested that the interaction between them varies as a function of scale (cf. Hinton and Aarninkhof, 1998). The results from this study confirm this for both the medium- and large-scales; as highlighted in Figure 9.8 (for example) the internal dynamics of the upper shoreface constrain the external forcings to varying degrees;
2. it also becomes clear that the different forcings have significant impacts over different scales; the cumulative effects of the hydrodynamic forcing only become significant after a minimum of 10 years; and
3. the significance of these forcings over the different time periods highlights the problems that modellers could have in predicting future behaviour; observations at this study site are only possible up to 32 years and, if forcings continue to evolve as suggested within this time period, then those relevant over time periods greater than the 32 years could be different yet again.



KEY : 1 : IJmuiden harbour moles act as a longshore boundary to the morphodynamic provinces of the nearshore bar system. Though conclusions have not been drawn concerning the nature of the impact upon the bars (e.g. Wijnberg, 1995), an influence must be enforced;

2 : it has been shown (e.g. Hinton and Aarninkhof, 1998) that the hydrodynamics only act upon the outer bar. The behaviour of the inner bars is regulated by that of the outer;

3 : this study shows that both the nearshore bar system and hydrodynamics play a role in the upper shoreface behaviour. The role of the former appears to be more significant over the shorter time periods;

4 : the moles interrupt the northwards littoral drift, causing sedimentation in profiles adjacent to them. These profiles typically do not exhibit closure;

5 : sediment is transported onshore from the middle and lower shoreface. However, over the shorter time scales it is insufficient to cause significant depth changes on this part of the shoreface;

6 : the acting processes are such that the upper shoreface has a cross-shore limit to significant depth change.

Figure 9.8. Diagram showing the processes which are important on the shoreface over the smaller time scales, < 5 years. Significant processes (in the form of internal dynamics and external forcings) only act upon the upper shoreface and not the middle and lower resulting in the observation of a shoreward depth of closure on the upper shoreface.

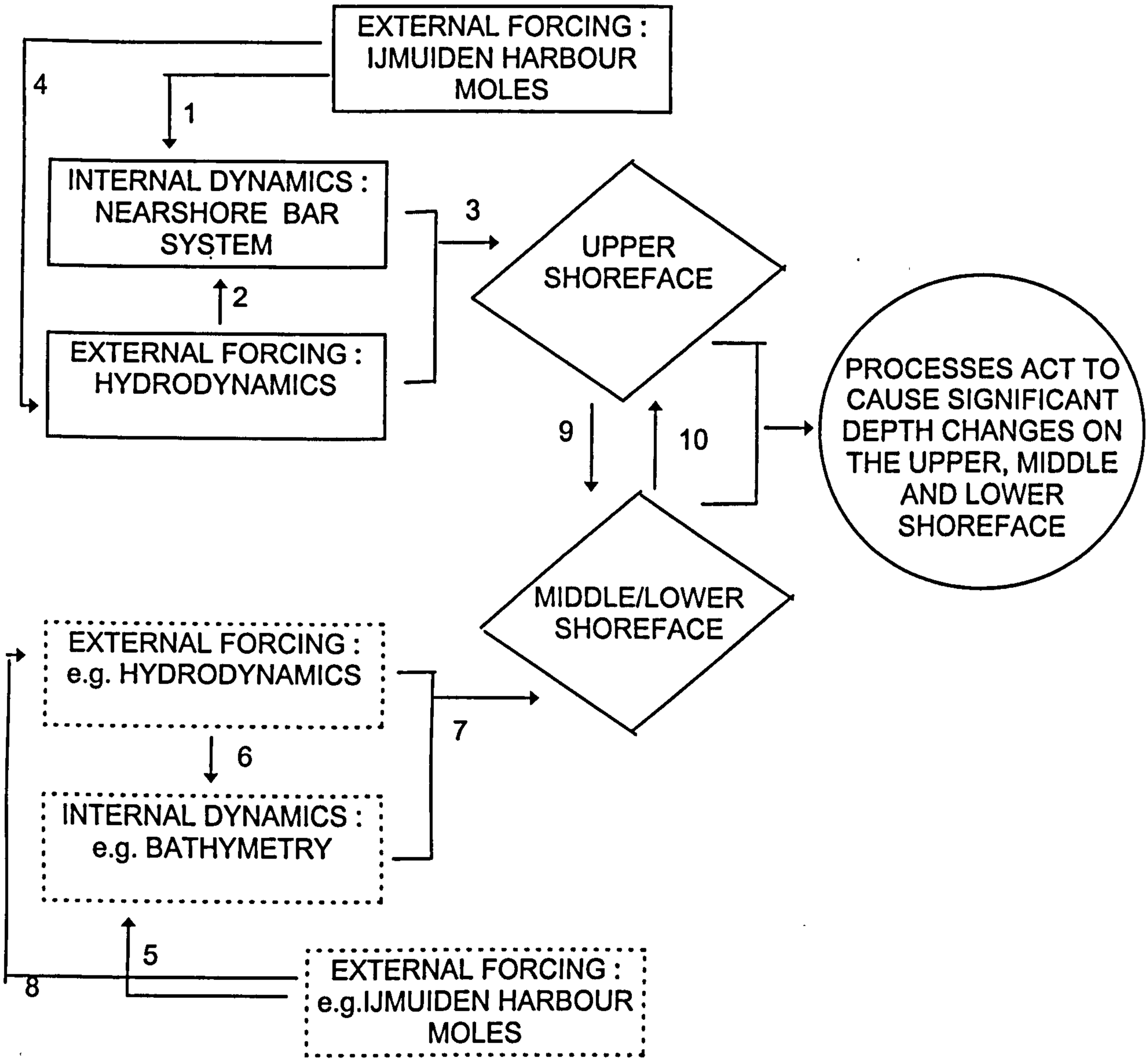


Figure 9.9. Diagram showing the processes which are important on the shoreface over the longer time scales, ≥10 years. Significant processes (in the from of internal dynamics and external forcings) act upon the upper, middle and lower shoreface. For key see the following page.

KEY : : controls are based upon literature rather than data

1 : IJmuiden harbour moles act as a longshore boundary to the morphodynamic provinces of the nearshore bar system. Though conclusions have not been drawn concerning the nature of the impact upon the bars (e.g. Wijnberg, 1995), an influence must be enforced;

2 : it has been shown (e.g. Hinton and Aarninkhof, 1998) that the hydrodynamics only act upon the outer bar. The behaviour of the inner bars is regulated by that of the outer;

3 : this study shows that both the nearshore bar system and hydrodynamics play a role in the upper shoreface behaviour. The role of the former appears to be more significant over the shorter time periods;

4 : the moles interrupt the northwards littoral drift, causing sedimentation in profiles adjacent to them. These profiles typically do not exhibit closure ;

5 : the IJmuiden harbour moles influence the shoreface bathymetry as they cause sedimentation in the adjacent profiles, increasing longshore gradients;

6 : the hydrodynamics induces sediment transport when critical bed shear stresses are exceeded. The erosion of sediment has been shown to result in shoreface steepening (as the sediment is transported onshore);

7 : both external forcings and internal dynamics are shown, within this study, to cause significant depth changes on the middle/lower shoreface;

8 : the moles interrupt the northwards littoral drift, causing currents to be deflected seawards. This results in their acceleration at the end of the moles which in turn causes scour holes to develop (Roelvink *et al*, 1999);

9 : gravity effects make a significant contribution to the sediment transport. Gradients are typically offshore and in the longshore, linking the upper with the middle/lower shoreface;

10 : sediment transport is dominantly in the onshore direction, again linking the upper and middle shoreface.

Figure 9.9 cont.. Diagram showing the processes which are important on the shoreface over the longer time scales, ≥10 years. Significant processes (in the from of internal dynamics and external forcings) act upon the upper, middle and lower shoreface.

9.5) APPLICATION TO GENERIC SHOREFACE MODELS

9.5.1) INTRODUCTION

Behavioural trends, both observed and projected, have enabled potential forcings and responses upon the shoreface to be identified and relative significance placed upon them. This has been discussed in detail in section 9.2 which takes the shoreface behaviour to be scale dependent, as previously described in the 'primary-scale relationship' (De Vriend, 1991) i.e. certain processes are more significant over different scales. Taking this approach has helped i) in the problem of the

limited knowledge of medium- and large-scale shoreface behaviour and ii) identify uncertainties and predictability limits, which typically increase with increasing scale (cf. De Vriend, 1993). The problem of predictability limits is of concern in modelling exercises, particularly over the large-scale. Indeed, international projects exist which investigate this in great detail e.g. the NICOP project has focused upon the predictability limits of process-based models. The observations made within this study have also been used to investigate the limits of two coastal models, one analytical and the other process-based. In addition, projections of the observed behaviour enabled comparison between future shoreface trends (as calculated using non-linear growth within this study) with those determined by large-scale behavioural models e.g. the Advection-Diffusion Model (ADM) of Niedoroda *et al* (1995). The results derived within this study relating to predictability limits, as identified through model validation, are now discussed.

9.5.2) APPLICABILITY OF SELECTED MODELS TO THE PREDICTION OF THE SHOREWARD CLOSURE

The two models tested through validation with the observations made within this study were both originally designed for the shoreface. The first (as discussed earlier in this chapter) is the analytical Hallermeier (1977, 1978) model, used to calculate closure values (Chapter 2). The second is the process-based UNIBEST-TC model which is designed to calculate the evolution of a single cross-shore profile (Chapter 5).

9.5.2.1) THE ANALYTICAL MODEL

It is shown (Chapter 8) that over the temporal periods 1, 5 and 10 years, the time-dependent Hallermeier (1977, 1978) model (Eq.2.6) over predicts the observed closure in 100% of cases; the overprediction by the model was in the range 1.3 m (Noord-Holland) to 4.9 m (Zuid-Holland).

Previous studies (e.g. Nicholls *et al*, 1998b) also show that Eq.2.6 calculates a *seaward limit* to the (shoreward) depth of closure. However, what this study also makes apparent is that the Hallermeier (1977, 1978) model has a greater tendency to overpredict on the morphodynamically less active coast e.g. Zuid-Holland. Therefore when applied to a coastline which has a weak morphodynamic signature, for example, one which has a smaller nearshore bar system, then one would expect the calculated values of Dc_s to be significantly deeper than the observed ones. This is an important conclusion when applying to coastlines with similar characteristics, especially if bathymetric measurements are either limited or non-existent. An additional limitation is that the

Hallermeier (1977, 1978) model was designed for the wave-dominated coastline and, although the majority of the worlds coastlines are wave-dominated, there are also a percentage which are tidally-dominated, an example is the United Kingdom. If Eq.2.6 were to be applied to these coasts there is a greater likelihood that the calculated closure values would deviate from the observed value to a greater degree than when used on the wave-dominated coasts due to the increased current energy in the system.

The Hallermeier (1977, 1978) model calculates a upper limit to the closure values as the computed temporal relationship is logarithmic i.e. there will be a temporal period for which an increase in the length of hydrodynamic data does not produce a significant increase in the calculated Dc_s value. However, this does take the assumption that the wave climate for each year within the increasing temporal period remains statistically similar e.g. the 12-hour exceeded wave height and associated wave period remain relatively constant. Although Eq.2.6 does predict a temporal relationship of the same form (logarithmic) as the observed values, the range of calculated values from time t to time $t+n$ is much larger than the observed. Hence this model overpredicts the deepening of the shoreward depth of closure. This is again an important note for those applying this model to morphodynamically inactive coasts; as the calculation and temporal relationship will be overpredicted.

Therefore the Hallermeier (1977, 1978) model has both spatial and temporal predictability limits of the form :

1. observed closure values are overpredicted, especially on morphodynamically inactive coasts;
2. predictions are made based upon a wave-dominated environment; and
3. the predicted values over-estimate the increase in closure values with time such that the annual value could also be used for the 5 and 10 year values.

9.5.2.2) THE PROCESS-BASED MODEL

UNIBEST-TC has been used in a preliminary investigation to calculate the evolution of a single cross-shore profile from a morphodynamically inactive coast. Whilst the profile extended from the active zone to the lower shoreface, it was shown that this model is only capable of correctly predicting the evolution of the most shoreward section i.e. the active zone and upper shoreface. It is suggested that if the model settings were significantly altered from the default values then the correct evolution of the middle and lower shoreface may be attained. However, in doing this it is

likely that the settings would vary from those found in the natural system; one of the drawbacks of any model of this nature is that any output can be obtained by altering the input.

It is clear that, on this coastline, UNIBEST-TC predicts the evolution of the shoreward depth of closure (within 1 metre of the observations) for all temporal periods with the exception of the 2 year period. This agreement is extremely good, providing encouragement for both the application of process-based models in this way and further testing of the model in a morphodynamically more active region. Although Dc_s values agree to the nearest metre, if examined to one decimal place, it is clear that the predicted temporal increase by UNIBEST-TC is five times greater than that observed i.e. the logarithmic relationship is more pronounced in the model output.

Whilst agreement is good over all temporal periods (1 to 10 years), the bathymetric output over the large-scale is doubtful when compared with observations. This confirms suspicions that process-based models have predictability limits on the large-scale. It therefore appears that, in the absence of long-term observations, the most viable option for determining long-term coastal behaviour is through the use of large-scale models e.g. the Shoreface Translation Model (STM) of Cowell *et al* (1995).

9.5.3) VALIDATION OF LONG-TERM SHOREFACE MODELS

It is only recently that models have been designed for the long-term. As introduced in Chapter 2, there are currently four models which have potential (cf. Buijsman *et al*, 1998a) for large-scale predictive purposes :

1. the Advection Diffusion Model (ADM) of Niedoroda *et al* (1995);
2. the Panel model of Stive and De Vriend (1995);
3. the Aggregated Scale Morphological Interaction between a Tidal inlet system and the Adjacent coast model (ASMITA) of Stive *et al*, 1997); and
4. the Shoreface Translation Model (STM) of Cowell *et al* (1995).

Examples of the model output are :

1. using the ADM. The cross-shore profile i) straightens in response to increasing rate of sea-level rise and hydrodynamic forcing, and ii) exhibits increased curvature with an increase in sediment input and grain size (Niedoroda *et al*, 1995);

2. using the Panel model. Onshore transport, sea-level rise and wind-induced transport are shown to induce shoreface activity over a 100 year period. The result is the progradation of the upper shoreface, steepening of the middle shoreface and flattening of the lower shoreface (Stive and De Vriend, 1995). Indeed observations from the Holland coast (the site to which the model was applied) show that this behaviour does occur over this scale (Stive *et al*, 1990); and
3. using the STM. Over a period of a century, the shoreface undergoes rotational deepening and steepening when acting as a sediment source (Cowell and Roy, 1998). In addition the entire shoreface is shown to undergo shoreward translation in response to rising sea-level (Buijsman *et al*, 1998a).

When tested at specific sites, comparisons between observations, typically derived from geological data (e.g. C^{14} dated sediment (Stive and De Vriend, 1995)), and the model output show that there is good agreement. The work carried out in this study can also be used to validate the results obtained from these models. More specifically it is the projections of shoreface activity over the long-term which can be used :

As the temporal period increases, all profiles will evolve from exhibiting non-active to partially-active shorefaces. Every profile will ultimately become fully active.

So although this study does not project the nature of the shoreface activity over the large-scale (i.e. if it steepens or flattens) in response to the forcings, it does provide confirmation that activity is to be expected over these scales. Indeed, the observations and subsequent projected trends made within this thesis and compared with the large-scale model output, are the first to be i) taken directly from bathymetric measurements; and ii) qualitatively validate these models.

As discussed in Chapter 2, the ADM has also been used to investigate the evolution of the depth of closure (as defined before this study revealed the presence of a re-opening zone) over time scales from 1 to 10 000 years (Nicholls *et al*, 1998c). It is shown that as the time period increases then i) the closure also increases such that ii) after 10 000 years the cross-shore profile is active to the shelf. Indeed, after 100 years (the minimum time period for when all profiles within Noord-Holland are fully active) the ADM predicts closure to be between[22] approximately 12 and 20 m

[22] depending upon the environmental input used; approximately 12m for sea-level rise and sediment input; approximately 20 m for hydrodynamic intensity

deep. Although this thesis supports the latter part of the output, i.e. the entire cross-shore profile will ultimately become active, it does not support the former. The behaviour of the shoreward depth of closure along the Holland coast is such that whilst the values increase with time, the increase is not great and is best described as a logarithmic relationship. Rather it is the cross-shore growth of the re-opening zone which results in the profiles becoming fully active. So whilst the predicted large-scale shoreface behaviour agrees with the observations made here, it is the detailed mechanics which differ. This study is therefore particularly useful as it highlights errors in large-scale model output as a result of differences with observations made directly from bathymetric measurements. Such feedback concerning model output can only prove useful to the modeller as it will aid towards an improvement in the model formulation.

9.6) IMPLICATIONS FOR SHOREFACE STUDIES

Although this study has concentrated on the Holland shoreface, the concepts obtained, both from observations and predictions, can be easily applied to other coastlines of similar characteristics. They can also be applied to those coastlines which have different characteristics to those of Holland e.g. tidally dominated or highly energetic. The concepts should prove particularly useful to those countries which have minimal levels of bathymetric data.

Perhaps the most fundamental principle which has arisen from this study is that the traditionally termed 'depth of closure[23]' is not always applicable, particularly over the medium- and large-scales. This is because, over these scales, significant activity can also be observed on the middle and/or lower shoreface. As a result a new nomenclature has been suggested; the 'shoreward depth of closure'. In addition the shoreface activity has also been classified into three main types as a function of the cross-shore extent of the activity (non-; partial-; and fully-active) (see section 9.2). The temporal behaviour of the shoreward depth of closure has also been identified (as discussed earlier) to be different over the long-term to that previously observed; there is little migration seawards. Instead it is the shoreface activity which causes the shoreward closure to 'disappear' from the profile as the activity typically 'grows' from the middle/lower shoreface in both the shoreward and seaward directions. Hence it is the shoreward growth of activity to the upper shoreface which results in profiles not exhibiting a shoreward depth of closure not the seaward growth of activity from the nearshore bar zone to the middle shoreface. It is therefore advised that

[23] defined as the seaward limit of significant depth change, but not the absolute limit to cross-shore sediment transport (Nicholls et al, 1996)

this nomenclature and the corresponding concepts be used in future studies which are concerned with the shoreface and its activity.

The cross-shore location of significant shoreface activity has direct implications for calculating sediment budgets. Shoreface activity[24] is, as shown in this study, restricted to the upper shoreface[25], over the short-, medium- and large-scales. Over longer time periods e.g. greater than 30 years, one would expect to observe significant depth changes on the middle and lower shoreface. Therefore when calculating, for example, sediment budgets for a coast with similar characteristics[26], over the smaller scales only the upper shoreface need be considered but for the very-large-scale activity in all shoreface zones (upper to lower) should be accounted for.

If the coastline is morphodynamically active, then it should be results from the Noord-Holland shoreface that are concentrated upon. That is, over the small scales shoreface activity need only be considered on the upper shoreface whilst for the medium it will potentially occur on the middle and/or lower shoreface and over the large-scale on the entire cross-shore profile. It is important that this large cross-shore extent of activity is accounted for e.g. if designing nourishment schemes which take the form of mounds on the middle/lower shoreface (Hands and Allison, 1991) then it will act as a bar[27] (if the dimensions permit) over the short-scale but as a sediment source over the larger-scales.

The preceding discussion makes the assumption that information is available about the morphodynamic nature of the coastline. If this is not the case the first step for the manager would be to plan and collect bathymetric measurements; valuable information can be gained from cross-shore profiles taken over monthly periods. There is also advice in here for those managers who have many years worth of data - do not stop measuring. As this study demonstrates there is a wealth of information to be gained from long-term bathymetric data sets, which are few and far between. The short-term profiles could be used in a process-based model e.g. UNIBEST-TC, to gain further ideas relating to the temporal development of the coast over the short- and medium-scales. However it is important to note that the output from such a model in this situation should be used as an indication of future behaviour, not as fact. This is because in this example the lack of knowledge of the coast will mean that it is unlikely that the model can be validated. If the

[24] as identified by a significant change in the bathymetry using a pre-selected change criterion of 0.25 m to 0.75 m.
[25] i.e. shoreward of 8 m water depth
[26] wave-dominated, morphodynamically inactive
[27] e.g. inducing wave breaking

financial budget allows, then it would also be useful if current measurements could be taken both of direction and velocity. These will enable details of the dominant current direction and sediment transport to be gained and so help determine if the shoreface acts as a source (as in the case of Holland over the long-term) or sink of sediment, over the various scales.

Existing data means that the role of the shoreface (as a sediment source or sink) is better understood over the short- and medium-scales. It is well known that during high energy conditions, sediment is transported offshore where deposition occurs to form a bar, whilst during lower energy conditions the sediment is transported onshore (Komar, 1998). Note that this is under conditions of minimal longshore transport. This behaviour has been observed within bathymetric data over the medium-scales where offshore transport due to storm groups[28] occurred, resulting in the erosion of the inshore zone[29] and accretion of the upper shoreface[30] (Lee *et al*, 1998; Birkemeier *et al*, 1999). Over the same scale, but during fair-weather conditions, onshore feed occurs from the upper shoreface to the inshore zone; these results have also been confirmed using sonar altimetry (Beaver *et al*, 1999). The results from this study show that, over the medium- and large-scale, the shoreface acts as a sediment source. However, the effects of the northwards longshore transport are great, especially in Noord-Holland (Stive *et al*, 1990), such that the upper shoreface, active zone and beach do not experience net accretion. This result holds significance for the investigation and understanding of the generic shoreface as it enforces the importance of the effects of longshore transport over the direction of cross-shore sediment transport; if longshore effects were non-existent along the Holland coast there would probably not be such a great need for such intensive coastal protection schemes. It also indicates that whilst the high-energy storms create abrupt upper shoreface changes (Lee *et al*, 1998; Birkemeier *et al*, 1999), once fair-weather conditions return the sediment transport reverts such that the shoreface can be observed to be evolving to some new form (e.g. towards equilibrium (see section 9.2)).

Whilst the results from this study will prove invaluable to managers and researchers of both the Holland and more global coasts, there are still some knowledge gaps concerning the shoreface behaviour, especially over the large-scale. These mainly take the form of process-knowledge; the data used within this thesis was bathymetric and were of limited use to the investigation into the processes acting upon the middle and lower shoreface over the scales investigated. The recommendations for further work which result from this study are given in the following section.

[28] groups of storms whose cumulative wave energy exceeded 4.25×10^{10}J
[29] 70 to 200 m from the landward boundary (dune base)
[30] 500 to 900 m from the landward boundary (dune base)

9.7) FUTURE WORK

This research, whilst providing a substantial amount of new information regarding shoreface behaviour over all scales (particularly the large-scale), also highlights gaps in this, and existing, knowledge and consequently the need for further research. This 'need' is now discussed.

It is only as a result of the large extent, both temporally and spatially, of the JARKUS data set, that it has been possible to obtain the results presented here. Therefore the first recommendation is that the coastal measuring programme that comprises the JARKUS data set continues, covering the entire shoreface (extending to, at a minimum, the base of the shoreface). It is also important that the programme continues at set, regular temporal intervals, which as it now stands, is 3 years. Not only is this data required to calibrate and verify coastal models over scales relevant to the coastal manager, but it is also needed to improve knowledge of shoreface behaviour over ever increasing temporal periods; although projections have been made within this study of shoreface behaviour, based upon observations, the extrapolations can only be proved with the passage of time. For example within this study the projections take two assumptions; i) the large-scale coastal behaviour over temporal periods greater than the 32 years will not deviate from the trends observed over periods less than, or equal to, the 32 years; and ii) no major anthropogenic influence will occur in the future which could cause deviations from the observed trends. The knowledge obtained will also prove vital in the formulation of models which are designed for scales equal to, and greater than, the large-scale e.g. the geological scale (as defined in this thesis; Table 1.1).

Additional recommendations for future work which result from this thesis are :

1. further evaluation of the processes which could potentially induce shoreface activity. Though this does not necessarily need to be performed on the Dutch coast, it would be useful to study this location as i) the process-knowledge could then be combined with the existing wealth of bathymetric data; and ii) there is already a coastal measuring programme running here (JARKUS). This point could be achieved using two methods :

   i) measurement techniques e.g. current measurements, especially in locations identified as exhibiting activity. For example on the flanks of the natural terrace located seawards of Petten (km 15). These measurements should include both flow direction and velocities at all times. Although short-scale experiments performed on other shorefaces lead to the conclusion that sediment initiation only occurs during high-energy events, (e.g. Snedden *et al*, 1988) it is important that the nature of current flow in regions of morphodynamic features are

understood. It is recommended that these measurements are made for extended periods of time; and

ii) modelling techniques which incorporate the controlling factors identified within this study e.g. localised changes in the slope gradients (Chapter 7);

2. identification of the processes which result in the two morphodynamic provinces separated by the IJmuiden harbour moles. As it is clear that the provinces result from the two different nearshore bar systems and not the hydrodynamics (which are uniform alongshore), the process identification should first be attempted by investigating probable causes upon the bar regions (cf. Wijnberg, 1995);
3. testing of the UNIBEST-TC model in a region which is morphodynamically more active than Zuid-Holland i.e. Noord-Holland. This would give more confidence in the use of this model for the purpose of calculating shoreface evolution. (The work at present represents a preliminary investigation into the potential application of UNIBEST-TC to predict significant shoreface activity;
4. applying very-large scale models (e.g. the ADM; Niedoroda *et al*, 1985) to the Holland shoreface and comparing the results with the projections made using observed trends. This would provide confidence in the use of such models; and
5. this research has been performed on a wave-dominated, uniform, closed coastline. However, not all the world's shorefaces share these characteristics. There is therefore a great potential here for further work incorporating different shorefaces e.g. the tidally-dominated shoreface of the UK. Perhaps the first step would be to test the Hallermeier (1977, 1978) model on a macro-tidal shoreface; it is likely that its calculation would be an underestimation as it was primarily designed for a wave-dominated environment. However, the results will give an indication of the processes which do control shoreface activity within this coastal environment.

10) CONCLUSIONS

10.1) INTRODUCTION

The research undertaken within this thesis has helped towards bridging the current knowledge gap within coastal morphodynamics between the medium- and geological-scales. Specifically this work has concentrated on the region known as the shoreface (Box 1.1), over all scales (Table 1.1) and has succeeded in providing a great deal of information not only for coastal scientists and managers of the study area but also for those interested in coasts which have similar characteristics[1], and, at the very basic level, for all coastlines.

The medium- and large-scale morphodynamic behaviour of the Holland shoreface (to depths of approximately 16 m) has been examined (Box 1.2) through the analysis of the bathymetric JARKUS data set (Chapter 3). The results derived from the data-orientated approach adopted (Figure 1.9) were used to validate predictions of the shoreface morphodynamic behaviour, calculated by existing analytical and process-based models. The observed behaviour was also projected beyond the 32 year data limit and will improve on current understanding of the timescales of shoreface evolution, beyond that already suggested by the short-scale fieldwork of Wright *et al* (1985) and the very-long-term modelling work of Niedoroda *et al* (1995).

The morphodynamic behaviour of the shoreface was categorised within this study as either active or inactive, depending on the depth change across a single profile over *t* years. The depth change of one cross-shore profile was identified by i) determining the change in depth values of one profile from two different years[2]; and ii) calculating the standard deviation of depth change between *x* number of the profiles through time[3]. Three depth change criteria were then used to identify whether the shoreface was significantly active or inactive; these were 0.25 m; 0.5 m; and 0.75m which represent 66%, 95% and 99.5% confidence that a real bathymetric change has occurred, respectively. The use of two methods and three criteria gave a greater degree of confidence in the results than if a smaller range of analysis had been used. The relationship between forcings and morphodynamic response was then studied through the correlation of the observed changes and i) internal dynamics (e.g. the nearshore bar system); and ii) external forcings (e.g. the hydrodynamics). Anthropogenic influences were also evaluated.

---

[1] e.g. wave-dominated, micro-tidal with a nearshore bar system
[2] this method is known as the fixed depth change method (fdc) (Chapter 5)
[3] this method is known as the standard deviation depth change method (Chapter 5)

It was expected, based upon the results of existing studies (e.g. Nicholls *et al*, 1996), that the larger spatial ($\leq$ 81 km alongshore; $\leq$ 3 km cross-shore) and temporal ($\leq$ 32 years) extent of the JARKUS data set would result in the observation that the seaward limit to significant depth change (or depth of closure (Box 1.4); Nicholls *et al* (1996)) would move offshore from the upper shoreface such that over the large-scale shoreface activity could be expected at the shoreface/shelf boundary (cf. Nicholls *et al*, 1998c). This expectation is illustrated in Figure 10.1. However, this research has not confirmed these expectations, instead the observed shoreface morphodynamic activity is such that :

1. a distinct cross-shore limit to significant depth change exists on the upper shoreface, particularly over the short-term (see section 10.2);
2. significant activity is observed on the middle/lower shoreface over the medium- and large-scales (see section 10.3); and
3. it is the cross-shore 'growth' of the middle/lower shoreface activity in the shoreward direction that ultimately results in no boundary between activity and inactivity on the upper shoreface (see section 10.3).

These observations are illustrated in Figure 10.2. The conclusion reached is that a new set of nomenclature is required to fully describe these shoreface morphodynamic features. It is proposed that :

1. the traditionally termed 'depth of closure' (Dc) be re-termed the 'shoreward depth of closure' (Dc_s);
2. the middle/lower shoreface activity be termed the 're-opening zone'; and
3. the seaward limit to significant depth change, observed on the middle/lower shoreface, be termed the middle/lower shoreface closure ($Dc_{m/l}$).

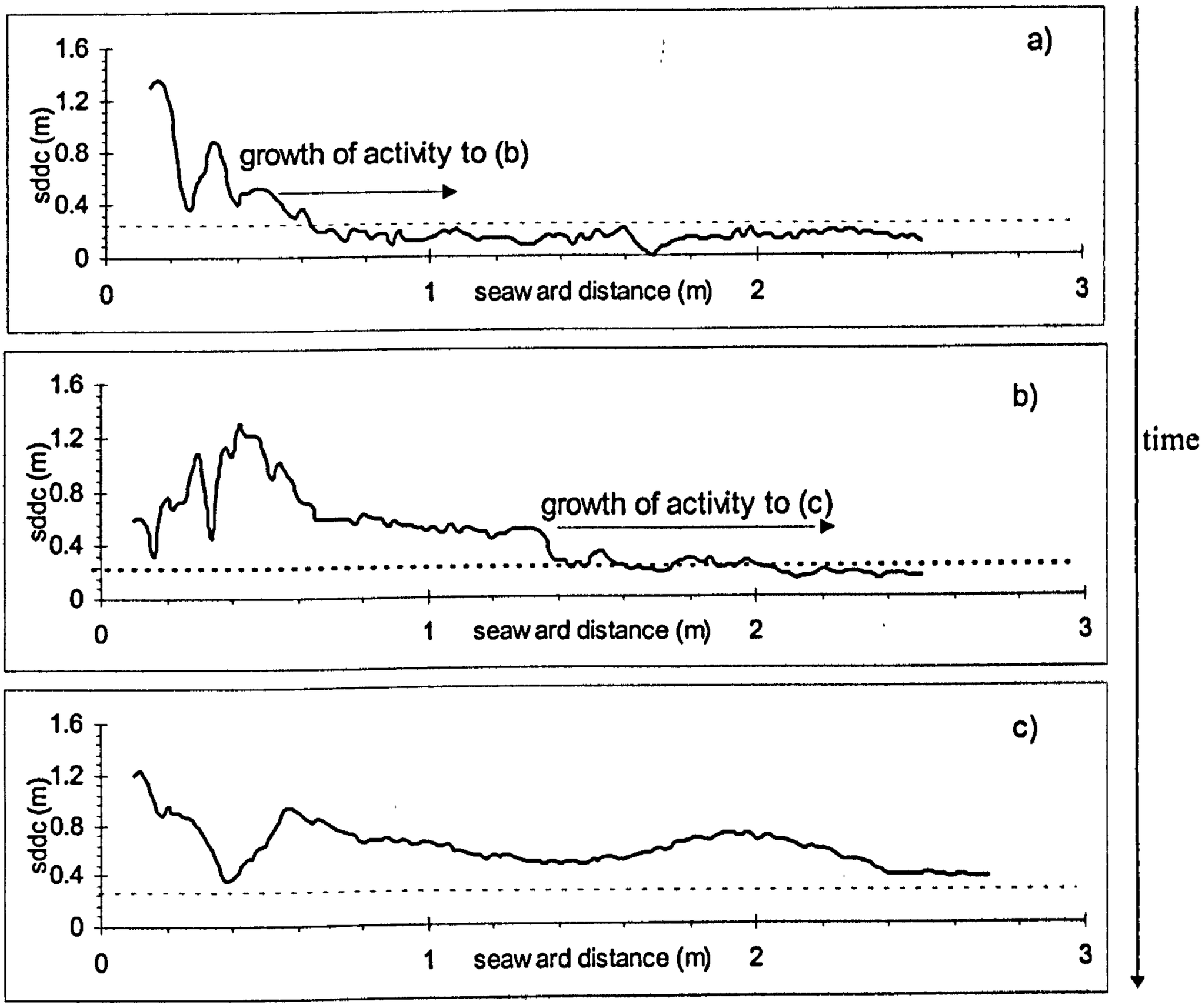


Figure 10.1. Sddc plots showing the expected shoreface evolution of the Holland coast. The top plot (a) represents the expectations for the short-scale, evolving to that of the bottom plot (c) on the large-scale. The dashed line represents the sddc fixed tail change criterion 0.25 m.

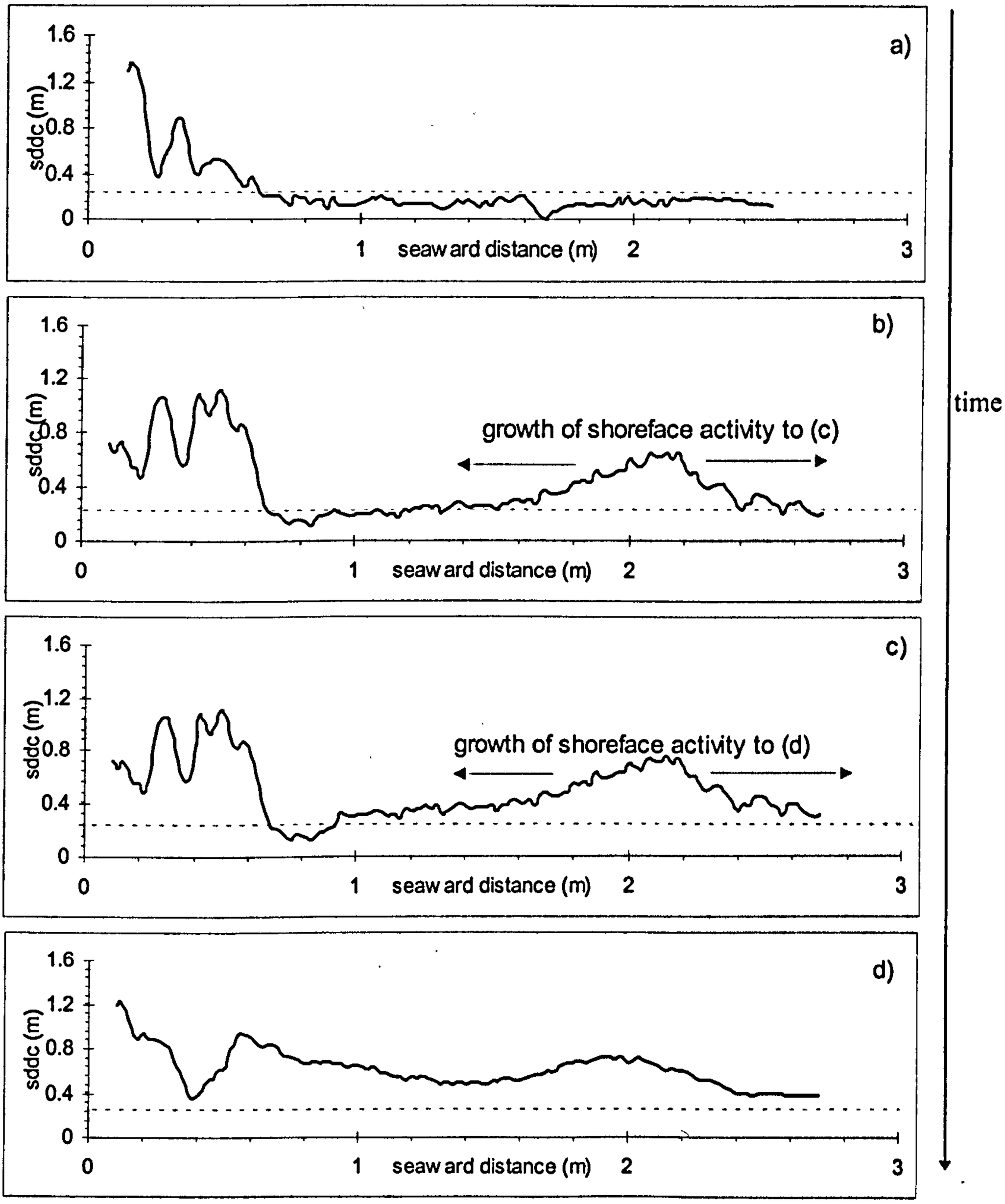


Figure 10.2. Sddc plots showing the observed shoreface evolution of the Holland coast. The top plot (a) represents the observations made on the short-scale, evolving to that of the bottom plot (d) on the large-scale. The dashed line represents the sddc fixed tail change criterion 0.25 m.

The identification of the 're-opening zone' has led to the classification of four types of shoreface behaviour, as a function of the cross-shore extent of shoreface activity :

1. an inactive shoreface. No morphodynamic activity is observed seaward of Dc_s;
2. a shoreward partially-active shoreface. The shoreface is active until the middle/lower shoreface;
3. a seaward partially-active shoreface. The shoreface exhibits re-opening i.e. the profile exhibits a Dc_s on the upper shoreface, becomes active on the middle/lower shoreface and finally may exhibit $Dc_{m/l}$ towards its seaward limit; and
4. a fully-active shoreface. Morphodynamic activity occurs along the entire shoreface i.e. the profile does not exhibit a shoreward closure.

All these morphodynamic features have distinct spatial- and temporal- characteristics, as summarised in the following sections.

10.2) THE SHOREWARD DEPTH OF CLOSURE

Although the traditionally termed Dc has been re-named the Dc_s it does not mean that the original concept becomes invalid. Instead the re-classification is a natural progression resulting from the extension of knowledge of shoreface morphodynamic behaviour to the large-scale; a 'depth of closure' does exist on the upper shoreface but it is often followed in the cross-shore by significant activity on the middle/lower shoreface over the medium- and large-scales. Dc_s is therefore a function of the upper shoreface, which may or may not be present depending upon the timescales of morphodynamic shoreface behaviour and the depth change criterion selected.

10.2.1) CHARACTERISTIC BEHAVIOUR

This study shows that not only are the characteristics (depth values; occurrence) of Dc_s strongly spatially- dependent within the Holland coast, but the occurrence of Dc_s is also temporally-dependent :

1. two alongshore provinces showing similar Dc_s characteristics exist within the Holland coast over all scales (Figure 6.5). The first province is Noord-Holland (km 16 to 54) and the second Zuid-Holland (km 57 to 97). The divisionary boundary between these provinces coincides with

the location of a major anthropogenic structure; the IJmuiden harbour moles. In the first province Dc_s is deeper and more variable than in the second province (e.g. mean depth values[4] are 7.3 m and 4.7 m, respectively; Table 6.1)). The controls which act upon Dc_s resulting in these distinct provinces are discussed in section 10.2.2; and

2. observations within Noord-Holland clearly show that as the temporal period increases, then the percentage of profiles exhibiting Dc_s decreases. This is such that Dc_s is more characteristic of the shorter temporal scales within this province. Although the occurrence of Dc_s decreases temporally in Zuid-Holland, the rate of the decrease is not as great as in Noord-Holland; a consequence of the longer morphodynamic timescales in this southern province. Hence Dc_s is also a characteristic feature over the medium- and large-scales in Zuid-Holland.

In contrast with existing studies (e.g. Nicholls *et al*, 1996), the depth value of Dc_s has a weak temporal relationship (Table 6.4) e.g. the mean depth values in Noord-Holland increase by 22% over the 32 years.

10.2.2) CONTROLLING FACTORS

Two major controls upon the Dc_s behaviour have been identified based upon :

1. the observation of two distinct provinces of Dc_s (Noord- and Zuid-Holland);
2. knowledge of the hydrodynamic and morphodynamic characteristics of the Holland coast; and
3. existing studies on the controls upon the depth of closure over the short- and medium-scales (e.g. Nicholls *et al*, 1998b).

Extreme wave conditions are the primary control upon Dc_s as previously suggested by the Hallermeier (1977, 1978) model (Figure 7.1) and related validation studies e.g. Nicholls *et al* (1998b). However this cannot act as the only control as the wave and general hydrodynamic climate of the Holland coast is relatively uniform alongshore[5] (Figure 4.8) unlike the Dc_s behaviour (Chapter 6; section 10.2.1). An examination of the morphodynamic characteristics of the Holland coast revealed that the nearshore bar behaviour can also be used to divide the coast into two alongshore provinces (Wijnberg, 1995). The boundaries of these provinces correlate with those of the Dc_s provinces (Figure 7.2). Indeed this study shows that the nearshore bar system controls Dc_s as a function of the degeneration depth of the outer bar (Figure 7.5); this depth is greater in Noord-

[4] over 20 years
[5] variation in significant wave height from north to south is of the order of 0.2 m

Holland (7 m versus 5 m) (Figure 7.4; Wijnberg, 1995) explaining why Dc_s is deeper in this province.

The potential anthropogenic control of the IJmuiden harbour moles upon Dc_s was also investigated using a morphodynamic rule-of-thumb[6] which describes the longshore extent of morphodynamic disturbance by a coastal feature (van Rijn, 1998). Surprisingly this large-scale structure was not shown to exert more control upon the behaviour of Dc_s than the 'natural' controls within Noord-Holland (Table 7.6). It has therefore been concluded from this study that the IJmuiden harbour moles do not significantly affect the temporal occurrence of Dc_s and so upper shoreface behaviour. (Note that it does affect the middle/lower shoreface activity, as summarised in section 10.3).

It is therefore concluded that the nearshore bar behaviour constrains the hydrodynamic control upon Dc_s.

10.2.3) THE TESTING OF PREDICTIVE MODELS

The reliability of two existing models; Hallermeier (1977, 1978) and UNIBEST-TC (Bosboom *et al*, 1997) was tested through the comparison of observed and calculated Dc_s values :

1. the analytical Hallermeier (1977, 1978) model is shown to overpredict Dc_s in 100% of cases over all scales (Figure 8.2). It therefore calculates a seaward limit to the observed closure. This results from the fact that this model only incorporates the hydrodynamics of the coastal system, and not, for example, the morphodynamics. A consequence of this is that the overprediction of Dc_s will be greater when applied to morphodynamically less active coasts (e.g. Zuid-Holland) than to morphodynamically highly active coasts; and
2. the process-based UNIBEST-TC model is shown to accurately predict Dc_s values (Figure 8.10). This results from the models incorporation of both the hydrodynamics and morphodynamics of the coastal profile. However it is shown that it is only the evolution of the upper shoreface which can be calculated confidently (Figure 5.8). This model is also shown to have temporal limitations resulting from inherent errors becoming significant over periods equal to, and greater than, 10 years. It is therefore concluded that process-based models designed for the short-term should not be used for long-term applications.

[6] which is an empirical estimation based upon the idea that flow construction has a maximum morphodynamic effect (Van Rijn, 1998) (Chapter 7).

10.3) MIDDLE/LOWER SHOREFACE ACTIVITY

Middle/lower shoreface activity is not typically observed over the short-scale and its occurrence over the larger scales is shown to be dependent upon the morphodynamic timescales within Noord- and Zuid-Holland. The evolution of this activity in both provinces is such that it 'grows' in the cross-shore direction so that ultimately the entire cross-shore profile undergoes significant depth changes. The characteristics of the middle/lower shoreface activity and the forcings which act upon it are now summarised.

10.3.1) CHARACTERISTIC BEHAVIOUR

As with Dc_s, middle/lower shoreface activity is both spatially- and temporally-dependent (Figure 6.9):

1. Noord-Holland is considerably more active on the middle/lower shoreface than Zuid-Holland, particularly if one discounts those profiles adjacent to the IJmuiden harbour moles (km 38 to 72). The inactivity of Zuid-Holland through the temporal periods investigated is such that accurate projections of the shoreface activity cannot be made; it is the projections of the Dc_s behaviour which are more important in this province (section 8.3.3). Two major zones of shoreface activity, both partially- and fully-active, exist; km 16 to 29 (Noord-Holland) and km 40 to 73 (central Holland); and
2. as the temporal period increases (and so morphodynamic activity typically increases) the shoreface evolves to the partially-active state. Extrapolation of observed trends (Chapter 8) show that all profiles within Noord- and central Holland ultimately become fully-active (after approximately 100 years in the naturally forced system of Noord-Holland and 50 years in the anthropogenically[7] forced system) i.e. no profile will exhibit Dc_s. Complete agreement between predictions made for different scenarios (e.g. the length of time for all profiles to become fully-active and for no profile to exhibit Dc_s) should not be expected as the method used, though reasonable, is still simplistic and heavily reliant upon the assumption[8] made. Therefore calculated temporal periods should be used as an indication of the broad timescale of future behaviour. The critical temporal periods identified within this study can be used as

[7] in this instance the anthropogenic forcing is the IJmuiden harbour moles, a large-scale structure extending 2.5 km offshore and 1 km alongshore

[8] the large-scale coastal behaviour over temporal periods greater than the 32 years will not deviate from the trends observed over periods less than, or equal to, the 32 years. For potential violations of this assumption see Chapter 5.

indicators of shoreface evolution at other sites with similar environmental characteristics e.g. morphodynamically active. However it is recommended that it is the ballpark value rather than the exact temporal period that it is used as i) morphodynamic and hydrodynamic characteristics will never be exactly the same; and ii) the extrapolation method is, as already stated, simplistic and dependent upon the assumption made.

10.3.2) CONTROLLING FACTORS

The observed middle/lower shoreface activity results from erosive processes (Figure 7.6; 7.8), which in combination with the net onshore cross-shore transport (e.g. Walstra *et al*, 1998), means that the Holland shoreface acts as a sediment source for the active zone, beach and dune systems. It is clear, from the observations made of the temporal growth of the shoreface activity (Figure 6.2), that the activity results from slow, steady, cumulative processes rather than fast, infrequent processes. The 5-year window between bathymetric measurements suggests that the processes are regular events occurring every year or so. This agrees with short-scale shorefaces studies which show that significant sediment motion does not occur during fair-weather periods (e.g. Snedden *et al*, 1988). Hence it can be suggested that the observed depth changes are caused by those wave-induced processes which result from regular, annual storms. The most significant process in this category has been shown to be wave asymmetry (Roelvink and Stive, 1990; Stive *et al*, 1990). Although the effects of 'daily' wave asymmetry are reduced in water depths greater than 15 m (Niedoroda and Swift, 1981; van Rijn, 1995; 1997), the increased wave heights during storms mean that the effects of wave-induced processes can result in sediment motion in the deeper water (cf. Snedden *et al*, 1988). It is the cumulative effects of this process during regular events which result in the significant depth changes observed in this study over the medium- and large-scales on the middle and lower shoreface.

Although it has not been possible to positively identify the controlling processes[9], tentative correlations have been made between factors which may accelerate the shoreface activity and effect based upon the geographical association of shoreface features and activity :

1. it is therefore suggested that the shoreface activity of km 16 to 29 is induced by the combination of i) localised bathymetric gradients (which are accentuated by the natural offshore terraces and the Hondsbossche and Pettermer seawall); ii) gravitational effects; and iii) hydrodynamics (e.g. near-bed flow) which induce the shoreface activity; and

[9] due to a lack of available measurements

2. the second main active zone (km 40 to 73) appears to be primarily induced by the IJmuiden harbour moles, as investigated using the morphodynamical 'rule-of-thumb' (Van Rijn, 1998). The harbour moles significantly effect the shoreface activity by inducing the cross-shore profiles to evolve to the fully-active state within shorter temporal periods (50 years) than in the natural system (100 years in Noord-Holland). The harbour moles affect the shoreface through the interruption to the natural northwards longshore currents, causing them to accelerate offshore inducing scour holes on the middle/lower shoreface, as is particularly obvious to the south of the harbour moles (Figure 6.14).

10.4) WHAT DOES THIS STUDY MEAN FOR CURRENT ASSUMPTIONS ON TIMESCALES OF SHOREFACE EVOLUTION AND THEIR INCORPORATION IN VERY-LARGE SCALE MODELS?

The observations (Chapter 6) and corresponding predictions (Chapter 8) made of the morphodynamic behaviour of the entire Holland shoreface (Figure 1.1) support existing work as listed below :

1. This research shows that over the smaller temporal periods the shoreface is only active to the morphodynamic feature known as the 'shoreward depth of closure' whilst as the time period increases to the medium-scales, significant morphodynamic activity (or significant morphodynamic response to forcings) can occur on the middle and lower shoreface ('re-opening') (Figure 6.2). This supports

   i) existing assumptions concerning the timescales of shoreface evolution i.e. the upper shoreface responds on a smaller timescale than the middle and lower shoreface (e.g. Wright *et al*, 1985); and

   ii)long-term models which incorporate this assumption, for example the Panel model (Stive and De Vriend, 1995); and
2. It is shown, that over the long-term, in Noord-Holland, the shoreface becomes fully-active. This leads to a qualitative validation of models which predict this behaviour e.g. the Advection-Diffusion Model of Niedoroda *et al* (1995). However, it also highlights the fact that not all profiles do become fully-active over this scales (as in Zuid-Holland), casting warning on the application of such models in morphodynamically inactive regions.

Besides supporting existing work, this thesis also extends the knowledge of shoreface evolution beyond that made in the stated assumption [10] by identifying that the cross-shore growth of significant shoreface activity[11] typically occurs both shoreward and seaward to the re-opening zone such that ultimately the shoreface is 'fully-active'.

In addition, the results from this work show that the timescales of shoreface evolution can vary alongshore within a primarily uniform coastline. Observations of the shoreface evolution show that Zuid-Holland is evolving at a much slower rate than Noord-Holland (a consequence of this is that it has not possible to calculate projections of the evolution of Zuid-Holland). The occurrence of more than one province with different timescales of morphodynamic activity within a uniform coastline means that the application of models used to formalise knowledge of the morphodynamic evolution of a coast and make predictions, may not be as straightforward as one may expect. For example two conceptual models were developed from the 'coastal tract cascade' concept (Cowell *et al*, 2000) for the i) the short-scale (Figure 9.8) and; ii) the medium- and large-scales (Figure 9.9) evolution of the Holland coast. However, the time scale of the morphodynamic activity in Zuid-Holland is such that the short-term model can also be applied to the longer time periods (< 30 years) in this province.

The conceptual models developed here will be applicable to coastlines of similar environmental characteristics e.g. wave-dominated, micro-tidal with a nearshore bar system, highlighting the processes which should be considered in the evolution of the shoreface. However, these models are difficult to apply qualitatively to other sites unless sufficient knowledge is available regarding environmental conditions e.g. of the nearshore bar system. The occurrence of the two provinces with different timescales of morphodynamic activity has meant that there is a wider applicability than there may have otherwise been. In instances where coastlines exhibit even smaller timescales of activity than Noord-Holland, it would be prudent to apply the medium- and large-scale conceptual model for this province to the short-scale for this example of coastline.

10.5) FUTURE WORK

This investigation provides a substantial amount of new knowledge regarding the morphodynamic behaviour of a wave-dominated, micro-tidal shoreface over the medium- and large-scales.

[10] cross-shore shoreface activity evolves from the upper shoreface in a seaward direction
[11] for this coastline

However there is still a need for further research on this topic, as discussed in Chapter 9, and summarised below :

1. the continuation of the JARKUS programme not only i) to the base of the shoreface; but also ii) at regular, set intervals through time and space;
2. further investigation of i) the processes which induce the medium- and long-term shoreface activity; and ii) the factors which may accelerate the effect of these processes;
3. further investigation of the causes behind the two very different morphodynamic provinces north and south of the IJmuiden harbour moles (cf. Wijnberg, 1995);
4. a more thorough study of the abilities of both process-based and very-long-term models to predict the morphodynamic behaviour of the shoreface. Observations and predictions made within this study can be used as validation; and
5. investigation of significant bathymetric changes upon shorefaces of different characteristics e.g. tidally-dominated.

10.6) SUMMARY

This work provides unique information relating to the evolution of shoreface morphodynamic behaviour, as conceptualised in Figure 10.3, over the large-scale for a wave-dominated, uninterrupted coastline characterised by a nearshore bar system. It shows that, over the medium- and large-scales, significant depth changes occur on the middle and lower shoreface, such that, in morphodynamically active regions, over the longer temporal periods, it should be expected that the entire shoreface is active. This has significant implications for morphodynamic modelling efforts, especially those which incorporate a fixed nearshore zone for sediment budgets. However, future work (e.g. verification of the processes inducing significant shoreface activity) is still required, as discussed in Chapter 9. Although the details of this work e.g. the length of time over which the entire shoreface is calculated to become active, has perhaps more relevance to coastlines of similar characteristics to the study area (the Holland coast), the main 'messages' could be applied globally e.g. as the temporal period increases then the cross-shore extent of morphodynamic activity also increases such that ultimately the entire shoreface can be expected to exhibit activity.

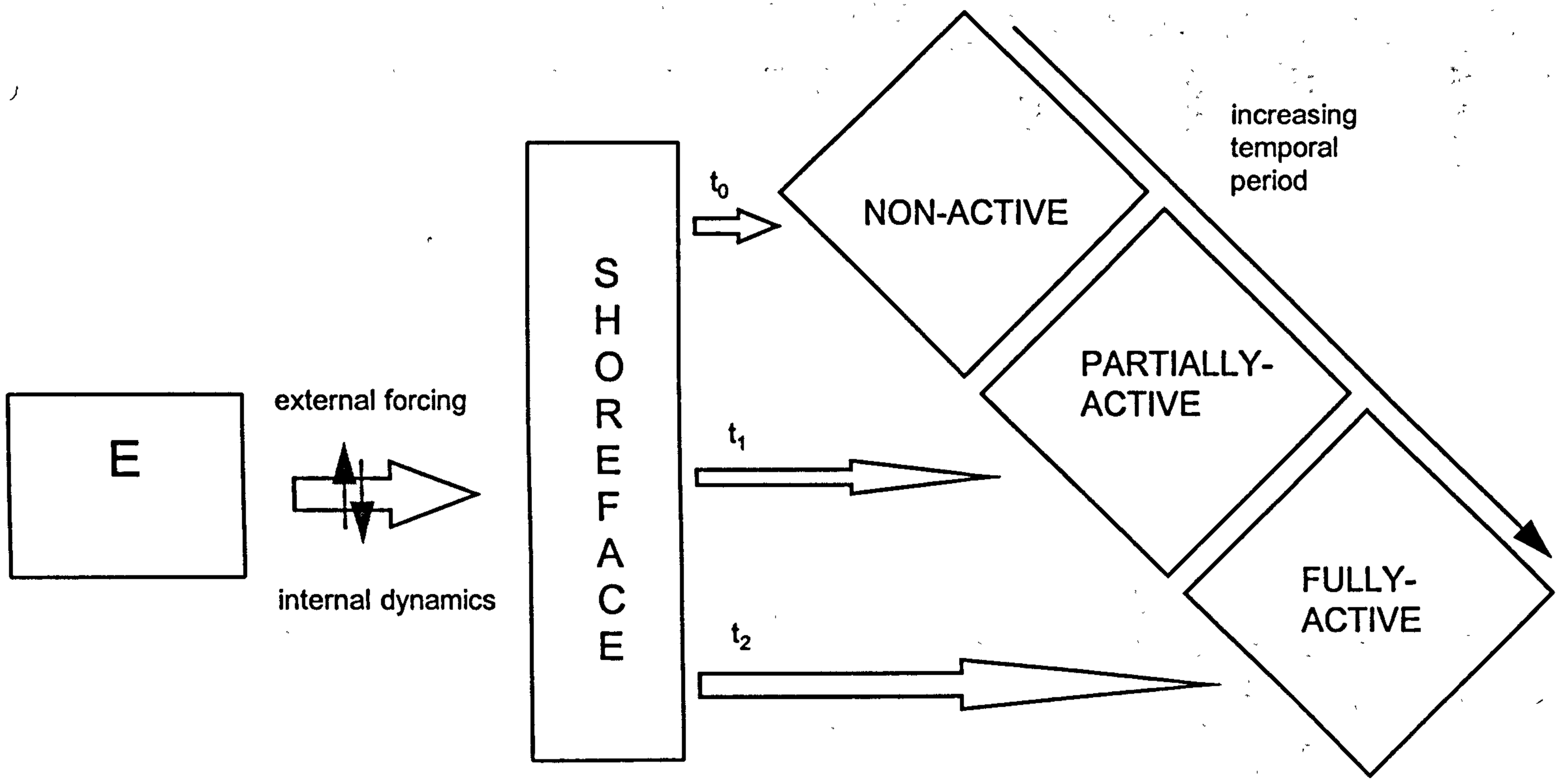


Figure 10.3. Conceptualism of the shoreface evolution over all temporal scales. Energy (E) acts upon the system, or shoreface, in the form of internal dynamics and external forcings. These two forms of energy also interact. The shoreface response is dependent upon the temporal scale of the morphodynamic shoreface behaviour. The response is such that after the smaller periods (t_0) the shoreface can be expected to be non-active whilst after the longer temporal periods (t_1 and t_2) the shoreface state is either partially-active or fully-active. In addition as the temporal period increases the shoreface will evolve from the non-active state to the partially-active and ultimately the fully-active state.

REFERENCES

Aarninkhof, S.G.J, and van Noort, J.K., 1998. ARGUS video observations and process models of the nearshore zone : how integrate data and models? 2 yearly scientific report (PACE). Abstract 1.2,#2, 4pp.

Aarninkhof, S.G.J, Hinton, C., and Wijnberg, K., 1998. The predictability of breaker bar behaviour. Proceedings of the 26th International Conference of Coastal Engineering, Copenhagen, ASCE, New York. pp.2409-2422.

Alphen, J.S.L.J., van, and Damoiseaux, M.A, 1988. Geomorfologische kaart van de Nederlandse kustwateren, schaal 1:250 000. K.N.A.G. Geografisch Tijdschrift, 22, pp. 161-167.

Alphen, J.S.L.J., van, and Damoiseaux, M.A, 1989. A geomorphological map of the Dutch shoreface and adjacent part of the continental shelf. Geologie en Mijnbouw, 68, pp. 433-443.

Alphen, J.S.L.J., van, Hallie, F.P., Ribberink, J.S., Roelvink, J.A., and Louisse, C.J., 1990. Offshore sand extraction and nearshore profile nourishment. Proceedings of the 22nd International Conference of Coastal Engineering, ASCE, New York. pp.1998 - 2009

Bakker, W.T., pers comm. 1998.

Bakker, W.T., and friends, 1998. Coastal dynamics. (in prep.)

Beavers, R., Howd, P., Birkemeier, W., and Hathaway, K., 1993. Evaluating profile data and depth of closure with sonar altimetry. Proceedings of Coastal Sediments 1999, pp. 479-490.

Beets, D.J., Valk, L., van der., and Stive, M.J.F., 1992. Holocene evolution of the coast of Holland. Marine Geology, 103, pp. 423-443.

Bergh, J, van den and Nijkamp, P., 1998. Economic aspects of global change impacts and response strategies in the coastal zone of The Netherlands. Journal of Coastal Conservation, 4, pp.161-168.

Birkemeier, W.A., and Mason, C., 1984. The CRAB : a unique nearshore surveying vehicle. Journal of Surveying Engineering, 110 (1), pp.1-7.

Birkemeier, W.A., 1985. Field data on seaward limit of profile change. J. Waterway, Port, Coastal Ocean Eng., ASCE 111, pp.598-602.

Birkemeier, W.A., Nicholls, R.J., and Lee G-H., 1999. Storm groups and morphologic change in the nearshore. Proceedings of Coastal Sediments 1999, ASCE, New York, pp. 1109-1122.

Boer, P.L. de., Oost, A.P., Cleveringa, J., Beets, D.J., Spek, A.J.F., van der., Cowell, P., Roy, P., Stive, M.J.F., and Vriend, H.J., de., 1997. The character of the Dutch coast from a geological perspective. First Annual PACE Workshop, Abstracts-In-Depth, Abstract #3.1, 5pp.

Bosboom, J., Aarninkhof, S.G.J., Reniers, A.J.H.M., Roelvink, J.A., and Walstra, D.J.R.,1997. UNIBEST-TC 2.0: overview of model formulations. Delft Hydraulics, Report No.H2305.42.

Bouwmeester, E.C., Kalf, R.B., and Walburg, L., 1995. Statistische analyse en voorspelling van de Nederlandse kustontwikkeling. Rijkswaterstaat, Den Haag, pp. 49 + figures.

Brink, K.H., 1987. Coastal ocean processes. Reviews of geophysics. 25(2), pp. 204-216.

Bruun, P., 1962. Sea-level rise as a cause of shore erosion. Journal of Waterways and Harbours Division, pp. 117-130.

Buijsman, M., and Stive, M.J.F., 1998. Impact of gas extraction and sea-level rise on the morphology of the Wadden Sea. 2 yearly scientific report (PACE). Abstract #3.8, 4pp.

Buijsman, M., Cleveringa, J., Stive, M.J.F., and Bosboom, J., 1998a. Long-term shoreface modelling (I). 2 early scientific report (PACE). Abstract #3.6, 4pp.

Buijsman, M., Stive, M.J.F., and Bosboom, J., 1998b. Long-term shoreface modelling (II). 2 yearly scientific report (PACE). Abstract #3.7, 4pp.

Capiobianco, M., Larson, M., Nicholls, R.J., and Kraus, N.C., 1997. Depth of closure: A contribution to the reconciliation of theory and practise. Proceedings of. Coastal Dynamics '97. ASCE, New York. p. 506 - 515.

Capobianco, M., 1998. Prediction of long-term coastal evolution toward a model-based methodology. Second Annual PACE Workshop, Abstracts-In-Depth, Abstract #2.2, 6pp

Carter, D.J.T., and Draper, L., 1988. Has the north-east Atlantic become rougher? Nature, 332, pp.494

Cleveringa, J., and Spek, A., van der, 1998. Preliminary results of the investigation of Holocene coastal deposits at Ypenburg (Rijswijk, The Netherlands); implications for the modelling of long-term coastal evolution. 2 yearly scientific report (PACE). Abstract #3.2, 4pp.

Cornaglia, P., 1977. On beaches. Translation of 1899 article by Felder, W.N. In: Fisher, J.S., and Dolan, R. (Eds), Beach processes and coastal hydrodynamics. Dowden, Hutchinson and Ross, Stroudsburg, Pa., pp. 11-26.

Cowell, P.J., Roy, P.S., and Jones, R.A., 1995. Simulation of large-scale coastal change using a morphological behaviour model. Marine Geology, 126 (1-4), pp. 45-61.

Cowell, P.J., and Roy, P.S., 1998. Linking dynamic and morphologic behaviour models. 2 yearly scientific report (PACE). Abstract #3.5, 6pp.

Cowell, P.J., Stive, M.J.F., Niedoroda, A.W., Swift, D.J.P., Buijsman, M., Nicholls, R.J., Roy, P.S., Kaminsky, G., Cleveringa, J., Reed, C.W., Boer, de, P.L., Capobianco, M., and Vriend, H.J.de., 2000. The coastal-tract : aggregated modelling of low-order coastal change. In prep, 49pp + figures.

Davis, R.A., and Hayes, M.O., 1984. What is a wave-dominated coast? Marine Geology, 60, pp.313-329.

Davison, A.T., Nicholls, R.J., and Leatherman, S.P., 1992. Beach nourishment as a coastal management tool: An annotated bibliography on developments associated with the artificial nourishment of beaches. Journal of Coastal Research, 8(4), pp. 984-1022.

Dean, R.G., 1990. Beach response to sea-level change. In : Mehaute, Le, B and Hanes, D.M (Eds). The Sea. John Wiley and Sons, New York, 9, pp. 869-887.

Dietz, R.S., 1963. Wave base, marine profile of equilibrium and wave built terraces : a critical appraisal. Geological Society American Bulletin, 74, pp. 971-990.

Dietz, R.S., and Fairbridge, R.W., 1968. Wave base. In: Fairbridge, R.W. (Ed), The encyclopaedia of geomorphology. Reinhold, New York, N.Y., pp. 1224-1228.

Dijkman, M.J., Bakker, W.T. and de Vroeg, J.H., 1990. Prediction of coastal evolution for the Holland coast. Proceedings of 22nd Coastal Engineering Conference, ASCE, New York. pp. 1935-1947.

Eid, E., and Hulsbergen, C.H., 1991. Sea level rise and coastal zone management. In: Jager, J., and Ferguson, H.L. (Eds), Climate change : science, impacts and policy. Cambridge University Press, pp301-310.

Eisma, D., 1968. Composition, origin and distribution of Dutch coastal sands between Hoek van Holland and the Island of Vlieland. Netherlands Journal of Sea Research, 2: 123-267.

Environment Transport Regions, 1998. Managing risk in coastal engineering. Issue of December 1998, pg8.

Everts, C.H., 1978. Geometry of profiles across inner continental shelves of the Atlantic and Gulf coasts of the U.S. Technical Paper 78-4, Coastal Engineering Research Centre, Ft. Belvoir, VA.

Everts, C.H., 1985. Sea level rise effects on shoreline position. Journal of Waterway, Port, Coastal and Ocean Engineering, 111, pp. 985-999.

Fenneman, N.M., 1902. Development of the profile of equilibrium of the sub-aqueous shore terrace. Journal of Geology, 10, 1.

Gracia, V., Jimenez, J.A., and Sanchez-Arcilla, A., 1997. Temporal and spatial variability of the depth of closure in the Ebro delta. First Annual PACE Workshop, Abstracts-In-Depth, Abstract #1.4, 4pp.

Gracia, V., Jimenez, J.A., Sanchez-Arcilla, A., Guillen, J., and Palanques, A., 1998. Short-term relatively deep sedimentation on the Ebro Delta coast. Opening the closure depth. Proceeding of the 26th International Conference of Coastal Engineering, Copenhagen, ASCE, New York, pp. 2902-2912.

Geological Survey of the Netherlands (1998). Map of grain size in upper 1 metre for the Netherlands coast.

Geological Survey of the Netherlands (1998). pers comm.

Gordon, A.D., and Roy, P.S., 1977. Sand movements in the Newcastle Bight. 3rd Australian Conference on Coastal and Ocean Engineering, Melbourne, pp.64 - 69

Graf, W.H., 1971. Hydraulics of sediment transport. New York, McGraw-Hill Book Co., pp. 513.

Gulliver, F., 1899. Shoreline topography. American Academy of Arts and Science Proceedings, 34, pp. 151-258.

Hallermeier, R.J., 1977. Calculating a yearly limit depth to the active beach profile. Technical Paper 77-9, Coastal Engineering Research Centre, Ft. Belvoir, VA.

Hallermeier, R.J., 1978. Uses for a calculated limit depth to beach erosion. Proceedings 16th Coastal Engineering Conference, ASCE, New York. pp. 1493 - 1512.

Hallermeier, R.J., 1981. A profile zonation for seasonal sand beaches from wave climate. Coastal Engineering, 4, pp. 253-277.

Hamm, L., 1999. An overview of field data sets made available within the PACE project. Final PACE Workshop, Abstracts-In-Depth, Abstract #1.4, 3pp.

Hands, E.B., 1977. Implications of submergence for coastal engineers. Coastal Sediments, pp. 149-166.

Hands, E.B., 1983. The Great Lakes as a test model for profile responses to sea level changes. In: Komar, P.D., (ed). CRC handbook of coastal processes and erosion. CRC Press, Boca Raton, FL.

Hands, E.B., and Allison, M.C., 1991. Mound migration in deeper water and methods of categorising active and stable depths. Proceedings Coastal Sediments '91, ASCE, New York. pp 1985-1999.

Hansen, M., and Lillycrop, W.J., 1988. Evaluation of depth of closure and its role in estimating beach fill volumes. Proceedings of the Beach Preservation Technology, Florida Shore and Beach Preservation Association, Florida. pp. 107-114.

Hayes, M.O., 1967. Hurricanes as geologic agents; case studies of Hurricane Carla 1961 and Cindy 1963 : University of Texas Bureau Economic Geology Report, Inv 61, 56p.

Healy, T., 1996. Sea-level rise and impacts on nearshore sedimentation : an overview. Geol Rundsch, 85, pp. 546-553.

Helmer, W., Vellinga, P., Litjens, G., Gossen, H., Ruijgrok, E., and Overmars, W., 1996. Growing with the sea : creating a resistant coastline. World Wildlife Fund for Nature Report, 35pp

Hinton, C., 1998. The spatial and temporal behaviour of sediment volume changes and depth of closure along the Holland coast. Rijkswaterstaat Report, 27pp + figures.

Hinton, C., and Aarninkhof, S.G.J., 1998. Effect of chronology upon morphological development : forcing induced behaviour vs. internal dynamics. Working document within PACE and NICOP. 15pp. + figures.

Hinton, C., and Nicholls, R.J., 1998. Spatial and temporal behaviour of depth of closure along the Holland coast. Proceedings of the 26th International Conference of Coastal Engineering, Copenhagen, ASCE, New York. pp. 2913 -2925

Hinton, C., Nicholls, R.J., and Dunsbergen, D.W., 1999. Profile re-opening on the shoreface of the Holland coast. Proceedings of Coastal Sediments 1999. pp. 535-550

Hoozemans, F.M.J., 1990. Long term changes in wind and wave climate on the North Sea. Proceedings of the 22nd International Conference of Coastal Engineering, ASCE, New York. pp. 1888-1894.

Houghton, J.T., 1991. Scientific assessment of climate change :summary of the IPCC working group I report. In : Jager, J., and Ferguson, H.L (Eds), Climate change : science, impacts and policy. Cambridge University Press, pp23-40.

Houwmann, K., and Hoekstra, P., 1994. Shoreface hydrodynamics. Report Part I: field measurements Egmond aan Zee. IMAU-report 94-2, Dept. of Physical Geography, Utrecht University, The Netherlands, 29 pp. + figures.

Hulscher, S.J.M.H., 1988. Generation and migration of shoreface bars due to low-frequency waves. 2nd Annual PACE Workshop, Abstracts-In-Depth, Abstract #4.3, 2pp.

Inman, D.L., Hany, M., Elwany, S., Jenkins, S.A., 1993. Shorerise and bar-berm profiles on ocean beaches. Journal of Geophysical Research, 98 (C10), pp. 18181-18199.

Jimenez, J.A., and Sanchez-Arcilla, A., 1993. Medium-term coastal response at the Ebro delta, Spain. Marine Geology, 114, pp. 105-118.

King, C.A.M., 1951. Depth of disturbance of sand on sea beaches by waves. Journal of Sedimentary Petrology, 21, pp131-140.

Knoester, D., 1990. De morfologie van de Hollandse kustzone (analyse van het JARKUS-bestand 1964 - 1986). Nota GWAO-90.010, Rijkswaterstaat/Dienst Getijdewateren, Den Haag, 85pp. (summary taken from van Rijn, 1995).

Komar, P.D., 1998. Beach processes and sedimentation (2nd ed). Prentice-Hall, Englewood Cliffs, New Jersey, 540pp.

Koomans, R.L., Meijer, R.J. de, and Venema, L.B., 1998. Cross-shore graded sediment transport : grain size and density effects. Proceedings of the 26th International Conference of Coastal Engineering, Copenhagen, ASCE, New York. pp.2463-2474.

Kraus, N.C., and Harikai, S., 1983. Numerical model of shoreline change at Orai beach. Coastal Engineering, 7, pp. 1-28.

Kriebel, D.L., and Dean, R.G., 1993. Convultion method for time-dependent beach profile response. Journal of Waterway, Port, Coastal and Ocean Engineering, 119(2), pp.204 - 225.

Lamb, H., 1985. Climate and its variability in the North-Sea-Northeast Atlantic region. In : The North Sea - a highway of economic and cultural exchange, pp27-38.

Lamb, H., 1991. Historic storms of the North Sea, British Isles and NW Europe, Cambridge University Press, 34pp + figures.

Larson, M., and Kraus, N.C., 1994. Temporal and spatial scales of beach profile change, Duck, N.Carolina. Marine Geology, 117, pp. 75-94.

Lee, G., Nicholls, R.J., Birkemeier, W.A., and Leatherman, S.P., 1995. A conceptual fairweather-storm model of beach-nearshore profile evolution at Duck, N.Carolina, USA. Journal of Coastal Research, 11, pp1157-1166.

Lee, G., Nicholls, R.J., and Birkemeier, W.A., 1998. Storm-driven variability of the beach-nearshore profile at Duck, N.Carolina, USA 1981 - 1991. Marine Geology, 148, pp.163-177.

Louisse, C.J., and Kirk, T.J., 1990. Coastal defence alternatives in The Netherlands. Proceedings of the 22nd Coastal Engineering Conference, ASCE, New York. pp. 1862 - 1875

Marsh, S.W., 1998. Volume calculation programme for beach and nearshore profile data. Internal Report, Flood Hazard Research Centre.

Marsh, S.W., Nicholls, R.J., Kroon, A., and Hoekstra, P., 1998. Assessment of depth of closure on a nourished beach: Terschelling, The Netherlands. Proceedings of the 26th International Conference of Coastal Engineering, Copenhagen, ASCE, New York. pp. 3110-3123.

Meene, van de, J.W.H., 1994. The shoreface connected ridges along the central Dutch coast, The Netherlands. PhD Thesis, Utrecht University, Department of Geography, The Netherlands. 222pp.

Nanninga, M., 1985. The accuracy of echo sounding - description in a mathematical model. Masters Thesis. Rijkswaterstaat, National Institute for Coastal and Marine Management/RIKZ.

Nicholls, R.J., Birkemeier, W.A., and Hallermeier, R.J., 1996. Application of the depth of closure concept. Proceedings of the 25th International Conference of Coastal Engineering,, Orlando (USA), ASCE, New York pp. 3874-3887.

Nicholls, R.J., and Birkemeier, W.A., 1997. Morphological and sediment budget controls on depth of closure at Duck, NC. Proceedings of Coastal Dynamics 1997, ASCE, New York. pp. 496 - 505.

Nicholls, R.J., Birkemeier, W.A., and Lee, G., 1998a. Evaluation of depth of closure using data from Duck, NC, USA. Marine Geology, 148, pp. 179-201.

Nicholls, R.J., Larson, M., Capobianco, M., and Birkemeier, W.A., 1998b. Depth of closure : improving understanding and prediction. Proceedings of the 26th International Conference of Coastal Engineering, Copenhagen, ASCE, New York. pp. 2888-2901.

Nicholls, R.J., Marsh, S., and Hinton, C., 1998c. Analysis of depth of closure and morphological behaviour on natural and forced coasts. 2 yearly scientific report (PACE), Abstract #1.3,5, 5pp.

Niedoroda, A.W., and Swift, D.J.P., 1981. Maintenance of the shoreface by wave orbital currents and mean flow : observations from the Long Island Coast. Geophysical Research Letters, 8(4), pp. 337- 340.

Niedoroda, A.W., Swift, D.J.P., and Hopkins, T.S., 1985. The shoreface. In: Davis, R.A. (Ed), Coastal sedimentary environment. Springer-Verlag, pp. 533-615.

Niedoroda, A.W., Reed, C.W., Swift, D.J.P., Arato, H, and Hoyanagi, K., 1995. Modelling shore-normal large-scale coastal evolution. Marine Geology, 126, pp. 181-199.

Pilkey, O.H., and Frankenberg, D., 1964. The relict-recent sediment boundary on the Georgia Continental Shelf. Bulletin Georgia Academy of Science XXII : 1-4.

Pilkey, O.H., Stanley, R.S., Riggs, S.R., Smith, A.W.S., Wu, H., and Pilkey, W.D., 1993. The concept of shoreface profile of equilibrium : a critical review. Journal of Coastal Research, 9 (1), pp. 255-278.

Pond, S., and Pickard, G.L., 1983. Introductory dynamical oceanography (2nd Ed). Butterwoth-Heinemann, 329pp.

Pool, R., 1989. Is something strange about the weather? Science 243(4896), pp.1290 - 1293.

Reniers, A.J.H.M., and Roelvink, J.A., 1995. Diagnostic studies NOURTEC. Calibration of the profile model UNIBEST-TC. Delft Hydraulics Report H1698.

Rich, J.L., 1951. Three critical environments of deposition and criteria for recognition of rocks deposited in each of them. Geological Society American Bulletin, 62, pp. 1-20.

Rijn, L.C., van, 1995. Sand budget and coastline changes of the central Dutch coast between Den Helder and Hoek van Holland. Report H2129, Delft Hydraulics, The Netherlands.

Rijn, L.C., van, 1997. Sediment transport and budget of the central coastal zone of Holland. Journal of Coastal Engineering, 32, 99.61-90.

Rijn, L.C., van, 1998, pers comm.

Rine, J.M. and Ginnsburg, R.N., 1985. Depositional facies of a mud shoreface in Surinam. Journal of Sedimentary Petrology, 55, pp. 633-652.

Roelse, P., 1990. Beach and dune nourishment's in The Netherlands. Proceedings of the 22nd Coastal Engineering Conference, ASCE, New York. pp.1984 - 1997

Roelvink, J. A., and Stive, M. J. F., 1990. Sand transport on the shoreface of the Holland coast. Proceedings of the 22nd Coastal Engineering Conference, ASCE, New York. pp. 1909 - 1921.

Roelvink, J.A., and Broker, I., 1993. Cross-shore profile models. Coastal Engineering 21, pp.163-191.

Roelvink, J.A., Boutmy, A.E.G., and Stam, J-M, T., 1998. A simple method to predict long-term morphological changes using complex model results. Proceedings of the 26th International Conference of Coastal Engineering, Copenhagen, ASCE, New York. pp. 3224-3237.

Roskam, A.P., 1988. Golfklimaten voor de Nederlandse kust. Rijkswaterstaat, Nota GWAO-88.046, 21pp. + figures.

Roskam, A.P., 1998. pers comm.

Rózynski, G., Zielder, R.B., and Pruszak, Z., 1998. Depth of closure and seabed variability patterns. Proceedings of the 26th International Conference of Coastal Engineering, Copenhagen, ASCE, New York. pp. 2926-2939.

Ruessink, B.G., and Kroon, A., 1994. The behaviour of a multiple bar system in the nearshore zone of Terschelling, The Netherlands: 1965-1993. Marine Geology, 121, pp. 187-197.

Ruessink, B.G., 1998. Infragravity waves in a dissipative multiple bar system. PhD Thesis, Utrecht University, 245pp.

Ruig, J.H.M. de, 1998. Coastline management in the Netherlands : human use versus natural dynamics, pp.127-134. In : Special Feature of Journal of Coastal Conservation 4, 105-168.

Ruig, J.H.M. de, 1989. De sedimentbalans van de gesloten Hollandse kust over de periode 1963 tot 1986. Nota GWAO-89.016/ZL-NXL89.42, Rijkswaterstaat, Den Haag, 43pp + figures (summary taken from van Rijn, 1995).

Ruig, J.H.M. de, and Louisse, C.J., 1991. Sand budget trends and changes along the Holland coast. Journal of Coastal Research, 7, pp. 1013-1026.

Short, A.D., 1992. Beach systems of the central Netherlands coast : processes, morphology and structural impacts in a storm-driven multi-bar system. Marine Geology 107, pp 03-13

Smith, J.D., and Hopkins, T.S., 1972. Sediment transport on the continental shelf off Washington and Oregon in light of recent current measurements. In: Swift, D.J.P., Duane, D.B., and Pilkey, O.H. (Eds). Shelf sediment transport, process and pattern. pp. 143-180.

Snedden, J.W., Nummedal, D., and Amos, A.F., 1988. Storm- and fair-weather combined flow on the central Texas continental shelf. Journal of Sedimentary Petrology, 58(4), pp.580-595.

Soulsby, R.L., 1987. The relative contributions of waves and tides to marine sediment transport. Report SR 125, 11pp + figures.

Southgate, H.N., 1995. The effects of wave chronology on medium and long term coastal morphology. Coastal Engineering 26, pp. 251-270.

Stive, M.J.F., and de Vriend, H.J., 1987. Quasi-3D current modelling: wave-induced secondary current. ASCE Speciality Conference 'Coastal Hydrodynamics', Delaware 1987.

Stive, M.J.F., 1989. Voorspelling ontwikkeling kustlijn 1990-2090. Kustverdediging na 1990, Technisch Rapport 5, Rijkswaterstaat, Den Haag, 66pp. + appendices.

Stive, M.J.F., Roelvink, J.A., and De Vriend, H.J., 1990. Large-scale coastal evolution concept. Proceedings of the 22nd Coastal Engineering Conference, ASCE, New York. pp. 1962 - 1974.

Stive, M.J.F., De Vriend, H.J., Nicholls, R.J., and Capiobianco, M., 1992. Shore nourishment and the active zone; a time scale dependant view. Proceedings of the 23rd Coastal Engineering Conference, ASCE, New York. pp. 2464-2473.

Stive, M.J.F., and De Vriend, H.J., 1995. Modelling shoreface profile evolution. Marine Geology, 126, pp. 235-248.

Stive, M.J.F., Guillen, J., and Capiobianco, M., 1996. Bar migration and duneface oscillation on decadal scales. 25th International Conference of Coastal Engineering, ASCE, pp. 2884-2896.

Stive, M.J.F., 1998. pers comm.

Stive, M.J.F., Cowell, P., Capobianco, M., Cleveringa J., Boer, P., de, Kaminsky, G., and Buijsman, M.C., 1999a. Concept and application of a 'coastal tract cascade'. Final PACE Workshop, Abstracts-In-Depth, Abstract #3.10, 8pp.

Stive, M.J.F., Cowell, P., Cleveringa J., Boer, P., de, and Capobianco, M., 1999b. Long-term Holland coast evolution. Final PACE Workshop, Abstracts-In-Depth, Abstract #3.11, 6pp.

Sunamura, T., and Kraus, N.C., 1985. Prediction of the average mixing depth of sediment in the surf zone. Marine Geology, 62, pp1-12.

Swart, H.E. de, and Falqués, A., 1998. Coastal morphodynamics. EC/MAST Advanced Study Course, Renesse 1998

Swift, D.J.P., 1976. Coastal sedimentation. In: Stanley, D.J. and Swift, D.J.P. (Eds). Marine sediment transport and environmental management. Wiley and Sons, New York., pp. 311-350.

Szmytkiewicz, M., Biegowski, J., Kaczmarek, L.M., Okroj, T., Ostrowski, R., Pruzack, Z., Rozynski, G., Skaja, M., and Zielder, R.B., 1997. Validation of coastal dynamics models. Final draft. Rijkswaterstaat, DWW-1149; IBW PAN, C2-30-VAL, 61pp + figures.

Terwindt, J.H.J., and Battjes, J.A., 1990. Research on large-scale coastal behaviour. Proceedings of the 22nd Coastal Engineering Conference, ASCE, New York. pp. 1975-1983.

Vessem, P., van, and Stolk, A., 1990. Sand budget of the Dutch coast. Proceedings of the 22nd Coastal Engineering Conference, ASCE, New York. pp. 1895-1908.

Vincent, C.E., Young, R.A., and Swift, D.J.P., 1983. Sediment transport on the Long Island shoreface, North American Atlantic Shelf : role of waves and currents in shoreface maintenance. Continental Shelf Research, 2(2/3), pp. 163-181.

Vriend H.J., de, 1991. Mathematical modelling and large-scale coastal behaviour, Part 1: Physical processes. Journal of Hydraulic Research, 29, pp. 727-740.

Vriend, H.J. de, Capobianco, M., Chesner, T., de Swart, H.E., Latteux, B, and Stive, M.J.F., 1993. Approaches to long-term modelling of coastal morphology : a review. Coastal Engineering 21. pp. 225-269.

Vriend, H.J. de, 1997a. Prediction of Aggregated-scale Coastal Evolution (PACE). Proceedings of Coastal Dynamics 1997, pp. 644-653.

Vriend, H.J. de, 1997b. How can we assess skill and predictability of morphological forecasts? NICOP Workshop on "How can we assess skill and predictability of morphological forecasts?".

Vriend, H.J. de, 1998a. Overall project summary : prediction of aggregated-scale coastal evolution (PACE). In : 2 yearly scientific report, 14pp.

Vriend, H.J. de, 1998b. State of the art in process-orientated MTM-modelling. EC/MAST Advanced Study Course, Renesse 1998.

Vroeg, H., de, 1987. Schematisering brandingsruggen m.b.v. jaarlijkse kustmetingen. Technische Universiteit Delft, Vakgroep waterbouwkunde, afstudeerverslag.

Walstra, D.J.R., Rijn, L.C., van, and Aarninkhof, S.G.J., 1998. Sand transport at the middle and lower shoreface of the Dutch coast. Report no. Z2378. Delft Hydraulics, The Netherlands.

WASA, 1998. Changing waves and storms in the northeast Atlantic? Bulletin of the American Meteorological Society, 79(5), pp. 741-760.

Waterman, R.E., Misdorp, R., and Mol, A., 1998. Interactions between water and land in the Netherlands. Journal of Coastal Conservation, 4, pp. 115-126.

Warrick, R., and Oerlermans, J., 1992. Sea-level rise. In : Houghton, J.T., Jenkins, G.J., and Ephraums, J.J. (Eds), Climate change : the IPCC Scientific Assessment. Chapter 9, pp257-282.

Westlake, S.J., 1995. NOURTEC : behaviour of a shoreface nourishment, Terschelling, The Netherlands. M.Sc. thesis, International Institute for Infrastructure, Hydraulic and Environmental Engineering, Delft, The Netherlands.

Westlake, S., Heinen, P.F., Knudsen, S., and Heddinga, P., 1996. Accuracy of NOURTEC bathymetric surveys. Rijkswaterstaat Report. 34pp + figures.

Wiersma, J. and van Alphen, J.S.L.J., 1988. The morphology of the Dutch shoreface between Hook of Holland and Den Helder (The Netherlands). In : Boer, P.L., de, et al (eds). Tide-influenced sedimentary environments and facies, pp. 101-111.

Willis, D.H., and Price, W.A., 1975. Trends in the application of research to solve coastal engineering problems. In: Hails, J., and Carr, A.P., (eds). Nearshore sediment dynamics and sedimentation. Wiley and Sons, pp. 111-122.

Wijnberg, K.M., 1995. Morphologic behaviour of a barred coast over a period of decades. PhD Thesis, Utrecht University, The Netherlands. 250pp.

Wijnberg, K.M., and Terwindt, J.H.J., 1995. Extracting decadal morphological behaviour from the high-resolution, long-term bathymetric surveys along the Holland coast using eigenfunction analysis. Marine Geology, 126, pp.301-330.

Wright, L.D., May, S.K., Short, A.D., and Green, M.O., 1985. Beach and surf zone equilibria and response times. Proceedings of the 19th International Conference of Coastal Engineering, ASCE, New York., pp2150-2164.

Wright, L.D., Boon, J.D., Green, M.O., and List, J.H., 1986. Response of the mid shoreface of the southern mid-Atlantic Bight to a 'northeaster'. Geo-Marine Letters, 6, pp. 153-160.

Wright, L.D., 1993. Micromorphodynamics of the inner continental shelf : a mid Atlantic Bight case study. Journal of Coastal Research, 15, pp. 93-124.

Wright, L.D., 1995. Morphodynamics of inner continental shelves. CRC Press Inc. 241pp.

Wright, L.D., Boon, J.D., Kim, S.C., and List, J.H., 1996. Modes of cross-shore sediment transport of the shoreface of the Middle Atlantic Bight. Marine Geology, 96, pp. 19-51.

Zitman, T.J., Stive, M.J.F., and Wiersma, J., 1990. Reconstruction of the Holocene evolution of the Dutch coast. Proceedings of the 22nd International Conference of Coastal Engineering, ASCE, pp. 1876-1887.

APPENDIX 4.1

Please see sleeve for the 'Geomorphological map of the Holland coast' (taken from Alphen and Damoiseaux, 1989).

APPENDIX 4.2

Please see sleeve for the 'Map of the upper 1 m of sediment of the Holland coast' (Geological Survey of The Netherlands, 1998).

APPENDIX 5.1

FURTHER EVALUATION OF THE METHODS USED

This study uses two techniques to determine shoreface in/activity; the fixed depth change (fdc) (Nicholls *et al*, 1996) and standard deviation of depth change (sddc) (Kraus and Harikai, 1983) (Chapter 5). Although these results qualitatively agree e.g. as the nature and extent of shoreface activity in both the cross-shore and long-shore, it is the magnitude of the activity which differs e.g. the actual depths of the shoreface activity. For example, as shown in Figure 5.1a, shoreface activity is only observed after the 10 year period using both methods. However, when using the fixed depth change method (fdc) the activity re-occurs at 1.85 km offshore whilst with the standard deviation method the re-opening zone commences at 1.79 km

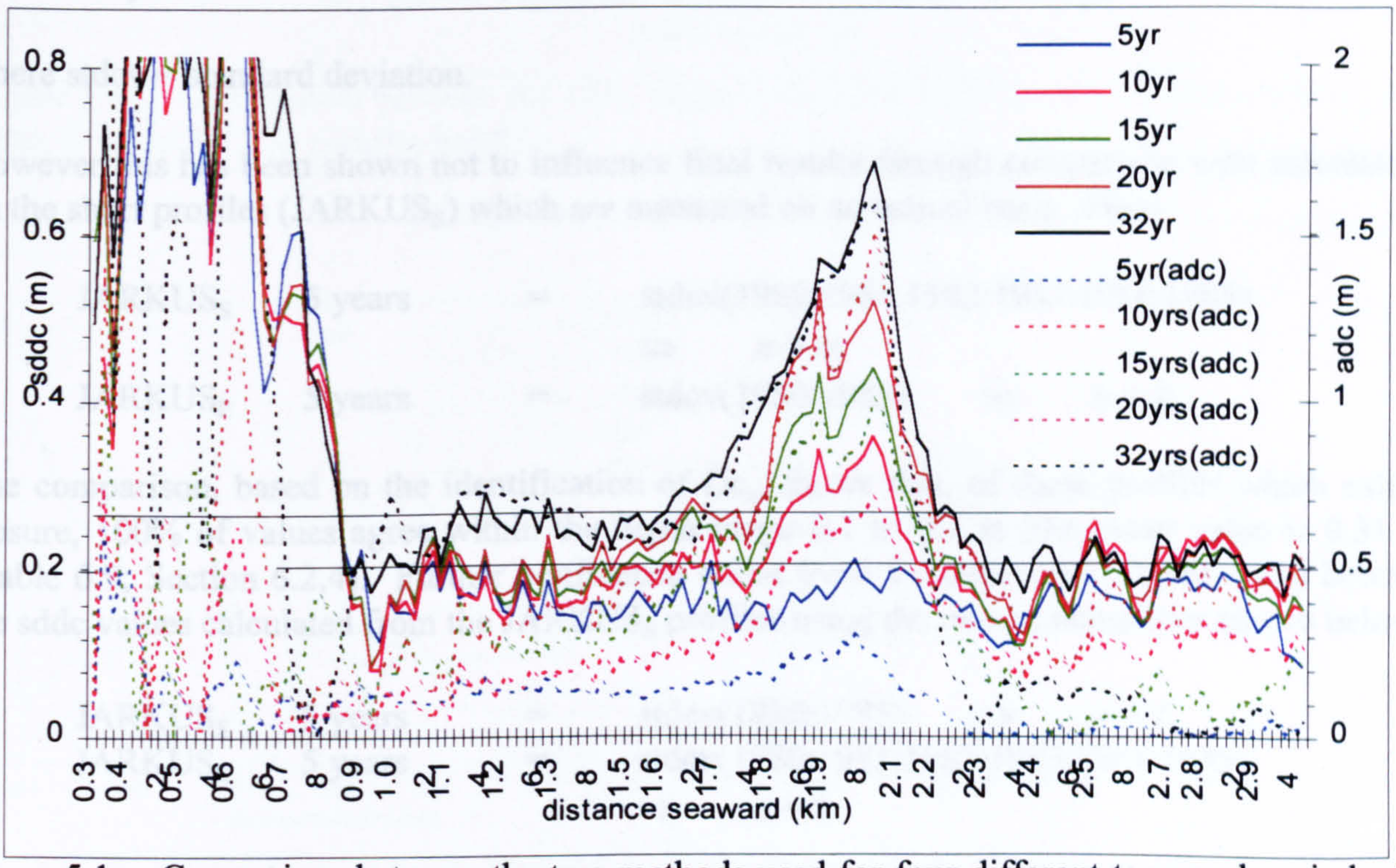


Figure 5.1a. Comparison between the two methods used for four different temporal periods; the calculation of the actual (or fixed) depth change (adc) and that of the standard deviation of the depths. Three depth change criteria are applied to the results of the methods to determine the location of shoreface in/activity within this thesis; here the recommended criteria are applied (Chapter 6); the 0.25 m (sddc) and 0.5 m (fdc). The input data is taken from a real profile; km 66.

This section aims to investigate the relationship between the two methods[1] as a function of time period. The sddc method, as shown in Table 5.1, calculates the standard deviation of depths at set distances offshore using Equation 5.1a.

[1] in which the fdc results are considered as the range of depths between years and so termed adc

$$\sigma = \sqrt{\frac{\sum x^2}{n} - \bar{x}^2} \qquad \text{Equation 5.1a}$$

where σ = standard deviation;
x = value;
$\bar{x}$ = mean value;
n = sample size.

A consequence of the temporal resolution of the JARKUS data set is that the smaller temporal periods will have a smaller value of n than the large :

e.g. 5 years = stdev(1965:1970) $\Rightarrow$ $n = 2$;
28 years = stdev(1965:1970:1975:1980:1985:1990:1993) $\Rightarrow$ $n = 7$.

where stdev = standard deviation.

However this has been shown not to influence final results through comparison with calculations on the short profiles ($JARKUS_S$) which are measured on an annual basis. Here :

$JARKUS_S$ 5 years = stdev(1980:1981:1982:1983:1984:1985)
$\Rightarrow$ $n = 6$;
$JARKUS_E$ 5 years = stdev(1980:1985) $\Rightarrow$ $n = 2$.

The comparison, based on the identification of Dc_s, shows that, of those profiles which exhibit closure, 100% of values agree within the depth range 0.1 to 0.7 m (the mean value is 0.31 m) (Table 6.9; Section 6.2.4). Further confidence arises from a comparison (Figure 5.1b) between the sddc values calculated from the $JARKUS_S$ profiles using the two combinations shown below :

$JARKUS_S$ 5 years = stdev(1980:1985) $\Rightarrow$ $n = 2$;
$JARKUS_S$ 5 years = stdev(1980:1981:1982:1983:1984:1985)
$\Rightarrow$ $n = 6$.

In order to ensure that the sddc results are not influenced by a single outlying value (a problem more important over the smaller time scales), sddc values are calculated for each possible combination and the mean calculated (Figure 5.1c) :

			combinations			sddc value used
e.g.	5 years	=	stdev(1965:1970)	=	a	
			stdev(1970:1975)	=	b	
			↓			$\Rightarrow(\sum a{:}f)/6$
			stdev(1985:1990)	=	e	
			stdev(1993:1997)	=	f	

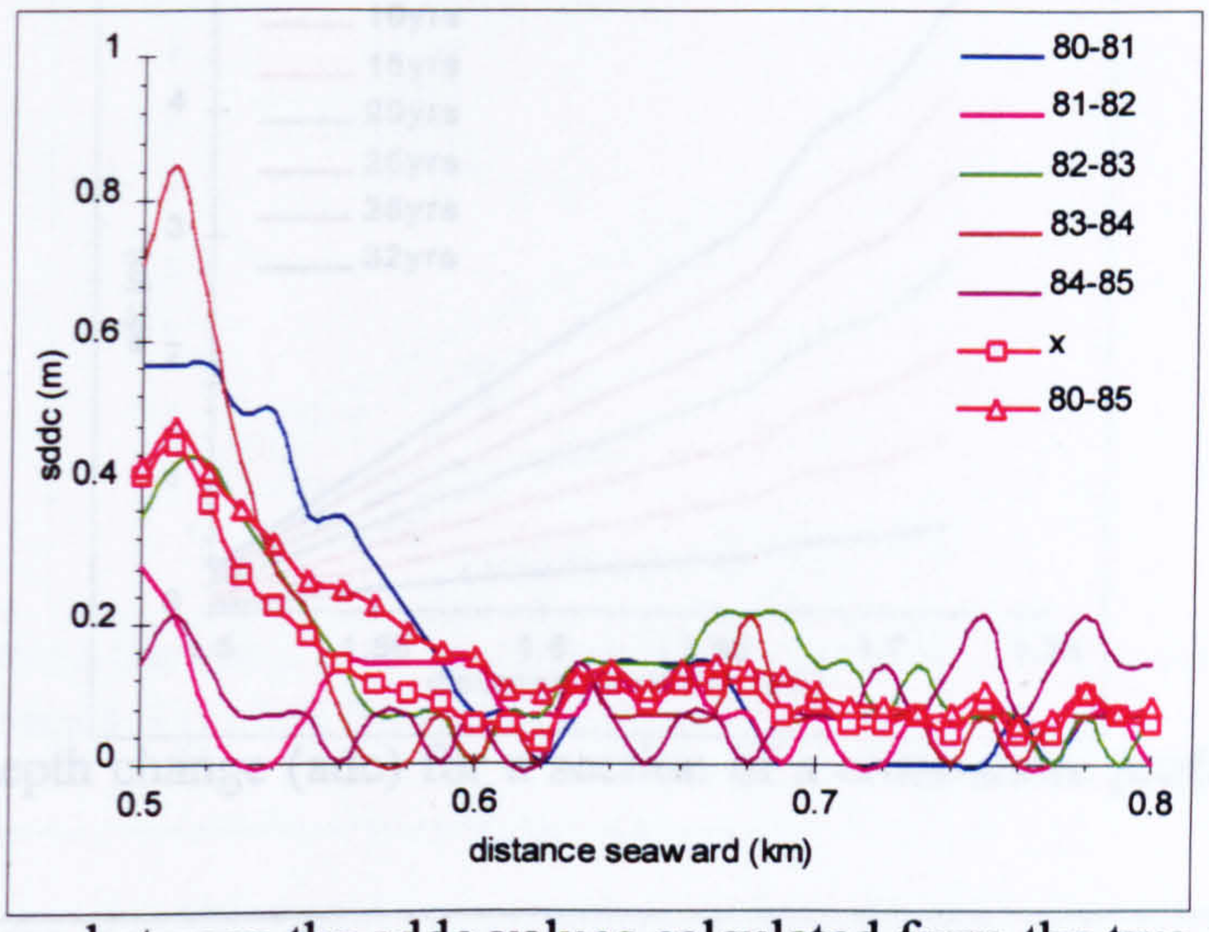


Figure 5.1b. Comparison between the sddc values calculated from the two combinations of years taken from JARKUS$_S$ (profile km 87).

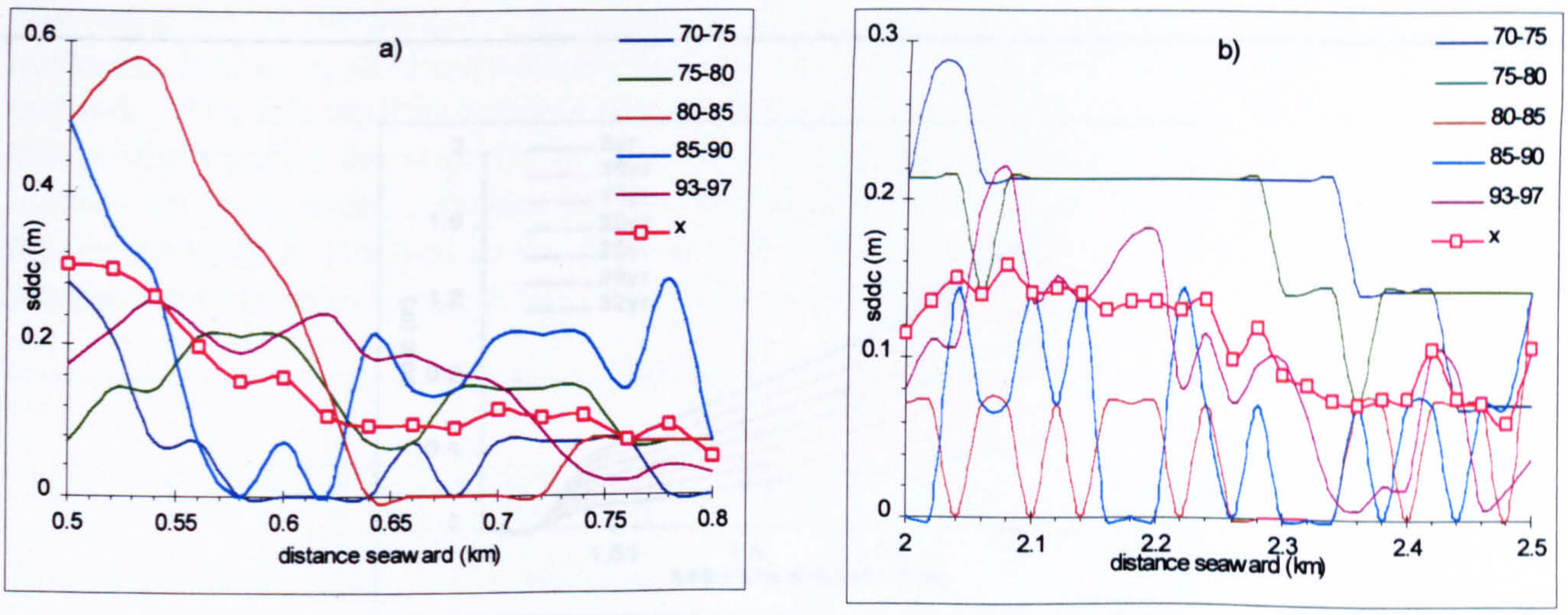


Figure 5.1c. Sddc calculations for each possible combination over the 5 year period and the resultant mean value used in this study. Calculations are made for two cross-shore sections of a real profile, km 87. The first (a) is for the highly active bar zone and the second (b) for the less active offshore.

The relationship between sddc and fdc is now explored in more detail by using a series of synthetic profiles which accentuate depth change spatially and temporally in order to highlight possible irregularities with the methods. The final computation performed here is based upon a cross-shore section of a real profile, km 66.

The first considers the evolution of a section of a cross-shore profile over 32 years for which the profiles change at set values through time and space, as shown in Figure 5.1d.

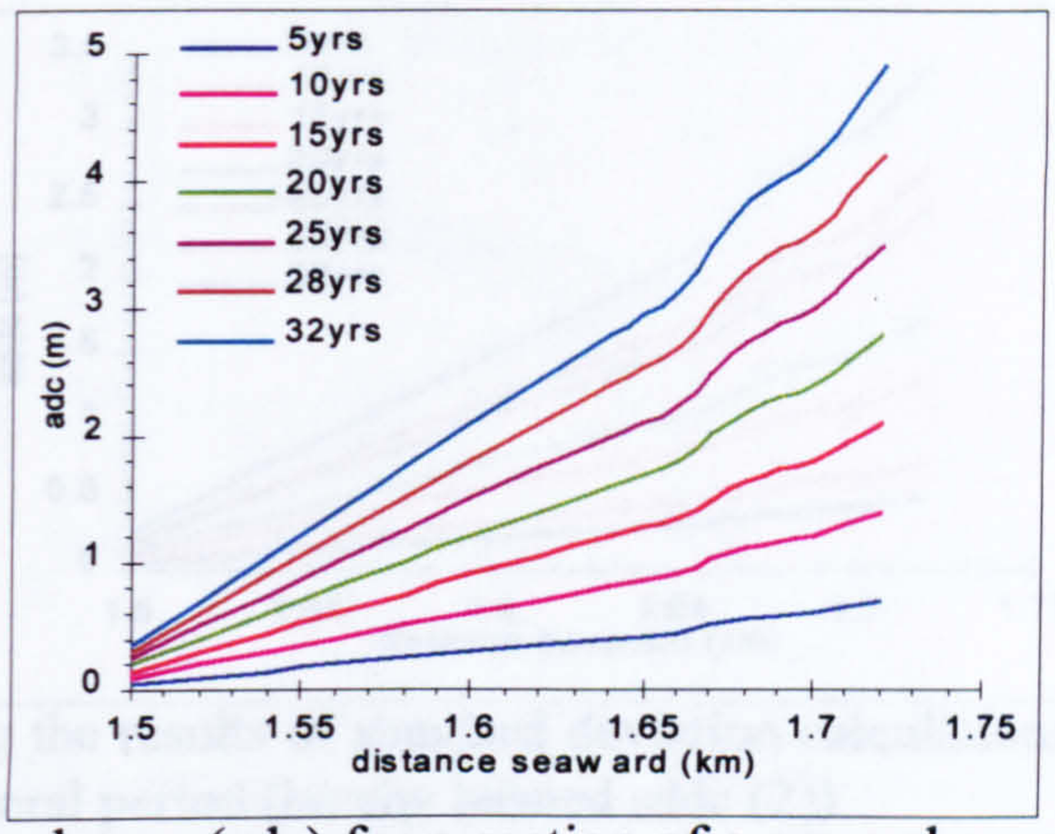


Figure 5.1d. Actual depth change (adc) for a section of a cross-shore profile for seven different temporal periods.

When these bathymetric depths are used in the sddc calculation, as applied in this study, it is clear that as the temporal period increases there is an accompanying increase in the standard deviation values, Figure 5.1e.

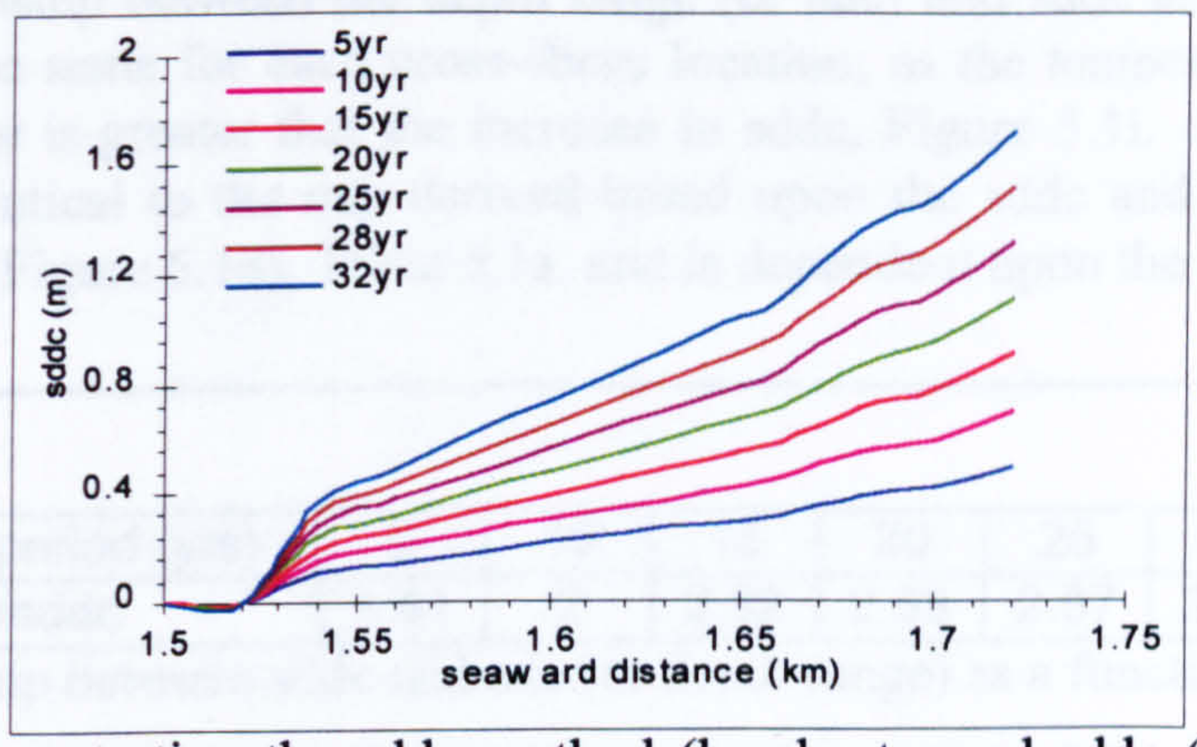


Figure 5.1e. Plot demonstrating the sddc method (hereby termed sddc (1)) when applied to a section of profile for which the actual change in depth is equal over all temporal periods (see Figure 5.1d).

If one applies the sddc method only using the start- and end-profiles of the stated temporal period e.g. :

10 years = standard deviation of 1965:1975 *not* the standard deviation of 1965:1970:1975 then the result is the same as the actual depth change (Equation 5.1b), Figure 5.1f.

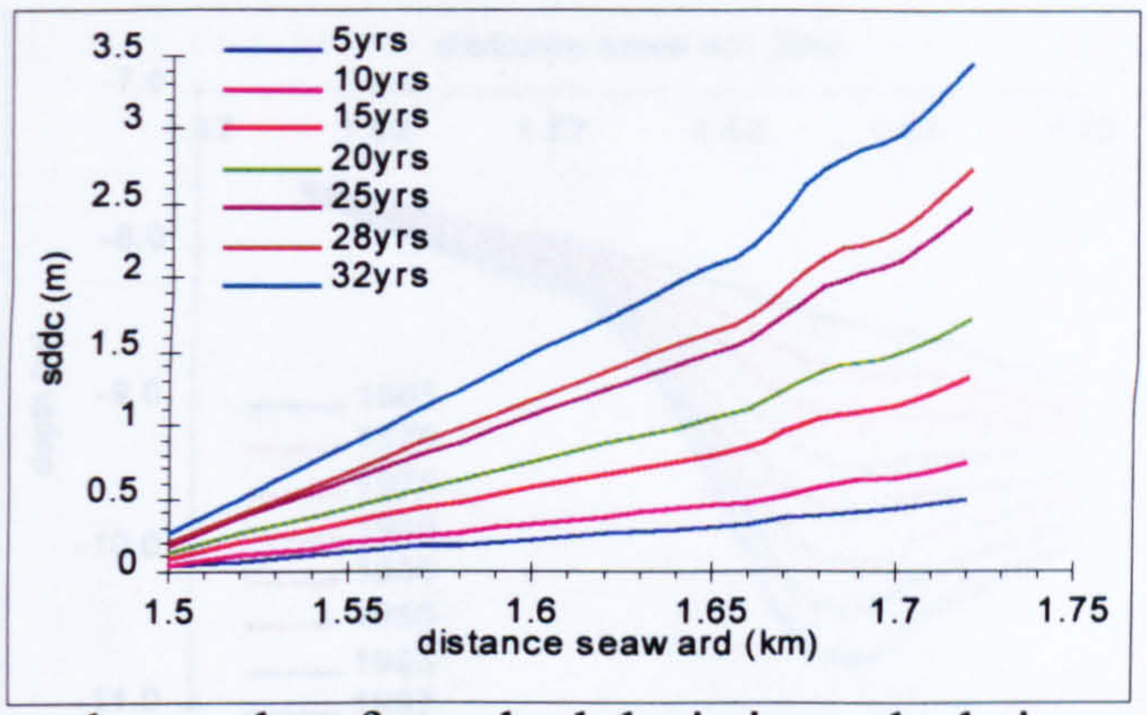


Figure 5.1f. Plot showing the results of standard deviation calculations using the start- and end-profiles of the stated temporal period (hereby termed sddc (2)).

The second synthetic profile changes at set values through time and increases with distance offshore (Figure 5.1g). The results[2] (Figure 5.1h) show that over 5 years the three methods calculate all locations to be inactive whilst over the 28 years[3] the sddc (1 and 2) methods show activity to commence at 1.6 km offshore and the adc method at 1.58 km offshore. Hence the representation of the temporal development of the shoreface in/activity is the same using all methods. However, as already stated, the identification of in/activity differs slightly between the methods. The relationship between the depth range (or adc) and sddc as a function of time for this profile remains the same for each cross-shore location; as the temporal period increases the increase in depth range is greater that the increase in sddc, Figure 5.1i. It should be noted that this relationship is identical to the one derived based upon the sddc and adc values of the first representative profile (Figure 5.1d), Table 5.1a, and is dependent upon the value of *n*.

temporal period (yrs)	5	10	15	20	25	28	32
adc/sddc	1.41	2	2.32	2.53	2.67	2.78	2.86

Table 5.1a. Relationship between sddc and adc (or depth range) as a function of time.

[2] using the recommended change criteria of 0.25 m for the sddc methods and 0.5 m for the fdc method.

[3] although the largest temporal period is 32 years, 28 years has been used here as it is reliant upon two different combinations of years (1965:1993; 1970:1997) rather than one (1965:1997). Hence taking the mean of these two combinations removes any potential bias of 'extreme' measurements.

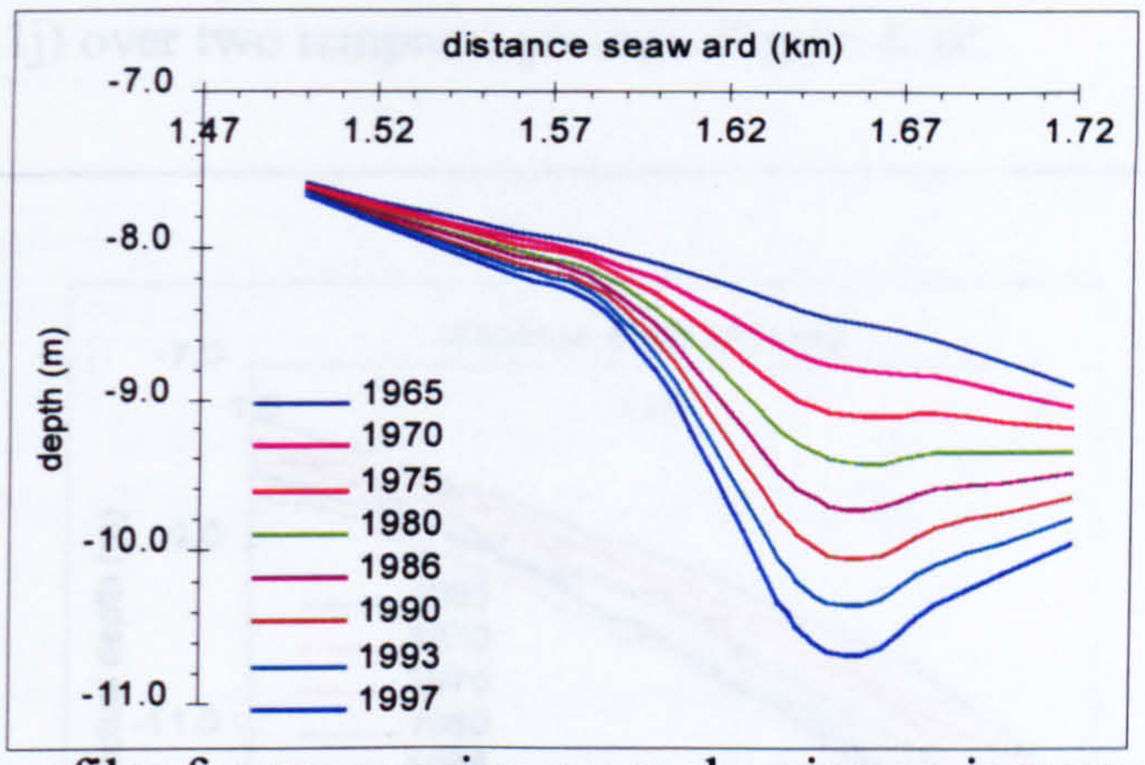


Figure 5.1g. Synthetic profiles for progressive years showing an increase in depth with time and distance offshore.

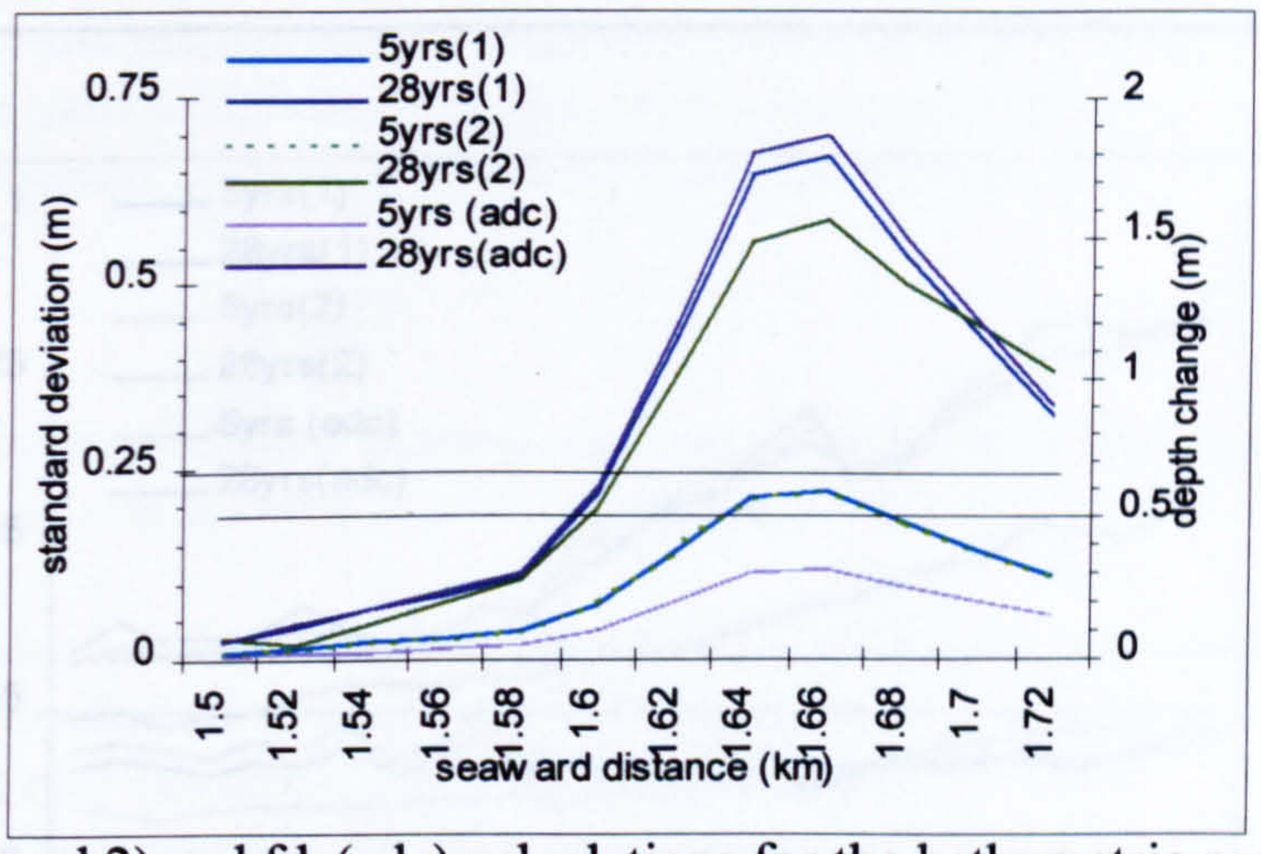


Figure 5.1h. Sddc (1 and 2) and fdc(adc) calculations for the bathymetric profiles of Figure 5.1f.

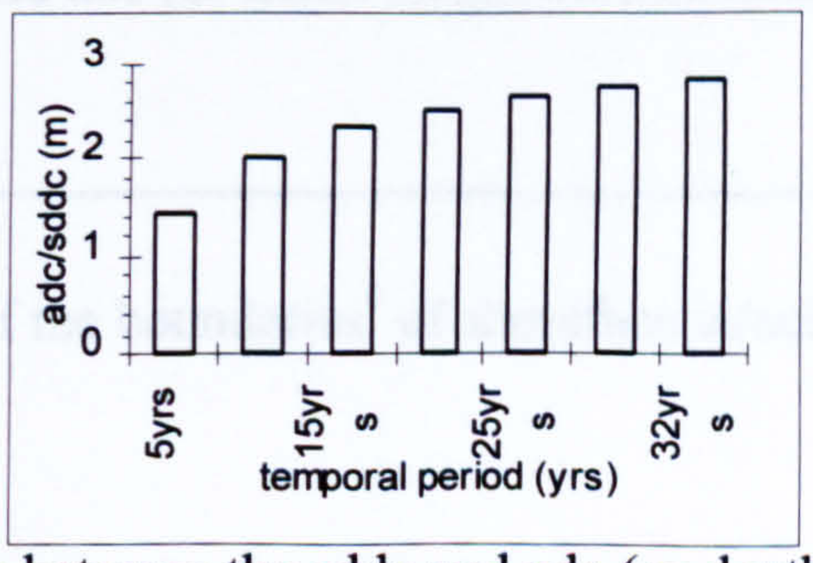


Figure 5.1i. Value of the ration between the sddc and adc (or depth range) values as a function of time.

These methods have also been applied to a cross-shore section of km 66 which steadily deepens through time (Figure 5.1j) over two temporal periods, Figure 5.1k.

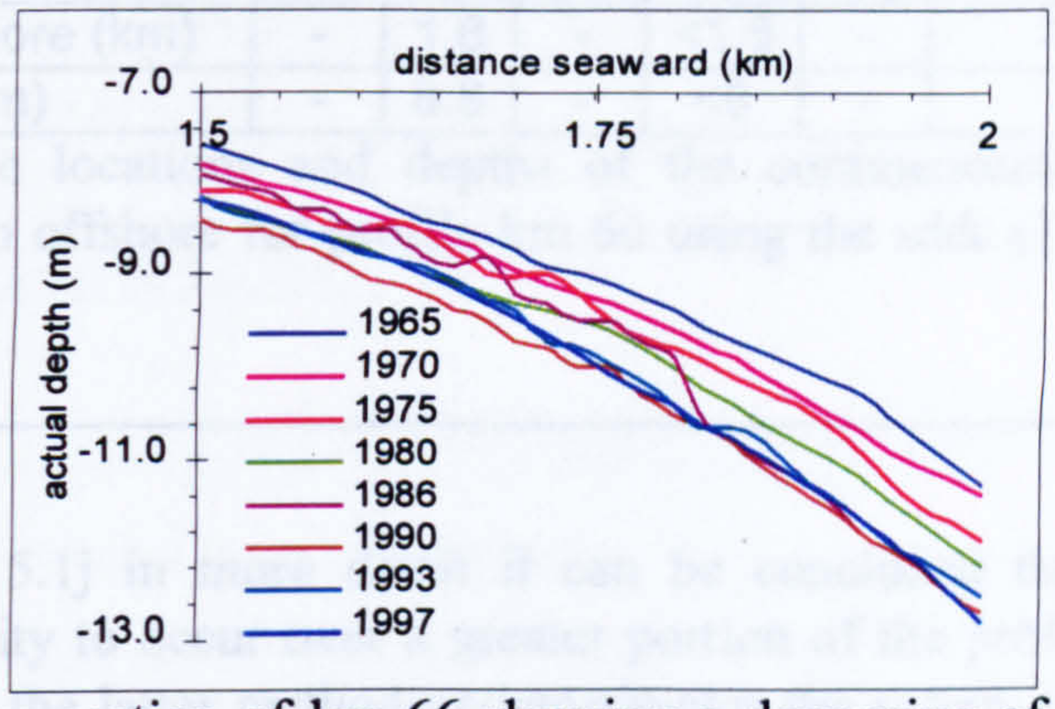


Figure 5.1j. A cross-shore section of km 66 showing a deepening of the profile from 1965 to 1997.

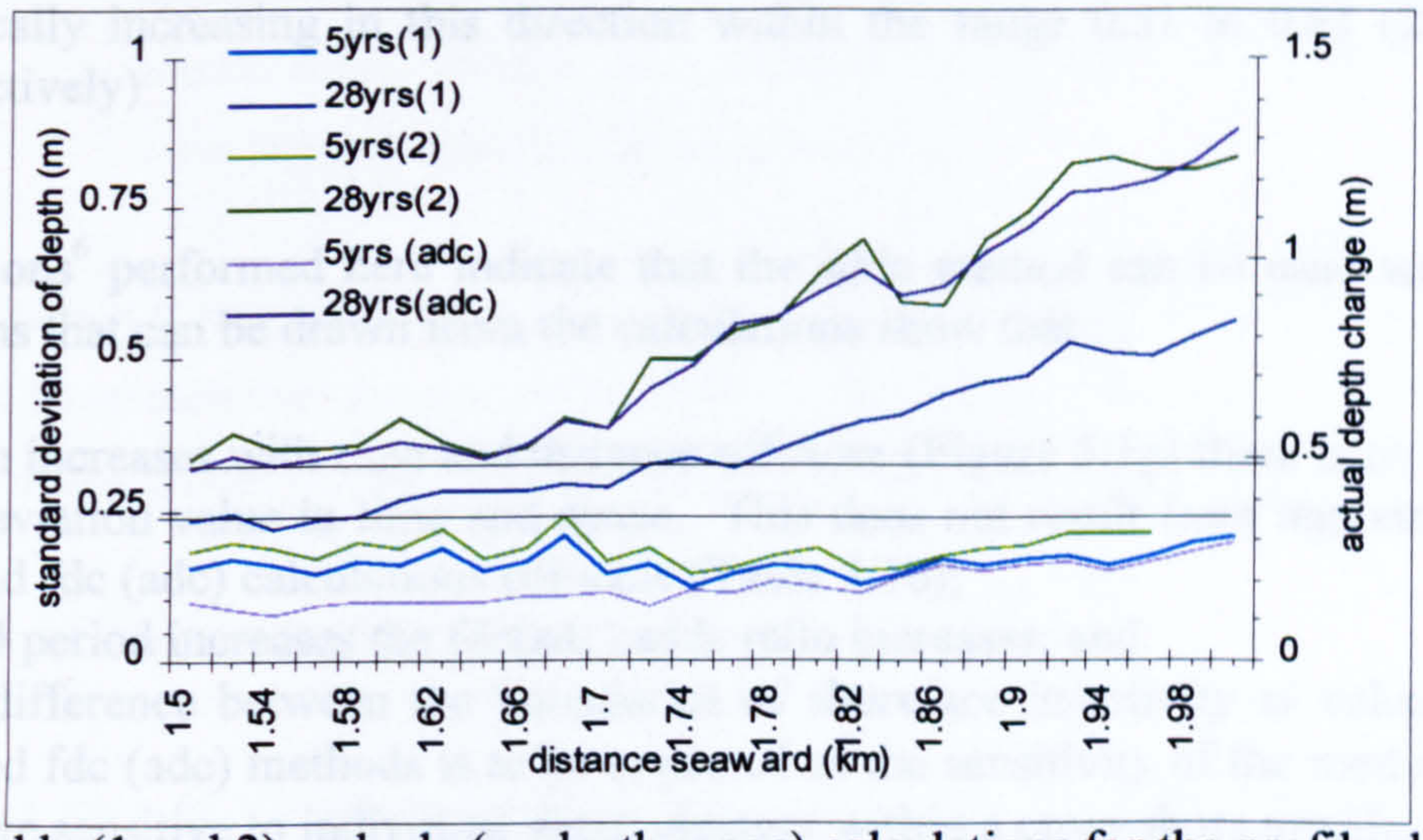


Figure 5.1k. Sddc (1 and 2) and adc (or depth range) calculations for the profile shown in Figure 5.1j.

In this example the positions of the boundaries[4] of shoreface in/activity are as in Table 5.1b.

[4] as given by the recommended change criteria

	sddc (1)		sddc (2)		adc (or depth range)	
temporal period (yrs)	5	28	5	28	5	28
distance offshore (km)	-	1.6	-	<1.5	-	1.52
depth (m)	-	8.6	-	<8	-	8.1

Table 5.1b. Cross-shore locations and depths of the commencement of shoreface activity between 1.5 km and 2 km offshore for profile km 66 using the sddc (1 and 2) and adc (or depth range) methods.

If one examines Figure 5.1j in more detail it can be concluded that the sddc (2) method[5] calculates shoreface activity to occur over a greater portion of the profile than the fdc and sddc (1) methods. In addition the latter method underestimates the extent of shoreface activity when compared to the fdc method. When calculating the adc:sddc ratio as a function of temporal period (as Figure 5.1i and Table 5.1a) it can be seen that, as in the previous examples, as the period increases then the adc (or depth range) increases at a greater rate than the sddc values. However, unlike the previous examples, the ratio does not remain constant for each distance offshore, typically increasing in this direction within the range 0.31 to 0.81 (28 and 10 year periods, respectively)

The computations[6] performed here indicate that the sddc method can be used with confidence. The conclusions that can be drawn from the calculations show that : :

1. when depth increases with time and distance offshore (Figure 5.1g) there is an increase in the standard deviation value in time and space. This does not result from temporal bias as both the sddc and fdc (adc) calculations coincide (Table 5.1b);
2. as temporal period increases the fdc(adc):sddc ratio increases; and
3. the slight difference between the boundaries of shoreface in/activity as calculated with the sddc (1) and fdc (adc) methods is to be expected as the sensitivity of the methods differ[7]; the latter is more sensitive to individual depth changes within a cross-shore profile.

[5] incidentally this method has not been used in this study, and is used here to further comparison between potential methods and the possibility of temporal bias.
[6] 1) the depth change for each temporal period is the same; 2) the depth increases with increasing temporal period and distance offshore
[7] see Chapter 6

APPENDIX 5.2
THE SUB-MODELS OF UNIBEST-TC

The five sub-models are summarised below. For further details e.g. working equations, the reader is referred to Bosboom *et al* (1997).

1) WAVE PROPAGATION MODEL

This sub-model is composed of three first order differential equations:

1) time-averaged wave energy balance;
2) roller balance equation for that energy contained in surface rollers in breaking waves. This equation allows for the fact that, after breaking, organised wave energy is first converted into turbulent kinetic energy before being dissipated through turbulence; and
3) horizontal momentum balance which takes into consideration the concept of breaker delay. Breaker delay allows for the fact that waves need a distance of one wave length to actually start/stop breaking.

Wave refraction is computed using Snell's Law. The three coupled equations are solved through numerical integration over the cross-shore profile. The output is then used by local models for the vertical velocity profile, concentration profile and bed-load transport.

2) MEAN CURRENT MODEL

Taking the case of alongshore uniformity, the depth-integrated cross-shore radiation stress is balanced by the wave set-up. The longshore radiation stress is balanced by a time mean bed shear stress associated with the longshore current. Secondary currents are driven due to vertical non-uniformity. An imbalance exists between the cross-shore wave radiation stress gradient and the pressure gradient due to wave set-up. This imbalance drives a circulation current which has a shoreward mass flux above the trough level and undertow (seaward return flow) below the trough level. In addition, shoreward directed near-bottom streaming exists in the wave boundary layer.

In order to represent the velocity distribution of the cross-shore circulation current and longshore current the horizontal momentum balance is used. The balance takes into account wind shear

stress, breaking-induced forcing, surface slope, wave boundary layer and also uses the parabolic eddy viscosity distribution.

3) WAVE ORBITAL VELOCITY MODEL

This sub-model consists of two parts:

1) wave asymmetry, where the mean wave energy and peak period are used as random wave input; and
2) bound long waves, and also an empirical relationship for the phase of the bound long wave relative to the short wave envelope.

A time series is produced which has the same characteristics of asymmetry, long waves and amplitude modulation as a random wave field.

4) BED LOAD AND SUSPENDED LOAD MODEL

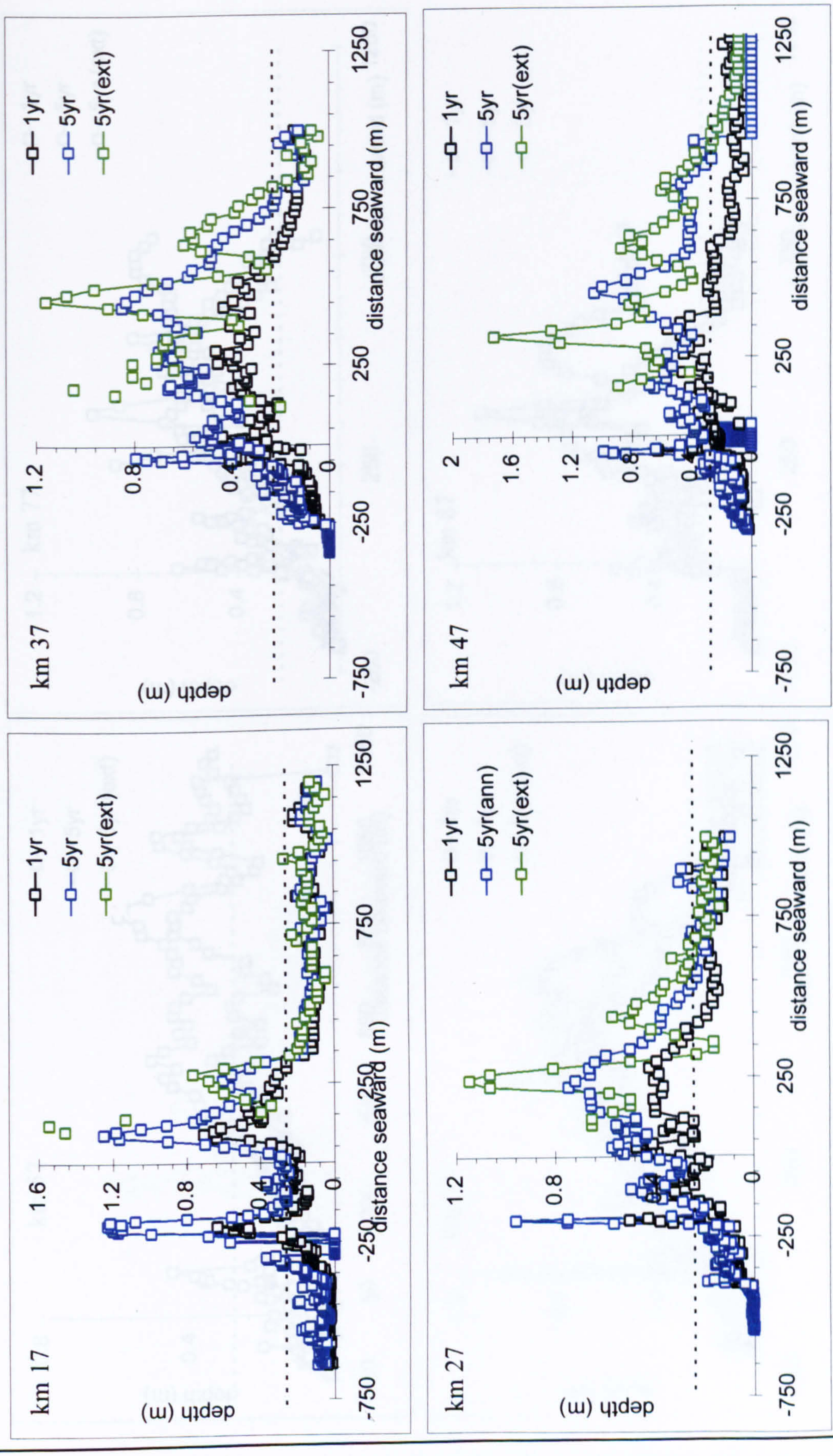
The bed load model takes the quasi-steady bed load formulation. At small shear stresses, transport is represented as individual particles moving over a rippled bed whilst at high shear stresses it is represented as sheet flow.

The suspended load model takes the wave-related suspended sediment transport to be small as compered to the current related suspended sediment transport. The former mode is defined as 'the transport of sediment particles by the oscillating fluid components'. The latter is defined as 'the transport of sediment particles by the time-averaged current velocities (longshore, rip and undertow currents).

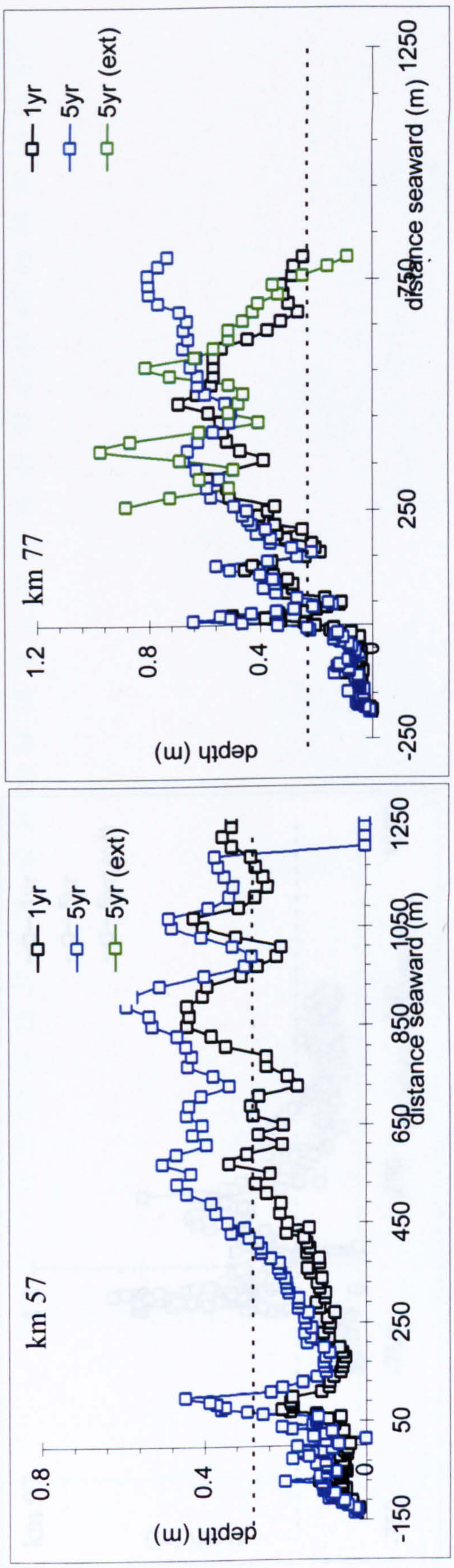
Both the bed load and suspended load models include computations of the time-averaged concentration profile and bed shear stresses.

5) BED LEVEL CHANGE MODEL

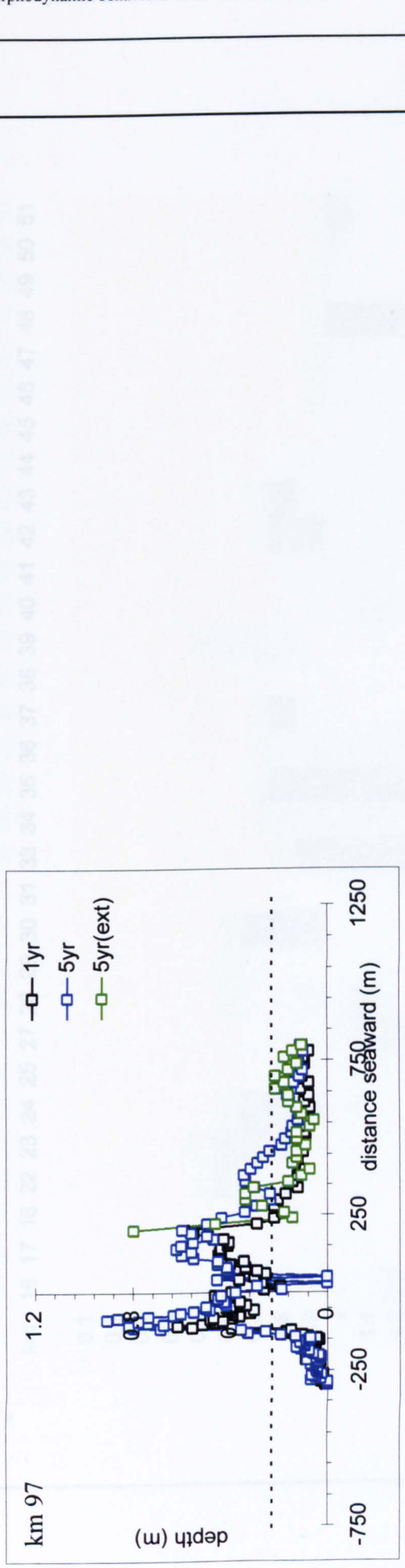
Bed level changes are computed from the depth-integrated mass balance after the computation of transport rates along the profile.



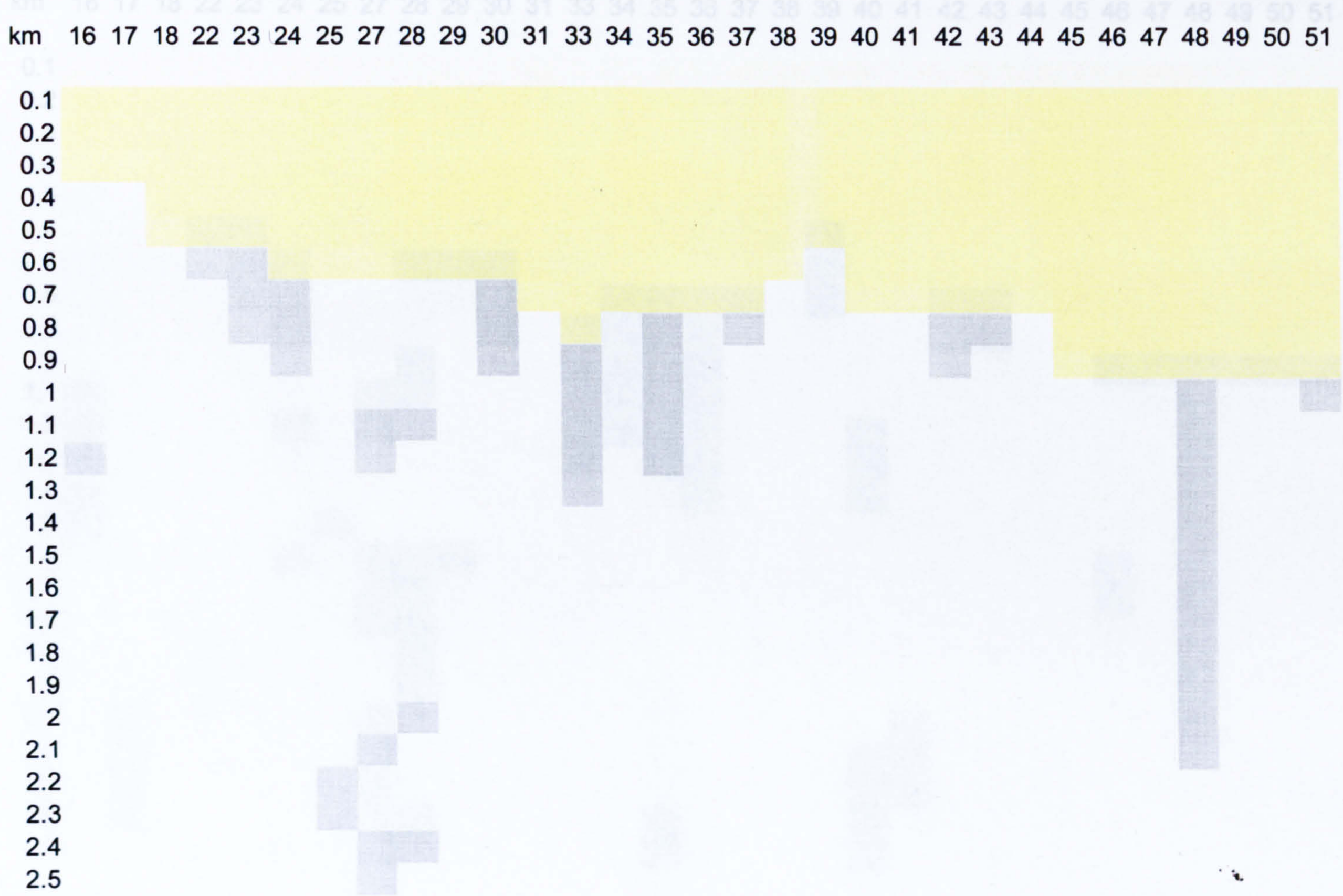
Appendix 6.1. Sddc plots of the JARKUS$_S$ versus JARKUS$_E$. The black line represents the sddc values derived over a 1 year period. The blue line represents the sddc values derived over the 5 year period using the JARKUS$_S$ and the green line represents the sddc values derived over the 5 year period using the JARKUS$_E$. It can be seen that 100% of Dc_s values agree within 1 m.



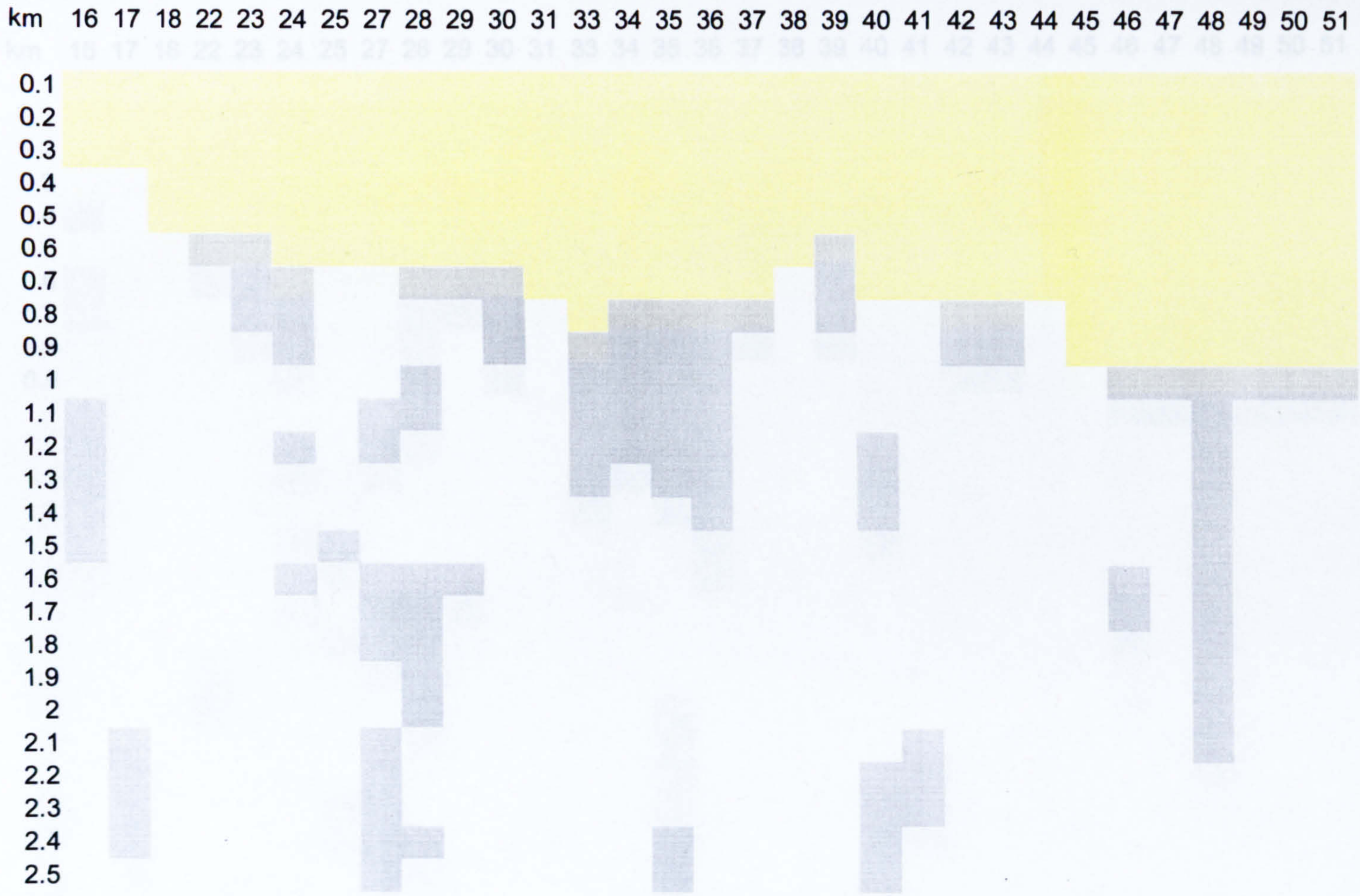
Appendix 6.1. cont.. Sddc plots of the JARKUS$_S$ versus JARKUS$_E$. The black line represents the sddc values derived over a 1 year period. The blue line represents the sddc values derived over the 5 year period using the JARKUS$_S$ and the green line represents the sddc values derived over the 5 year period using the JARKUS$_E$. It can be seen that 100% of Dc$_s$ values agree within 1 m.



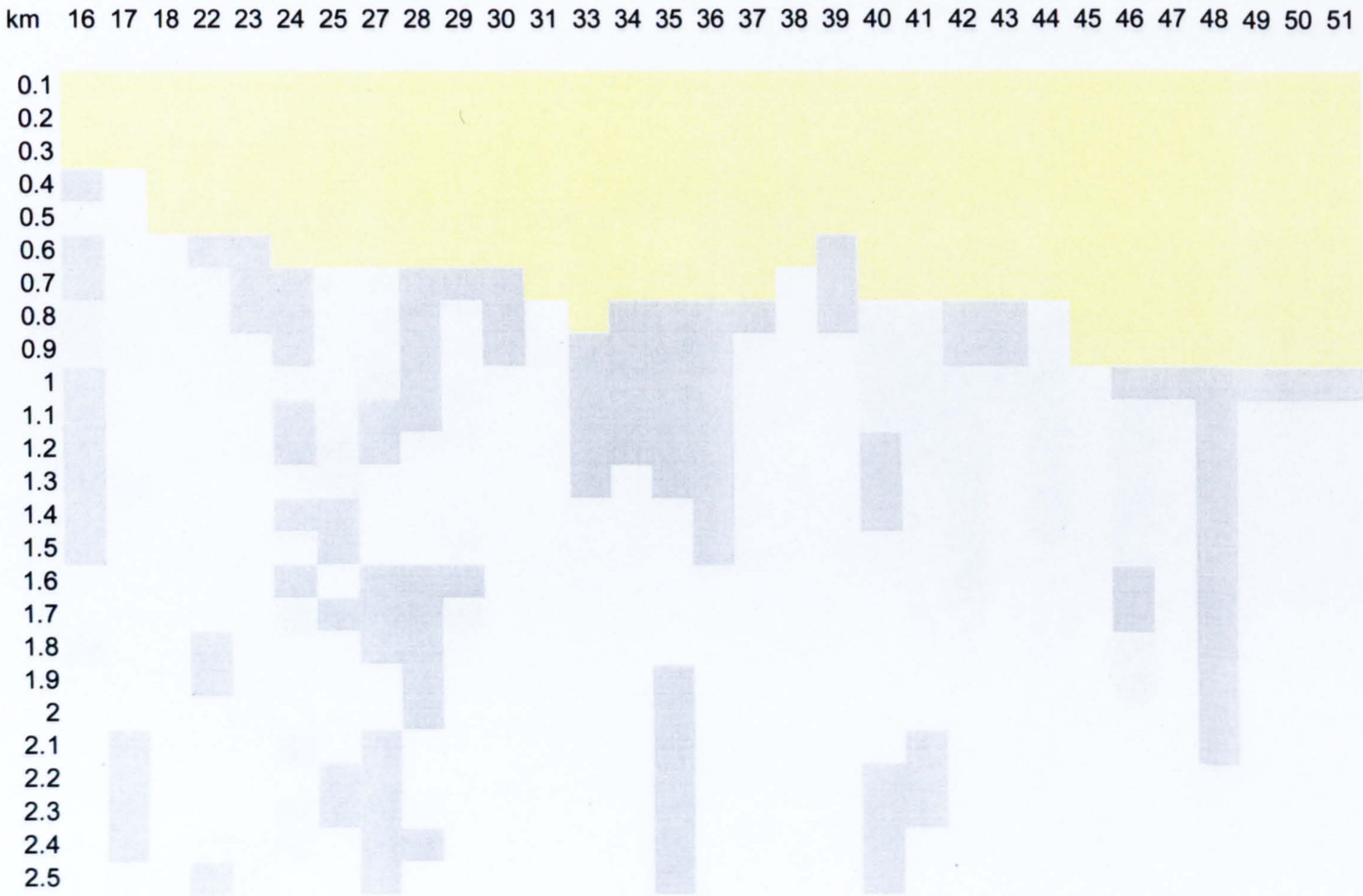
Appendix 6.1. cont. Sddc plots of the $JARKUS_S$ versus $JARKUS_E$. The black line represents the sddc values derived over a 1 year period. The blue line represents the sddc values derived over the 5 year period using the $JARKUS_S$ and the green line represents the sddc values derived over the 5 year period using the $JARKUS_E$. It can be seen that 100% of Dc_s values agree within 1 m.



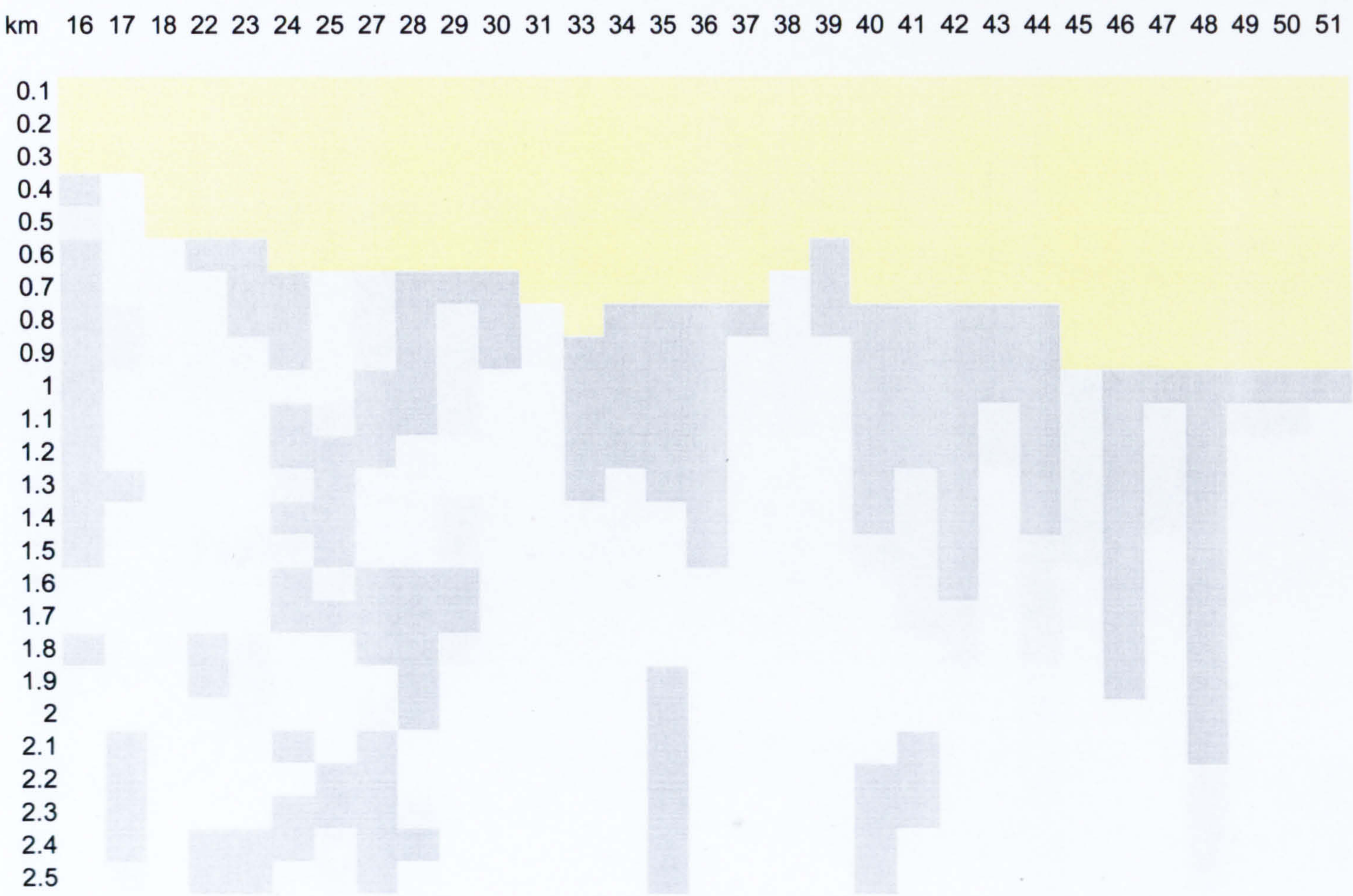
Appendix 6.2. Shoreface activity after 5 years in Noord-Holland. The method used is the fixed tail sddc (0.25 m criterion).



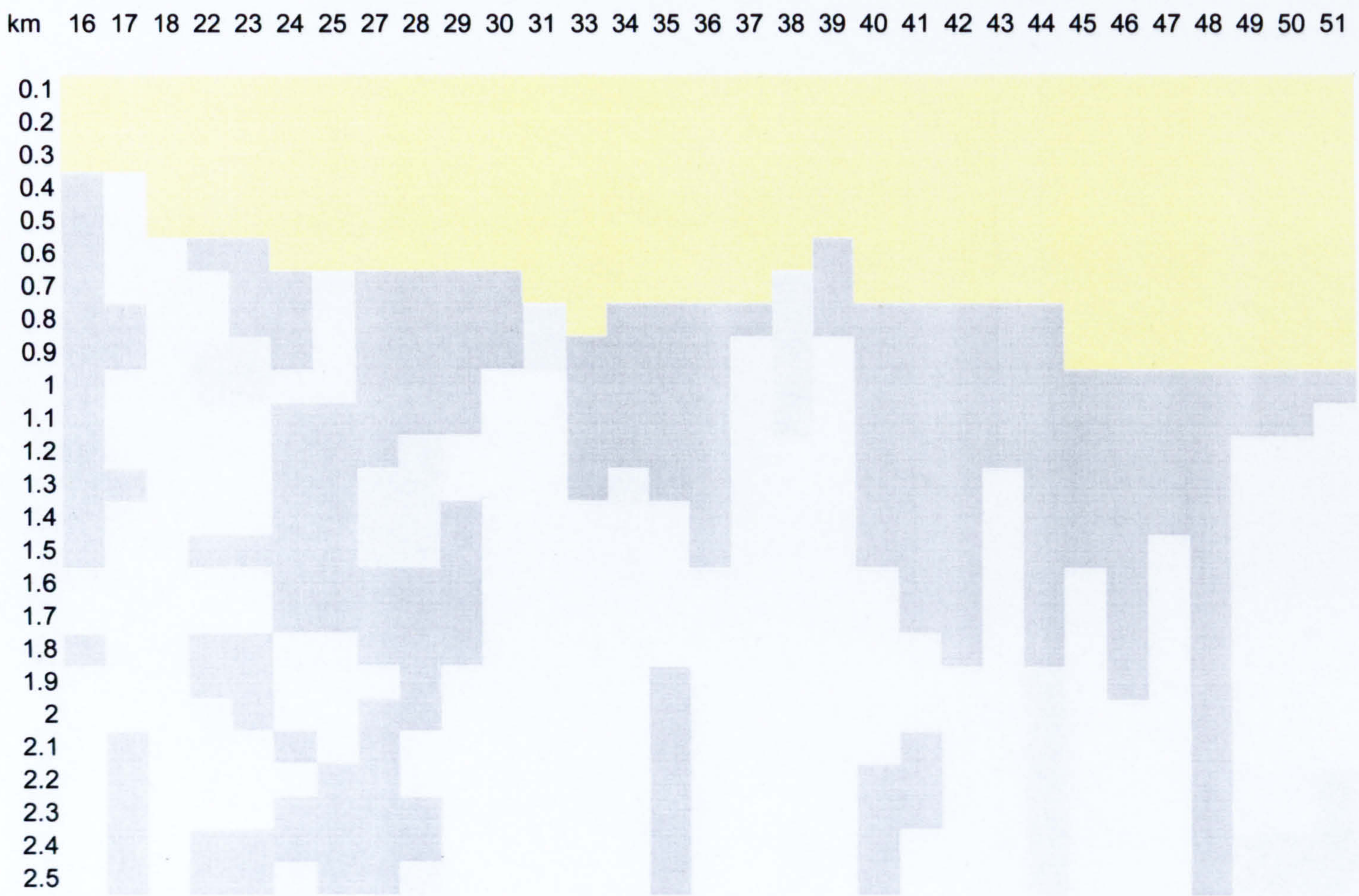
Appendix 6.2 cont.. Shoreface activity after 10 years in Noord-Holland. The method used is the fixed tail sddc (0.25 m criterion).



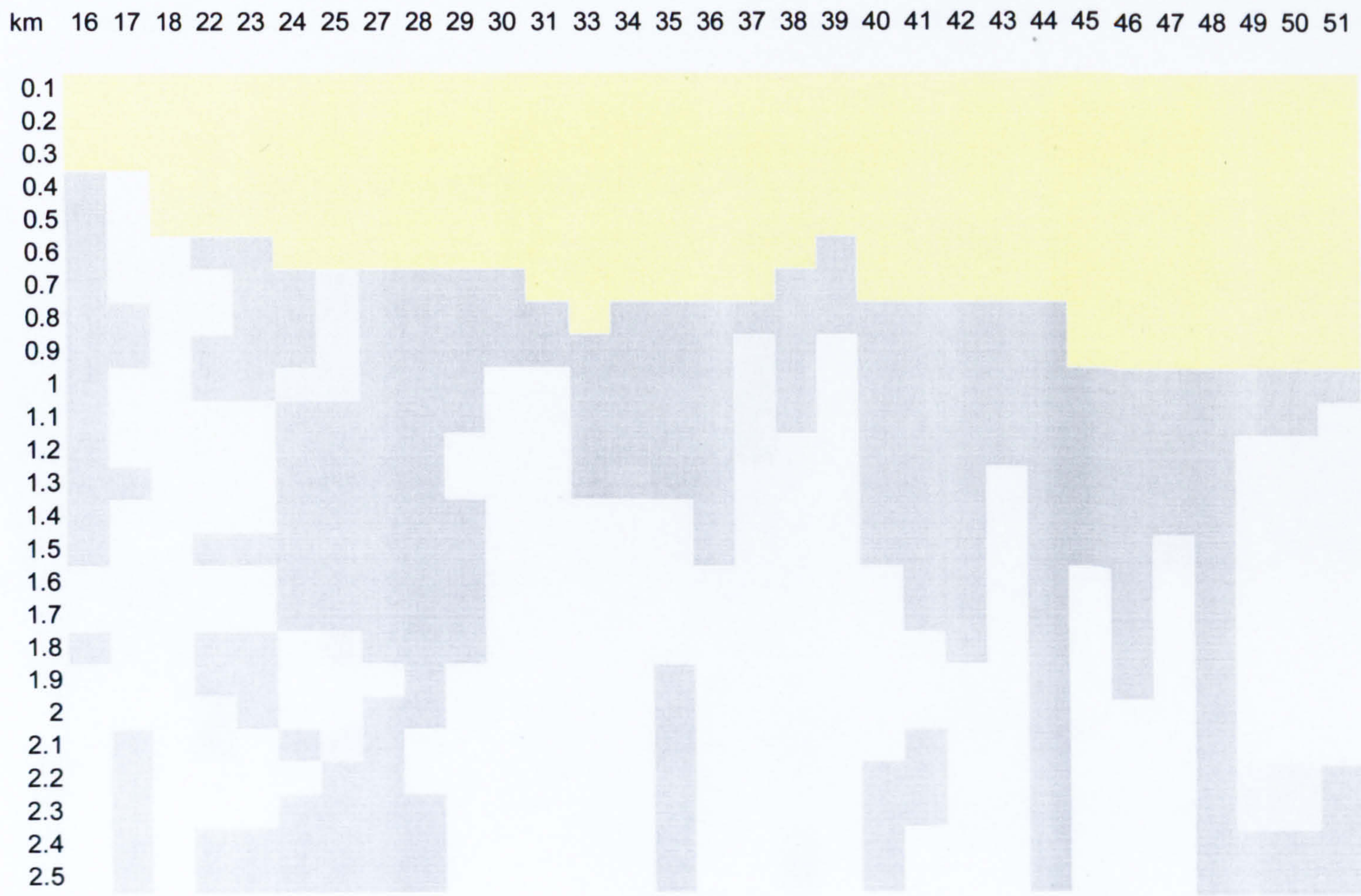
Appendix 6.2 cont.. Shoreface activity after 15 years in Noord-Holland. The method used is the fixed tail sddc (0.25 m criterion).



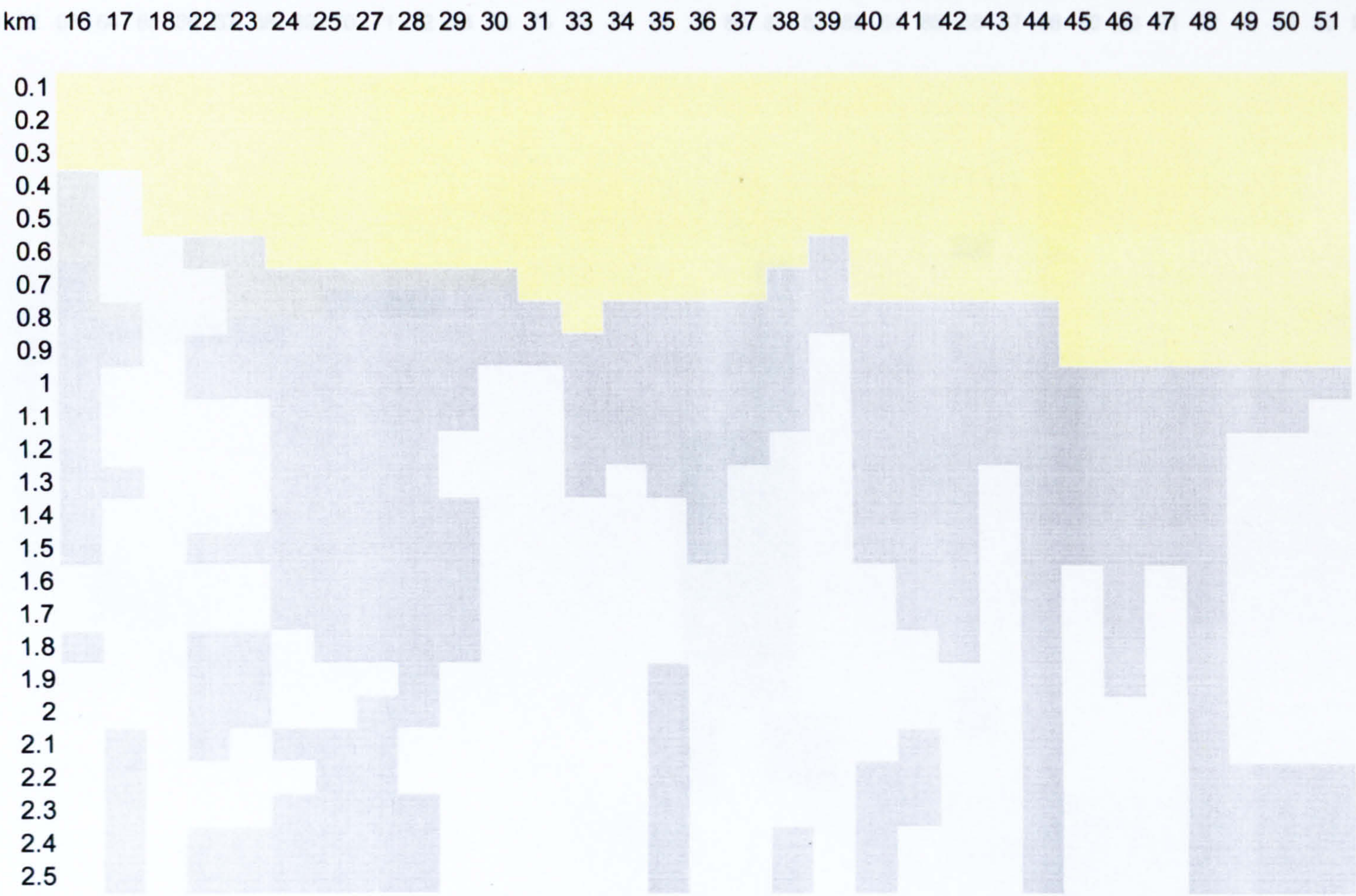
Appendix 6.2 cont.. Shoreface activity after 20 years in Noord-Holland. The method used is the fixed tail sddc (0.25 m criterion).



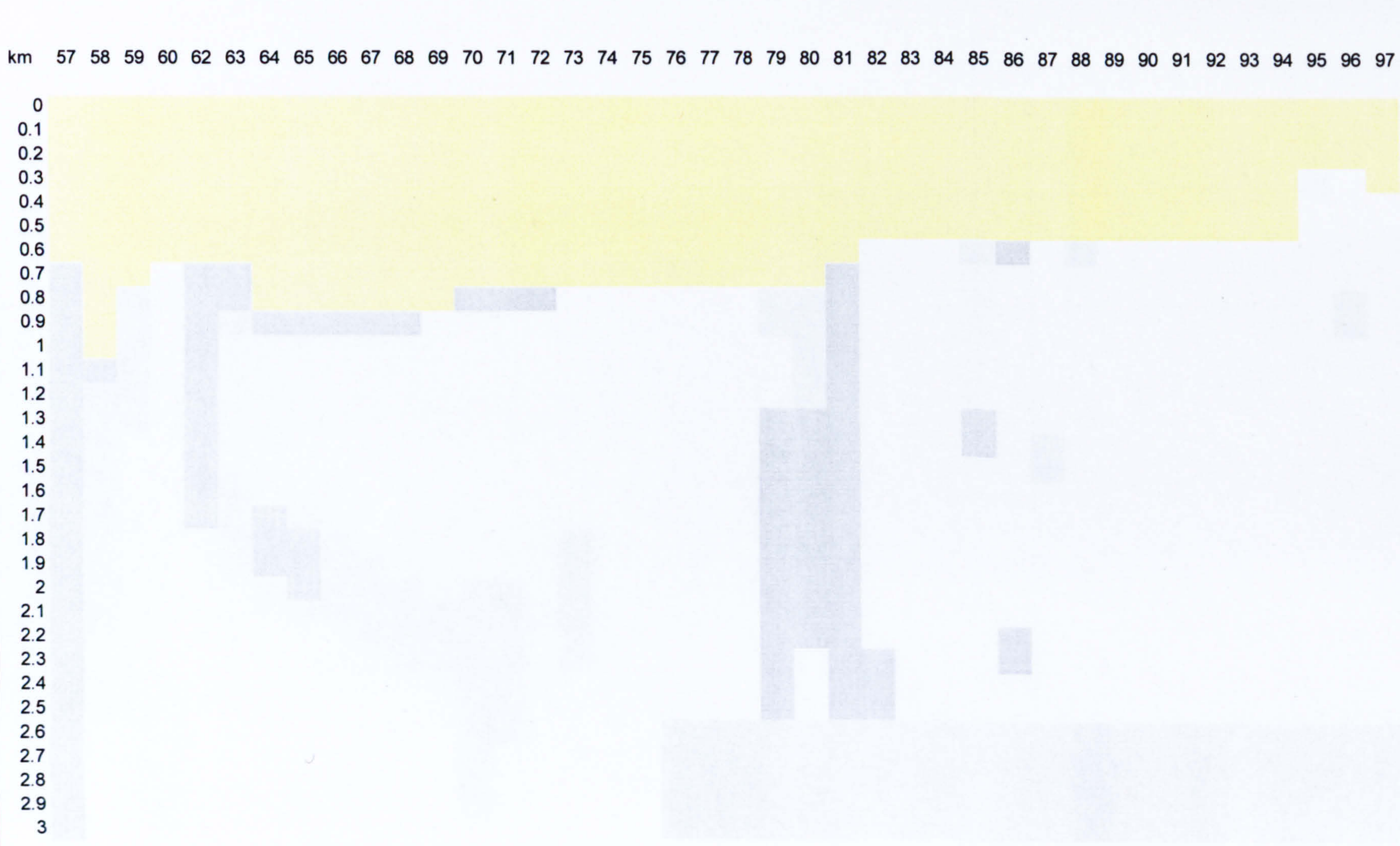
Appendix 6.2 cont.. Shoreface activity after 25 years in Noord-Holland. The method used is the fixed tail sddc (0.25 m criterion).



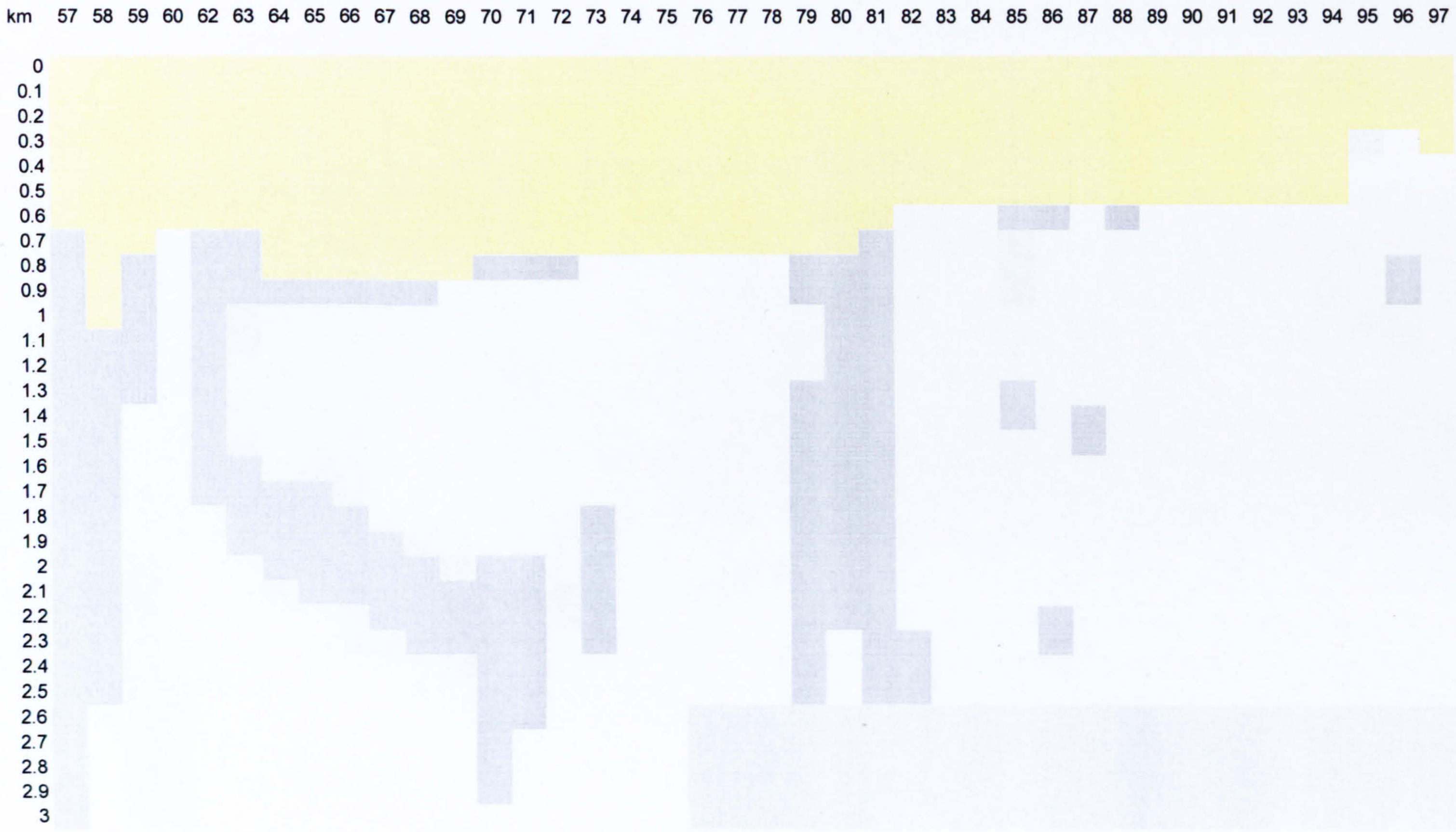
Appendix 6.2 cont.. Shoreface activity after 28 years in Noord-Holland. The method used is the fixed tail sddc (0.25 m criterion).



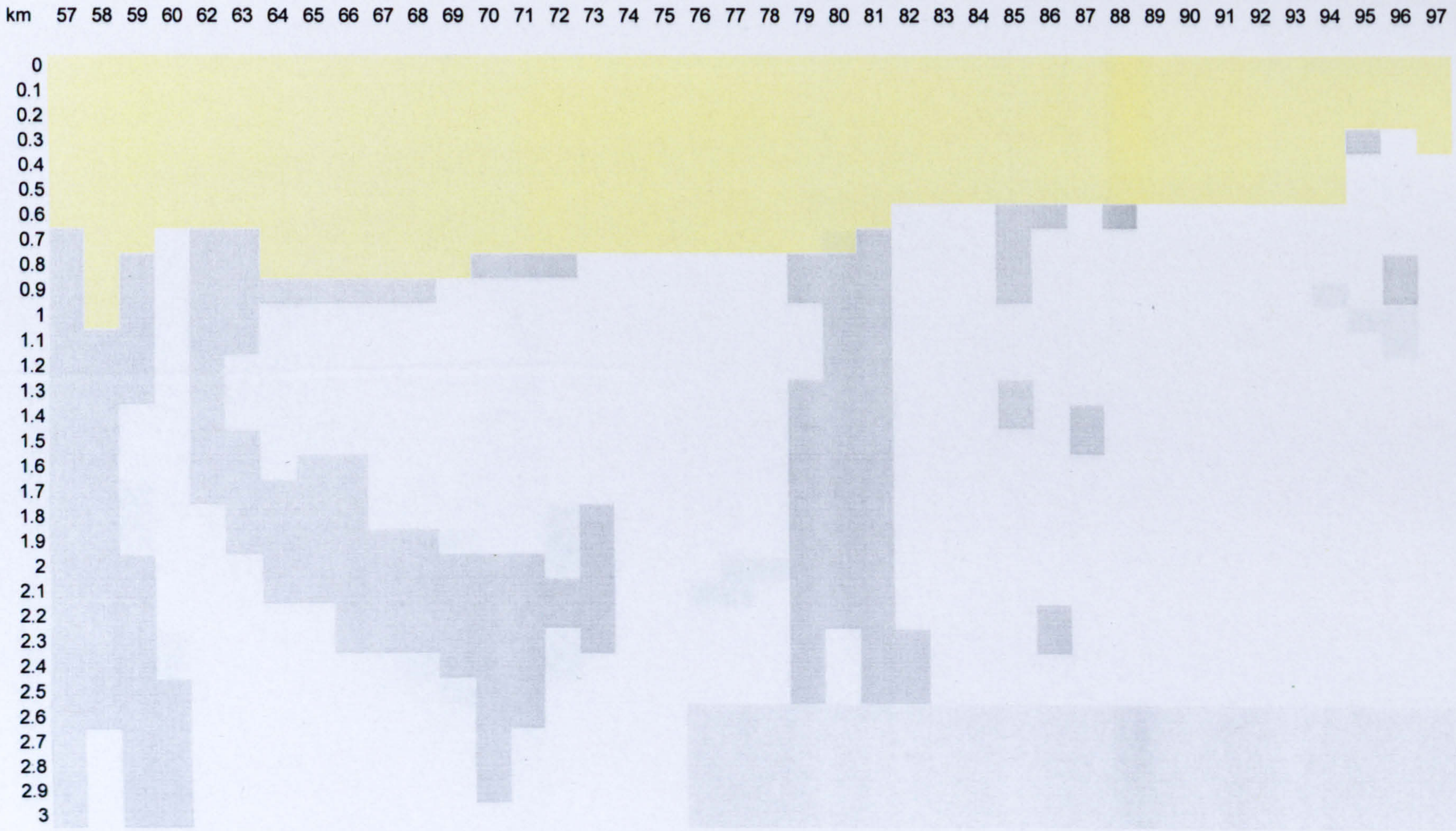
Appendix 6.2 cont.. Shoreface activity after 32 years in Noord-Holland. The method used is the fixed tail sddc (0.25 m criterion).



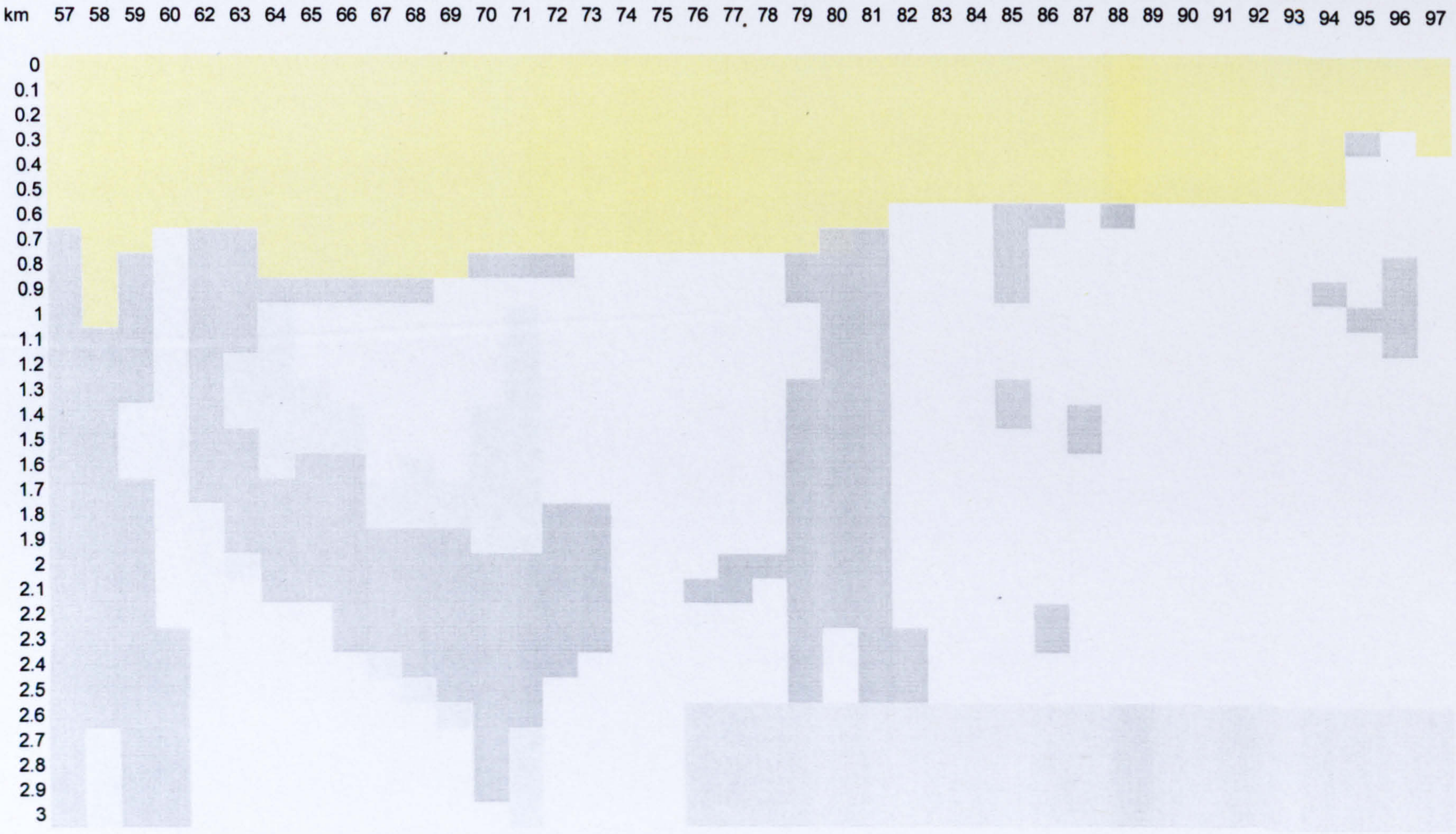
Appendix 6.2. cont. Shoreface activity after 5 years in Zuid-Holland. The method used is the fixed tail sddc (0.25 m criterion). (Periods 25 years and 32 years do not exist for km 72 - 97).



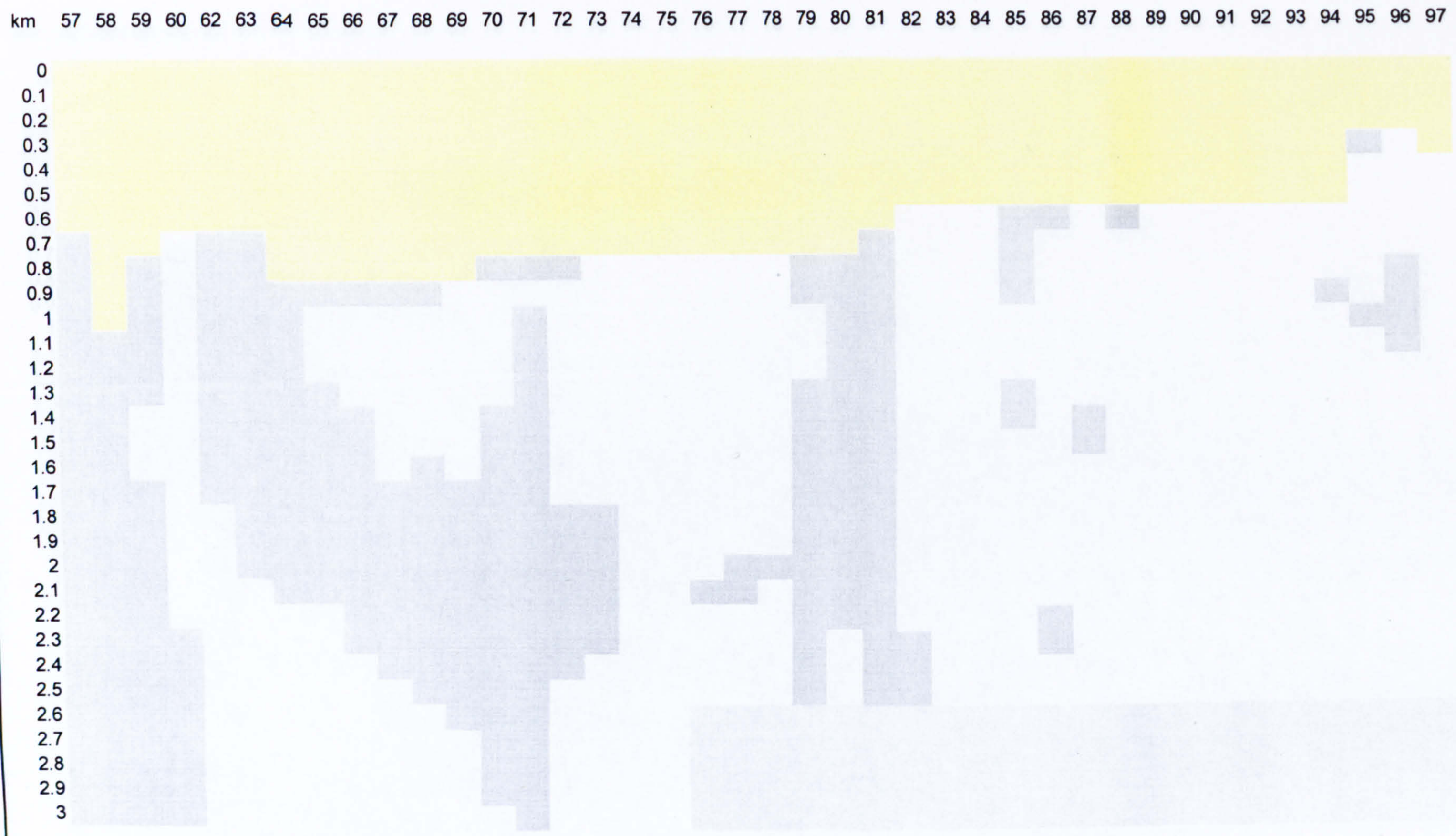
Appendix 6.2. cont. Shoreface activity after 10 years in Zuid-Holland. The method used is the fixed tail sddc (0.25 m criterion). (Periods 25 years and 32 years do not exist for km 72 - 97).



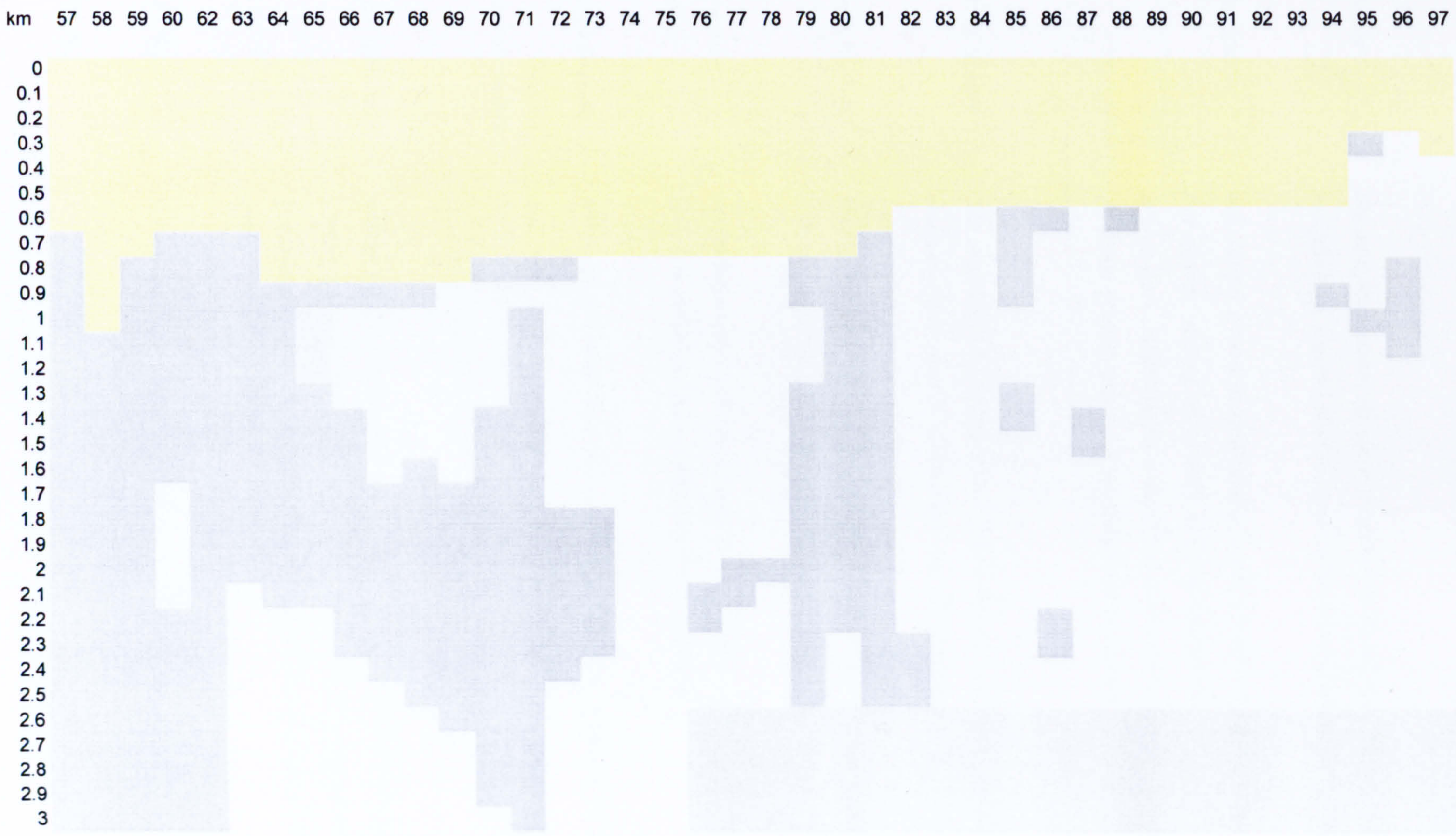
Appendix 6.2. cont. Shoreface activity after 15 years in Zuid-Holland. The method used is the fixed tail sddc (0.25 m criterion). (Periods 25 years and 32 years do not exist for km 72 - 97).



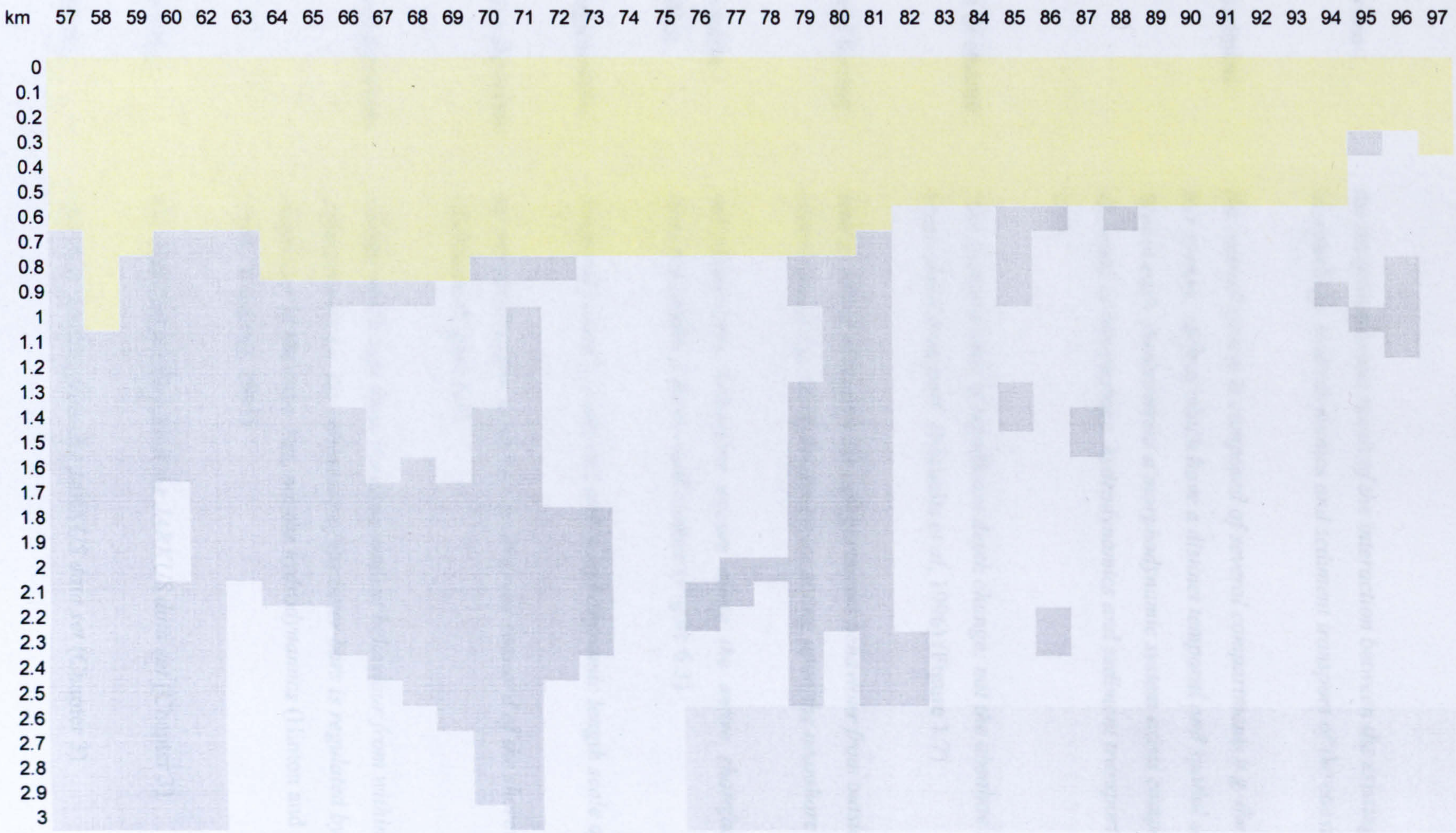
Appendix 6.2. cont. Shoreface activity after 20 years in Zuid-Holland. The method used is the fixed tail sddc (0.25 m criterion). (Periods 25 years and 32 years do not exist for km 72 - 97).



Appendix 6.2. cont. Shoreface activity after 25 years in Zuid-Holland. The method used is the fixed tail sddc (0.25 m criterion). (Periods 25 years and 32 years do not exist for km 72 - 97).



Appendix 6.2. cont. Shoreface activity after 28 years in Zuid-Holland. The method used is the fixed tail sddc (0.25 m criterion). (Periods 25 years and 32 years do not exist for km 72 - 97).



Appendix 6.2. cont. Shoreface activity after 32 years in Zuid-Holland. The method used is the fixed tail sddc (0.25 m criterion). (Periods 25 years and 32 years do not exist for km 72 - 97).

GLOSSARY

Behaviour :	*the morphodynamic result of the interaction between the existing morphology, hydrodynamics and sediment transport of the coastal system*
Compartment :	*the coastal system is composed of several compartments e.g. the nearshore bar system, each of which have a distinct temporal and spatial scale. Within each compartment a morphodynamic system exists composed of the elements of morphology, hydrodynamics and sediment transport* (Figure 1.6).
Depth of closure :	'*the seaward limit of significant depth change; not the absolute limit to cross-shore transport*' (Nicholls *et al*, 1996) (Figure 1.7)
External forcing :	*energy which acts upon the compartments behaviour from outside the compartment e.g. the hydrodynamics acting upon the nearshore bar system*
Fully-active shoreface :	*morphodynamic behaviour occurs along the entire shoreface i.e. the profile does not exhibit a shoreward closure* (Figure 6.3)
Geological-scale :	*temporal period of centuries and morphodynamic length scale of 100 km*
Inactive shoreface :	*no morphodynamic behaviour is observed seaward of the shoreward depth of closure* (Figure 6.3)
Internal dynamics :	*energy which acts upon the compartment behaviour from within the compartment i.e. the behaviour of the inner bars is regulated by the behaviour of the outer bar, not the hydrodynamics* (Hinton and Aarninkhof, 1998; Wijnberg, 1995)
$JARKUS_E$:	*the extended profiles from the JARKUS data set* (Chapter 3)
$JARKUS_S$:	*the short profiles from the JARKUS data set* (Chapter 3)

Large-scale :	*temporal period of decades and morphodynamic length scale of 10 km* (Stive *et al*, 1990)
Medium-scale :	*temporal period of years and morphodynamic length scale of 1 km* (Stive *et al*, 1990)
Middle/lower shoreface closure :	*the limit to significant depth change observed towards the seaward limit of the profile* (Figure 6.2)
Morphodynamic :	*the form and structure of the coastal system*
Re-opening :	*the significant depth change observed on the middle and/or lower shoreface* (Figure 6.2)
Seaward partially-active shoreface :	*the shoreface exhibits re-opening i.e. the profile must fist exhibit a shoreward depth of closure in order to re-open and may exhibit a middle/lower shoreface closure* (Figure 6.3)
Shoreface :	'*the fixed offshore zone bound on the landward side by the seaward slope of the outer breaker bars and bound on the seaward side by the transition from a concave profile to nearly horizontal bottom*' (Houwman and Hoekstra, 1994) (Figure 1.1)
Shoreward depth of closure :	*the limit of significant depth change located on the upper shoreface. Over scales equal to, and greater than, the medium-scale significant depth changes may also be observed on the middle/lower shoreface* (Figure 6.2)
Shoreward partially-active shoreface :	*the shoreface is active until the middle/lower shoreface* (Figure 6.3)
Short-scale :	*temporal period of storms/seasons and morphodynamic length scale of 100 m* (Stive *et al*, 1990)

PUBLISHED PAPERS

On the predictability of nearshore bar behaviour

Stefan Aarninkhof[1], Claire Hinton[2] and Kathelijne Wijnberg[3]

Abstract

The analysis of field observations of surf zone dynamics has revealed some 'unexpected' behaviour of the coastal system, generally referred to as 'free behaviour', which is behaviour that is unrelated to similar patterns in the external forcing. Present-day process-based modeling concepts are not capable to deal with these free modes of behaviour. In order to assess the validity of model-based predictions of bar dynamics, the relative importance of free behaviour versus forced response in the surf zone needs to be addressed. This work aims to contribute to the debate, by investigating the sensitivity of breaker bar behaviour to chronology effects from coastal profile modeling at a multiple-barred beach, with probabilistic forcing conditions. The results show chronology effects merely affect the predicted height of the bars, rather than their location which is remarkably consistent over the various runs. The latter observation has raised the question up to what extent predicted bar behaviour is controlled by model characteristics (concept, parameter settings), rather than system and forcing characteristics.

Introduction

Over the years, nearshore sand bar behaviour was believed to show a rather consistent pattern of delayed response to the wave energy input, featuring a rapid straightening of the outer bar during storms, and a gradual development of a crescentic bar pattern via some intermediate stages during subsequent periods of low-energy exposure (e.g. Wright and Short, 1984; Lippmann and Holman, 1990). However, another field observation of bar behaviour has been presented by Southgate and Möller (1998). They applied a fractal

[1] Netherlands Centre for Coastal Research, Delft University of Technology, c/o WLIDELFT HYDRAULICS, p.o. box 177, 2600 MH Delft, The Netherlands
[2] Flood Hazard Research Centre, Middlesex University, Queensway, Enfield, London, EN3 4SF, UK
[3] Netherlands Centre for Coastal Research, Institute for Marine and Atmospheric Research, Utrecht University, p.o. box 80115, 3508 TC Utrecht, The Netherlands

analysis technique to the Duck, NC, data base (10.5 years of monthly cross-shore surveys) to indicate the existence of self-organized (or free) behaviour in a coastal system. They arrive at the conclusion that the profile behaviour has a fractal structure and is uncorrelated to the input variations, but only within a certain time window. The width of this time window varies with the cross-shore location, featuring a maximum of 30-40 months well inside the surf zone. Within these time windows, the process of self-organization seems to be dominant, while outside, the profile behaviour is well-correlated to the forcing factors.

Considering the vast amount of plans for human interference in coastal systems (like large-scale land reclamations, artificial islands in sea and beach nourishments), the need for model-based predictions of coastal behaviour on the time scale of years to decades is evident. It would be interesting to see how the present generation of process-based profile models predict bar behaviour on these time scales, and up to what extend they are be able to deal with the types of 'unexpected' behaviour as given above. In the end a model-based investigation of bar dynamics might contribute to our understanding of the balance of free versus forced behaviour in coastal systems. This study is a first start to addressing these questions.

Concepts in relation to morphodynamics of breaker bar systems

Bed dynamics in the coastal zone occur at various time scales. At the smallest scale bedforms like ripples and mega ripples evolve (minutes to hours). Moving up, the evolution of features like nearshore bars becomes apparent (days to years). Channels on ebb deltas may evolve over decadal time scales, while at a time scale of centuries, we may for instance observe the steepening of the shore face, or changes in the global shoreline orientation. In this paper, the ripple scale is referred to as 'micro-scale', the nearshore bar scale (and tidal channel scale) as 'meso-scale', and the larger scales as 'macro-scale'.

Physical processes at a certain scale level will be in dynamic interaction with coastal behaviour of a similar scale. This is what is called the primary-scale relationship (De Vriend, 1991), see Figure 1.

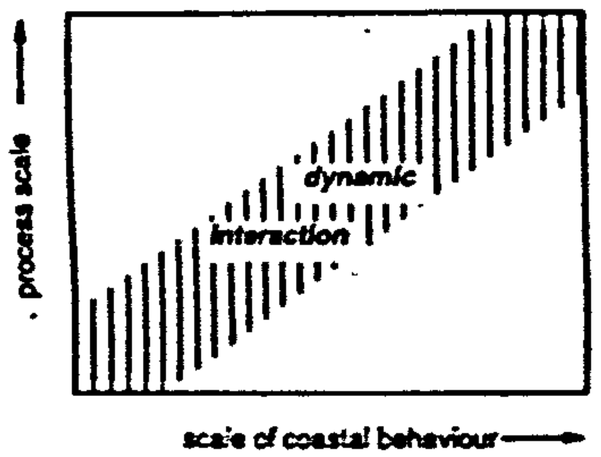


Fig. 1: Primary-scale relationship (after De Vriend, 1991)

A physical process at a certain scale acts as an extrinsic condition (or constraint) for dynamics at a lower scale level, whilst it is just noise for dynamics at a higher level. Within one scale level, a feedback between response and forcing is observed. For example, for the nearshore bars, wave energy input generates a flow field (FF) in the nearshore zone, causing sediment transport (ST) gradients across the bars and hence morphologic changes (MC), which again affect the nearshore flow field, see Figure 2. Furthermore, a coastal system is stochastically forced, dissipative and features various components which are highly non-linear (like transport rates). It is because of these characteristics that a coastal system might easily allow for unpredictable behaviour in a deterministic sense (De Vriend, 1998), i.e. the system develops very complex patterns that could be modeled in detail, however, without being able to predict when and where they occur (cf. turbulence).

These considerations allow us to schematize the coastal system of consideration, viz. that of nearshore bars. The morphodynamics at this scale level are supposed to be in dynamic interaction with the incoming wave energy and tide-induced variations in water level elevation. Larger scale phenomena like sea level rise and variations in the tidal current pattern act on the system as a constraint via the macro level, as they are affected by features at this higher level. Also, physical constraints like jetties are considered as a macro-level induced constraints, while a weak constraint might result from the lower level by means of bed-form induced friction. Besides forced response, possibly represented by the consistent tendency of bars to straighten during storm conditions, free behaviour needs to be taken into account. This results in the schematization as given in Figure 2. Though the meso-level breaker bar system also affects the lower and higher scales, these relations have been ignored in Figure 2.

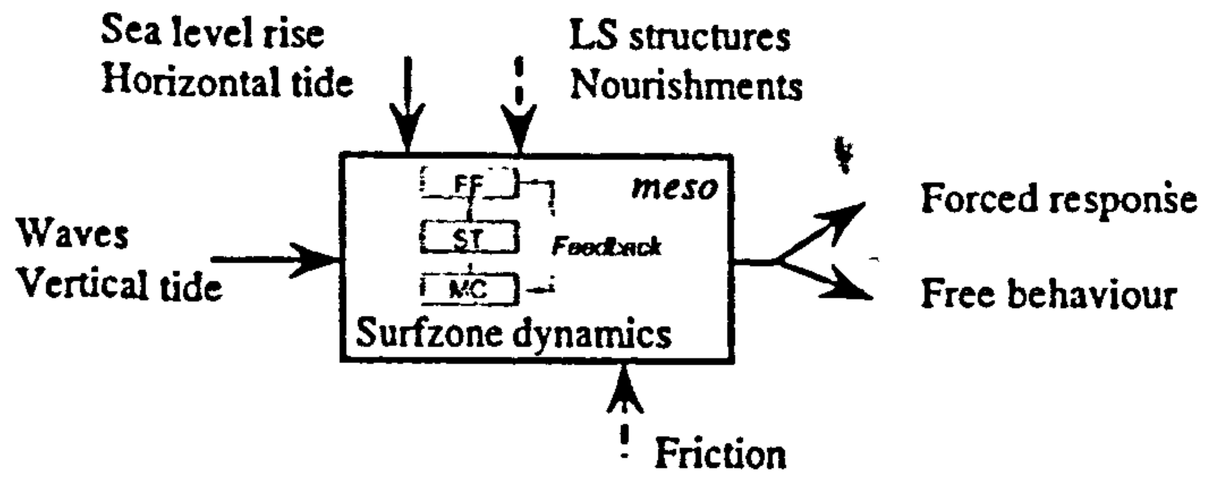


Fig. 2: Schematization of a meso-scale coastal system

In order to assess the predictive skills of profile models, the relative importance of forced response versus free behaviour needs to be determined, which requires the analysis of bar behaviour from both field observations and model simulations.

Positioning of present study

As stated, the predictability of breaker bar behaviour needs be assessed along two different ways:

1. By analyzing bar dynamics from field observations, in relation to the forcing conditions. This requires long time series of bar morphology, with high resolution in time. ARGUS-stations, which collect hourly video observations of the nearshore zone (Holman *et al*, 1993), provide such type of data. Different techniques to quantify bathymetry from video observations are presently under development, based on the inverse modeling of wave dissipation patterns (Aarninkhof *et al*, 1997) or wave celerities (Stockdon, 1997).
2. By investigating breaker bar behaviour from simulations with a process-based coastal profile model, both in terms of the sensitivity to various model parameters, as well as regarding the effect of different forcing sequences with similar statistics.

On the longer term, we aim at a comparison of both approaches, however, the present paper only discusses an initial step into the second approach. It concerns a model-based investigation of bar dynamics at Noordwijk, The Netherlands. Multiple model runs have been made, using different time series of hydrodynamic conditions with nevertheless similar statistical characteristics. If a considerable variability in final profile evolution over the various runs is observed (indicating the importance of chronology effects), the system's response is interpreted to be forced. Alternately, the dynamical quantities of the system might show fractal statistics (in space or time), indicating self-organized response or free behaviour.

The present work treats the sensitivity of model-predicted bar behaviour to chronology effects. To that end a model regarding a multiple-barred coastal system has been set up and calibrated, which will be the subject of the next sections.

1DV-model simulations of bar dynamics at Noordwijk, The Netherlands

Description of model concept

To do the model simulations, WL|DELFT HYDRAULICS' 1DV coastal profile model UNIBEST-TC has been applied. The UNIBEST-TC model consists of a wave, flow, transport and bed level change module, for which the initial formulations are given in Roelvink and Stive (1989). Although they arrive at a satisfactory calibration of the hydrodynamics in terms of wave height, wave set-up and flow moments, the Bailard transport formulation did not result in a correct description of transport rates, despite an extension of the original Bailard formulation to account for additional stirring of sediment by surface breaking-induced turbulence which penetrates toward the bottom. Consequently, the development and migration of the outer bar were (amongst others) simulated insufficiently.

Later on, the formulation for the breaking-induced turbulence was replaced by the roller concept after Svendsen (1984), and, for heuristic reasons, a breaker delay function was introduced (Roelvink *et al*, (1995)). Moreover, the transport formulations were modified according to Ribberink and Van Rijn (see Van Rijn *et al*, 1995) without however, significantly changing the basic concept of the quasi-steady transport model. These new formulations allowed for the modification of transport rates by means of breaker delay and slope effects (Bosboom *et al*, 1997), that finally resulted in the mimicking of cyclic bar behaviour. However, a robust validation of these formulations has not been performed yet.

Model set-up

The numerical model has been set up for a characteristic profile along the Central Dutch coast. Bed elevations along this coast have been surveyed yearly since 1963, which makes its long-term behaviour relatively well understood. A profile at Noordwijk was chosen because this site is also monitored with ARGUS cameras, which gives a reference to short- and medium-term behaviour. The actual profile applied was surveyed in 1980 and extends to 2500 m off-shore; it features 3 bars, which exhibit cyclic behaviour over about a 4 year time span (Wijnberg, 1995).

Time series for the off-shore hydrodynamic conditions have been generated from a wave-climate, measured 6 km off-shore of Noordwijk in 18 m water depth, at 3-hour intervals during a 12-year period of time. The statistics of the wave heights and angles of incidence that occur in the time series obey the frequencies of occurrence as prescribed by the measured wave climate. The adjoining wave period and mean water level elevation have been chosen accordingly, depending on the randomly selected wave height and angle of incidence. At presence, tidal variations are not accounted for, which allows for a simplification of the problem by means of a reduction of the number of independent variables.

The computational grid extends from 2500 m off-shore (14.9 m water depth) to the dune foot; wave conditions measured at 6 km off-shore are translated to the seaward boundary of the model, taking into account the effects of shoaling and refraction. The horizontal grid spacing decreases towards the shore so that a higher resolution is obtained in the active zone, yielding a total of 147 grid points. The time step characteristically amounts 0.25 days for short term runs (180 days).

Sensitivity of bar behaviour to model parameters

Three model parameters are of particular importance in view of bar behaviour, viz. the breaker parameter γ, the breaker delay parameter λ and the subaquous angle of natural repose $\tan(\varphi)$. γ merely affects the migration of bars, while λ and $\tan(\varphi)$ are important with respect to the growth, maintenance, and damping of bars. Their role in the model formulations, as well as their effect on final profile evolution is shortly discussed here.

The wave breaking parameter γ stems from the Battjes-Janssen wave propagation model and affects the maximum local wave height H_{max}, which is determined as a function of local water depth h and wave steepness, according to

$$H_{max} = \frac{0.88}{k}\tanh\left(\frac{\gamma kh}{0.88}\right) \qquad \text{(Eq. 1)}$$

where k is the wave number. Waves smaller than H_{max} are assumed to be non-breaking and Rayleigh distributed, while all waves higher than H_{max} are breaking. An increase of γ allows for higher wave heights at a certain depth, hence shifting the process of wave dissipation to more shallow water. Consequently, an increase of undertow-induced off-shore directed transport rates is induced, yielding a faster off-shore migration of the breaker bars. Figure 3 illustrates this, showing the final profile evolution after 50 days in case of a constant wave height H_{rms} = 1.5 m.

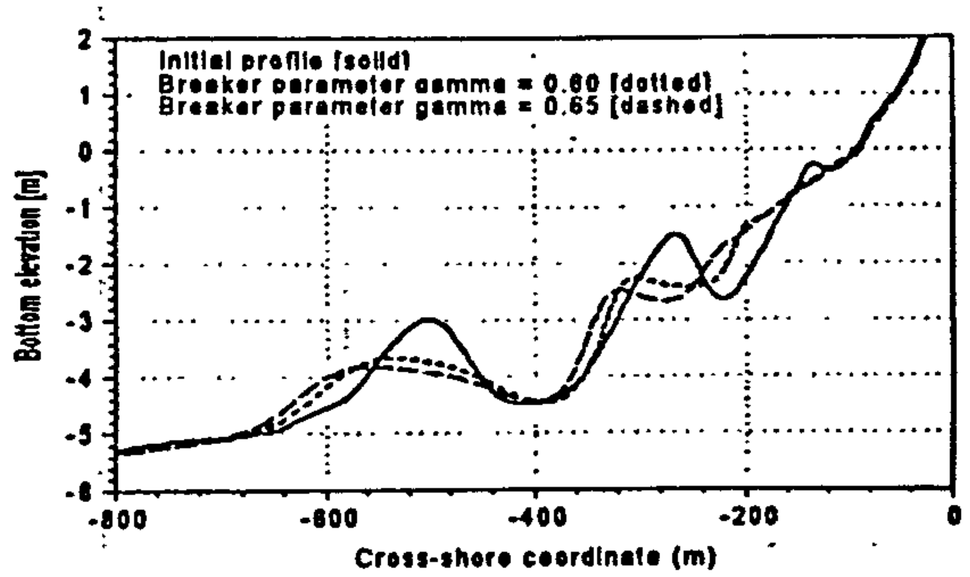


Fig. 3: Effect of breaker parameter γ on final profile evolution

The concept of breaker delay (Roelvink *et al*, 1995) was introduced based on field observations of breaking waves, which showed that waves – having inertia – need a distance of the order of one wave length to actually start or stop breaking. Roelvink *et al.* accounted for this by replacing the local water depth h in Eq. 1 with a seaward weighted reference depth h_r. Consequently, slightly higher waves are allowed at the seaward flank of breaker bars while the concept also allows for ongoing wave breaking in the trough – because of the seaward weighted water depth - hence shifting the undertow currents somewhat towards the trough. The latter allows for offshore-directed sediment transport towards the bar crest, which originally suffered from heavy erosion in the concept without breaker delay. In this way some sediment accumulates in the region close to the bar crest, yielding a better-preserved bar shape. Figure 4 shows the effect of breaker delay after 50 days of constant forcing conditions with H_{rms} = 1.5 m.

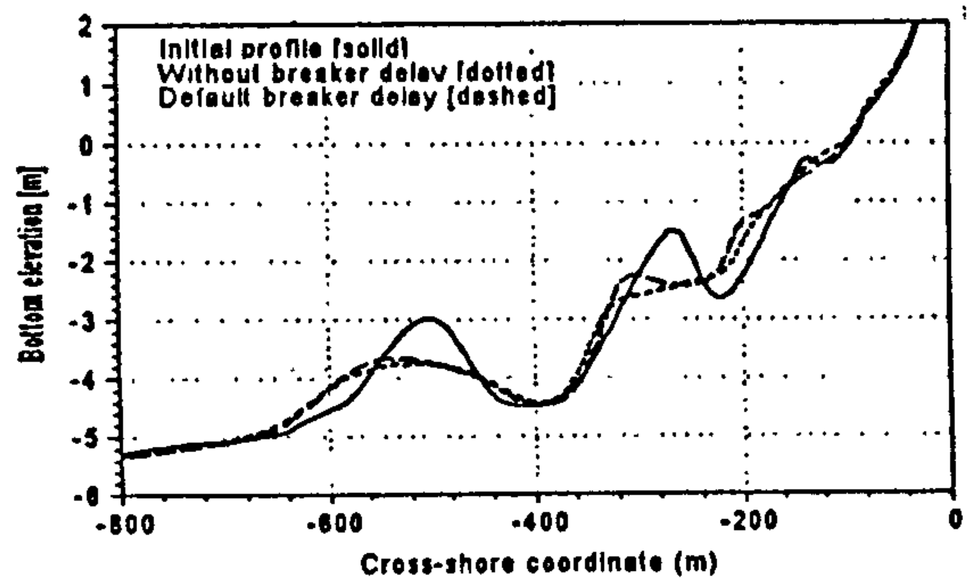


Fig. 4: Effect of breaker delay on final profile evolution

The subaquous angle of natural repose tan(φ) accounts for slope effects (Bosboom *et al.*, 1997) and affects the computed transport rates in two ways. First, the threshold criterion for the initiation of motion is adapted using the Schoklitsch factor. With increasing tan(φ), the non-dimensional critical shear stress θ_{cr} (according to Shields) decreases in case of upslope transport, and increases for downslope transport. In other words, upslope transport is stimulated with increasing tan(φ), downslope transport hindered. Second, bed load transport rates are affected by means of a Bagnold multiplication factor β_s, which increases with increasing tan(φ) in case of upslope transport, and decreases in conditions of downslope transport. Again, upslope transport rates are facilitated by increasing values of tan(φ), downslope rates hampered. Both modifications to the computed transport rates result in the same effect: a higher value of tan(φ) stimulates accumulation of sediment around the bar crest, hence bar development, a lower value causes the damping of bars.

Figure 5 shows the effect of different subaquous angles of natural repose on the final profile evolution after 50 days in case of a constant wave height H_{rms} = 1.5 m. The values of tan(φ) are constant along the beach profile, though generally, they are set to decrease somewhat in off-shore direction, to facilitate the damping of bars at deeper water.

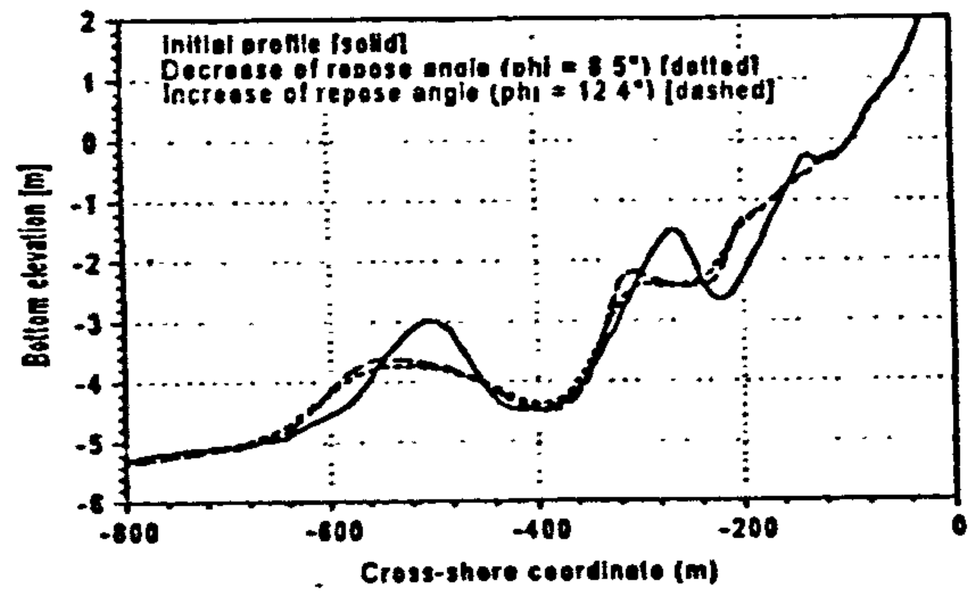


Fig. 5: The effect of tan(φ) on final profile evolution

Selection of appropriate model settings

As a robust validation of the modified transport module has not been performed yet, the present model can be considered as a (for heuristic reasons) modified version of the original model according to Roelvink and Stive (1989). The heuristic element lies in the transport formulation, and is dealt with by adopting appropriate settings of the wave breaking parameters and the slope effect. Though this might enable a satisfactory representation of cyclic bar behaviour, it does not guarantee that the morphodynamic concept of the model is fully correct.

Lacking local field data on surf zone hydrodynamics, the model has been tuned by carefully choosing the parameters of relevance as mentioned above, such that it represents medium-term bar behaviour reasonably well. Whenever possible, default settings have been applied. In order to obtain sufficient damping of bars at deeper water, the value of φ needed to be lowered to 9.1° at deeper water as compared to 12.4° at the waterline. The resulting bar behaviour is shown in Figure 6.

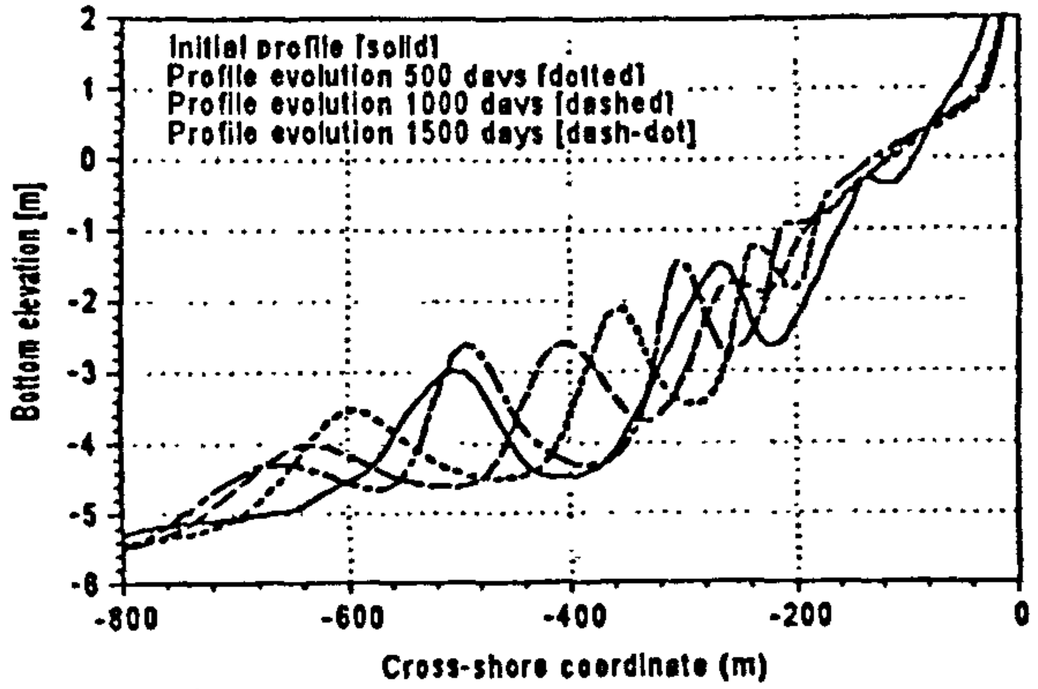


Fig. 6: Bar behaviour in calibrated model

Clearly, the erosion and formation of the steep berm around the waterline are not realistic. This might be attributed to the absence of tidal variations, cf. Southgate (1995). However, in view of bar behaviour, the 4-year bar cycle is clearly recognized while a new bar is being generated in the upper part of the profile.

Overview of model runs

In order to test model-predicted bar behaviour on its sensitivity to chronology effects, multiple model runs have been made with statistically similar input conditions. The sequence of wave events was randomly generated as described above. The statistics of each time series were determined by means of its mean wave height, the standard deviation around the mean and the lowest respectively highest wave of the series.

Statistics of various series show good comparison, as can be seen from 5 representative cases in the table below.

	Statistics of wave height H_{rms}			
Series	Mean	SD	Min	Max
# 01	0.91	0.57	0.23	4.04
# 02	0.89	0.57	0.23	3.51
# 03	0.88	0.54	0.23	4.04
# 04	0.88	0.53	0.23	3.56
# 05	0.89	0.54	0.23	4.04

Table 1: *Wave height statistics of generated time series*

25 Randomly generated time series at 3 hour intervals have been generated for use in the short-term computations, yielding 25 different profile evolutions after 180 days. Each of the 25 time series were then sorted based on wave height, both ascending and descending. This again yielded 25 different realizations of bathymetry after 180 days for both sortings.

Results of short-term (180 days) tests on chronology

In case of the random wave input, general bar behaviour seems to be consistent throughout the 25 cases. All of the three bars migrate seaward, over rather similar distances of about 75 m. Figure 7 shows the mean profile evolution after 180 days, averaged over 25 runs (lower panel), as well as the cross-shore variability in final profile evolution by means of the standard deviation of final bottom elevation over 25 runs and its extreme realizations (upper panel). Maximum variability occurs around the initial location of the bars and their final positions, indicating that the system has not run through a full cycle yet. Moreover, it points out that the horizontal variability (i.e. the variability in the final location of the bars) is rather weak, whereas the vertical variability is more significant: the standard deviation amounts up to 10-15% of the absolute changes of bottom elevation, which is in good correspondence with values found by Southgate (1995). Vertical variability slightly decreases towards the shore.

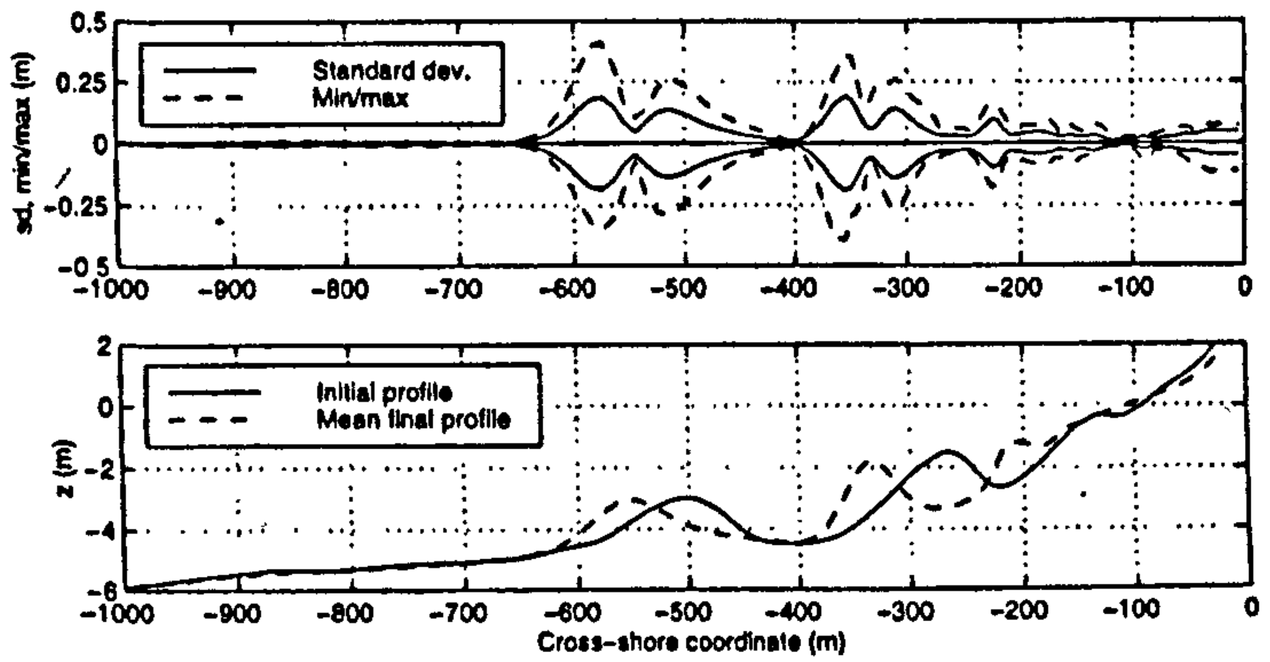


Fig. 7: Variability in final profile evolution (180 days) over 25 runs, random waves

The results of the runs with sorted input conditions are given in Figure 8. Analogous to the upper panel of Figure 7, the upper and middle panel of Figure 8 show the cross-shore variability in final profile evolution expressed in terms of the standard deviation and extreme realization over 25 runs, for the cases of ascending and descending wave heights respectively. The lower panel visualizes the mean profile evolution for both cases, averaged over 25 runs.

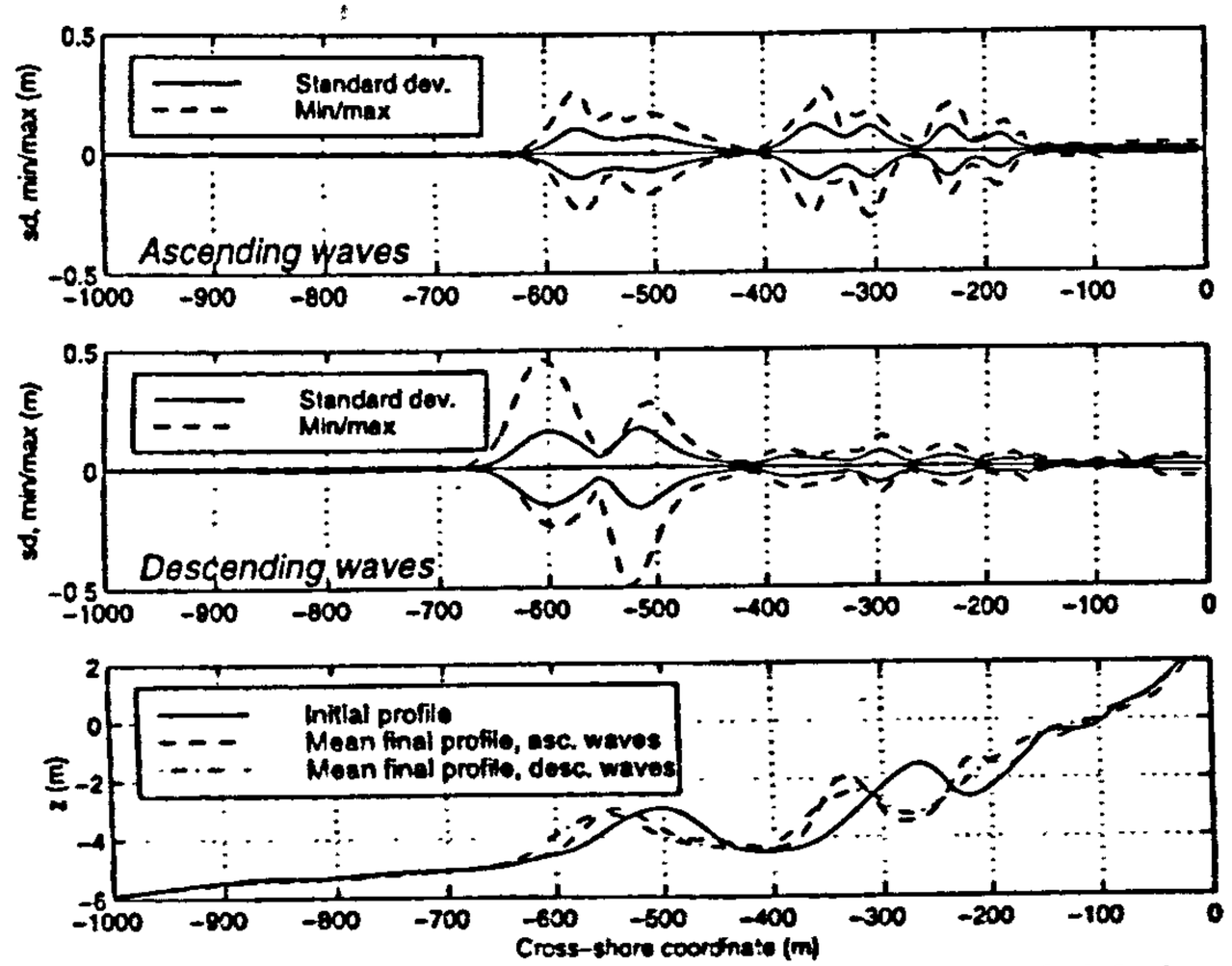


Fig. 8: Variability in final profile evolution in case of sorted wave height input

Again, the observed mean bar behaviour is remarkably consistent: after 180 days, all bars have migrated off-shore over a distance of about 75 m, though the bar-shape tends to be

better preserved in the case of ascending wave heights. The variability in final profile evolution clearly differs amongst the 2 cases: the system exposed by ascending wave heights shows moderate variability over 25 runs, which is rather constant along the profile, featuring relatively minor extremes around the initial and final locations of the bars. The case of descending wave heights, on the other hand, shows large variability around the outer bar which drops to almost zero through the central and inner surf zone, indicating very consistent behaviour of the middle and inner bar over the 25 runs.

Discussion

The results described above generally show a decrease of vertical variability in bottom elevation towards the shore, indicating a weaker response of inner surf zone morphodynamics to chronology-related variations in the input conditions. This can be explained from the presence of the outer bar, which filters the wave climate for the central and inner region of the surf zone with respect to high waves, hence reducing the temporal variations in the central and inner surf zone wave conditions. Apparently, the behaviour of the inner bars is not only controlled by the forcing conditions, but also by internal parameters like the height of the outer bar, which might more easily allow for free behaviour in this region. This observation is in accordance with Southgate (1998) who states that 'generally, fractal responses are found at locations ... where the temporal variations of wave forcing conditions are relatively weak'.

The important role of the outer bar in view of central and inner surf zone morphodynamics is also observed from the runs with sorted wave height input. Significant changes of the outer bar are assumed to be induced by the highest waves of the input time series, therefore the outer bar, in case of descending wave heights, is affected at the very beginning of the simulated time period, whilst in the case of ascending waves, this occurs only at the end of the 180-days period. Consequently, the height of the inner bars after 180 days is more reduced in case of descending wave heights, as they are exposed to more energetic wave conditions during the simulation period. This again stresses the importance of internal system parameters like the height of the outer bar in view of the morphodynamics of the central and inner region of the surf zone.

Nevertheless, though it seems like the observed vertical variability in bottom elevation along the cross-shore profile can be explained reasonably well, the absence of variability in the final position of the bars has not been explained yet. Particularly, the close correspondence between the position of the outer bar resulting from runs with ascending and descending waves respectively - suggesting that bar migration depends on the cumulative amount of energy input rather than the sequence of events – would indicate that chronology is of hardly any importance to the morphodynamics of the outer bar at Noordwijk. This seems counter-intuitive since bars are expected to migrate onshore during periods of low-energetic conditions, and off-shore during storms. Hence the question is raised up to what extend predicted bar behaviour is controlled by model characteristics (concept, parameter settings), rather than system and forcing characteristics.

Apparently, this might be not the only source of unpredictability that arises when addressing the possibility of model-based predictability of long-term bar behaviour. Generally, we can identify 4 possible sources of unpredictability:

1. The limited time horizon of predictability of wave conditions.
2. The numerical discretization of model equations.
3. The model concept, i.e. the dimension of the concept (1DV in the present case) and the schematization of real-world physics in terms of model equations.
4. The complexity or 'irregularity' of natural beach behaviour.

The first source is related to the limited horizon of predictability of weather conditions (characteristically up to 10 days), hence wave conditions, and forms a fundamental limitation to the deterministic predictability of bar behaviour, both from model runs and field observations. However, knowing statistics on the wave climate from long-term field measurements, the probabilistic approach based on randomly generated, realistic time series of wave events seems the best way to cope with this problem.

Also the second source is fundamentally related to the application of a process-based modeling approach. Even in case of a 'perfect' model concept, small errors, caused by the inevitable discretization of model equations, tend to accumulate to become significant in case longer-term computations, justifying the question which part of the model prediction is realistic behaviour and which part can be considered to be error-induced noise. The unrealistic damping of bars after 1 cycle can be attributed to this accumulation of errors, either concept- or discretization-related. Given a certain model-concept, the application of sufficiently small computational steps and the careful selection of parameter settings are ways to reduce this source of unpredictability as much as possible.

The third source of unpredictability seems to play an important role in the present study. Although the model predicts the 4-year bar cycle reasonably well, some essential characteristics of bar behaviour as observed in the field are clearly missing in the present model. The absence of onshore migration (and adjoining growth) of bars during periods of low-energetic conditions and the weak sensitivity of the behaviour of the outer bar to chronology effects can be mentioned in this respect. Further investigation of the present model concept and parameter settings in terms of bar behaviour is necessary to improve acceptability of a model-based approach to assess the predictability of bar behaviour. Questions to be addressed in this respect are: What are the governing processes causing the consistent off-shore movement of sand bars? What is the effect of the initial profile? Would long-period swell affect the predicted bar behaviour? Would the same behaviour be observed at different sites?

Regarding the fourth aspect, it might be questioned whether process-based numerical models will ever be capable to predict natural 'irregular' behaviour, commonly referred to as free behaviour of coastal systems. Nevertheless, a fundamental understanding of the relative importance of forced response versus free behaviour will help to assess the validity of model-based predictions of coastal morphodynamics. Both the analysis of

ARGUS video-based observations of bar behaviour and the investigation of model-based predictions are expected to attribute to the assessment of this balance.

Conclusion

The present study has attempted to contribute to our understanding of sand bar dynamics by means of coastal profile modeling of a multiple-barred beach with probabilistic forcing conditions. In the case of 180-days simulations, chronology effects turn out to play a role throughout the surf zone, the importance of which increases with distance off-shore. Chronology effects merely affect the predicted height of the bars, rather than their final location which is remarkably consistent over the various runs. Moreover, the onshore migration of bars during periods of low-energetic wave conditions was not clearly observed. These observations raise the question up to what extent predicted bar behaviour is controlled by model characteristics (concept, parameter settings), rather than system and forcing characteristics. Further investigation of the model concept and a sensitivity analysis, more extensively than the one presented in this paper, are needed to address this problem.

Acknowledgements

The present study has been performed in the PACE project, in the framework of the EU-sponsored Marine Science and Technology Programme (MAST-III), under contractno. MAS3-CT95-0002. It was cosponsored by the NICOP fund, DELFT HYDRAULICS and Utrecht University. The ARGUS video technique has been developed with funds generated by the Coastal Imaging Lab, Oregon State University.

References

Aarninkhof, S.G.J, Janssen, P.C. and Plant, N.G. (1997). Quantitative estimations of bar dynamics from video images. *Proc. of Coastal Dyn. Conf.*, Plymouth, UK, 1997

Battjes, J.A. and Janssen, J.P.F.M. (1978). Energy loss and set-up due to breaking in random waves. *Proc. of 16th Conf. on Coastal Eng.*, ASCE, pp. 569-587

Bosboom, J., Aarninkhof, S.G.J., Reniers, A.J.H.M., Roelvink, J.A. and Walstra, D.J.R. (1997). Unibest-TC 2.0. Overview of model formulations. Delft Hydraulics report H2305.42

Holman, R.A., Sallenger Jr, A.H., Lippmann, T.C. and Haines, J.W. (1993). The application of video image processing to the study of nearshore processes. *Oceanography*, Vol. 6, No 3.

Lippmann, T.C. and Holman, R.A. (1990). The spatial and temporal variability of sand bar morphology. *J. Geoph. Res.*, 95(C7): 11575-11590.

Lippmann, T.C, Holman, R.A. and Hathaway, K.K. (1993). Episodic, nonstationary behavior of a double bar system at Duck, North Carolina, USA, 1986-1991. J.Coastal Res., 15(SI): 49-75.

Rijn, L.C. van, Reniers, A.J.H.M., Zitman, T. and Ribberink, J.S. (1995). Yearly-averaged sand transport at the -20 m and -8 m NAP depth contours of the Jarkus-profiles 14,40,76 and 103. Delft Hydraulics report H1887.

Roelvink, J.A., Meijer, Th.J.G.P., Houwman, K., Bakker, R. and Spanhoff, R. (1995). Field validation and application of a coastal profile model. *Proc. Conf. Coastal Dynamics*, ASCE, pp. 818-828.

Roelvink J.A., and Stive, M.J.F. (1989). Bar generating cross-shore flow mechanisms on a beach. *J. of Geophysical Research*, 94: 4785-4800.

Southgate, H.N. (1995). The effects of wave chronology on medium and long term coastal morphology. Coastal Engineering 26:251-270

Southgate, H.N. and Möller, I. (1998). Fractal properties of beach profile evolution at Duck, North Carolina. Submitted to *JGR Oceans*.

Stockdon, H. (1997). Estimations of wave phase speed and nearshore bathymetry using video techniques. M.Sc. Thesis, Oregon State University, College of Oceanic Atmospheric Sciences, Augst 1997.

Svendsen, I.A. (1984). Wave heights and set-up in a surf zone. *Coastal Eng.*, 8:303-329

Vriend, H.J. de (1991). Mathematical modelling and large-scale coastal behaviour, Part 1: Physical processes. *Journal of Hydraulic Research* 29, pp. 727-740.

Vriend, H.J. de (1998). On the predictability of coastal morphology. In: Proc. 3rd Marine Science and Technology Conf., Lisbon, 1998.

Wijnberg, K.M.(1995). Morphologic behaviour of a barred coast over a period of decades. Ph.D. Thesis, Utrecht University, Utrecht, The Netherlands, Netherlands Geographical Studies 195, KNAG, 245 pp.

Wright, L.D. and Short, A.D. (1984). Morphodynamic variability of surf zones and beaches: a synthesis. *Marine Geology* 56, 93-118.

Spatial and Temporal Behaviour of Depth of Closure along the Holland Coast

Claire Hinton* and Robert J. Nicholls*

Abstract

Depth of closure has been identified and its characteristics investigated over larger temporal (≥ 25 years) and spatial (< 100 kilometres) scales than previous research. In addition to the 'normal' shoreward closure produced by breaking waves and cross-shore bar migration, at longer timescales (≥10 years) shoreface morphodynamics also produce significant profile changes. The shoreward closure is primarily controlled by wave breaking with a secondary control of bar morphodynamics. Shoreface changes are slow and steady and as timescale increases, so more profiles exhibit re-opening in depths typically greater than 10 metres. This is then usually followed by the re-closure of the profile on the middle/lower shoreface. Such phenomena have not been observed in past studies of this type and result from the large temporal and spatial extent of the data set used here. Over long time scales (≥ 10 years) such changes have a coastal engineering significance.

Introduction

The application and scope of coastal engineering schemes i.e. shore protection and land reclamation, is increasing. For example, the present Dutch coastal policy is to maintain its coastline at its 1991 position for the foreseeable future. In order to ensure the long-term reliability of such projects it is vital that coastal evolution over the same temporal scale is understood. So, with the advent of focused research within this field, many relevant concepts are being developed through both observation and predictive techniques.

A key concept in beach morphodynamics is depth of closure (Dc). Dc represents the 'seaward limit of '*significant*' depth change' (Nicholls *et al*, 1996); it does not, however, refer to an absolute depth beyond which there is no cross-shore sediment transport. Therefore, it is seen to act as a morphodynamic boundary separating a landward, morphodynamically active region from a more seaward inactive region, where vertical changes are less than the criterion chosen to define closure. (Figure 1.)

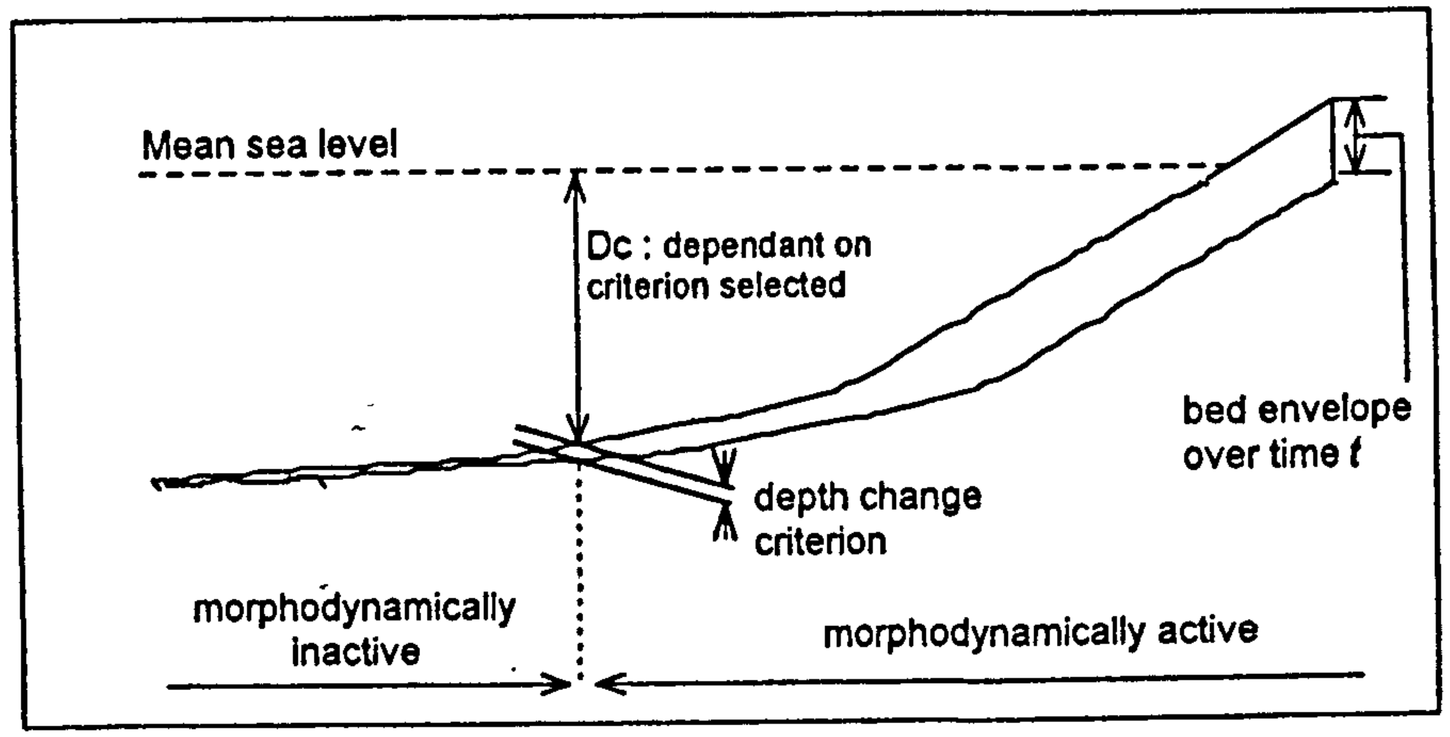


Figure 1. Zonation of a cross-shore profile over time t where Dc represents the seaward limit of significant depth change using the depth change criterion shown (adopted from Hallermeier, 1981).

Dc is of fundamental importance in coastal sediment budgets and associated applications such as beach and shoreface nourishment. Specific examples of its use are; i) as a boundary between active and inactive zones it allows for the correct placement of offshore mounds; location in the active region could provide material for onshore feed (Hands and Allison, 1991); and ii) as the limit of morphological change enabling the volume of beach fill material to be calculated (Davison *et al*, 1992).

In this paper the Large Scale Coastal Evolution concept of Stive *et al* (1990) is used to distinguish different scales of closure behaviour. The three scales are i) Large-Scale which has a morphodynamic length scale of 10 km and time scale of decades; ii) Medium-Scale with a morphodynamic length scale of 1 km and time scale of years; and iii) Small-Scale which has a morphodynamic length scale of 100 m and time scale of storms to seasons.

Closure has previously been investigated on the Medium-/Short-Scale (Garcia *et al*, 1997; Nicholls *et al*, 1996, 1998; Nicholls and Birkemeier, 1997). For example the Duck, North Carolina data has a 12 year time span and extends 1.2 km alongshore and 0.8 km cross-shore (Nicholls *et al*, 1996). These investigations have shown that Dc is time- and space-scale dependant (cf. Capiobianco *et al*, 1997). In particular, as the time interval increases then closure increases in depth.

The control of the extreme wave conditions upon closure is used in the analytical Hallermeier (1978) model to predict Dc. It has been adapted to a time-dependant form:

$$d_{l,t} = 2.28H_{e,t} - 68.5\left(\frac{H_{e,t}^{\ 2}}{gT_{e,t}^{\ 2}}\right) \qquad (1)$$

where: $d_{l,t}$ = closure (Dc) (referenced to MLW);
$H_{e,t}$ = significant wave height exceeded 12 hours per t years;
$T_{e,t}$ = associated wave period; and
g = acceleration due to gravity.

Field validation of Equation 1 has shown that it provides a *limit* to the observed closure on micro-tidal, wave-dominated, sandy coasts during i) storms; and ii) annual periods (Nicholls *et al*, 1996, 1998). This suggests that spatially similar regions of closure will exist; a less energetic hydrodynamic environment will result in shallower closure values than those in a more energetic environment (cf. Marsh *et al*, 1998).

Most closure studies are limited to the surf zone and upper shoreface due to survey constraints (a maximum depth of 8m is reached at Duck, North Carolina; Lee *et al*, 1998). The JARKUS data set used here offers the opportunity to extend analysis to the Large-Scale; 100 km alongshore, 25 years (1965 to 1990) and 16 m depth. In addition this will allow the existence of '*significant* depth changes' on the shoreface at depths exceeding previous observations of closure to be investigated (as previously recognised by Stive *et al*, 1990).

Study Area

The study area is the Holland coast bound from Den Helder in the north to Hoek van Holland in the south. (Figure 2.) It is a closed coast uninterrupted by tidal inlets or barrier islands, allowing the determination of Dc characteristics in a wave-dominated, alongshore uniform environment. Anthropogenic interventions are mainly smaller-scale beach nourishment schemes, although the Petten sea dike (km 20 - 26) and Ijmuiden harbour moles (km 55/56) are present in the north and centre of the coast, respectively.

The study area is a micro-tidal, wave-dominated sandy coast with multiple bars. The bars extend to a maximum depth of approximately 8 m. The mean tidal range is 1.4 m in the north increasing to 1.7 m in the south. Peak tidal velocities generally do not exceed 1 ms^{-1}. The annual mean wave height is 1.2 m (associated wave period 5 sec); whilst the extreme annual wave height is 5.3m (associated wave period 7.7 sec) (Roskam, 1988). The wave climate is relatively similar along the length of the coast, deviations in wave height from north to south are in the order of 0.2 m.

Cross-shore bathymetric measurements have been measured by the Rijkswaterstaat since 1963 at regular, fixed locations alongshore. The measurements are held within the JARKUS data set. They have a vertical accuracy of 0.25 m which is the standard

deviation of the measurements, as determined within this study. An independent study, using both stochastic and systematic error sources, has also determined the accuracy of the data to be 0.25 m (Nanninga, 1985). Annual (short) profiles extend 0.8 km seaward, equivalent to a depth of approximately 6 m, with alongshore spacing of 0.25 km. In addition there are five-yearly long profiles ('doorlodingen') which extend to a minimum 2.5 km seaward, equivalent to approximately 15 to 16 m depth, and have an alongshore spacing of 1km. (Figure 3.) It is due to the greater cross- shore extent of the doorlodingen that it is analysed in this study; primary analysis indicates that Dc is not observed in the annual data even over a 1 year period. In addition, the most northern and southern profiles are rejected due to the tidal influence of the Marsdiep and the Europort inlets, respectively. The total study area therefore covers an alongshore distance of 81 km (km 16 to 97; Figure 2).

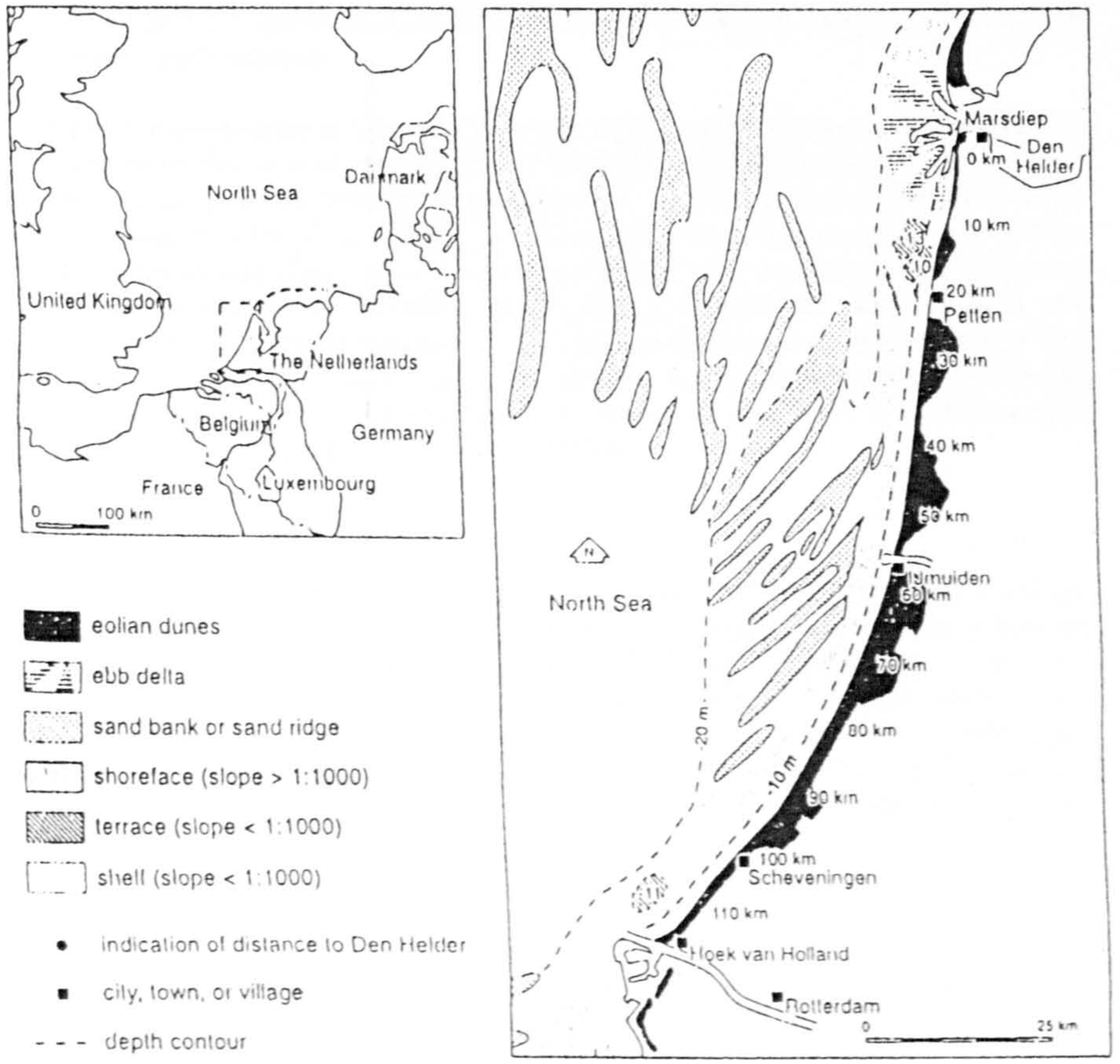


Figure 2 Location map showing the closed Holland coast. (Wijnberg, 1995)

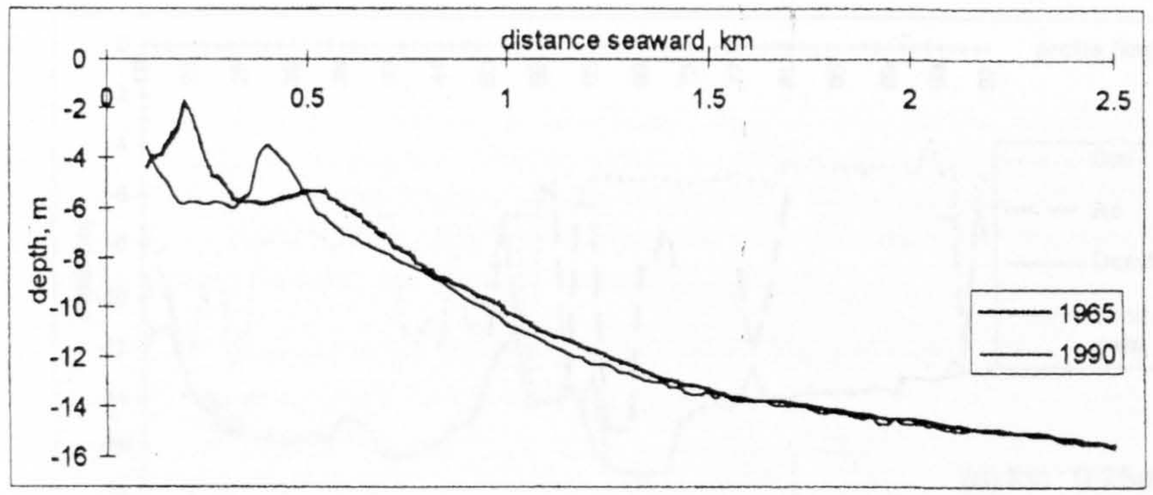


Figure 3. Example of the bathymetry along the closed coast using the doorlodingen from 1965 and 1990, located at km 31 (Noord-Holland).

Data Analysis

Values of Dc have been derived using two methods: i) the standard deviation of depth change (Kraus and Harikai, 1983) and ii) the fixed depth change (Nicholls *et al*, 1996). This analysis has been performed for all profiles over a range of temporal periods, 5, 10, 15, 20 and 25 years.

Standard deviation of depth change (sddc)

This is a simple method, effective in both dealing with large data sets and removing bias from outlying values. Variation in the standard deviation of elevation is shown as a function of the cross-shore distance for x number of profiles from the same alongshore location. Dc is then equated to that point at which the standard deviation reaches a constant, non-zero tail, which often has a value of about 0.25 m (the measurement accuracy). (Figure 4.)

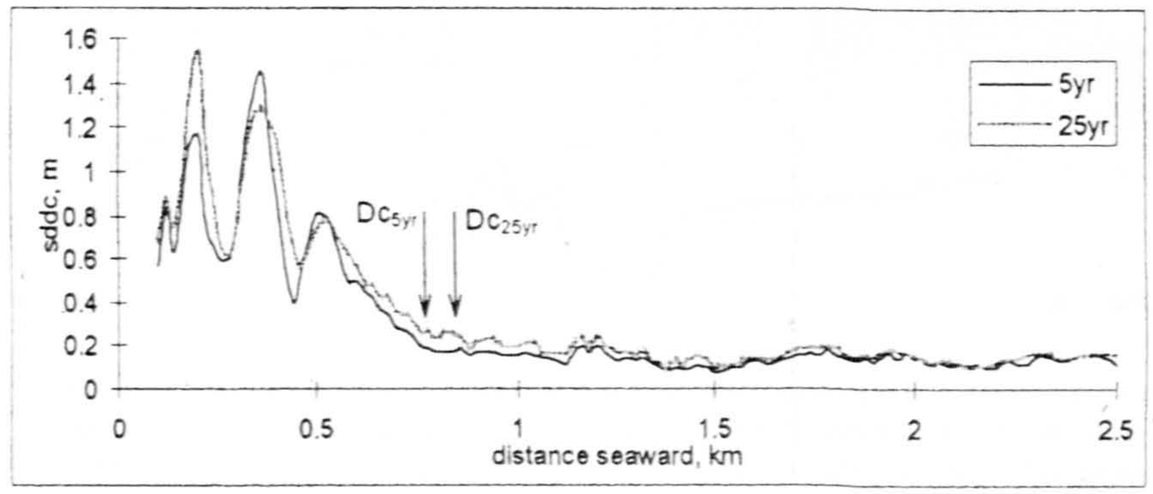


Figure 4. Sddc for km 31 which exhibits closure at a seaward distance of approximately 0.8 km for all time periods. ($Dc_{5yr} \approx 8$ m depth; $Dc_{20yr} \approx 9$ m depth)

Fixed depth change (fdc)

Dc can also be equated to that point at which, for 2 profiles from the same location, the depth variation is equal to, or less than, a pre-selected criteria. Here two criteria are selected: 0.25 m and 0.5 m. This means that there is 66% and 95% confidence that a real change in the bathymetry has occurred, respectively, assuming that the data measurement errors are normally distributed with a standard deviation of 0.25 m.

Results

General

Both methods produce similar results for all profiles along the Holland coast; the fdc criteria of 0.5 m generally gives the more landward value of closure as it allows the greatest depth variation.

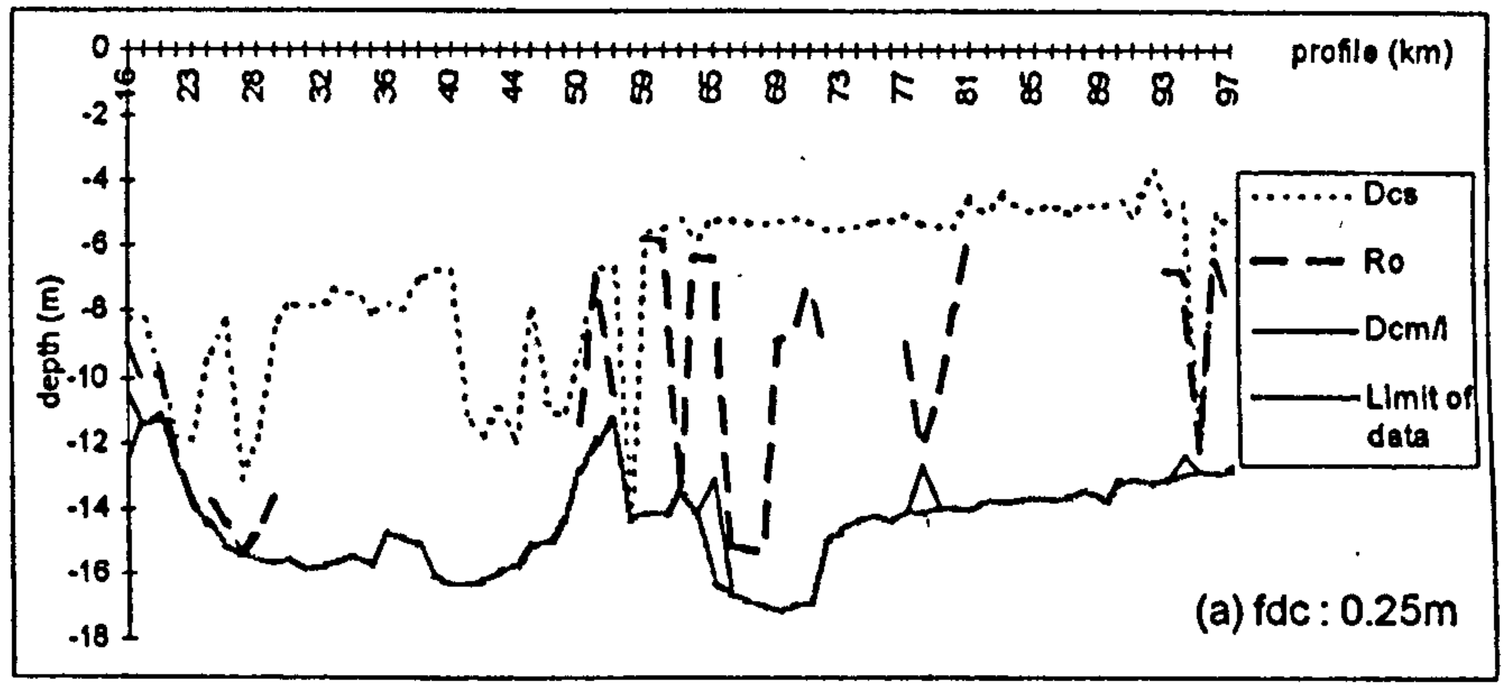
Upon the examination of all results it became apparent that, in some instances, not only does the profile close at some distance x from the shore, but the profile re-opens and then usually re-closes towards its seaward limit. Such behaviour can be most clearly seen using the sddc plots. (Figure 5.) These phenomena are hereafter termed i) the shoreward closure (Dc_s); ii) the re-opening point (Ro) and associated re-opening zone; and iii) the middle/lower shoreface closure ($Dc_{m/l}$), respectively. Re-opening is only observed over the longer time scales (>10 years) and at distances offshore greater than 1.5 km (typically 12 m water depth). In addition, as the temporal period is increased the number of cases in which this behaviour occurs increases (18% of profiles re-open after 10 years increasing to 37% over 20 years).

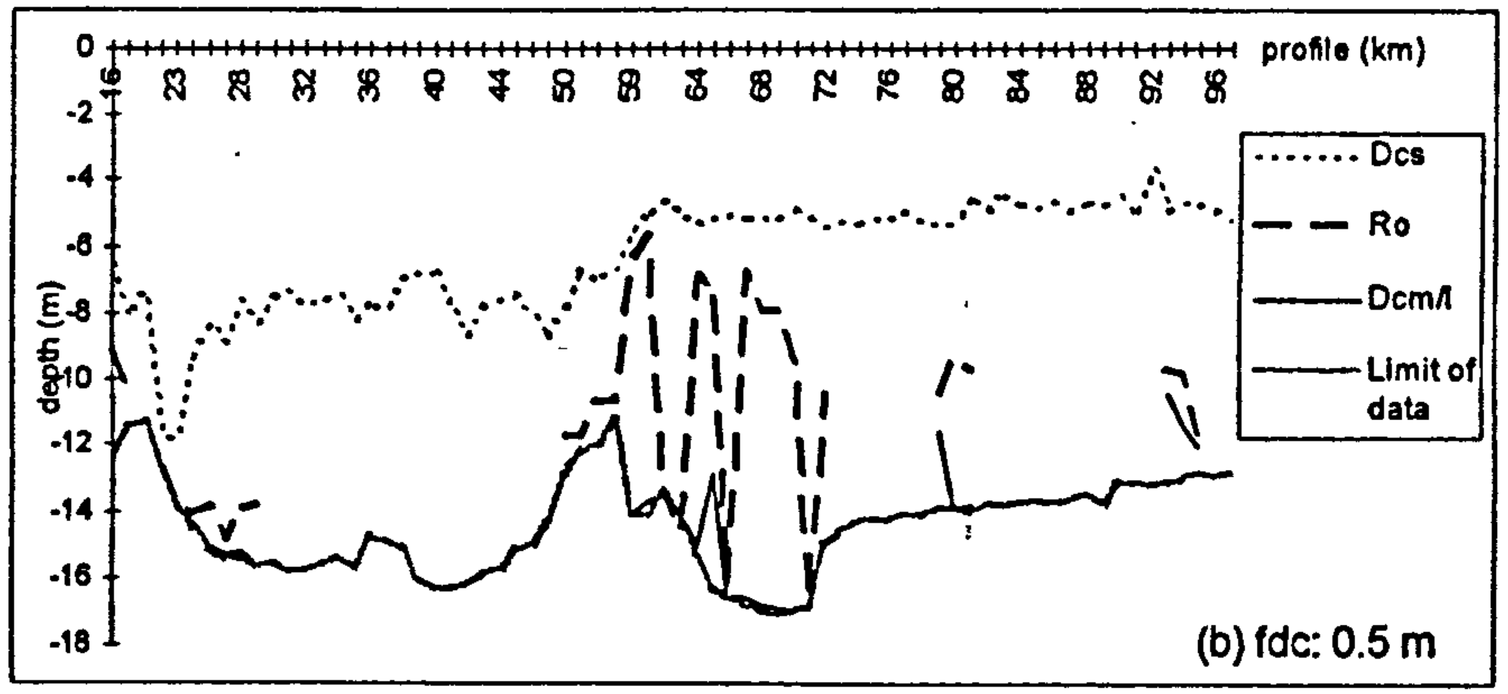
Large-Scale Behaviour

All three 'modes' of behaviour only exist in temporal periods greater than one decade; therefore the observed behaviour during the 20 year period will be concentrated on here. The results from both methods show similar spatial behaviour. (Figure 6.) However, the sddc method does give a greater proportion of profiles which do not close; as sddc depends on a self-selecting non-zero tail, it was hard to extract exact values of the re-opening zone and middle/lower shoreface closure using this method. A fixed non-zero tail could overcome this problem and may be used in subsequent analysis.

Shoreward closure

It is apparent in Figure 6 (a) and (b), that two distinct alongshore regions exist. The first is in the north (Noord-Holland), and can be sub-divided into two; km 16 to 24 and 25 to 54 where Dc_s is quite deep ($\bar{x}$ = 8.5 m) and irratic. In the south (Zuid-Holland), km 55 to 97, a different regime is observed; Dc_s is shallow ($\bar{x}$ = 5.0 m) and relatively





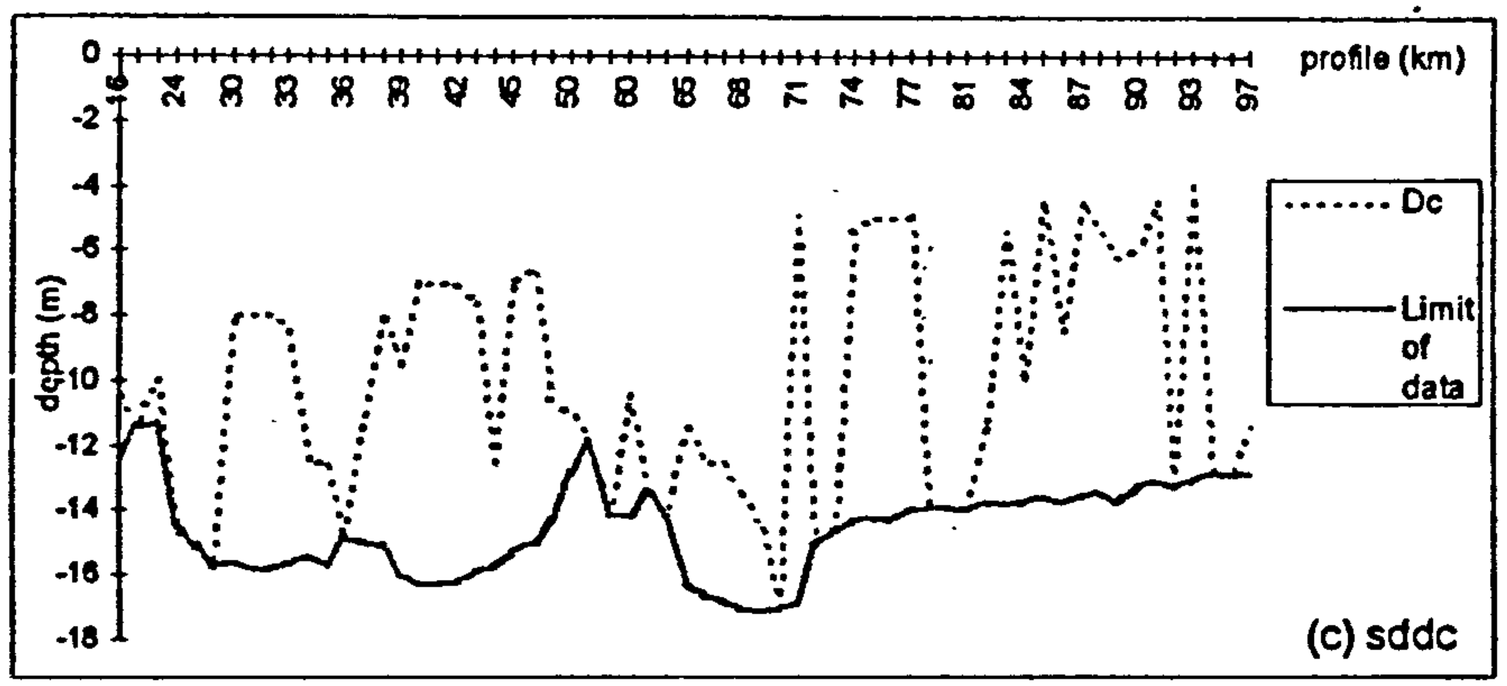


Figure 6. The spatial characteristics of the shoreward closure (Dc_s), re-opening point (Ro) and middle/lower shoreface closure ($Dc_{m/l}$) over 20 years using (a) fdc analysis (criteria 0.25 m); (b) fdc analysis (criteria 0.5 m), and (c) sddc analysis. The seaward limit of the data set is also shown.

constant in depth. (Table 1.) Interestingly, the regions observed here are bound by the two major anthropogenic influences on this coast; the Petten sea dike (km 20 - 26)and Ijmuiden harbour moles (km 55/56).

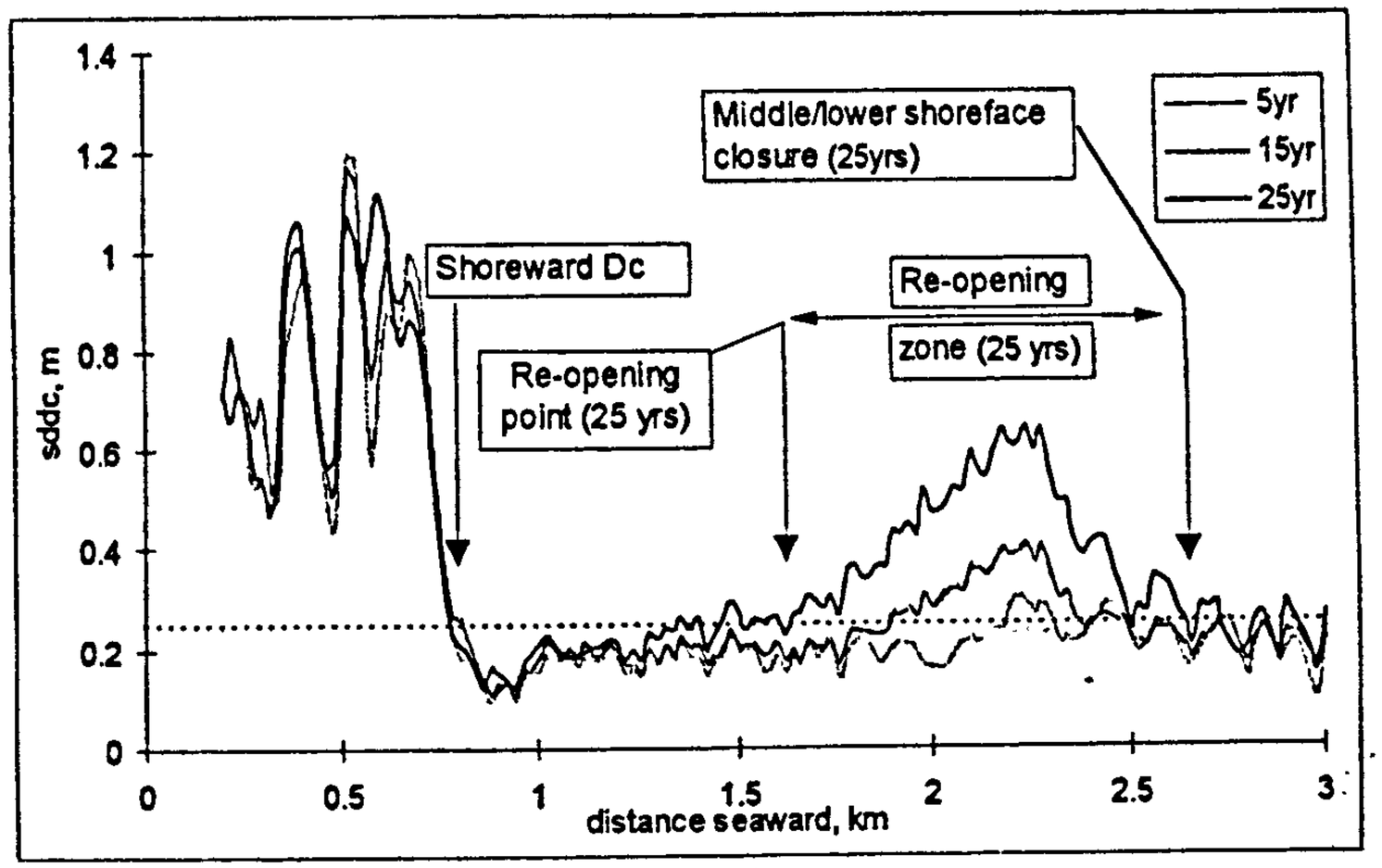


Figure 5. Sddc at km 69 which exhibits re-opening and subsequent closure for time periods of 15 and 25 years.

REGION	MEAN DEPTH (m)	STANDARD DEVIATION (m)
1) km 16 - 24	9.2	2.2
2) km 25 -54	7.7	0.6
3) km 55 - 97	5.0	0.3

Table 1. Characteristics of the shoreward closure over 20 years in the 3 regions, as given by the fdc criteria of 0.5 m.

Application of Hallermeier (1978)

The shoreward closure can be compared with a value calculated using Equation 1. The input data is a time series of wave heights and associated periods measured over a five year period at a station offshore from Ijmuiden, in 18 m water depth. Given the alongshore similarity of the wave climate this is a reasonable comparison for all observed Dc_s. The calculated value for this study is 9.2 m (relative to MLW) over a 5 year period (1980 to 1985). (Hydrodynamic data is insufficient at present to allow calculation over a 20 year period) This predicted value is a limit to the observed value over the same period, and over 20 years (Table 1), and is consistent with the behaviour

Re-opening and middle/lower shoreface closure

The re-opening zone represents a 'significant' depth change on the shoreface, as defined by the criteria selected. This behaviour is typically followed in the cross-shore by middle/lower shoreface closure. Those instances in which it does not re-close may result from data limitations. It is hypothesised that if the measurements were extended in the seaward direction then re-closure would be observed.

Re-opening does not occur along the whole of the Holland coast. (Figure 6.) It occurs in four alongshore zones defined in Table 2.

RE-OPENING ZONES	MEAN DEPTH (m)	STANDARD DEVIATION (m)
1) km 16 -29	13.0	1.9
2) km 47 - 72	10.3	3.4
3) km 77 - 81	9.8	0.5
4) km 91 - 92	10.0	1.1

Table 2. Characteristics of the re-opening point by longshore zone, over 20 years, as given by the fdc analysis (using a 0.5 m criterion).

Discussion

General

This data has shown a shoreward closure in 5 m to 8 m depth similar to that observed at other sites such as Duck, North Carolina (Nicholls *et al*, 1996, 1998). As the time scale increases it has also shown *significant* profile changes seaward of this shoreward closure.

Shoreward closure

Dc_s appears to be primarily a function of sediment movement under extreme breaking waves (cf. Nicholls *et al*, 1996). Comparison of closure predicted with Equation 1 and that observed on the Holland coast suggests that this is also true here. These preliminary calculations show that Hallermeier (1978) can be used as a predictive tool for the seaward *limit* of Dc_s along the Holland coast. Similar results have also been observed in past studies; at Terschelling, The Netherlands (Marsh *et al*, 1998) and Duck, North Carolina (Nicholls *et al*, 1996, 1998). Interestingly, Dc_s does not appear to increase with time scale as rapidly as Equation 1 would suggest.

Alongshore variation of closure defines two main regions; i) Noord-Holland, which can be further sub-divided into two, and has a mean closure of 8 m; and ii) Zuid-Holland which has a mean closure of 5 m. This indicates that processes, in addition to extreme waves, exist which play a role in the morphological behaviour of the active zone over time scales greater than 5 years. Other factors which have been shown to be of some importance in past studies are i) pre-event outer bar volume (at the Small-Scale); and ii) sediment budget (at the Middle-Scale) (Nicholls and Birkermeier, 1997).

Scale); and ii) sediment budget (at the Middle-Scale) (Nicholls and Birkermeier, 1997). Wijnberg (1995) classified the Holland coast using bar behaviour, defined using eigenfunction analysis which shows both i) the different time scales of active bar behaviour; and ii) the along- and cross-shore migratory behaviour. For the area studied here, three regions of similar behaviour were observed; 1) km 16 - 23; 2) km 24 - 55; and 3) km 57 - 97. These directly correlate with the three regions identified using Dc_s. (Figure 7).

The multiple bars in Holland migrate offshore at different rates and ultimately disappear; the morphological cycle repeats every 15 years in regions 1) and 2) (Noord-Holland) and every 4 years in Zuid-Holland. The degeneration of the outer bar in the Noord-Holland system occurs at a greater depth than in Zuid-Holland. This agrees with the greater closure depths observed in Noord-Holland as compared to Zuid-Holland. It is therefore concluded that shoreward closure is primarily controlled by extreme breaking wave conditions with the bar morphodynamics acting as an additional control, similar observations have been made on the meso-tidal barrier island of Terschelling, The Netherlands (Marsh *et al*, 1998).

Re-opening and middle/lower shoreface closure

This behaviour has not been systematically observed in previous studies. Activity on the shoreface has, however, been recognised in past studies (Stive *et al*, 1990), although the processes which control this behaviour are poorly understood. The occurrence and size of the re-opening zone is seen to be time-dependant; as the time period increases, the extent (both in the cross-shore distance and degree of depth variation) steadily increases. This suggests that this behaviour is due to slow, cumulative change, rather than fast, infrequent events. Indeed, the middle/lower shoreface behaviour has been indicated to be morphodynamically weakly varying (Stive *et al*, 1990). In most cases the re-opening is associated with a local shoreface steepening. Roelvink and Stive (1990) and Stive *et al* (1990) have shown that the significant depth change observed on the shoreface represents the effect of the onshore transport of material to the active zone. The specific location of this phenomena within four zones along the Holland coast may help towards the identification of the controlling processes; at present only tentative correlations between process and response have been made. It is expected that this behaviour will be related to hydrodynamic parameters, as with the shoreward closure. It is hypothesised that it is the asymmetry of shoaling waves which are the primary influence, with an additional forcing introduced by tidal and wind- induced currents, which become more significant in the offshore (Komar, 1976; Stive *et al*, 1990).

In addition the two major anthropogenic structures along the closed coast, the Petten sea dike (km 20 - 26) and Ijmuiden harbour moles (km 55/56), are located in the two largest re-opening zones, km 16 -29 and km 47 - 72 respectively. These can influence offshore behaviour. The Ijmuiden harbour moles, which are 2.5 km in length, have influenced tidal excursion and so accretionary/erosive behaviour for substantial distances, tens of kilometres, from the structure (Roelvink *et al*, 1998). Other morphodynamic controls should be considered. For example, shoreface-connected ridges are present from km 45 - 65 (Van de Meene, 1994), coinciding with the

occurrence of re-opening. These ridges are mapped to minimum depths of 14 m although they may occur further onshore.

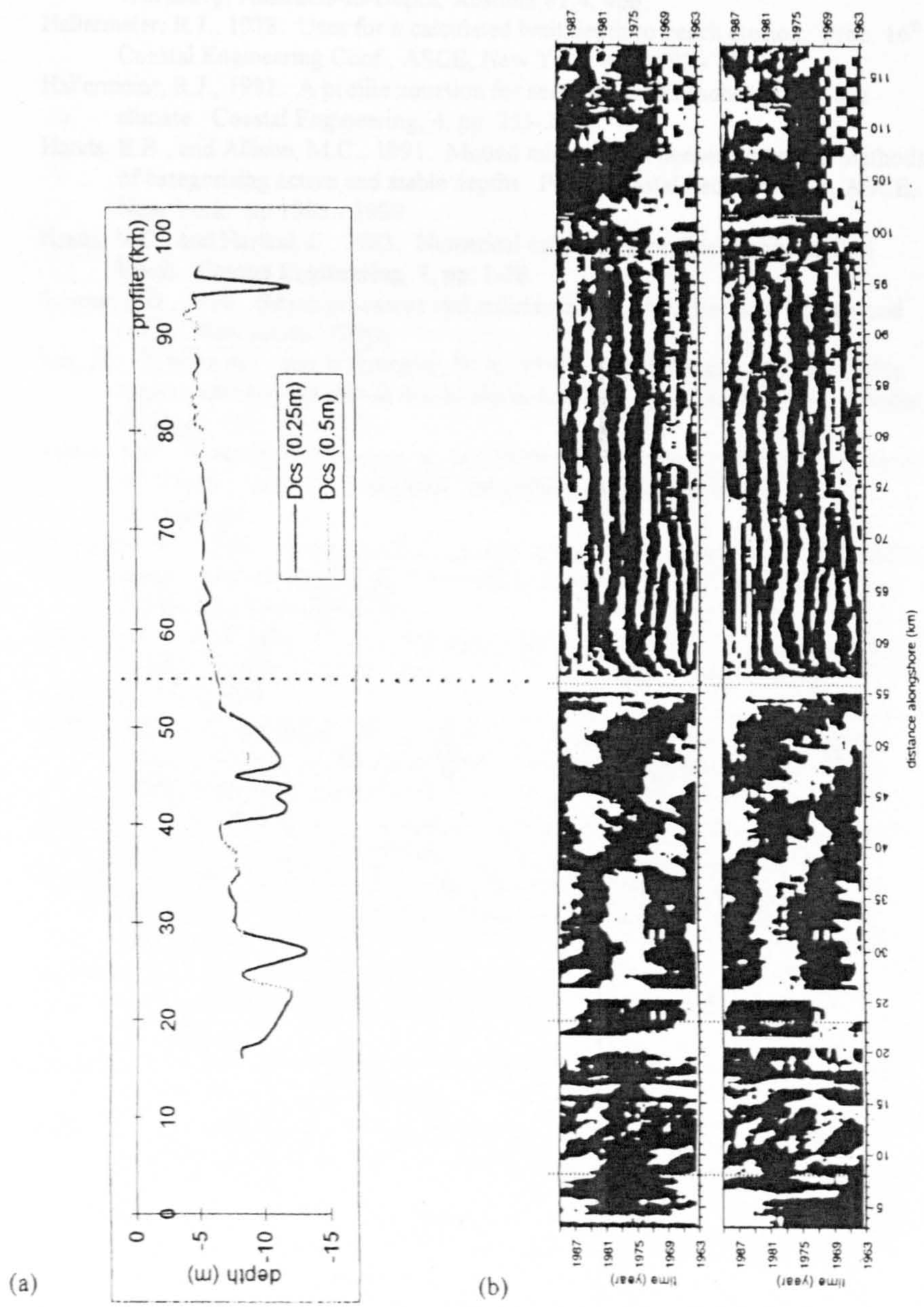


Figure 7. Alongshore correlation between the shoreward depth of closure (a) and bar

Conclusion

The large temporal and spatial extent of the JARKUS data set has enabled Large-Scale closure behaviour to be determined. The profile closes at depths of 5 m to 8m (shoreward closure). In addition, as the time scale increases *significant* profile changes are observed in four alongshore zones seaward of the shoreward closure; re-opening of the profile occurs and is typically followed in the cross-shore by middle/lower shoreface closure. All of the observed characteristics are temporally dependant.

Shoreward closure shows alongshore variation with deeper values observed in the north. It is hypothesised that D_c is primarily under the control of wave breaking, as seen by the generalised value given by the Hallermeier (1977, 1981) formulation. An additional control is imposed by bar behaviour (Wijnberg, 1995). Profile re-opening and the subsequent middle/lower shoreface closure is identified in four distinct zones along the closed coast. The possible hydrodynamic, morphodynamic and anthropogenic controls are being investigated.

In addition to the obvious engineering applications of closure, e.g. for the calculation of beach fill volumes, the occurrence of the re-opening zone reminds users that *significant* depth changes can occur seaward of the shoreward closure. It is vital that this is taken into consideration by engineers, especially over decadal and longer time scales.

Acknowledgements

This work was carried out as part of the PACE project, within the EU sponsored Marine Science and Technology programme (MAST-III) under contract number MAS3-CT95-002. The JARKUS data set is collected by Rijkswaterstaat/RIKZ (the Dutch National Institute for Coastal and Marine Management) and made available within the PACE project. The authors would like to thank all those involved in its collection and processing.

References

Capiobianco, M., Larson, M., Nicholls, R.J., and Kraus, N.C., 1997. Depth of closure: A contribution to the reconciliation of theory and practise. Proc.Coastal Dynamics '97. ASCE, New York. pp. 506 - 515.

Davison, A.T., Nicholls, R.J., and Leatherman, S.P., 1992. Beach nourishment as a coastal management tool: An annotated bibliography on developments associated with the artificial nourishment of beaches. Journal of Coastal Research, 8(4), pp. 984-1022.

Garcia, V., Jimenez, J.A., and Sanchez-Arcilla, A., 1997. Temporal and spatial variability of the depth of closure in the Ebro delta. First Annual PACE Workshop, Abstracts-In-Depth, Abstract #1.4, 4pp.

Hallermeier, R.J., 1978. Uses for a calculated limit depth to beach erosion. Proc. 16th Coastal Engineering Conf., ASCE, New York. pp. 1493 - 1512.

Hallermeier, R.J., 1981. A profile zonation for seasonal sand beaches from wave climate. Coastal Engineering, 4, pp. 253-277.

Hands, E.B., and Allison, M.C., 1991. Mound migration in deeper water and methods of categorising active and stable depths. Proc. Coastal Sediments '91, ASCE, New York. pp 1985 - 1999.

Kraus, N.C., and Harikai, S., 1983. Numerical model of shoreline change at Orai beach. Coastal Engineering, 7, pp. 1-28.

Komar, P.D., 1976. Beach processes and sedimentation. Prentice-Hall, Englewood Cliffs, New Jersey, 429pp.

Lee, G., Nicholls, R.J., and Birkemeier, W.A., 1998. Storm-driven variability of the beach- nearshore profile at Duck, North Carolina, USA, 1981 - 1991. Marine Geology, 148, 163 - 177.

Marsh, S.W., Nicholls, R.J., Kroon, A., and Hoekstra, P., 1988. Assessment of depth of closure on a nourished beach: Terschelling, The Netherlands. These proceedings.

Nanninga, M., 1985. The accuracy of echo sounding - description in a mathematical model. Masters Thesis. Rijkswaterstaat, National Institute for Coastal and Marine Management/RIKZ.

Nicholls, R.J., Birkemeier, W.A., and Hallermeier, R.J., 1996. Application of the depth of closure concept. Proc. 25th ICCE, Orlando (USA), ASCE, New York pp. 3874-3887.

Nicholls, R.J., and Birkemeier, W.A., 1997. Morphological and sediment budget controls on depth of closure at Duck, NC. Proc. Coastal Dynamics 1997, ASCE, New York. pp. 496 - 505.

Nicholls, R.J., Birkemeier, W.A., and Lee; G., 1998. Evaluation of depth of closure using data from Duck, NC, USA. Marine Geology, 148, pp. 179-201.

Roelvink, J. A., and Stive, M. J. F., 1990. Sand transport on the shoreface of the Holland coast. Proc. 22nd Coastal Engineering Conf., ASCE, New York. pp. 1909 - 1921.

Roelvink, J.A., Boutmy, A.E.G., and Stam, J-M, T., 1998. A simple method to predict long-term morphological changes using complex model results. These proceedings.

Roskam, A P., 1988. Golfklimaten voor de Nederlandse kust. Rijkswaterstaat, Nota GWAO-88.046, 21pp. + figures.

Stive, M.J F., Roelvink, J.A., and De Vriend, H.J., 1990. Large-scale coastal evolution concept. Proc. 22nd Coastal Engineering Conf., ASCE, New York. pp. 1962 - 1974.

Van de Meene, J.W.H., 1994. The shoreface connected ridges along the central Dutch coast; The Netherlands. PhD Thesis, Utrecht University, Department of Geography, The Netherlands. 222pp.

Wijnberg, K.M., 1995. Morphologic behaviour of a barred coast over a period of decades. PhD Thesis; Utrecht University, The Netherlands. 250pp.

PROFILE RE-OPENING ON THE SHOREFACE OF THE HOLLAND COAST

Claire Hinton[1], Robert Nicholls[1] and Daan Dunsbergen[2]

Abstract: The shoreface dynamics of the long JARKUS profiles are investigated over 32 years, 81 km alongshore and ≥ 2.5 km cross-shore. The morphodynamic activity on the shoreface is sub-divided into three types; i) inactive shoreface (no morphodynamic activity is observed seaward of the shoreward depth of closure (at 5 to 8 m water depth)); ii) partially active shoreface ('re-opening' of the shoreface profile i.e. the profile *must* first exhibit a shoreward closure); and iii) fully active shoreface (the profile *does not* exhibit a shoreward closure and so is morphodynamically active along the total cross-shore distance). At Large-Scales (≥ 10 years; ≥ 10 km alongshore) it is found that the percentage occurrence of type ii) increases rapidly with time until 20 years when an almost constant value is reached. Simultaneously the percentage occurrence of type iii) increases linearly with time so that, after 32 years 33% of profiles are fully active on the shoreface. It is hypothesised that shoreface activity results from slow, cumulative rather than occasional, extreme processes. Extrapolation beyond the data limits suggest that after approximately 90 years, all profiles along the Holland coast will exhibit morphodynamically active shorefaces. This work verifies that the middle/lower shoreface is morphodynamically active at decadal scales. These changes are occurring at

[1] Flood Hazard Research Centre, Middlesex University, Queensway, Enfield, Middlesex, EN3 4SF. UK.
[2] Rijkswaterstaat, National Institute for Coastal and Marine Management/RIKZ, PO Box 20907, 2500 EX Den Haag, The Netherlands.

timescales which mean that they *must be* considered within coastal management. Further, these results suggest that the onshore feed of sediment from the shoreface will have profound implications for long-term sediment budgets (cf. Stive *et al.*, 1990).

INTRODUCTION

In order to successfully implement coastal management schemes it is important that we are able to judge the impact of changes in coastal processes. This is especially important over the Medium- and Large-Scale (Table 1) for it is over these temporal scales that many of today's projects are designed. Hence many significant and fundamental concepts are being developed, through both predictive and observative techniques.

Table 1. The Coastal Scales Defined by Stive *et al. (1990).*

SCALE DESCRIPTION	MORPHODYNAMIC LENGTH SCALE	TIME SCALE
Large-Scale	10 km	decades
Medium-Scale	1 km	years
Short-Scale	100 m	storms-seasons

One of the many key concepts in beach morphodynamics is depth of closure (Dc). Depth of closure plays an important role in coastal sediment budgets and associated applications for example beach nourishments. In the former, closure can be used as the seaward boundary of morphological change in sediment budget models (Kana, 1995) whilst in the latter it enables the volume of beach fill material to be calculated (Davision *et al.*, 1992).

Closure represents the 'seaward limit of *significant* depth change' (Nicholls *et al.*, 1996); it does not however refer to an absolute depth beyond which there is no cross-shore sediment transport. This definition has been derived from investigations into the Short and Medium-Scale characteristics of closure within wave-dominated, micro-tidal sandy coastal environments (Nicholls *et al.*, 1996). Such studies have shown Dc to be time- and space-dependant (Garcia *et al.*, 1997; cf. Capiobianco *et al.*, 1997; Rózynski *et al.*, 1997; Marsh *et al.*, 1998). It is also shown that closure generally occurs on the upper shoreface (typically 6 to 8 metres depth) within these temporal scales. Breaking waves are concluded to act as the primary control upon its cross-shore location (Nicholls *et al.*, 1996).

Depth of closure is less investigated and understood on the Large-Scale; the controls on closure are likely to vary with scale (Nicholls et al, 1998). The Large Scale Coastal Evolution concept (Stive *et al.*, 1990) describes the evolution of the coast at decadal scales to vary between mean trend (e.g. geological processes), fluctuating (e.g. boundary constraints) and asymptotic (e.g. morphodynamic constraints) behaviour. The morphological development of a coastline is temporally- and spatially-dependant and is often positively coupled. This is related to the assumption of 'primary-scale relationship'; '*a process of a certain scale will be in dynamic interaction with coastal behaviour of a*

similar scale' (De Vriend, 1991). The JARKUS data set from the Netherlands has allowed closure to be studied at the Large-Scale; 32 years, 16 metres depth and 100 km alongshore.

Hinton and Nicholls (1998) demonstrated that, over the Large-Scale, more than one closure may occur across a single cross-shore profile; in some instances not only does the profile close at some distance x from the shore, but the profile re-opens more seaward on the shoreface and then usually re-closes towards its seaward limit on the lower/middle shoreface (Figure 1). These phenomena have been termed i) the shoreward closure (Dc_s); ii) the re-opening point (Ro) and re-opening zone; and iii) middle/lower shoreface closure ($Dc_{m/l}$), respectively.

Ro has only been observed over the longer time scales (≥ 10 years) and at distances offshore greater than 1.5 km (typically 10 metres water depth), (Hinton and Nicholls, 1998). Although unobserved in past studies of this kind, morphodynamic activity on the shoreface has been previously recognised (Stive *et al.*, 1990; Wright *et al.*, 1991; Niedoroda *et al.*, 1995). This study aims to investigate this shoreface characteristic over the large temporal (≤32 years) and spatial (<100 km) scales, using the JARKUS data set.

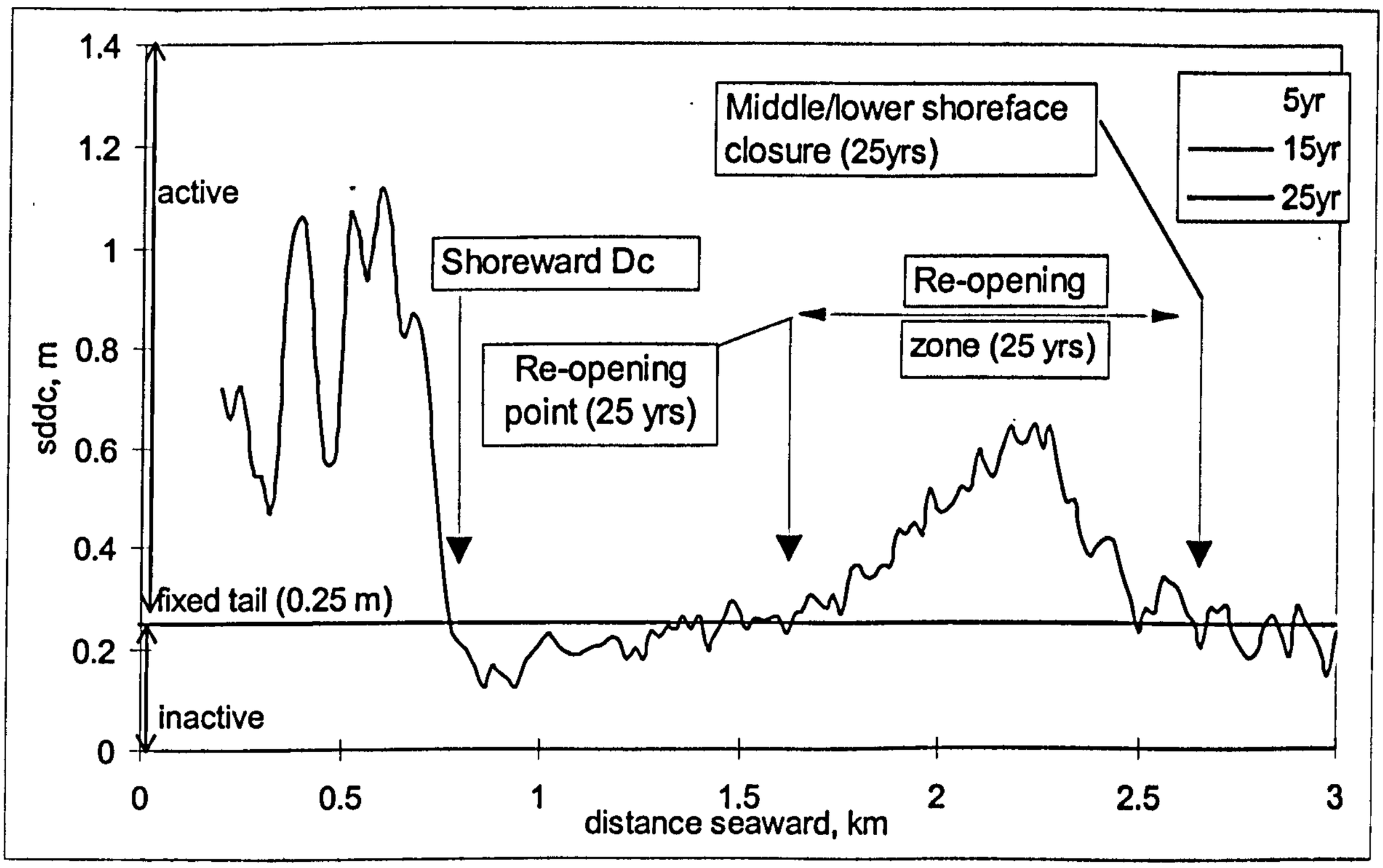


Figure 1. Standard deviation of depth change plot which clearly shows re-opening and subsequent closure for time periods of 15 and 25 years (km 69). (In the present study a fixed tail (value 0.25 m) is used to define morphodynamic activity and inactivity) (after Hinton and Nicholls, 1998).

STUDY AREA : THE HOLLAND COAST

The study area (approximately 100 km alongshore) is the Holland coast bound from Den Helder in the north to Hoek van Holland in the south. (Figure 2.) It is a wave-dominated, sandy coastline backed by large dunes and uninterrupted by tidal inlets or barrier islands. The main anthropogenic interventions are the Petten sea wall (km 20 - 26) where the dike replaces the dune system, and the IJmuiden harbour moles (km 55/56). Some relatively minor beach nourishment schemes are also present along the study area.

Multiple bars are present along the coastline and extend to a maximum depth of approximately 8 metres. The mean tidal range is 1.4 metres in the north increasing to 1.7 metres in the south, peak tidal velocities do not generally exceed 1 ms^{-1}. The annual mean wave height is 1.2 m (associated wave period 5 sec), whilst the extreme annual wave height is 5.3m (associated wave period 7.7 sec) (Roskam, 1988). The hydrodynamic climate is relatively uniform alongshore; variations in wave height from north to south are of the order of 0.2 m.

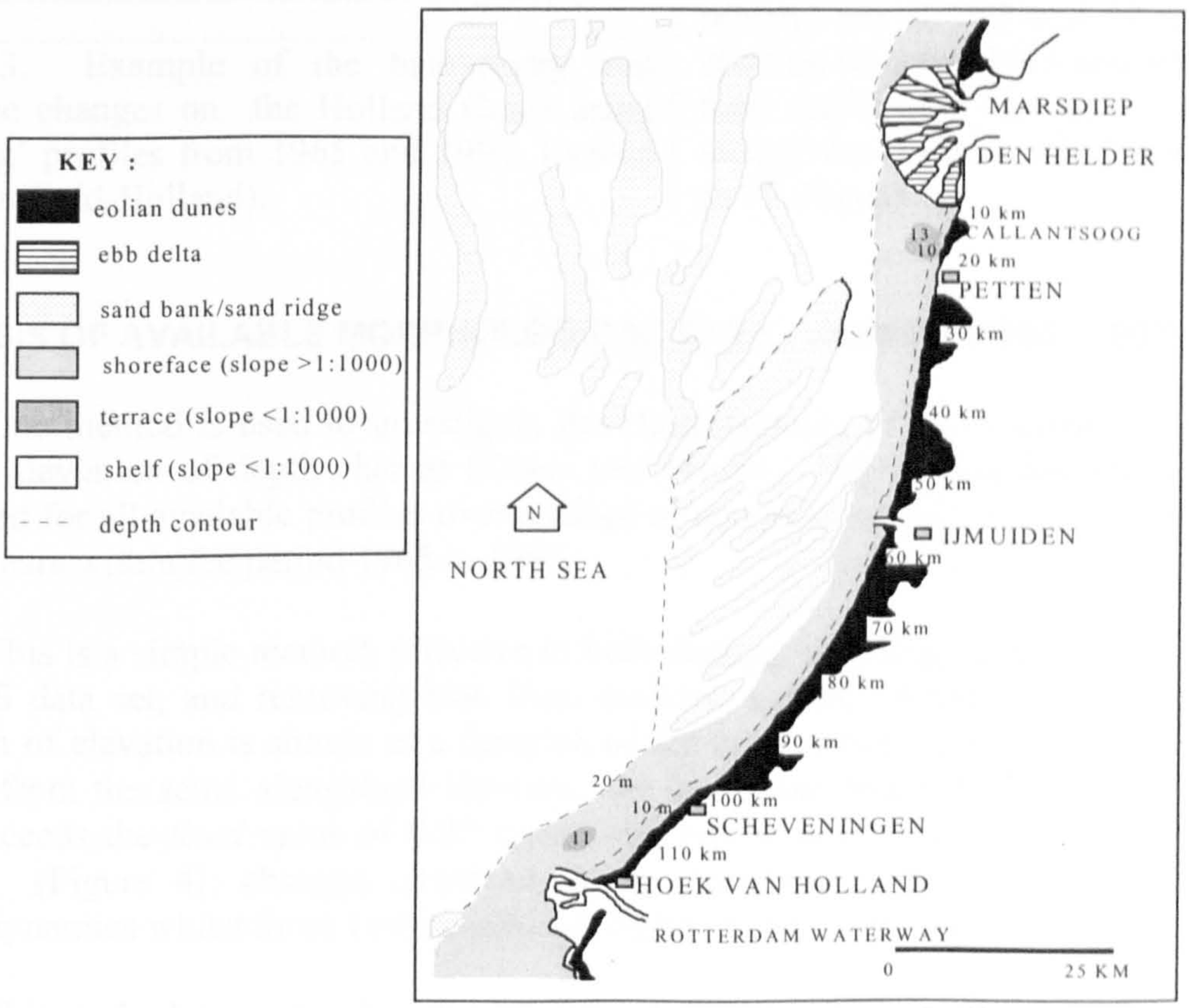


Figure 2. Location map showing the closed Holland coast. (Wijnberg, 1995).

Cross-shore bathymetry has been measured by the Rijkswaterstaat since 1963 at regular, fixed locations alongshore. These measurements are held within the JARKUS data set (Hamm, 1997). They have a vertical accuracy of approximately 0.25 metres, the value of the constant, non-zero tail within the standard deviation of depth change calculations. This accuracy value has also been determined by an independent study which uses both stochastic and systematic error sources (Nanninga, 1985).

Two types of cross-shore profile measurements exist. One is the annual (short) profiles which extend 0.8 km seaward, equivalent to a depth of approximately 6 metres, with alongshore spacing of 0.25 km. The second is the less frequent (generally) five-yearly (long) profiles, these extend to a minimum 2.5 km seaward, equivalent to approximately 15 to 16 metres depth, and have an alongshore spacing of 1 km. (Figure 3.). Data is available for 1965, 1970, 1975, 1980, 1985, 1990, 1993 and 1997.

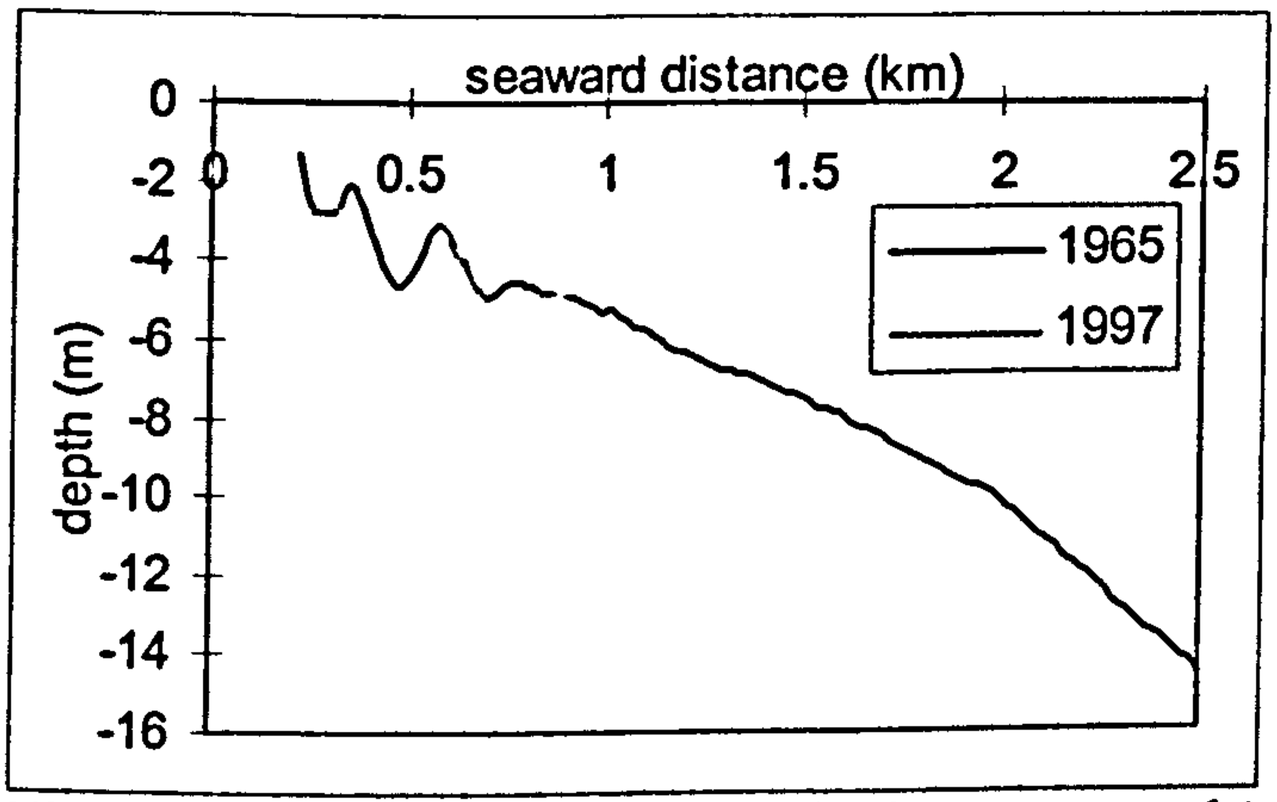


Figure 3. Example of the bathymetry and shoreface changes on the Holland Coast using the 'long' profiles from 1965 and 1997, located at km 70 (Zuid-Holland).

The long profiles are analysed in this study as previous investigation (Hinton and Nicholls, 1998) has shown that the re-opening behaviour is typically observed at distances offshore greater than 1.5 km. The most northern and southern profiles are rejected due to the tidal influence of the Marsdiep and the Europort inlets, respectively. In addition, profiles km 52, 53 and 72 to 97 are missing for years 1993 and 1997. The total study area therefore covers an alongshore distance of 81 km (km 16 to 97; Figure 2).

ANALYSIS OF AVAILABLE MORPHOLOGICAL DATA : JARKUS (1965 - 1997)

One method is used to investigate the characteristics of the re-opening zone; the standard deviation of depth change (Kraus and Harikai, 1983). This analysis has been performed for all available profiles over a range of temporal periods; 5, 10, 15, 20, 25, 28 and 32 years within the period 1965 to 1997.

This is a simple method, effective in both dealing with large data sets, such as the JARKUS data set, and removing bias from outlying values. Variation in the standard deviation of elevation is shown as a function of the cross-shore distance for x number of profiles from the same alongshore location. In this paper when the standard deviation value exceeds the *fixed* value of 0.25 metres the profile is undergoing *significant* depth changes (Figure 4); changes observed in the nearshore zone mainly relate to bar morphodynamics whilst those further offshore equate to shoreface morphodynamics.

This study defines the shoreface as a fixed zone in which its landward boundary is formed by the outer slope of the outer breaker bar and the seaward boundary by the transition from a concave profile to a nearly horizontal bottom (Houwman and Hoekstra, 1994). The shoreface is then further divided into the upper shoreface, or active zone, which extends to 8 metres water depth, the middle shoreface (8 to 12 metres water depth) and the lower shoreface (12 to 20 metres water depth) (Stive *et al.*, 1990).

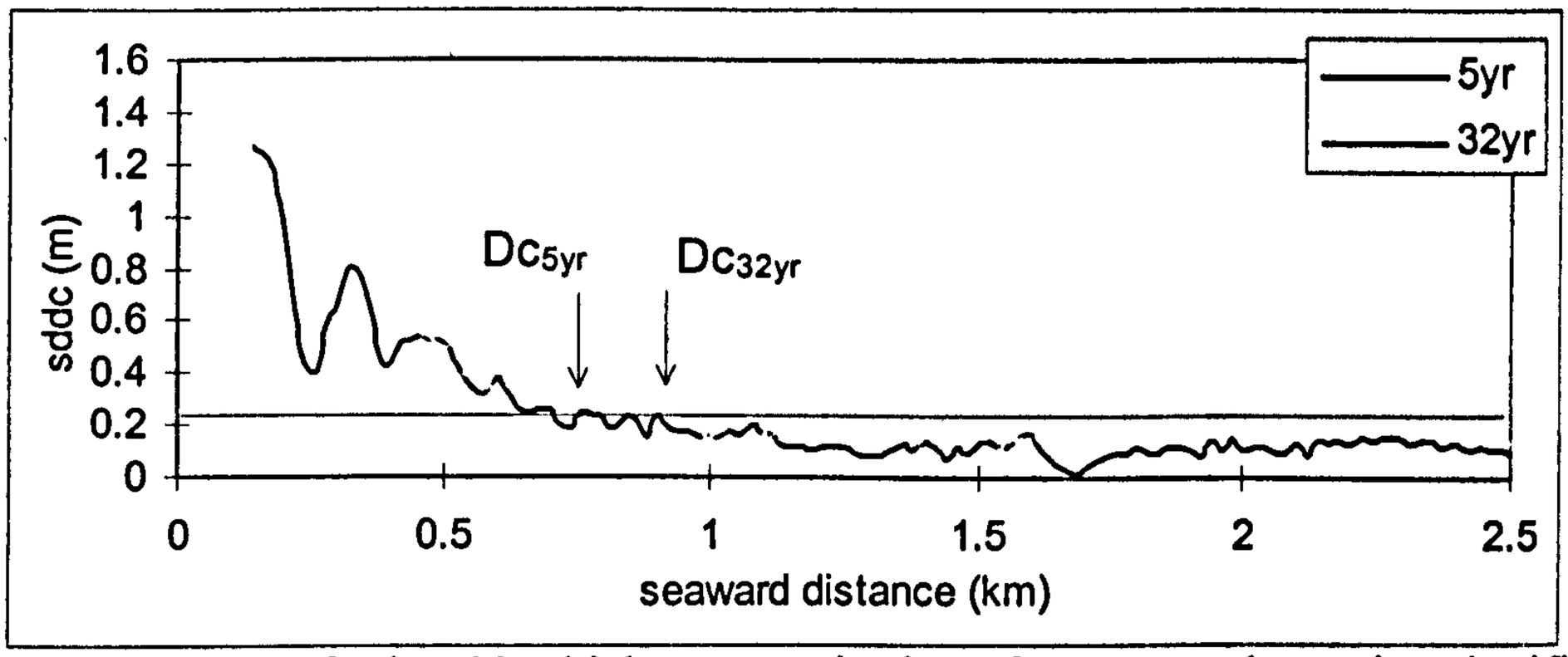


Figure 4. Sddc plot for km 30 which uses a criterion of 0.25 m to determine significant depth changes. Closure is exhibited in the range 0.7 to 0.9 km offshore for all time periods. ($Dc_{5yr} \approx 8.5$ m depth; $Dc_{32yr} \approx 9.5$m depth).

In this study the morphodynamic behaviour of the shoreface is divided into three types and the latter two examined in more detail (see Figure 1) :

1. inactive shoreface. No morphodynamic activity is observed seaward of Dc_s;
2. partly active shoreface. The shoreface exhibits re-opening i.e. the profile *must* first exhibit a Dc_s in order to re-open; and
3. fully active shoreface. It occurs upon the whole shoreface i.e. the profile *does not* exhibit a shoreward closure and so is morphodynamically active along the total cross-shore distance.

In addition to considering the coastline as a whole (km 16 to 97), it is also examined from km 16 to 71 to remove any bias from the missing data; km 72 to 97 for temporal periods 25, 28 and 32 years.

OBSERVATIONS AND PREDICTIONS OF RE-OPENING USING THE JARKUS DATA SET (1965 - 1997)

General

The sddc method allows the observation of the shoreward closure and re-opening zone (or, partial shoreface activity). A fully active shoreface can also be observed. (Shoreface activity represents significant depth change, within the depth change criterion chosen.) Shoreface activity (both partial and full) predominately occurs over the longer time scales ($\geq$ 10 years) (and so is a Large-Scale process) and also increases in occurrence with temporal period (i.e. 21% of profiles have partially active shorefaces after 10 years increasing to 31% after 32 years (km 16 - 71)). Additionally the shoreface activity investigated here does not occur at all alongshore locations and is also typically found in depths equal to, or greater than, 10 metres. Therefore as previously seen with the shoreward closure (Nicholls *et al.*, 1996), shoreface activity is temporally- and spatially-dependant. (Figure 5). This dependence will be described further in the following sections.

Temporal Characteristics

Partial and fully active morphodynamic behaviour is predominately observed over the longer time periods ($\geq$ *10 years*). As the temporal period is increased (from 5 to 32 years) the occurrence of shoreface activity along the *Holland coast also increases.* (Table 3).

Table 3 clearly shows that there is some bias produced by the missing data. Therefore, the remainder of this work will concentrate solely on the alongshore area from km 16 to 71. The relationship between the number of profiles showing partial shoreface activity and time interval is positively correlated with an r^2 value of $0.89_{(95\% \text{ significance})}$. A similar relationship exists for the number of profiles showing full shoreface activity; the r^2 value is $0.96_{(95\% \text{ significance})}$. Figure 6 shows that the occurrence of partial shoreface activity rapidly increases until the 20 year time period when the rate of increase slows. However, the occurrence of activity across the whole shoreface increases throughout the whole time period at a rate which increases with time. This indicates that, as the temporal period increases beyond a critical value (20 years), the percentage of profiles which exhibit partial shoreface activity reaches an almost constant value. This is the result of the profiles which first close on the upper shoreface (Dc_s) decreasing in occurrence and those profiles active along the whole shoreface continuing to increase in occurrence. (Figure 7).

Table 3. Percentage Occurrence of Shoreface Activity with Increasing Temporal Period. (Note: i) an additional boundary has been made at km 71 to remove bias from missing data; ii) partial = partially active shoreface (re-opening); iii) full = fully active shoreface).

TIME PERIOD (yrs)	PARTIAL (km 16 - 97)	PARTIAL (km 16 - 71)	FULL (km 16 - 97)	FULL (km 16 - 71)	TWO TYPES COMBINED (km 16 -97)	TWO TYPES COMBINED (km 16 -71)
0	0	0	0	0	0	0
5	7	4	1	2	8	6
10	21	21	4	6	25	27
15	27	32	7	11	34	43
20	33	36	10	15	43	51
25	32	32	28	28	60	60
28	33	33	27	27	60	60
32	31	31	33	33	64	64

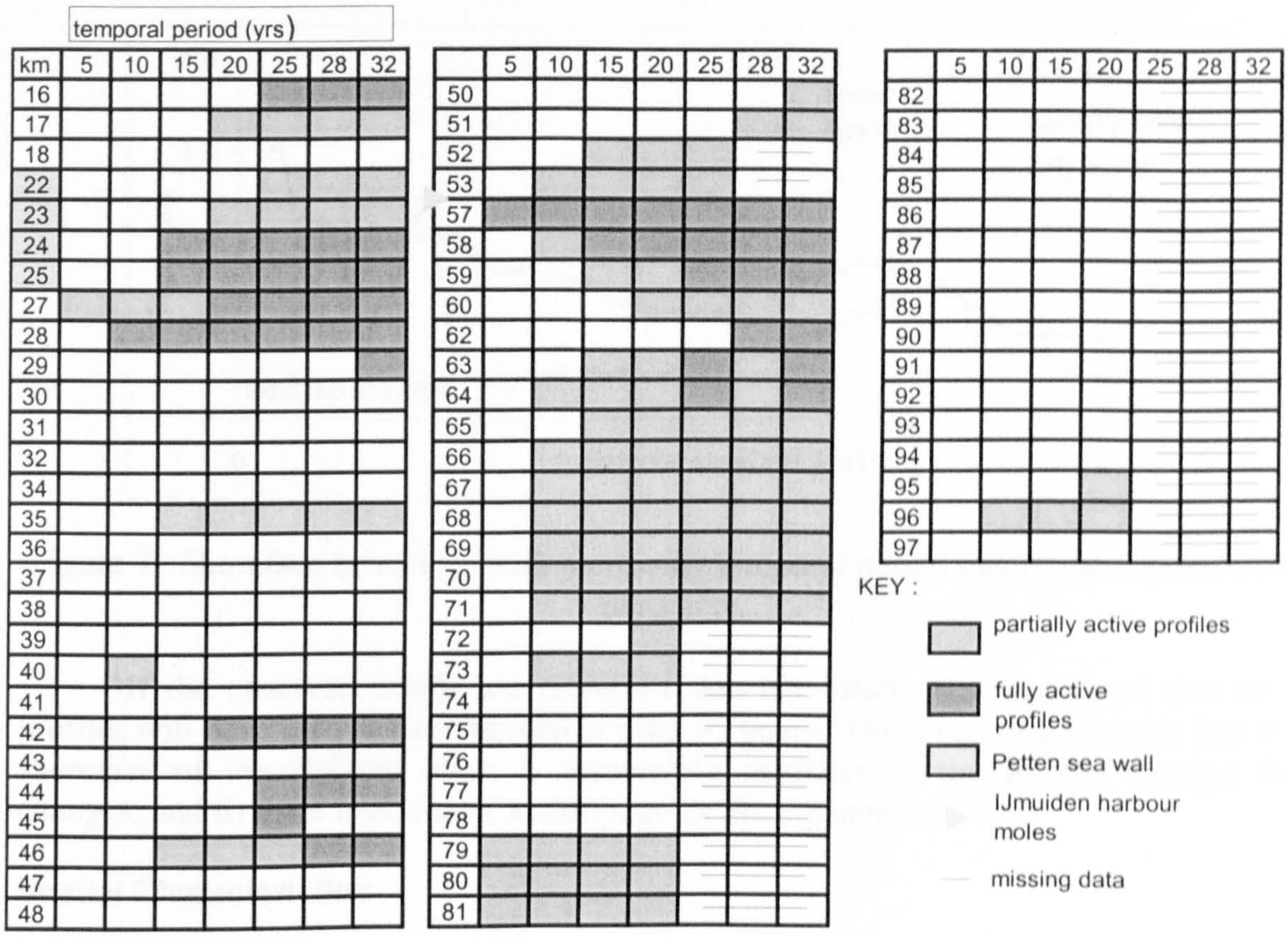


Figure 5. Spatial distribution of morphodynamic activity along the Dutch shoreface for different temporal periods (1965 - 1997).

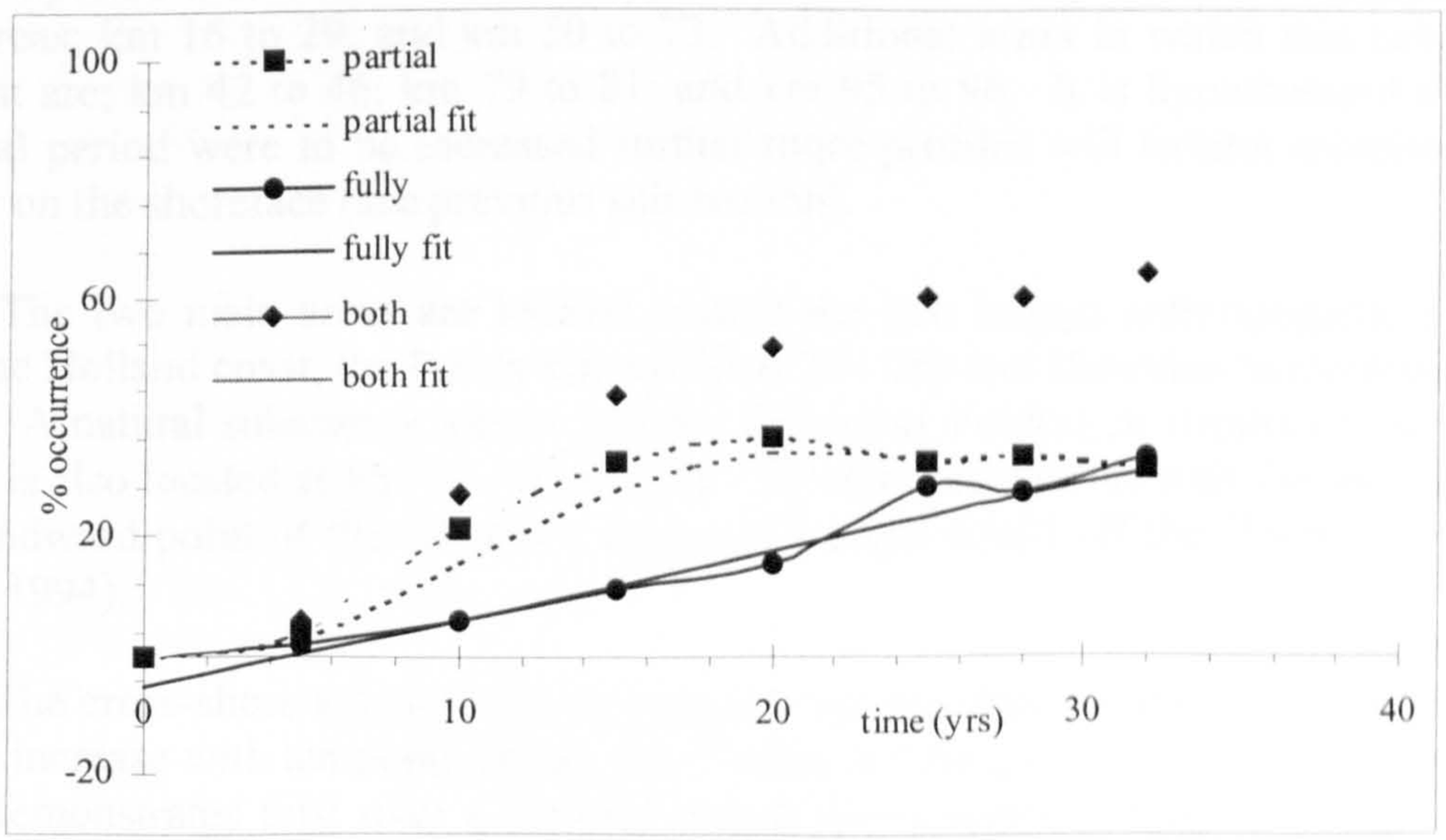


Figure 6. Observed and predicted relationship between the percentage occurrence of the three types of shoreface activity and temporal period. Partial and both take an exponential fit and full a linear fit. (Note: partial = activity which occurs after shoreward closure; full = activity across the whole shoreface; both = combined partial and full)

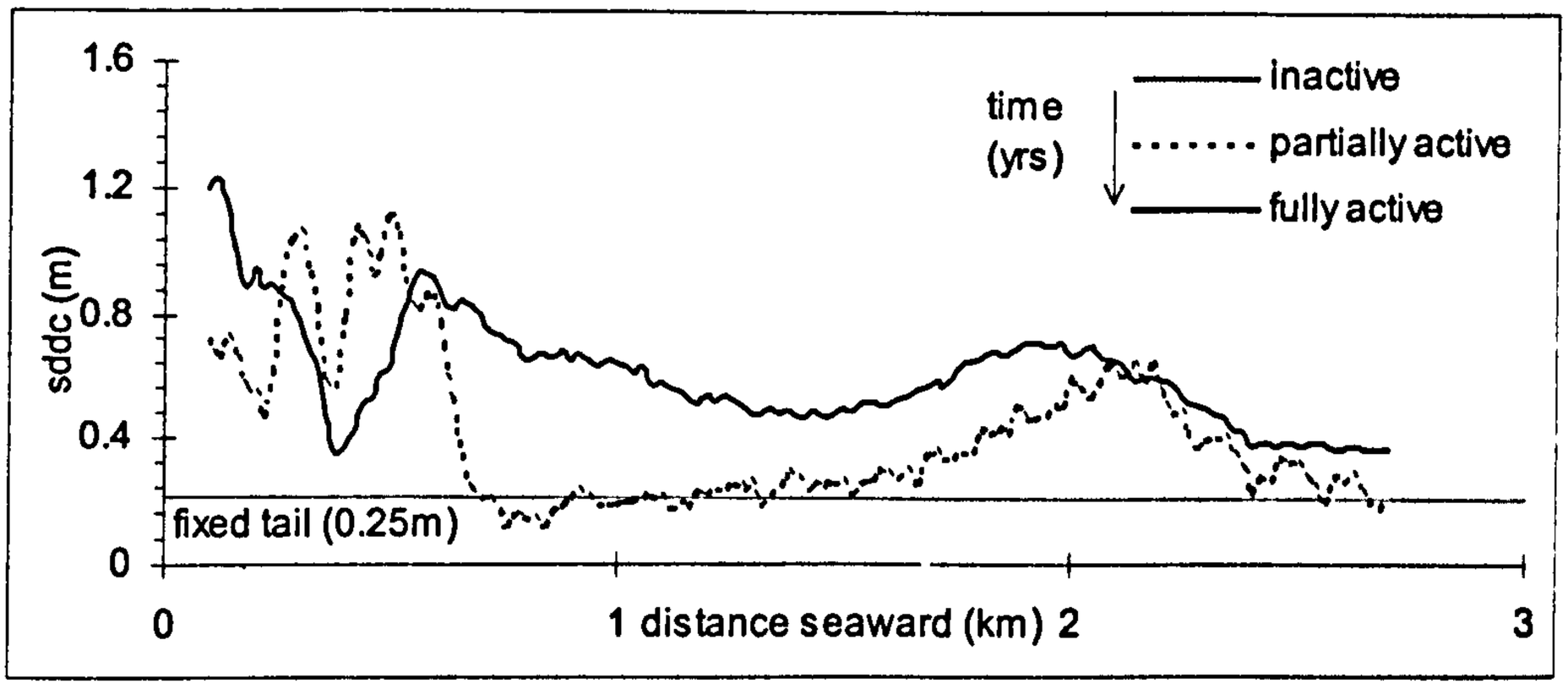


Figure 7. Shoreface behaviour with increasing temporal period based upon classification used here.

If the observed trends are projected into the future, it is estimated that all the profiles will have fully active shorefaces after 95 years. However, this assumes that i) the shoreface of the Holland coast is responding similarly to the forcing causing these changes; and ii) there is no major anthropogenic disturbance.

Spatial Characteristics

Morphodynamic activity upon the shoreface (both as partially and fully) is not an alongshore uniform characteristic of the Holland coast (within the data limit). As the temporal period increases it becomes apparent that the activity becomes clustered in two main areas; km 16 to 29; and km 50 to 73. Additional areas in which this behaviour is apparent are; km 42 to 46; km 79 to 81; and km 95 to 96. It is hypothesised that if the temporal period were to be increased further more profiles will exhibit morphodynamic activity on the shoreface (see previous sub-section).

The two main areas are located around the two largest anthropogenic structures along the Holland coast; the Petten sea wall (km 20 - 26) and IJmuiden harbour moles (km 55/56). A natural submarine terrace (named Pettermer Polder), at depths of the order 10 metres, is also located at km 15 - 20. Km 50 - 73 also corresponds with the location of the most landward point of the shoreface connected ridges found off the Holland coast (Van Meene, 1994).

The cross-shore extent of the re-opening zone (partially active shoreface zone) also tends to increase with temporal period; the r^2 value is $0.69_{(95\% \text{ significance})}$. (Figure 8). Figure 1 also demonstrates this; over a 15 year period the re-opening zone of km 69 covers a cross-shore distance of approximately 0.5 km whilst over 25 years it covers approximately 1.0 km. This is due to the offshore movement of the seaward boundary, whilst the landward moves little over the period of observations. This means that the middle/lower shoreface closure ($Dc_{m/l}$) is tending to deepen on these profiles.

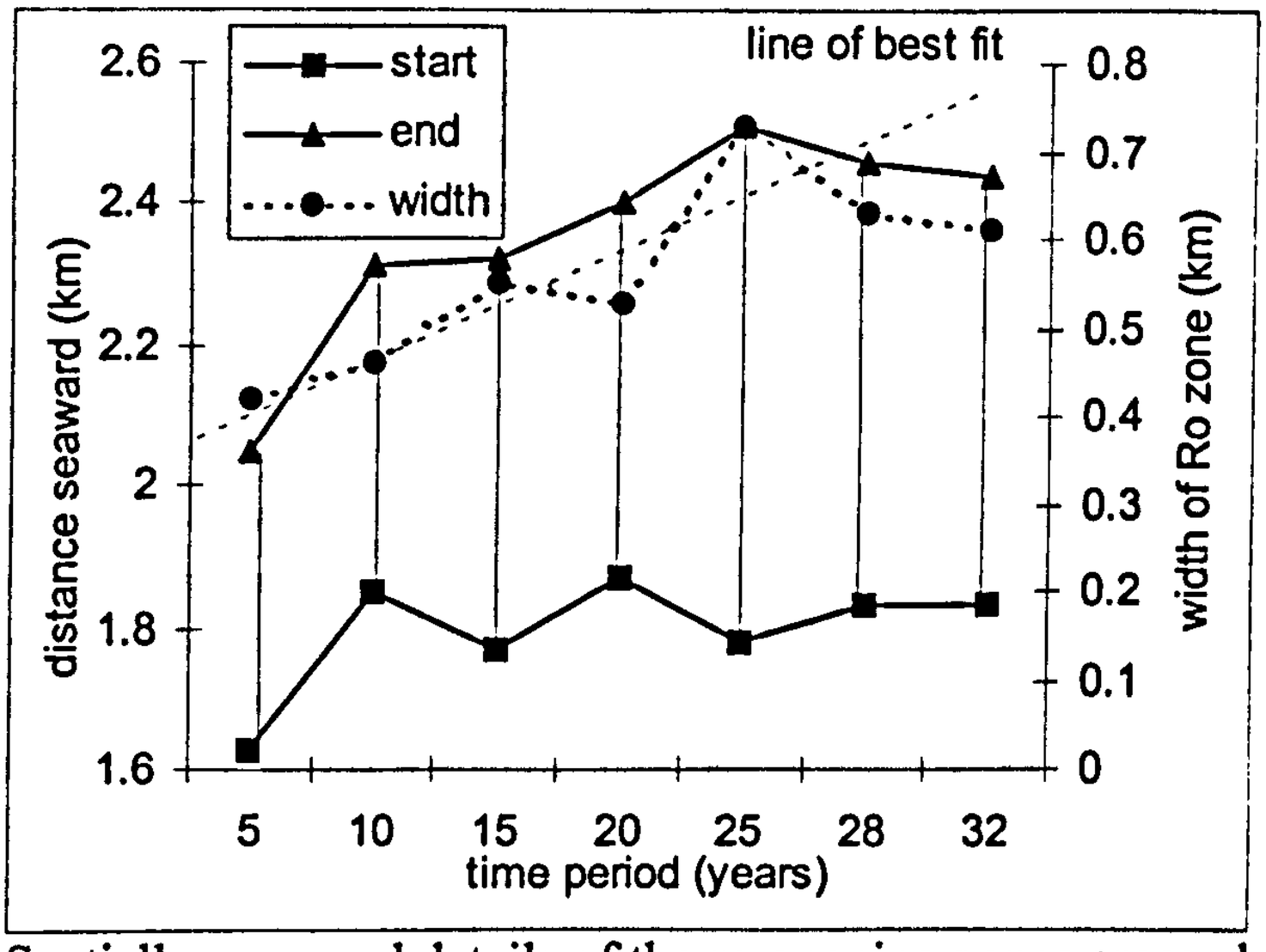


Figure 8. Spatially-averaged details of the re-opening zones cross-shore width through time (km 16 - 71). (Note: i) re-opening zone relates to the width of the partially active shoreface; and ii) the largest width is observed over 25 years, this may result from the fact that it could be an outlier - see Figure 6)

CAUSES AND CONTROLS UPON PROFILE RE-OPENING ALONG THE DUTCH SHOREFACE

The JARKUS data set allows the observation of significant profile changes on the middle and lower shoreface (8 to 20 metres depth) of the Dutch coast over the Large Scale (>10 km; decades). Other process-based, geological and modelling approaches have previously suggested that changes on the shoreface do occur (Niedoroda *et al.*, 1985; Stive *et al.*, 1990; Roelvink and Stive, 1990; Cowell *et al.*, 1995; Stive and De Vriend, 1995), resulting from tidally-dominated sediment transport at the most seaward boundary and wave-dominated sediment transport at the most shoreward. Field observations of this behaviour, however, remain concentrated at the Short Scale (Wright *et al.*, 1991; Wright *et al.*, 1994; Wright 1993); Wright (1993) measured sediment transport upon the inner shelf off the US Mid Atlantic coast (depth < 30 metres) over monthly periods. Lack of data over the longer time periods has restricted knowledge of shoreface processes. The JARKUS data set used here can but aid towards an improved understanding of such processes.

The shoreface is predominately friction-dominated. The lower shoreface is known as the transition zone between the friction- and geostrophic-dominated environments (Niedoroda *et al.*, 1985). Sediment is predominately agitated by waves and advected shorewards by bottom currents and wave asymmetry (Wright, 1993). The size and occurrence of the re-opening zone of the Dutch shoreface is seen to be time-dependant. This suggests that the observed behaviour is the result of slow steady change due to cumulative processes (such as regular storms) rather than infrequent, extreme events. Morphodynamic activity across the whole shoreface (i.e. *no* Dc_s) is increasing with time ($r^2 = 0.96_{(95\% \text{ significance})}$) again suggesting that cumulative processes are important. Partial

shoreface activity (i.e. that which occurs after Dc_s) rapidly increases with time until 20 years when its occurrence reaches an almost constant value. If this behaviour continues to increase with time as the data suggests, then the entire Dutch shoreface is expected to be active within coastal management time scales (approximately 90 years).However, this assumes that the shoreface of the Holland coast is responding in an uniform manner to the forcing that is producing these changes. The spatial patterns suggest this assumption might not be valid and such a prediction is only indicative.

In the majority of cases the re-opening can be associated with shoreface erosion (1965 to 1997). This agrees with sand budget results (Hinton, 1998; Ruig and Louisse, 1991; Van Vessem and Stolk, 1990; Van Rijn, 1995) which show that a large amount of sand is lost from the shoreface due to onshore transport. Roelvink and Stive (1990) and Stive *et al.* (1990) have also argued that the loss of sediment from the shoreface (which ultimately results in shoreface steepening) results in the feeding of the active zone. This has profound implications for the sediment budget of the Holland coast, as already noted by Stive *et al.* (1990).

The shoreface activity is so widespread in occurrence that it must be a natural feature of the shoreface evolution on this coast. However, it may be accentuated by anthropogenic influences. From the 32 years worth of data, shoreface morphodynamic activity is seen to be concentrated in two main areas along the Holland coast; km 16 - 29; and km 50 - 73. Additional, smaller, areas of shoreface activity exist; km 42 - 46; km 79 - 81; and; km 95 - 96. The two main areas are located around the two largest anthropogenic influences on the Holland coast; the Petten sea wall (km 20 - 26) and IJmuiden harbour moles (km 55/56). In addition km 16 - 29 is in the vicinity of Pettermer Polder (km 15 - 20), a natural submarine terrace at 10 metres depth. All of these can influence shoreface behaviour. The Petten sea wall acts as a headland, protruding seaward of the adjacent coastline. This could cause profile re-opening as the area of shoreface seaward of the sea dike steepens faster than that adjacent to it due to resistance of coastline erosion by the dike. The profiles km 16 to 20 undergo significant depth changes on the shoreface due to the natural terrace, which undergoes migration in the direction of the dominant flood tidal current (north-easterly) (cf. Walstra *et al.*, 1998). The IJmuiden harbour moles, which are 2.5 km in length, have influenced tidal excursion and so the accretionary/erosive behaviour of the shoreface for distances of tens of km from the structure (Roelvink *et al.*, 1998).

An increase in the cross-shore extent of the partially active shoreface accompanies an increase in temporal period ($r^2 = 0.69_{(95\% \text{ significance})}$). This is to be expected, as with the increase in occurrence of shoreface morphodynamic activity with time; a larger temporal period allows more time for change to occur. The formation of a re-opening zone is attributed to slow, cumulative processes i.e. storms. It has been shown that the long-term trend in the wind and wave climate along the Dutch coast is for; i) an increase in wind velocity and wave height; and ii) a change in wind direction from south-westerly to westerly (Hoozemans, 1990). Though this is for the period 1859 to 1982, projections indicate a continuation of these trends. If the wave climate continues to intensify, re-opening is likely along greater cross- and along-shore stretches of the Dutch coast.

CONCLUSION

Previous studies have observed depth of closure on the upper shoreface of the Holland coast (Hinton and Nicholls, 1998). Three types of shoreface activity have been defined; i) inactive (no morphodynamic activity is observed seaward of the shoreward depth of closure (Dc_s) at 5 to 6 m water depth); ii) partly active (the shoreface re-opens i.e. the profile *must* first exhibit a Dc_s in order to re-open); and iii) fully active (this occurs across the whole shoreface i.e. the profile *does not* exhibit a shoreward closure and so is morphodynamically active across the total cross-shore distance). This study shows that shoreface activity is temporally- and spatially- dependant;

- as the time period increases the number of profiles which have partially active shorefaces also increases up to 20 years when the number of profiles which re-open reach a constant value. It is hypothesised that the number will ultimately decrease to zero as the entire shoreface of the Holland coast becomes active;
- as time increases the number of cases of fully active shorefaces also increases;
- as the time period increases the cross-shore extent of the re-opening zone increases;
- shoreface activity over 32 years is concentrated within two main areas (km 16 - 29; and km 50 - 73) which are associated with; i) the Petten sea wall and Pettermer Polder; and ii) IJmuiden harbour moles. (It is hypothesised that this human influence accentuates shoreface dynamics; and
- significant depth changes on the shoreface can be attributed to the onshore loss of sediment from the shoreface.

Projections of the observed behaviour suggest that *all* profiles along the Holland shoreface will be morphodynamically active within *management time scales* ($\approx$ 90 years). It is important that this is considered in coastal schemes which include the middle/lower shoreface; significant depth changes *do* occur seaward of the shoreward depth of closure at Large-Scales.

It is suggested that the controls on shoreface morphodynamics and resulting shoreface activity are slow and continual, for example storms, rather than extreme and infrequent. In order to further understand shoreface dynamics the controlling processes need to be defined and quantified. Unfortunately no observations of shoreface processes over the long-term exist. Morphology-based studies such as this combined with process-based studies over the short-term (Wright, 1993) and modelling efforts (Roelvink and Stive, 1990) can be a means to this end.

ACKNOWLEDGEMENTS

This work was carried out as part of the PACE (Prediction of Aggregated-Scale Coastal Evolution) project, within the EU sponsored Marine Science and Technology programme (MAST-III) under contract number MAS3-CT95-002. It also falls within the framework of the Rijkswaterstaat research programme KUST-2000, which aims to improve the morphological knowledge of the Dutch coast. The JARKUS data set is collected by Rijkswaterstaat/RIKZ (the Dutch National Institute for Coastal and Marine

Management) and made available within the PACE project. The authors would like to thank all those involved in its collection and processing.

REFERENCES

Capiobianco, M., Larson, M., Nicholls, R.J., and Kraus, N.C., 1997. Depth of closure: A contribution to the reconciliation of theory and practise. Proc. Coastal Dynamics '97. ASCE, New York. pp. 506 - 515.

Cowell, P.J., Roy, P.S., and Jones, R.A., 1995. Simulation of large-scale coastal change using a morphological behaviour model. Marine Geology, 126(1-4), pp. 45 - 61.

Davison, A.T., Nicholls, R.J., and Leatherman, S.P., 1992. Beach nourishment as a coastal management tool: An annotated bibliography on developments associated with the artificial nourishment of beaches. Journal of Coastal Research, 8(4), pp. 984-1022.

Garcia, V., Jimenez, J.A., and Sanchez-Arcilla, A., 1997. Temporal and spatial variability of the depth of closure in the Ebro delta. First Annual PACE Workshop, Abstracts-In-Depth, Abstract #1.4, 4pp.

Hallermeier, R.J., 1978. Uses for a calculated limit depth to beach erosion. Proc. 16th Coastal Engineering Conf., ASCE, New York. pp. 1493 - 1512.

Hamm, L., 1997. Prediction of Aggregated-Scale Coastal Evolution. Task force on data sets. Summary of available data sets. Sogreah Ingenierer, Grenoble, France.

Hands, E.B., and Allison, M.C., 1991. Mound migration in deeper water and methods of categorising active and stable depths. Proc. Coastal Sediments '91, ASCE, New York. pp 1985 - 1999.

Hinton, C., 1998. The spatial and temporal behaviour of sediment volume changes and depth of closure along the Holland coast. Rijkswaterstaat Report.

Hinton, C., and Nicholls, R.J., 1998. Spatial and temporal behaviour of depth of closure along the Holland coast. Proc. 26th ICCE, Copenhagen, ASCE, New York. (in press).

Hoozemans, F.M.J, 1990. Long term changes in wind and wave climate on the North Sea, Proc. 22nd ICCE, ASCE, New York. pp. 1888 - 1894.

Houwman, K.T., and Hoekstra, P., 1994. Shoreface sediment dynamics. Report part II, Coastal Genesis Project.

Kana, T.W., 1995. A mesoscale sediment budget for Long Island, New York. Marine Geology, 126, pp. 87-110.

Kraus, N.C., and Harikai, S., 1983. Numerical model of shoreline change at Orai beach. Coastal Engineering, 7, pp. 1-28.

Lee, G., Nicholls, R.J., and Birkemeier, W.A., 1998. storm-driven variability of the beach-nearshore profile at Duck, North Carolina, USA, 1981 - 1991. Marine Geology, 148, pp.163-177.

Marsh, S.W., 1998. Volume calculation programme for beach and nearshore profile data. Internal Report, Flood Hazard Research Centre.

Marsh, S.W., Nicholls, R.J., Kroon, A., and Hoekstra, P., 1998. Assessment of depth of closure on a nourished beach: Terschelling, The Netherlands. Proc. 26th ICCE, Copenhagen, ASCE, New York. (in press).

Meene, van de, J.W.H., 1994. The shoreface connected ridges along the central Dutch coast, The Netherlands. PhD Thesis, Utrecht University, Department of Geography, The Netherlands. 222pp.

Nanninga, M., 1985. The accuracy of echo sounding - description in a mathematical model. Masters Thesis. Rijkswaterstaat, National Institute for Coastal and Marine Management/RIKZ.

Nicholls, R.J., Birkemeier, W.A., and Hallermeier, R.J., 1996. Application of the depth of closure concept. Proc. 25th ICCE, Orlando (USA), ASCE, New York pp. 3874- 3887.

Nicholls, R.J., and Birkemeier, W.A., 1997. Morphological and sediment budget controls on depth of closure at Duck, NC. Proc. Coastal Dynamics 1997, ASCE, New York. pp. 496 - 505.

Nicholls, R.J., Birkemeier, W.A., and Lee, G., 1998. Evaluation of depth of closure using data from Duck, NC, USA. Marine Geology, 148, pp. 179-201.

Nicholls, R.J., Larson, M., Capiobianco., and Birkemeier, W., 1998. Depth of closure: improving understanding and prediction. Proc. 26th ICCE, Copenhagen, ASCE, New York. (in press).

Niedoroda, A.W., Swift, D.J.P., and Hopkins, T.S., 1985. The shoreface. In: Coastal sedimentary environment, Ed., Davis, R.A. pp. 533 - 615.

Niedoroda, A.W., Reed, C.W., Swift, D.J.P., Arato, H, and Hoyanagi, K., 1995. Modelling shore-normal large-scale coastal evolution. Marine Geology, 126, pp. 181-199.

Rijn, L.C. van, 1995. Sand budget and coastline change of the central Dutch coast between Den Helder and Hoek van Holland. Report H2129, Delft Hydraulics. The Netherlands.

Roelvink, J. A., and Stive, M. J. F., 1990. Sand transport on the shoreface of the Holland coast. Proc. 22nd Coastal Engineering Conf., ASCE, New York. pp. 1909 - 1921.

Roelvink, J.A., Boutmy, A.E.G., and Stam, J-M, T., 1998. A simple method to predict long-term morphological changes using complex model results. Proc. 26th ICCE, Copenhagen, ASCE, New York. (in press).

Roskam, A.P., 1988. Golfklimaten voor de Nederlandse kust. Rijkswaterstaat, Nota GWAO-88.046, 21pp. + figures.

Rózynski, G., Zielder, R.B., and Pruszak, Z. Depth of closure and seabed variability patterns. Proc. 26th ICCE, Copenhagen, ASCE, New York. (in press).

Ruig, J.H.M. de, and Louisse, C.J., 1991. Sand budget trends and changes along the Holland coast. Journal of Coastal Research, 7, pp.1013-1026.

Stive, M.J.F., Roelvink, J.A., and De Vriend, H.J., 1990. Large-scale coastal evolution concept. Proc. 22nd Coastal Engineering Conf., ASCE, New York. pp. 1962 - 1974.

Stive, M.J.F., De Vriend, H.J., Nicholls, R.J., and Capiobianco, M., 1992. Shore nourishment and the active zone; a time scale dependant view. Proc. 23rd Coastal Eng. Conf., ASCE, New York. pp. 2464-2473.

Stive, M.J.F., and De Vriend, H.J., 1995. Modelling shoreface profile evolution. Marine Geology, 126, pp. 235 - 248.

Vessem, P. van, and Stolk, A., 1990. Sand budget of the Dutch coast. Proc. 22nd Coastal Eng. Conf., ASCE, New York. pp.1895-1908.

Vriend de, H.J., 1991. Mathematical modelling and large-scale coastal behaviour, Part 1: Physical processes. Journal of Hydraulic Research, 29, pp. 727-740.

Walstra, D.J.R., Rijn, L.C., van, and Aarninkhof, S.G.J., 1998. Sand transport at the middle and lower shoreface of the Dutch coast. Report no. Z2378. Delft Hydraulics, The Netherlands.

Wijnberg, K.M., 1995. Morphologic behaviour of a barred coast over a period of decades. PhD Thesis, Utrecht University, The Netherlands. 250pp.

Wright, L.D., Boon, J.D., Kim, S.C., and List, J.H., 1991. Modes of cross-shore sediment transport of the shoreface of the Middle Atlantic Bight. Marine Geology, 96, pp. 19-51.

Wright, L.D., 1993. Micromorphodynamics of the inner continental shelf: a Middle Atlantic Bight case study. Journal of Coastal Research, 15, pp. 93 - 124.

Wright, L.D., Xu, J.P., and Madsen, O.S., 1994. Across-shelf benthic transports on the inner shelf of the Middle Atlantic Bight during the Halloween storm of 1991. Marine Geology, 115, 61.

< 63 mu

63 – 150 mu

150 – 210 mu

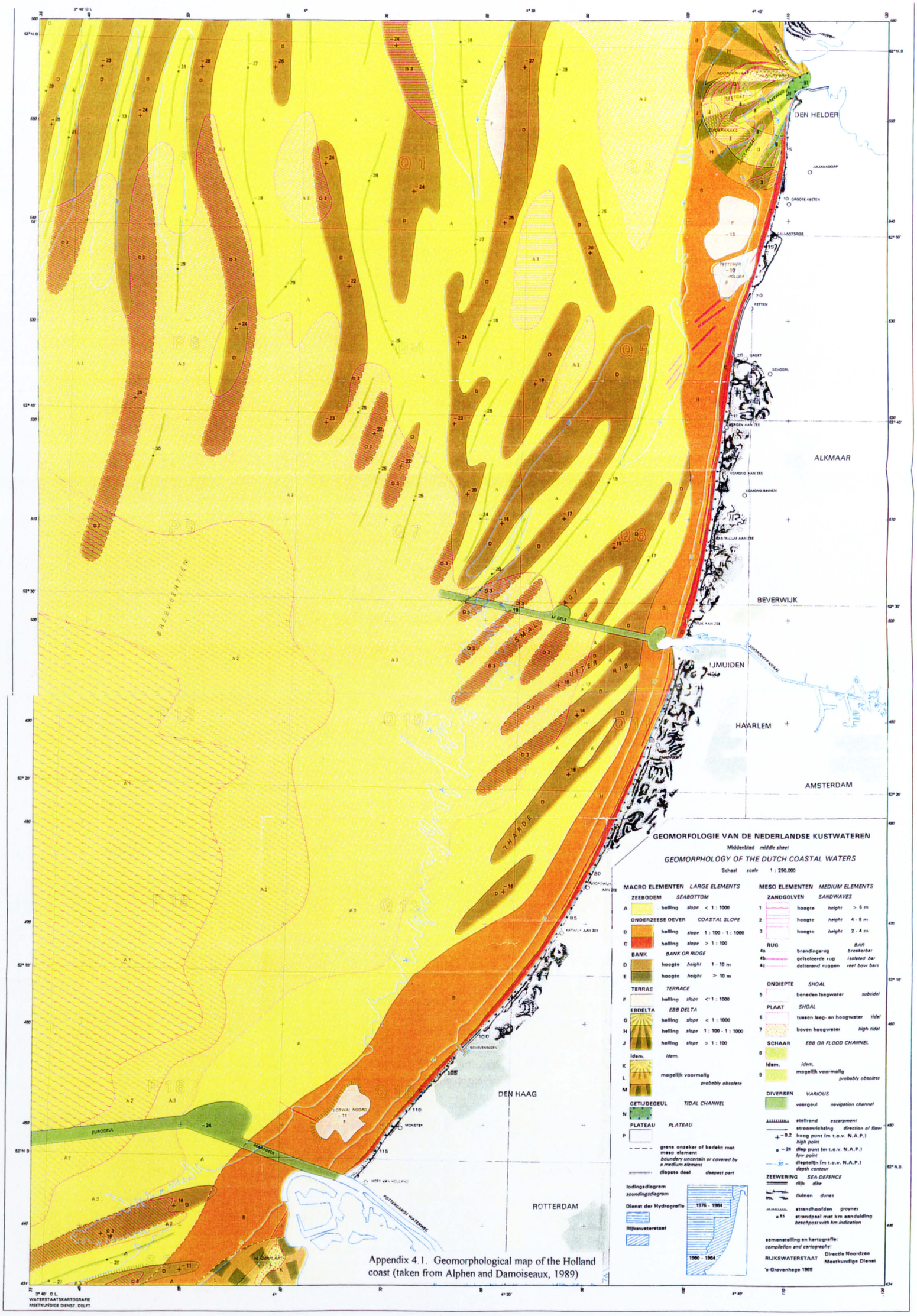
210 – 300 mu

300 – 420 mu

420 – 600 mu

> 600 mu

Appendix 4.2. Map of the upper 1 m of sediment of the Holland coast (Geological Survey of the Netherlands, 1998)



Appendix 4.1. Geomorphological map of the Holland coast (taken from Alphen and Damoiseaux, 1989)