The interpretation of seabed dynamics on the Netherlands Continental Shelf

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M.Sc. thesis

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Preface

The report laying in front of you, is the result of a seven month investigation at the Hydrographic Office in the Hague. Written as the completion of my study Civil Engineering at the University of Twente, this assignment was issued by the Department for Water Engineering and Management in combination with the Hydrographic Office. Over the last half year, I studied the process of chart making and the influence of seabed dynamics on the planning of resurvey efforts. The experiences I had as a 'member' of the team, will cross my mind every time I use nautical charts on board my parents' sailing yacht from now on. This report could, off course, not be completed without the patience and help of several involved persons.

First, I would like to thank the members of my graduation committee, starting with my daily supervisor Leendert Dorst. His patience, valuable assistance, and critical comments, made it all a lot more bearable. Furthermore my gratitude goes to Suzanne Hulscher and Pieter Roos for their assistance and support.

I would also like to thank my friends (especially my diving buddies!) and roommates, for making my student years in Enschede a great time! Finally, but certainly not least, my gratitude goes to my family for their support in the hard times! Love you!

Bregt Huizenga
Enschede
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Abstract

To ensure the safety of navigating vessels on the Netherlands Continental Shelf (NCS), the Hydrographic Service surveys the Shelf with Multi Beam Echo sounders. The deployment of the survey vessels is done according to a survey policy, which contains resurvey frequencies for each specific area. The survey policy is based on four factors: Minimum depth, draught, shipping intensity and seabed dynamics. Based on the survey policy, yearly survey instructions are issued. These instructions are resulting from a comparison of the age of the contents of the source databases and the maximum age allowed by the survey policy. The current problem is now the result of reliability problems of the survey vessels and the relatively high frequencies of the survey policy. When compared to neighboring countries, these frequencies are rather ambitious, and the question is now if it is possible to reduce these frequencies with the aim to optimize the survey policy.

In this study, we focus on optimization of the survey policy by means of the interpretation of seabed dynamics. In the southern NCS, several bed forms are present, which have a strong influence on the navigation safety in the shallow sections. Over the last years, a project has been initiated that analyses selected areas in the southern NCS with a statistical method called deformation analysis. This method approximates the seabed with a spatial representation, which is then analysed with a temporal testing procedure to discuss the dynamic character. However, to include the results of this statistical analysis in the reconsideration of the resurvey frequencies of the survey policy, a proper interpretation of the detected dynamics is mandatory. In this study we introduce an approach to zoom in on the most critical areas (areas with the highest risk), based on the factors minimum depth, draught, shipping intensity and influence of human interventions. This last factor is included due to the increased spatial use of the NCS, and recent area planning. We call this selection of the critical areas, the initial prioritization. To quantify the factors for this prioritization, interviews have been executed at the Hydrographic Service. Furthermore, we use a background chapter on the technologies and methods of surveying to become more familiar with the different error sources.

The prioritized areas of the NCS are now included in the further procedure of this study. Based on the background knowledge of the statistical testing procedure, a method is designed that calculates the maximum depth variation within a grid (an area that includes nodes with interpolated depths). In this study, we focus on a zero dimensional method that analyses each node within this grid individually. By calculating the maximum depth variation within the grid, we can characterize the seabed dynamics. This method has been applied on a test area. For this test area, five different scenarios with varying levels of simulated dynamics are tested. The resulting maximum depth variations can be used for a quick characterization of the seabed. Furthermore, we combine the requirements for the area in which the grid is located, to interpret this maximum depth variation. To gain more accurate results and for estimation of pattern dynamics we need a regional approach.

For the interpretation of the dynamic character of the seabed, we need a temporal and spatial generalization. By comparing the difference in maximum depth variations over different time scales, we can check if the current resurvey frequency of the survey policy is suitable for this location. If the difference is small, we generalize the results in a temporal way. For the spatial generalization we require detailed information on seabed composition, flow properties, and depth. If we find considerable levels of seabed dynamics on one location, and we find another area with the same physical properties, a spatial generalization is possible. Both temporal and spatial generalization must be executed with great cause and after further research in this field.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

The North Sea is known for its high shipping intensity and its densely used territory. With some of the world's largest ports (for instance Rotterdam, Antwerpen, London and Hamburg) situated along the coast, safety of shipping is of great importance. Due to the relatively small depths, high tidal amplitudes and its unique location, under keel clearance (UKC[1]) is a core problem in ensuring this safety. The seabed of the continental shelf of the North Sea is dynamic, with bed forms migrating across the seafloor. This variable seabed is the main interest regarding water depth. The Hydrographic Service of the Royal Netherlands Navy (NLHS[2]) is responsible for the monitoring of the Netherlands Continental Shelf (NCS) (depicted in **Figure 1.1**).

Figure 1.1: The Netherlands Continental Shelf. The dark grey area is the territorial zone, while the light grey area is the Exclusive Economic Zone *(La Mer, 2006)*.

[1] The distance between the keel and the seafloor

[2] Royal Netherlands Hydrographic Service

The NLHS operates on the basis of a survey policy, which gives resurvey frequencies for specific regions of the continental shelf. These frequencies are partly based on the factor seabed dynamics. However, areas with high levels of seabed dynamics are difficult to survey with a fixed frequency. Over the last years, more attention has been given to this dynamic character of the seafloor, which resulted in the Seafloor Monitoring project. This project is based on a statistical method to analyse time series of depth data. The desired result from this project is that the resurveying of specific parts in the North Sea is scheduled more efficiently. To do this, a necessary step is to interpret the results from this statistical method, with the aim to reconsider the resurvey frequencies of the current survey policy. In the following section, we introduce the factor seabed dynamics in greater detail to offer a short background in the dynamic character of the Netherlands Continental Shelf.

1.1 Seabed morphology

In general, five types of seabed patterns are identified for the North Sea, presented in order of increasing wavelength in **Table 1.1**. The most important aspects of seabed morphology for nautical charting are amplitude growth and migration. When looking at the directions with respect to the principal tidal axis, there is a large diversity between the bed form types, which implies a complicated topography of the seafloor. It is possible that they occur together leading to superimposed bed forms that can have significant heights.

Table 1.1: Seabed patterns of the North Sea *(Knaapen, 2004)*

Type	**Wavelength** [m]	**Max. Ampl.** [m]	**Migr. rate**	**Dir. w.r.t. tidal streams** [deg]
Ripples	~ 1	~ 0.01	~ 1 m/hour	-
Mega-ripples	~ 10	~ 0.5	~ 1 m/day	$0-20$
Sand waves	~ 500	~ 10	~ 10 m/year	$70-90$
Long bed waves	~ 1500	~ 5	~ 1 m/year	$50-60$
Tidal sandbanks	~ 5000	~ 10	~ 1 m/year	$0-30$

The presence of sand wave patterns are largely dependent on the composition of the seabed. With a high percentage of sand in the sediment, the likelihood of sand wave patterns increases significantly. As can be read in *Hulscher and Van den Brink (2001)*, the occurrence of sand waves in the North Sea is almost exclusively restricted to sandy beds (varying from sand to gravelly sand). On locations where a moderate or high percentage of gravel is present, sand waves do not occur. In **Figure 1.2**, the occurrence of sand wave patterns and tidal sand banks in the North Sea are depicted.

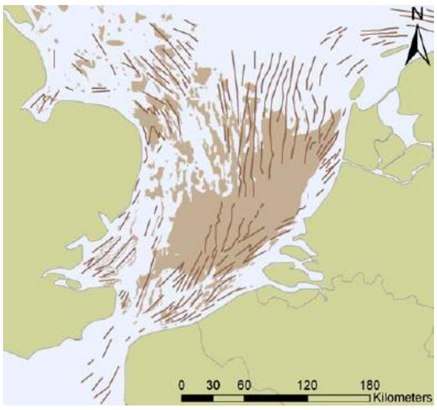

Figure 1.2: Sand wave (brown areas) and sand bank (lines) occurrence in the North Sea *(Van der Veen et al., 2006)*

North of the island of Texel, almost no sand waves are found anymore. The southern NCS however is covered with sand wave patterns, and around 30 metres deep. Sand banks are more widespread and are often located closer to the coastline.

1.1.1 Sand waves and their properties

Sand waves only occur in seas with a noncohesive sand bed and a strong tidal motion *(Knaapen and Hulscher, 2002)*. Sand waves are capable of migrating across the seafloor with a speed of around 10 metres per year, depending on the flow conditions (**Table 1.1**). Due to this migration phenomenon, sand waves have a significant influence on water depth in shallow areas of the North Sea. Sand waves have a typical wavelength of several hundreds of metres and reach heights of 30 % of the average water depth. For example sand waves in the Noord-Hinder area (west of Rotterdam, halfway between the Netherlands and the English coast) have, according to *Németh et al. (2007)*, a wavelength of 300 metres and an amplitude of 6 metres. A typical example of a sand wave pattern in the North Sea is given by **Figure 1.3**.

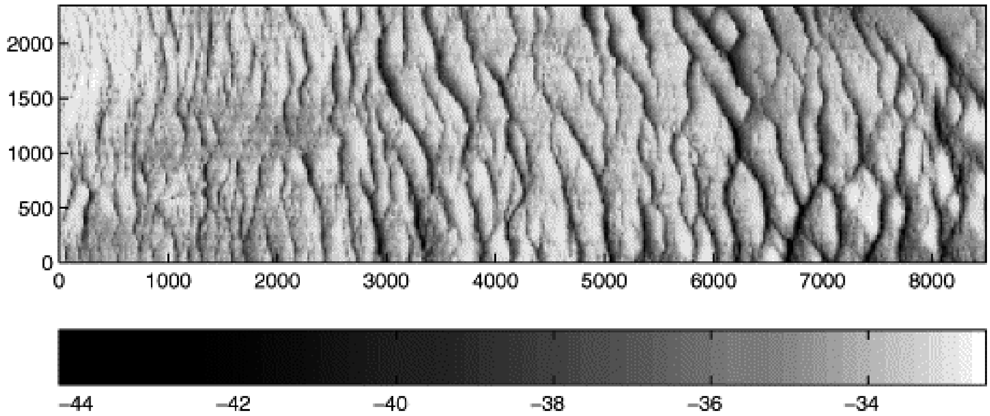

Figure 1.3: The image shows bathymetry measurements of an area near the Euro channel. The horizontal coordinates are given in metres (for x- and y-direction), and the gray scale bar gives the seabed level below mean sea level (in metres). Courtesy Rijkswaterstaat, North Sea Directorate.

Another problem is the exposure of pipelines resulting from migrating bed forms *(Németh, 2003)*, which leads to a potential failure point (resulting in high repair costs, or necessary rerouting of the previously installed pipelines). Also, sand wave regeneration is important in areas that are dredged. In *Knaapen and Hulscher (2002)*, the regeneration speed of sand waves is modeled, which can be used in the optimization of dredging activities. Vertical flow circulation patterns are crucial in the dynamics of sand waves, with a strong near bed circulation and weaker reversed circulation in the top section of the water column. Resulting from these flow patterns is a net sediment transport to the crests of the sand waves, which causes the pattern to grow *(Hulscher, 1996)*. After dredging, which implies removal of a part of the crests, the sand wave regenerates to its equilibrium form. The regeneration speed of the sand wave used to be represented by a linear trend. But because the growth speed directly after dredging is much higher than this linear trend suggests, a different approach is mandatory. For this purpose, *Knaapen et al. (2006)* proposed a regeneration model based on a Landau equation *(Knaapen and Hulscher, 2002)*.

1.1.2 Relevance of sand waves

The reason that sand waves are of great importance for the NLHS, is their amplitude and their migration. Ripples and mega-ripples have a small amplitude and are therefore not posing a significant threat for shipping. Long bed waves and tidal sandbanks have very low migration speeds which makes them rather stable. With migration speeds in the order of several metres per year, the sand waves can become a threat for shipping on the North Sea. Increasingly large ships demand more draught[3], which leads to narrow margins with respect to under keel clearance (UKC).

1.2 Problem definition

The goal of this project is to describe how depth surveys and the results of the deformation analysis method (introduced in Chapter 5) can influence the survey policy of the Royal Netherlands Navy. The step between the data analysis process and the actual choice for a survey moment for that specific area, is not taken by a procedure yet. Resulting from the steadily increasing backlog with respect to the survey policy, a method for the optimization of the survey efforts is mandatory. If we speak of an optimization of the survey policy, it is important to indicate the difference between areas with high levels of seabed dynamics and areas with no (or low) dynamics. For the latter areas, it might be possible to reduce the survey frequency, while the frequency at the first locations cannot be reduced (or even need an increase). So, for areas with high levels of bed dynamics, it is important to interpret the results from the statistical data analysis. Proper interpretation leads to a better understanding of what actually happens at the sea floor and how it can be a factor in the future planning of survey moments. Also, planned projects or ideas that are still at the drawing board, need to be accounted for when estimating a proper resurvey frequency for a specific region. For example, the construction of a Maasvlakte II have significant influence on the behavior of bed forms in that region and thus creates a potentially hazardous situation for the Rotterdam approach route.

1.2.1 Research questions

The problem definition leads to the following central questions:

1. What is the current method for the construction of the survey policy, and how is the method of deformation analysis used as a tool for the involved data analysis process?
2. Can we use the proposed method for the interpretation of seabed dynamics for the benefit of improving the survey policy, and what results can we expect from this method?
3. How performs the proposed method on a small test area, and how can we generalize this in a spatial and temporal way?

[3]Depth minus UKC

1.3 Structure

To elaborate the structure of this report, we construct a flowchart that describes the relation between the chapters. As can be seen in **Figure 1.4**, we start with Chapter 2: Mapping the North Sea, which describes the used technologies and processes in chart making. In combination with Chapter 3: Interviewing at the NLHS, we now have a proper basis to make an initial prioritization of the areas on the NCS with the highest risk for navigation (Chapter 4: The initial prioritization). We now continue with a background chapter on the statistical data analysis that is used for the estimation of seabed dynamics. Based on this background and the initial prioritization of Chapter 4, we introduce a method for the interpretation of seabed dynamics in Chapter 6. We finalize this study by discussing the performance of this method in Chapter 7.

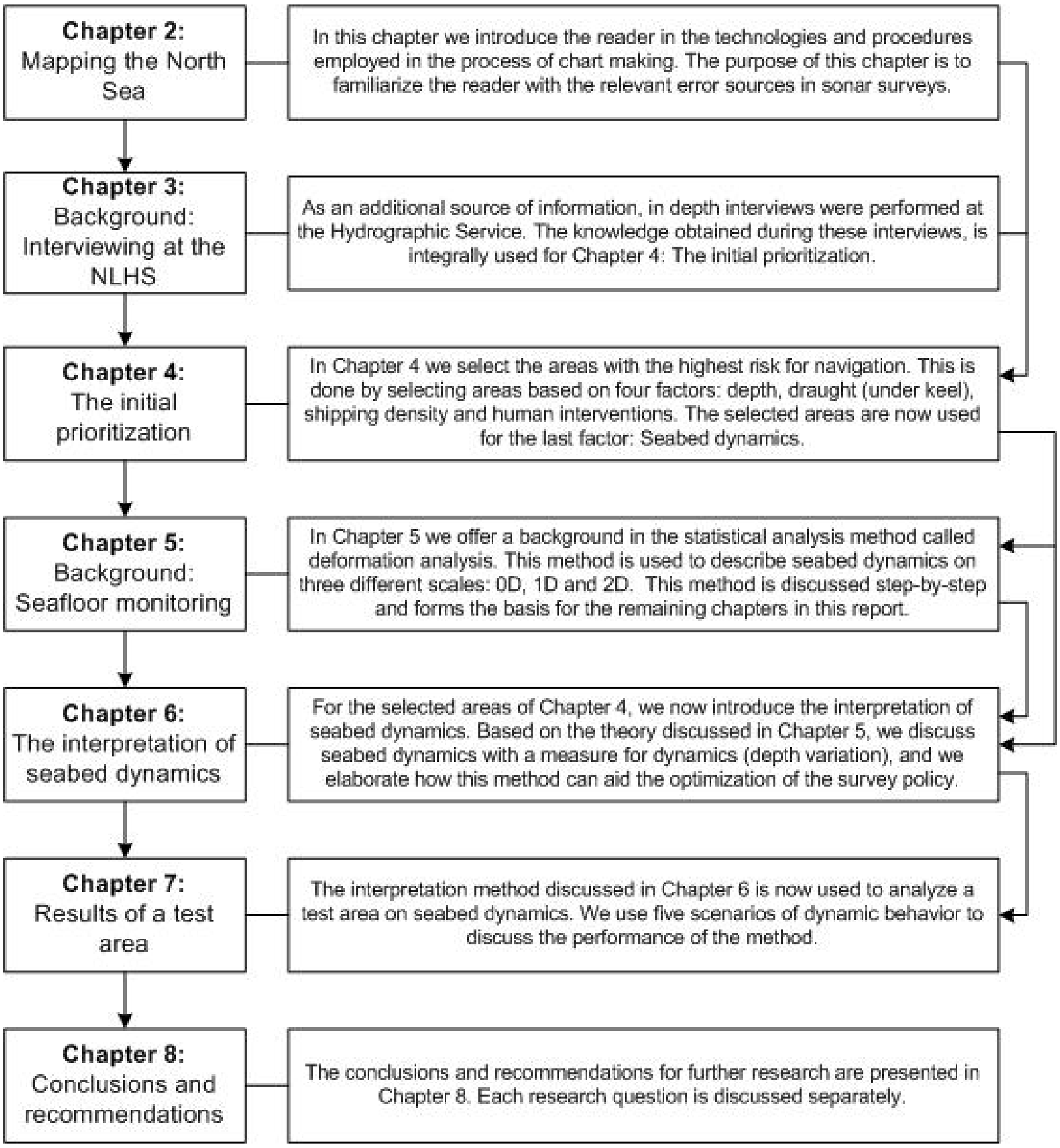

Figure 1.4: In this flowchart we shortly describe the structure of the report and we define how the chapters connect to each other. The arrows on the righthand side are showing that some chapters are necessary as a basis for the next chapter.

Chapter 2

Background: Mapping the North Sea

2.1 Introduction

In the nautical world, the nautical charts for oceans, shallow shelf seas and coastal waters are well known. As a prerequisite for safe ship navigation across the globe, it is of great importance that these nautical charts are up to date and are a reliable source of information. Over the last decades, the need for adequate nautical charts has been emphasized by the use of large draught VLCC (Very Large Crude Carrier) ships, the need to protect the environment, changing trade patterns (for example shipping routes), the growing need for seabed resources and the UNCLOS (United Nations Convention on the Law Of the Sea) affecting the areas under the influence of nations. As defined in the Hydrographic Dictionary *(International Hydrographic Organization, 1994)*, a nautical chart is a graphic representation of the marine environment which shows the nature and form of the coast, the general configuration of the sea bed with inclusion of water depths, potential dangers for navigation, man-made objects in the water (buoys, offshore platforms and similar objects) and other features interesting for the chart user. To guarantee the safe navigation of the areas with a high shipping intensity, the International Maritime Organization (IMO) developed the SOLAS (International Convention for the Safety of Life at Sea) international treaty which has been initiated to ensure that hydrographic surveying is carried out adequately and according to the requirements for safe navigation. Other goals of the convention are to obtain the greatest possible uniformity in charts, and to ensure that hydrographic and nautical information is made available on a worldwide scale in a coordinated way.

The North Sea, is characterized by intensely used shipping lanes and relatively shallow waters. On the Netherlands Continental Shelf (NCS), shipping routes are leading to the ports of Rotterdam, Antwerp and Amsterdam (the latter reachable through the IJmuiden entrance), or are heading to the UK, Germany and Scandinavia. The purpose of this chapter is to describe how nautical charts are made at the NLHS from the depth measurements to the final product. This is important to understand their procedures and needs. Furthermore, we use this chapter to elaborate the different error sources. All technologies described, introduce error sources in the measurement of depths. By giving more detail in the procedure of chart making, these possible errors are given perspective.

2.2 The design of the NCS survey policy

A primary task for the production of nautical charts is the gathering of depth data of the particular area of interest. At the RNLN, data acquisition is done with two survey vessels: HNLMS Snellius and HNLMS Luymes, based in Den Helder. These HOV-s[1] operate on basis of the survey policy designed in 2003 by the POM[2] department of the NLHS. In this policy, the NCS is divided into subsections which are categorized into five classes of resurvey frequency (2, 4, 6, 10 and 15 years). These resurvey classes are implying that the available depth information will become outdated and possibly incorrect. Furthermore, the less frequently visited areas are still based, in great extent, on single-beam depth measurements (see Section 2.4.2). Although not directly critical, these regions will be resurveyed in the future with the use of multi-beam echo sounders to offer complete ensonification of the NCS. Next to these five classes, three other categories are specified of which two are surveyed by Rijkswaterstaat (areas near the coast and the entrances of the Euro-channel and IJ-channel). The final category includes the so called critical areas in the selected track, located in high intensity shipping routes with minimum under keel clearances (surveyed every two years). The survey policy can be seen in **Figure 2.1**.

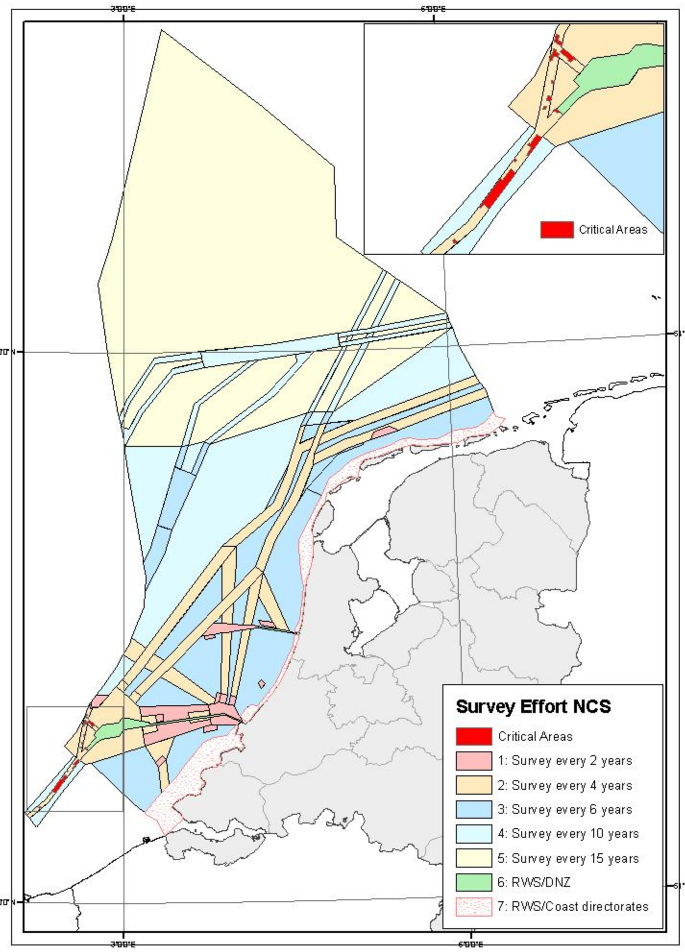

Figure 2.1: Survey policy of the Royal Netherlands Navy *(Hydrographic Service, 2003)*

[1]In Dutch: Hydrografisch Opnemings Vaartuig
[2]Planning, Operations and METOC, with METOC denoting METeorology and OCeanography

The current survey policy is based on four factors: Minimum depth, draught, shipping intensity and seabed dynamics. Areas with a maintained depth are designed such that a deep draught vessel should be able to navigate the route under all conditions of tide, swell or sea-state. For some areas however, for instance the Rotterdam approach route, this cannot be guaranteed and ships must wait for safe navigation conditions *(Hydrographic Service, 2002)*.

Seabed dynamics is less easily to include as a factor for designing resurvey frequencies. In the 2003 survey policy, seabed dynamics are included in a deterministic way. Areas with high seafloor dynamics are prioritized above less dynamic areas (see Appendix A). The year plan is derived from this general survey policy. It contains the areas which need to be surveyed in that specific year. The year plan results from an analysis of three aspects: the age of all surveys in the database (see Section 2.6 on bathymetric data management), a comparison of the age with the survey policy (**Figure 2.1**) and the survey priority (thus how to choose one area over another, when both areas are scheduled in the same year plan). The challenge of designing a correct year plan is the prioritization, which should ideally be based on a scientifically sound procedure.

Although the new HOV-s were built with the general survey policy in mind, the actual amount of realized Hydrographic Days (days with 24 hours of surveying) of the vessels has been too low to comply with the survey policy. This results in an backlog of around 800 days on the initial plan, which increases each year. This backlog has great implications for the design of the year plan, which aims to keep all the areas updated. In **Figure 2.2** the year plans for 2007 and 2008 are presented. As can be seen in the 2008 survey instructions, the amount of areas that are scheduled for resurveying is significantly higher than in 2007.

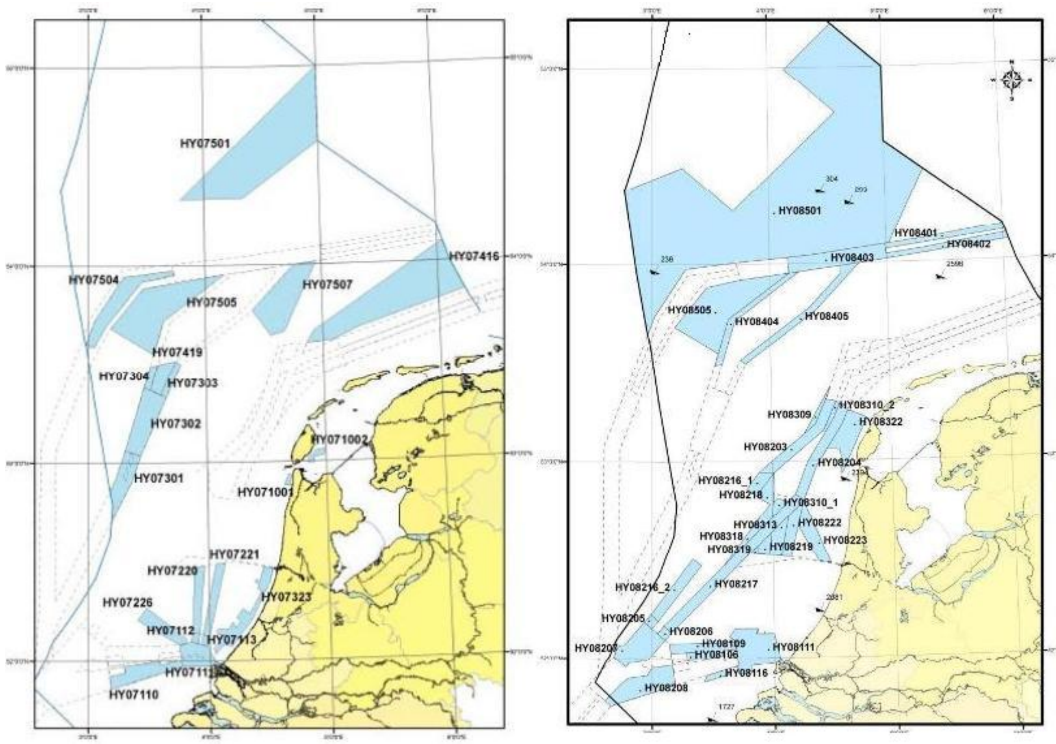

Figure 2.2: In this image we present the year plans for 2007 (left) *(Hydrographic Service, 2007)* and 2008 (right) *(Hydrographic Service, 2008)*. As can be seen, the amount of areas that are scheduled for resurveying is higher in 2008.

The emphasis of this backlog lays on the areas in the Northern NCP, which includes some locations that were last surveyed more than fifteen years ago. As can be seen in **Figure 2.2**, the Northern part of the NCS is partly included in the year plan. The areas around the port entrances (also scheduled), categorized as category 1 or 2 in the resurvey scheme, were last surveyed a few years ago. With the current deployment of the HOV-s in mind, the number of Hydrographic Days necessary to survey all the specified areas is too high to be accomplished. The increasing backlog becomes apparent when looking for example at the realized Hydrographic Days in 2006. Of the 256 planned recording days of the year plan, only 118 were realized, which is caused by malfunctions of the HOV-s, out of area work (the journey to the Netherlands Antilles and Aruba) and various other activities (for more details: see the interview registration in Appendix A). To decrease this backlog in Hydrographic Days, more work is scheduled for 2008. This implies more required Hydrographic Days, and to comply with this, the survey speed of the HOV-s is to be increased from 8 knots to 9.7 knots *(Hydrographic Service, 2008)*.

2.3 Data quality

Another important aspect in the bathymetric surveying of the NCS is that all activities must comply to the standards stated by the International Hydrographic Organization (IHO) in the publication S44 *(International Hydrographic Organization, 1998)*. In this document a classification of surveys is included, together with requirements on data attribution, the elimination of doubtful data and other specifications. The HOV-s of the RNLN have been equipped with a variety of sensors to meet these requirements, which includes:

- Differential Global Positioning System (DGPS): uses a reference receiver with a known location and a dynamic receiver on board the vessel. The reference receiver transmits a correction to the dynamic receiver, which can improve accuracy to approximately 2 metres in x- and y- direction.
- Long Range Kinematic GPS (LRK GPS): a differential GPS system that offers accuracy in the order of a few centimetres up to ranges of 40 kilometres.
- Single-Beam Echo Sounder (SBES): discussed in Section 2.4.2.
- Multi-Beam Echo Sounder (MBES): discussed in Section 2.4.3.
- Side Scan Sonar (SSS): discussed in Section 2.4.4.
- Motion sensor: discussed in Section 2.4.5.
- Sound Velocity Profiler: discussed in Section 2.4.6.
- Depth sensors (tide gauges): discussed in Section 2.5.2.
- Data processing equipment: for correction of bathymetric data the computer suite QINSy (Quality Integrated Navigation System) is used. This software package for hydrographic applications, is capable of subtracting tidal corrections and cleaning (filtering) of bathymetric data (single-beam and multi-beam). QINSy delivers reduced multi-beam data.

For the actual survey, echo sounding is the most common technique. Thanks to rapid technological advances, imaging of the seabed can now be done far more accurately than in the past. The use of multi-beam technology has led to a significant improvement in data coverage. The advance in positioning systems (DGPS, LRK GPS) resulted in a higher accuracy of the acquired data. The quality of the multi-beam data is not necessarily better than SBES data because multi-beam systems only improve the coverage. The actual quality of the data depends on the swath angle[3]. These aspects of multi-beam systems are covered in more detail in Section 2.4.3. All sensors described above introduce an error source in the surveyed depth, and thus influence the accuracy of the data.

[3]Angle between the vertical and the beam

2.4 Technologies

2.4.1 Introduction

Insight in echo sounding theory is necessary to understand the principle of depth measurement, also known as bathymetry. In hydrographic surveying the depth is determined from the observation of acoustic travel time. The basic components *(De Jong et al., 2003)* of an echo sounder used in bathymetric surveying are a transmitter (which generates the acoustic pulses), a T/R switch (which passes the power from the transmitter to the receiver), a transducer (which produces the acoustic signal, receives the echo and converts it back into an electric signal), a receiver (which amplifies the recorded echo signal and sends it to the recording system) and a recorder (which measures the time interval between the transmission signal and the reflection echo, calculates the travel time and stores the data as depth information). A simple graphic representation of the principle is given in **Figure 2.3**. Currently, three technologies are used in hydrographic surveying: Single-Beam Echo Sounders (SBES), Multi-Beam Echo Sounders (MBES) and Side Scan Sonars (SSS). These technologies are described in Section 2.4.2, 2.4.3 and 2.4.4 respectively. Finally, in Sections 2.4.5 and 2.4.6, the motion sensor and sound velocity profiler are discussed.

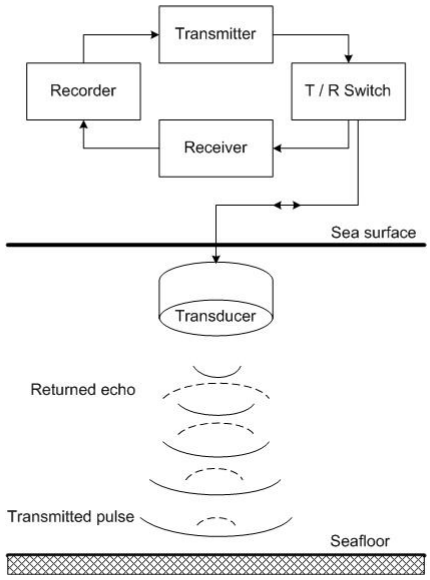

Figure 2.3: Basic Echo sounding system

2.4.2 Single-Beam Echo Sounder

Single-beam systems are based on a single acoustic signal which is directed vertically, if the platform is stable. The footprint (the ensonified area) is determined by the beam width of the transducer and the depth of the water column. The beam width is defined as the angle between lines at which the acoustic energy of the initial signal has fallen to half of the energy along the main axis (the vertical). In acoustic terms, this means an intensity decrease of three decibel. The total beam width is calculated by multiplying this angle by two (on each side of the main axis). For conventional single-beam sounders, the beam width is in the order of 3°. Currently, sounders with a narrower beam are available, which are capable of producing more accurate data. Using a wide beam, can be misleading if, for example, a large boulder is registered first (see **Figure 2.4**). Narrow beam sounders (which surveys only a small section of the bottom at a time) are often used to meet the IHO Special and Order 1 requirements *(De Jong et al., 2003)*. Disadvantage of these narrow beams is the susceptibility to motion influence, which implies a higher sensitivity for external influences like the wave climate.

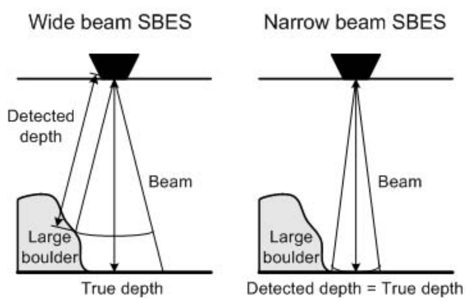

Figure 2.4: Wide beam SBES versus narrow beam SBES

2.4.3 Multi-Beam Echo Sounder

Multi-beam technology is a swath system that measures a swath of the seabed extending outwards from the sonar transducer. It offers the possibility of complete seabed coverage, something that hardly can be offered by single-beam systems. Typical for multi-beam echo sounders is that the transducer segments the echo into multiple beams. Multi-beam echo sounders are thus capable to acquire more depth information at one moment than single-beam systems. Because the survey vessel is a moving platform, it is very important to accurately measure the ship's movements and its location. Motion sensors are thus necessary equipment (see Section 2.4.5). Especially heave correction (discussed in Section 2.4.5) is important because this can have significant influence on data quality. In **Figure 2.5**, the multi-beam echo sounder technology is pictured as a hull mounted system below the water line. The transmitted signal is very wide in across track direction (perpendicular to the ship's heading) and narrow in along track direction (parallel to the ship's heading). The transducers are placed at an angle (a dual head system is pictured, but other multi-beam configurations are available), which leads to some overlap of footprints directly below the survey vessel. At maximum swath angle, the footprint becomes larger and more elongated in shape, which is caused by the larger distance traveled and the angle of inclination, respectively.

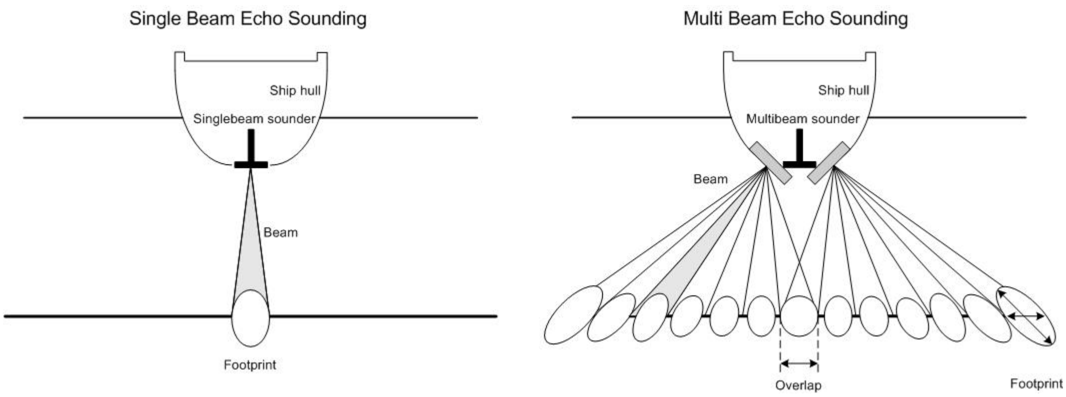

Figure 2.5: Single-beam versus Multi-beam

In the recorded echo, two types of information can be identified: depth, and reflectivity, which is related to the signal strength. The cycle of one transmission and one reception is named a 'ping'. With the recorded echo, depth (D) and across-track position (y) can be calculated (see **Figure 2.6**). In the absence of errors, D and y are given by Equations (2.1) and (2.2) (for single-beam echo sounders, Equations (2.1) and (2.2) can be used with ψ equal to zero). Both values are relative to the position of the echo sounder:

$$D = \frac{1}{2} c \Delta T \cos\psi, \tag{2.1}$$

$$y = \frac{1}{2} c \Delta T \sin\psi. \tag{2.2}$$

Here, c is the speed of sound in water (approximately 1500 m/s at sea, see Section 2.4.6), ΔT the time lapse between the beam transmission and the matching reflection signal, and ψ the swath angle (see **Figure 2.6**). When planning a multi-beam survey, the survey line spacing is chosen according to the specifications of the swath width of the used sounder. To avoid gaps in the surveyed data and to increase reliability, a level of overlap is created between the survey trakcs. Furthermore, cross-lines are sailed for quality control. Equations (2.1) and (2.2) are not sufficient for the actual situation, because different sources of error need to be accounted for. Typical errors are those resulting from depth measurement, acoustic propagation, beam steering, beam angle, transducer misalignment, attitude (heave, pitch and roll of the recording vessel, see Section 2.4.5), system calibration and tides and other water level effects. The charted depths are a summation of observed depth, instrumental corrections, dynamic draught correction (also known as squat, the draught component that depends on the vessel speed), sound velocity correction and water level correction (tidal reduction to Lowest Astronomical Tide, see Section 2.5.2).

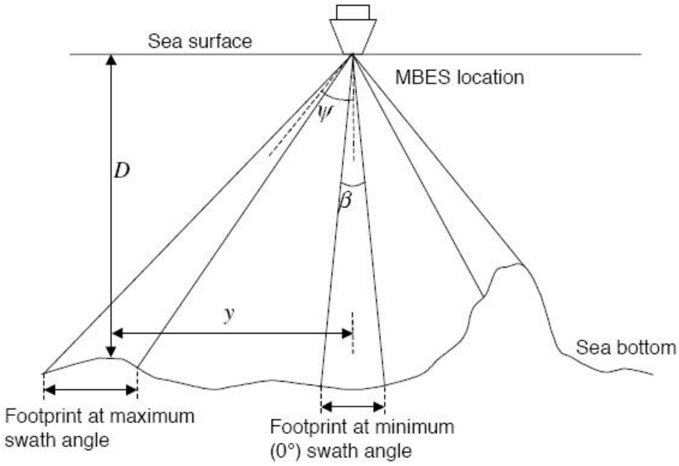

Figure 2.6: Multi-beam footprints (from: *(De Jong et al., 2003)*)

2.4.4 Side Scan Sonar

Side Scan Sonars (SSS) are systems which are usually not directly fixed to the hull of the survey ship. The system uses a towfish equipped with a sonar (SOund NAvigation and Ranging) to detect obstructions like wrecks and similar objects on the sea floor. The technology is usually used as additional equipment and is also used for the purpose of chart making. Often, SSS is used in the field for object detection and investigation (like a wreck or a container). In **Figure 2.7**, the principle of Side Scan Sonar is shown.

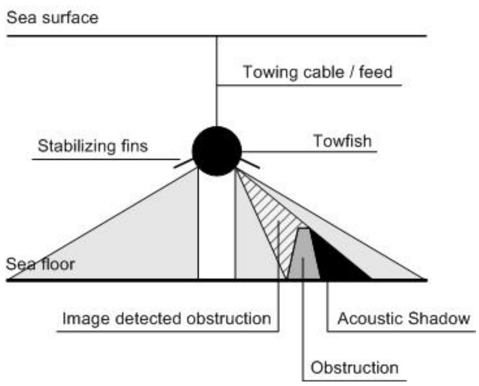

Figure 2.7: Side Scan Sonar

2.4.5 Motion measurement

To increase the quality and the accuracy of bathymetric data, it is necessary to correct the movements of the survey platform. A vessel at sea has three axes and six degrees of freedom (three translations: lateral movements along the ships axes, and three rotations). In **Figure 2.8**, these six degrees of freedom are pictured in relation to the Center of Gravity (CG) of the vessel. Because lateral movement along the two horizontal axes are corrected by the horizontal positioning system, the required motion measurements are roll, pitch and. Also, the relative position of the motion sensor is an important factor for motion correction. For example, a large distance between the echo sounder and the position of the motion sensor causes pitch induced heave, meaning that a pitch movement creates an heave movement at the motion sensor position and a different heave movement at the echo sounder location. This difference must be corrected for. When in range of LRK GPS (Section 2.2), heave (and pitch induced heave) can be corrected using this system instead.

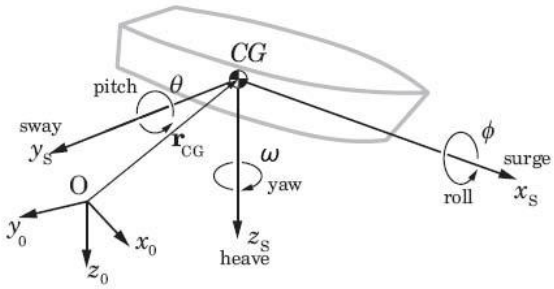

Figure 2.8: Rotation axes of a vessel. For each axis we identify a translation (movement along the ship's axis) and a rotation *(Kreuzer and Pick, 2003)*.

2.4.6 Sound Velocity Profiling

The velocity of sound in water is essential for the processing and interpretation of bathymetric data, as water depths are calculated by multiplying the one way travel time by the sound velocity. Because sound velocity in water can vary from approximately 1400 to 1575 m/s *(Engineering-Toolbox, 2008)*, depending on temperature, salinity, and pressure, a sound velocity profiler is used to provide corrections under local conditions.

Temperature variations in the vertical direction have significant influence on depth measurements. A thermocline (a sudden decrease in water temperature) for example can cause a sound velocity variation in the order of 4.5 m/s per degree decrease in temperature *(International Hydrographic Organization, 2005)*. Below the thermocline, the water temperature tends to a constant value, and the influence on sound velocity variation decreases. Salinity is defined as the quantity of dissolved salts and other minerals in the water, and is calculated for the locations of interest to correct depth measurements. For single-beam data, it is sufficient to use the average sound velocity in the vertical direction. For multi-beam data however, ray tracing[4] is necessary to compensate for refraction between different layers of water, especially at larger swath angles. This refraction is often the main cause of error for MBES data.

[4] The full calculation of the path of a sounding beam through a water column containing variable sound velocity layers

2.5 Reference systems

2.5.1 Introduction

When conducting hydrographic surveys, it is critical to reference the acquired data to the required vertical and horizontal datum. To correct the tidal influence on depth measurements, the vertical datum is used as a plane of reference, while the horizontal datum is used for position measurement. Sections 2.5.2 and 2.5.3 introduce the datums used at the NLHS. The definitions used in this section are taken from the Hydrographic Dictionary *(International Hydrographic Organization, 1994)*.

2.5.2 Vertical datum

At the NSHC[5], the agreement is to use LAT (Lowest Astronomical Tide). LAT is the lowest water level that can occur as a result of the tidal effects of astronomical bodies and local geographical circumstances. In the Netherlands, the transition from the MLLWS (Mean Low Low Water Springs) to LAT started in 2006, and gradually all products of the NLHS will be corrected to LAT. As can be seen in **Figure 2.9**, LAT is lower than the previously used MLLWS, leading, in general, to a decrease in charted depth of up to 6 decimetres *(Kwanten and Elema, 2007)*. North of Hook of Holland, an increase in charted depth can be seen, which is due to an incorrect estimation of the MLLWS datum at this location, which has now been corrected.

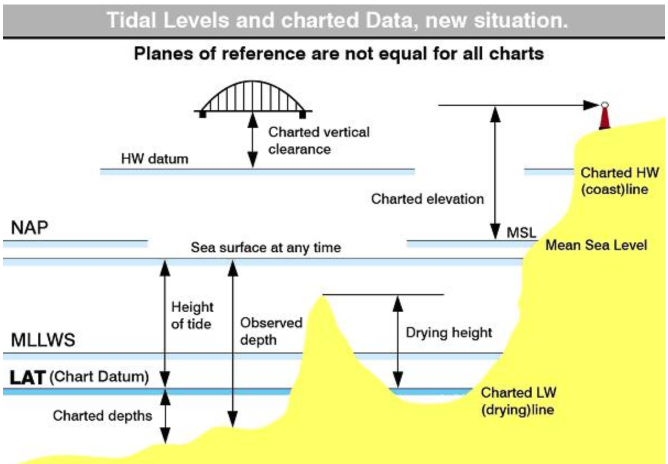

Figure 2.9: Tidal levels *(Kwanten and Elema, 2007)*. The geoid coincides with the MSL (Mean Sea Level).

When LAT is used over the entire North Sea, the charted depth is always guaranteed during normal weather. The transition from MLLWS to LAT has no influence on the UKC (Under Keel Clearance) of ships, because the difference between the datums is compensated by adding more tidal rise to the actual water levels above LAT.

[5]**N**orth **S**ea **H**ydrographic **C**ommission - members in alphabetical order: Belgium, Denmark, France, Germany, Iceland, Netherlands, Norway, Sweden and the United Kingdom.

Using a reference datum (which is based on water level measurements) requires that the recorded depth data must be reduced to the used system. To achieve this, three possible reduction methods are available:

1. LRK GPS (discussed in Section 2.2). Because of the limited range of this system, LRK GPS can only be used for the coastal zone.

2. Pressure sensors (tide gauges). These gauges are usually placed on the seabed to measure pressure variations, which are used to calculate depth changes over time.

3. Interpolation between permanent tide gauges.

This offshore tidal reduction introduces a considerable additional error source. Further away from the coast, this error often is the largest in the error budget.

2.5.3 Horizontal datum

The horizontal datum used at the RNLN is defined as WGS84, or World Geodetic System 1984. According to the *International Hydrographic Organization (2005)*, the system represents an Cartesian OXYZ system with the origin (O) at the center of the Earth's conventional mass, and the Z-axis directed to the conventional North Pole. Commonly, we use geographic coordinates in this system. By referring all acquired bathymetric data to this system, the produced charts can be used seamlessly worldwide. The vertical positioning is relative to the ellipsoid, which is the best mathematical approximation of the shape of the earth. When compared to horizontal positioning w.r.t. to the geoid, which is defined as a Mean Sea Level (MSL) surface extended continuously though the continents *(International Hydrographic Organization, 1994)*, the main differences are caused by irregularities in the mass of the Earth. WGS84 is regarded as the best *global* ellipsoid. For practical purposes, WGS84 positions are assumed equal to ETRS89[6], which is its regional realization for Europe. Differences include plate tectonics. A Universal Transversal Mercator (UTM) projection is used for positioning as well. For this purpose, the Earth is divided into 60 zones, which are used in constructing an UTM- coordinate. For example in the Netherlands, a coordinate includes an Easting in m, a Northing in m, the zone number 31, and the used horizontal datum, WGS84.

2.6 Bathymetric data management

At the RNLN, the Production department is responsible for the gathering of data, the analysis and processing of the incoming information and the actual publication of the products. The input data comes from the HOV-s, Rijkswaterstaat, the Offshore industry (information on cables, pipelines and platforms), the Netherlands Land Registry Office (topographic information) and multiple other sources. After the processing at the HOV-s, the data is further analysed in the post- processing phase to deliver cleaned depth information. After this stage, the data is stored in BAS (Bathymetric Archive System) in a 5 x 3 metre grid, containing the depth information for each cell. By combining the data of BAS in 25 x 15 metre grid cells in the Representative Bathymetric File (RBB), the minimum depth for each grid cell is obtained. From the RBB, the depth information comes into the TLDB[7] system , in which the representative depth data are combined with topographic information and information of the other sources specified above. In TLDB, are now drawn. After colouring, and including buoys, landmarks and other information, the actual navigational chart takes its final shape.

We now proceed to Chapter 3 in which we introduce the interviewing phase of this investigation. Combined with the knowledge obtained in this chapter, we have a proper basis for the further steps in this study.

[6]**E**uropean **T**errestrial **R**eference **S**ystem 1989

[7]Topographic Lines and Depths File

Chapter 3

Interviewing at the NLHS

3.1 Introduction

Interviews are conducted at the POM department of the NLHS. The goal of these interviews is to gain knowledge on survey planning, and on how seabed dynamics are currently included. We use the knowledge obtained during these interviews in combination with the background described in Chapter 2, for the prioritization of the areas with the highest risks for navigation. This prioritization is described in Chapter 4.

This chapter will shortly introduce the interview methodology that is used for the formulation of the interviews and the actual conversations. Furthermore, we introduce the respondents and a short summary of the interviews. The full methodology, used questions and a combined registration of the interviews can be found in Appendix A.

3.2 Methodology

Important for a quality interview is a proper methodology and preparation. In this investigation a combination of different interviewing styles is chosen. Instead of choosing for a highly structured or a highly unstructured interview, which are described in *Millar et al. (1992)*, we opt for a method that falls between these two types. We call this type moderately structured and it is characterized by a high level of topic control (we use the topics discussed in Section 3.3), a fixed number of questions, a semi-variable question sequence and variable response alternatives. By giving the respondents the freedom to answer the questions in their way, the interview obtains a conversation style. The methodology is elaborated in more detail in Appendix A.1. We now introduce nine question topics, each with a fixed number of questions.

3.3 Question topics

The formulated questions are ordered into topics to obtain a structured and logical sequence. The chosen topics are (sequenced):

1. **General survey policy:** this category involves the current method of survey planning and the factors that are relevant in this process.
2. **Evolution of the survey policy:** includes questions on the development of the resurvey frequencies, and how seabed dynamics were accounted for in previous survey policies.
3. **Technology:** involves questions on equipment reliability, accuracy and expected improvements.
4. **External influences:** this category includes questions on external assignments.
5. **Data management:** included to gain knowledge on how data is transferred through the several departments of the NLHS.
6. **National cooperation:** involves questions on the collaboration with the Directorate-General of Public Works and Water Management (within the NHI[1]).
7. **Cooperation with foreign countries:** this category includes questions on the cooperation with foreign hydrographic offices, and how this cooperation can lead to survey policy standardization.
8. **Expected developments in Hydrographic surveying:** includes questions on the necessity of hydrographic surveying, and the expected developments in optimizing the survey policy.
9. **Seafloor monitoring:** includes questions on the currently used method of seafloor monitoring, and what results are expected with respect to the adaptation of the survey policy of the NCS.

For each topic we now formulate interview questions. These questions are included in Appendix A.2.

[1]Netherlands Hydrographic Institute

3.4 Respondents

To use the results from the interviews for the purpose of this investigation, it is important to interview selected people with a level of knowledge that, when combined, covers the subject as complete as possible. In this section, an overview is presented of the organizational structure of the NLHS. On basis of this structure a selection is made of the required interviewees. **Figure 3.1** shows the organizational structure in a top-down visualization, with all departments and subdepartments.

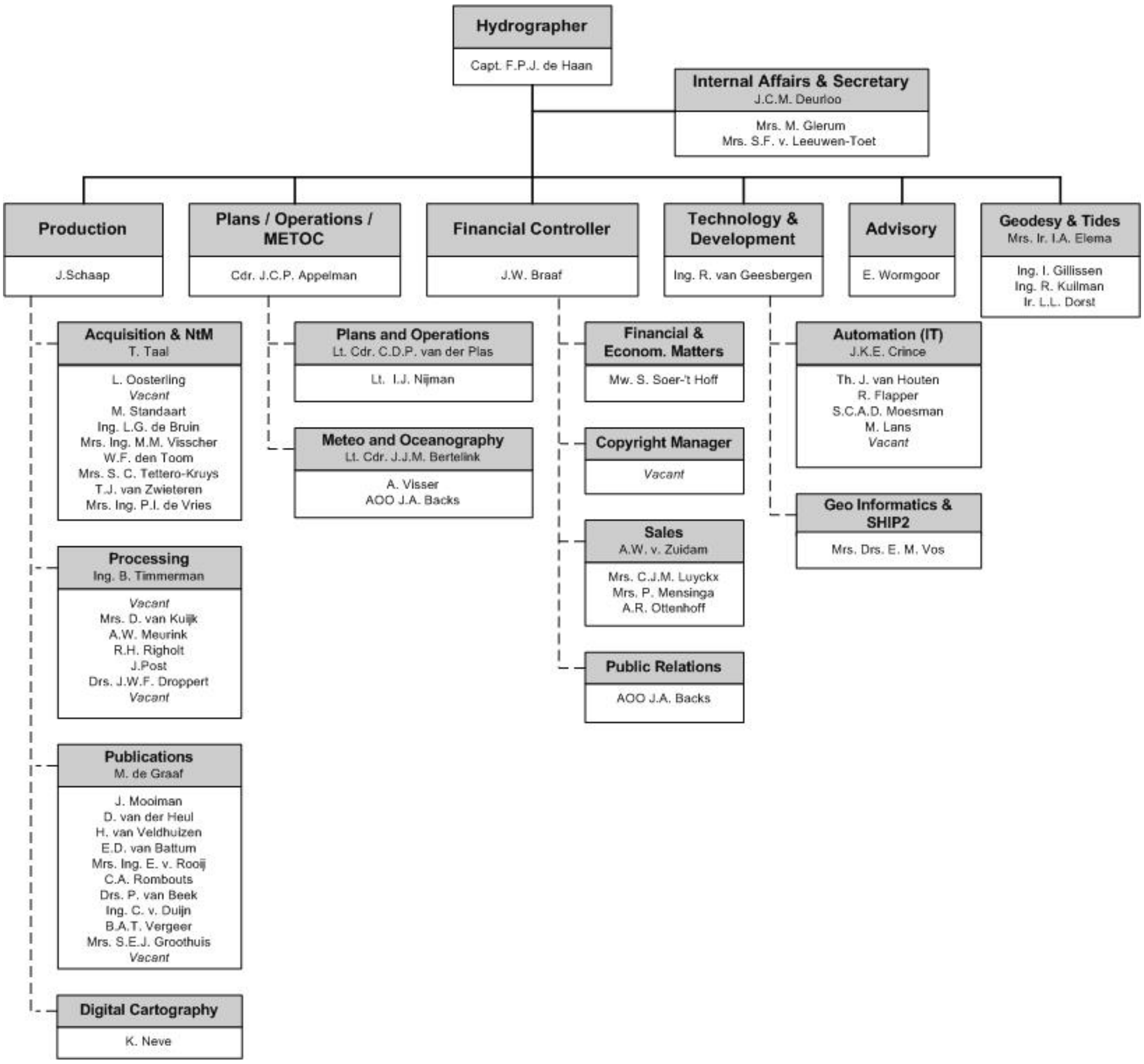

Figure 3.1: Organizational structure of the Hydrographic Bureau per 1 September 2007 (*NLHS (2007)*)

The interviews are scheduled with the employees of the POM section because they are responsible for the planning of the resurvey activities on the NCS. As an additional source, the head of the section Production is asked some specific information on the production process.

Each interview is based on the same set of questions, with the same level of variance in question sequence. Because not all respondents are expected to be capable of giving an answer on each specific question, the respondent is given the choice to skip questions (when they feel that their answer is nonexistent). The ninth question category is implicitly used during the other questions, but the respondents did not give in-depth responses in this field. The questions are thus removed from the results presented in Appendix A.3). The respondents are listed below:

- Captain J.C.P. Appelman. Head of POM
- Lieutenant Commander C.D.P. van der Plas
- Lieutenant I.J. Nijman

3.5 Interview results

The goal of the interviews is to form a complete image of the problems leading from the current survey policy. In this section, the results of the interviews are presented as a short summary per topic.

1. General survey policy: The survey requirements of the survey policy are the result of a comparison between the age of the contents of the source databases and the maximum age allowed by the survey policy. The areas that are overdue (hydrographic survey backlog), are prioritized in the yearly survey instructions. These survey instructions are based solely on the status of each individual area in relation to the 2003 survey policy. The factors minimum depth, draught, shipping intensity, and seabed dynamics are not directly included in this year plan, but are used for the design of the survey policy. The factor seabed dynamics is currently included in a deterministic way, and areas that are characterized by high levels of seabed dynamics are, depending on its location, prioritized above less dynamic areas. Shipping intensity is included in the survey policy based on risk factors. Risk sources are: UKC, specific types of cargo and the sediment composition of the seabed. A different aspect that can be seen in the current survey policy, is the inclusion of the deeper sections of the NCS. This is mainly done to search the area periodically for obstructions and wrecks. These deeper areas are also included in the IHO specifications for hydrographic surveying *(International Hydrographic Organization, 1998)*.

2. Evolution of the survey policy: Currently, a new survey policy is under development that includes new insights in deformation analysis results, recent area planning, new developments in shipping intensity, changes in spatial use and technological advances in survey techniques. The current survey policy is an evolution of the survey policy of 1997. Compared to this survey policy, which consisted of four resurvey categories, the first category frequency is reduced from one year to two years as a result of the project Sea bottom Dynamics Monitoring. However, the amount of categories has increased from four to five (excluding the areas surveyed by RWS and the special category of the critical areas in the selected track). Comparing the latest two policies, shows that the survey areas have changed due to changes in spatial use of the NCS. A further development in the current policy is the introduction of MBES for the acquisition of depth information.

3. Technology: When looking at the NCS, approximately 10 % is covered with multi-beam surveys. The rest of the data stored in the databases is still based on single-beam recordings. The character of the available data (single-beam or multi-beam) is not a factor in prioritizing the survey areas for the year plan. The introduction of new survey techniques did not resulted in different resurvey frequencies, but it did increase the probability that the planned work for that specific year is completed within the estimated time frame. However, the introduction of the new HOV-s did not yet lead to the expected efficiency improvements. This is mainly caused by reliability problems, and to reach the stated objectives of the survey policy this reliability must increase significantly.

4. External influences: External assignments should not affect the designed year plan, because the required amount of Hydrographic Days leaves space for these assignments. In reality however, the frequent technological problems are causing delays, which means that the available days for external activities is less than anticipated in advance. For 2008, no large external assignments are planned, to reduce the backlog (which has already increased to over 800 Hydrographic Days). In the field of accidents or calamities, no direct influence is present because these are normally handled by the Coastal directorates of Rijkswaterstaat. Furthermore, Rijkswaterstaat and the NLHS assist each other in the survey efforts when the capacity is available.

5. Data management: The data management is largely ship-bound, meaning that the processing and quality control of the raw data is done on board by qualified surveyors. The commander of the vessel is responsible for the quality of the data that is transferred to the NLHS. Once arrived at the office, a detailed evaluation of the data is done by the specialist departments. When an error is found, the data is transferred back to the commander of the HOV responsible for the delivery of the data. Small errors are often solved internally at the office.

6. National cooperation: Both RWS as the NLHS have their own areas of responsibility, but their individual plans are discussed in the periodical meetings of the NHI (Netherlands Hydrographic Institute), or directly. The scheduled areas for that year are also transferred to TNO-NITG[2], which depict the locations within the survey areas where bottom samples are required. Furthermore, SSS images are transferred to NITG for the construction of geological maps and acoustic seabed classification.

7. Cooperation with foreign countries: Cooperation between foreign countries is limited to the exchange of survey policies between neighbouring countries. Cooperation on a greater scale is not yet implemented, but at the last NSHC (North Sea Hydrographic Commission) conference, the harmonization of the survey policies in the wider North Sea has been initiated. This may lead to more efficient planning of resurvey efforts. The standardization procedure for survey policies is currently in its starting phase, which means that increased efficiency can be expected in the future. However, standardization is a difficult task, because each area has different characteristics and thus different requirements. Determining resurvey frequencies is thus largely a national responsibility. When compared to foreign countries, the resurvey frequencies of the NLHS are well justified and they will only be reduced on proper scientific basis. Progress is thus expected in the development of guidelines in resurvey strategy and not directly in more uniform resurvey frequencies.

8. Expected developments in Hydrographic surveying: As already discussed previously, a reduction in resurvey frequencies is only realistic if there is a proper scientific foundation. In the field of seabed dynamics, we can expect developments that will contribute to a more optimized survey policy. Furthermore, the deployment of the HOV-s and their efficiency must be upgraded to a higher level to realize a decrease in the accumulated backlog. A development that is expected in a different category is the inclusion of new activities in the task package of the HOV-s.

[2]The Netherlands Institute for applied Geosciences

Chapter 4

The initial prioritization

4.1 Introduction

We use the knowledge obtained from the interviews and the background presented in Chapter 2 for the next phase in this project: the initial prioritization of the most relevant areas on the NCS in terms of navigational safety. As came forward in the previous chapters, the current resurvey policy is based on four factors. Three factors are now used to distinguish the most relevant areas on the NCS: minimum depth, draught and shipping intensity. As an additional factor, we introduce human interventions. This factor is mainly interesting due to the expected area development and its influence on the development of the new survey policy. We now formulate a criterium for each factor on which we can exclude areas from the further procedure of this investigation. The factor seabed dynamics is excluded in this phase, because this factor is covered individually in Chapter 6 and Chapter 7. The selected relevant areas of the NCS are now included in the discussion of the last factor, seabed dynamics. In Section 4.3 we introduce the proposed method for the initial prioritization.

4.2 Risks

The factors described in the previous chapters have a variable character, and a proper risk analysis is thus mandatory to guarantee safe margins for navigation. The quantification of risks is rather difficult, because information on, for example, traffic intensity are highly susceptible to variances. For estimating the risk, an assessment of the consequences must be made if something goes wrong. Each risk can be seen as a product of probability and consequences. It can be said that the areas prioritized below, are characterized by low safety margins, leading directly to dangerous situations if changes in bathymetry remain undetected. Typical risks are grounding, sinking, damage to platforms, and damage to fishing equipment, all leading to possible damage claims. It is therefore highly important to execute the initial prioritization of next the section with reliable safety margins. The safety margins reflect automatically in a larger selected area, because the filter on which we exclude areas is rather intolerant.

4.3 Method

The factors are elaborated below to discuss its relevance in prioritizing areas of the NCS. For the purpose of this investigation, we base this prioritization on information acquired from Rijkswaterstaat, nautical publications and the results from the interviews executed at the NLHS (see Chapter 3 and Appendix A). This does not mean that the excluded areas are not important, but they are merely given a lower priority than the selected area(s). This lower priority is not defined as a strict resurvey frequency but it only distinguishes these areas from the high priority areas selected in this procedure. In the end, a lower priority means that the necessity for frequent resurveying of these areas is absent in terms of navigational safety. In the following paragraphs we include an in depth explanation of how we exclude areas of the NCS based on the four factors. We start with a summation of the factors and the criteria on which the areas are excluded.

1. **Minimum depth (Figure 4.1):** To check each area of the survey policy on least depth, depth contours are drawn. Based solely on minimum depth, areas of the NCS are given a lower priority.
   Criterium: All areas shallower than 40 metres are included.

2. **Draught (Figure 4.1):** For the areas where deep draught vessels are navigating (including anchoring areas), a larger depth is required. To remain within safety margins, these areas are given a higher priority than the areas which are dominated by small vessels.
   *Criterium: All areas that are restricted by a depth restriction or a maximum allowed draught (**Table 4.1**), are included.*

3. **Shipping intensity (Figure 4.2):** This factor is relevant to locate the areas where the probability of a grounding is highest. Areas that are not used for large (cargo) shipping and fishing purposes, are given a low priority to save time for surveying of more frequently visited areas.
   Criterium: All areas that contain shipping lanes are included, as well as the intersections between the shipping lanes.

4. **Human interventions (Figure 4.3):** Human interventions like dredging and the construction of offshore wind farms, have an influence on the behavior of the seabed. These areas with recent or planned human interventions are likely to receive a higher priority.
   Criterium: All areas that contain wind farm initiatives are included.

We start the initial prioritization with the factor minimum depth. The minimum depth is depending on the character of the seafloor. For typical North Sea conditions sand waves reach their fully saturated (evolved) state at $\sim$ 20 % of the water depth *(Németh and Hulscher, 2003)*. The maximum draught of the largest vessel, the *Berge Stahl*, is approximately 23 metres with a required UKC of 1 metre. This leads, together with the maximum expected amplitude of sand waves, to a depth of 30 metres. However, squat, pitch and roll influences (see also Section 2.4.5) are influencing the minimal required depth. With the largest vessels, this effect can be considerably. Furthermore, we are limited to the available depth contours at the NLHS. In **Figure 4.1** the depth contours of 0, 10, 20, 30, 40 and 50 metres are included. Due to the properties described above, the 30 metre depth contour is not suitable for the initial prioritization. Therefore we include a safety margin, and we set the depth at **40 metres**. All areas which are deeper are now excluded. As can be seen, the areas deeper than 40 metres are almost exclusively located in the northwestern section of the NCS. Interesting to note is the fact that in the survey policy of the NCS, the areas deeper than 30 metres are already categorized in the lower resurvey categories. This is mainly based on the specifications given by the IHO *(International Hydrographic Organization, 1998)* (see Appendix B).

The factor draught is influenced by squat, pitch and roll effects, as already discussed above. For the benefit of this first step, minimal requirements and guaranteed depths for the southern North Sea are obtained from the Deep Draught Planning Guide *(Hydrographic Service, 2002)* and Rijkswaterstaat. Due to the large variety of passing vessels, strict requirements for each section can not be given. The values presented in **Table 4.1**, are used for the maximum allowed draught on the NCS.

Table 4.1: Draught requirements and guaranteed depths. Taken from the Deep Draught Planning Guide *(Hydrographic Service, 2002)* and Rijkswaterstaat.

Location	Guaranteed depth [m]	Max. allowed draught [m]
Dover Strait	26.5	n.a.
Noordhinder South	28.5	n.a.
Noordhinder Junction	27.3	n.a.
Euro channel	n.a.	22.85
Deep Water (DW) routes	20.7	n.a.
IJ channel	n.a.	17.38

All the areas described in **Table 4.1**, are included in **Figure 4.1** as the colored sections. We now can now exclude areas based on the information given above and the assumption that all large vessels follow the described requirements. All the colored areas are included in the further procedure, because each of them is restricted by a guaranteed depth or a maximum allowed draught. The areas that are included based on this factor are labeled orange in **Figure 4.4**.

The third factor that we introduce is shipping intensity. The recorded intensity on the NCS is given in the Traffic Intensity map presented by Rijkswaterstaat *(Noordzeeloket, 2003)*. In this map, nine intensity categories are given that characterize an area for the average number of ships per 1000 square kilometres on a specific moment. The densities presented are based on all vessel traffic for the southeastern part of the North Sea, and on route-bound traffic only (thus excluding fishing, supply and recreation vessels) for the rest of the North Sea. In the field of this investigation, we prioritize areas with a high intensity above areas with a low intensity. The areas with a low to moderate intensity are excluded from further analysis. The Traffic Intensity map is transferred to GIS[1], for scale purposes and is included in **Figure 4.2**. On this chart we can see that the intensity increases when approaching the coastline. Furthermore, the main shipping lanes (including the Deep Water routes) are high intensity sections. We now include only the charted shipping lanes, anchoring areas and the intersections between the charted shipping lanes in the further analysis. The majority of these sections are located in the southeastern part of the North Sea. In **Figure 4.4**, the prioritized areas selected with this factor are labeled with a red color.

Regarding seabed dynamics, recent human interventions can have an impact on the behavior of the seafloor. For example in the approach channel of Rotterdam, the maximum allowed draught is 22.85 metres (see summation above), which is guaranteed by frequent dredging activities. These dredging activities remove the crests of the present sand waves in the area, which influences their regeneration. A different aspect of human interventions are the planned construction projects on the NCS. As can be seen on the map for wind farm initiatives on the shelf *(Noordzeeloket, 2007)*, available space and their location with respect to shipping routes become significant influences. The area directly around a wind farm is influenced by the presence of these turbines. This area is called the *Area of influence* which is defined in *Van der Veen et al. (2007)* as the area outside the wind farm, where the absolute seabed change due to the presence of the wind farm is more than 10 centimetres. The Area of influence is determined by the environmental parameters water depth, flow velocity, median grain size of the seabed and the angle between the wind farm and the flow. Next to these environmental aspects, design parameters are also important. Typical design parameters that influence the size of the Area of influence, are the diameter of the turbine, the spacing between adjacent turbines and the drag coefficient of the structure.

[1] **G**eographical **I**nformation **S**ystem

We combine all influences mentioned above together with their impact on the Area of influence in **Table 4.2**. The impacts presented in this table, are valid for wind farms with a rectangular shape. In reality, wind farms can have all kinds of shapes, which may influence the size of each impact. However we assume that the impacts described in the table below are valid for other wind farm designs as well.

Table 4.2: Parameters that affect the size of the *Area of influence* around offshore wind farms. The last column *Impact* describes the effect of the size of the Area of influence with increasing parameter values.

Parameter	Impact on *Area of influence*
Water depth	Decrease
Flow velocity	Increase
Median grain size D_{50}	Increase
Angle between wind farm and flow	Two peeks at 30 degrees and 210 degrees
Diameter of turbine	Increase
Spacing between turbines	Decrease
Drag coefficient turbine	Increase

Based on **Table 4.2**, we conclude that the most optimal location for wind farms with minimal influence on seabed morphodynamics in mind, is a deeper section of the NCS with a high level of spacing between the turbines. However, when looking at the wind farm initiatives for the NCS presented in **Figure 4.3** (based on *(Noordzeeloket, 2007)*), we see that most initiatives are located close to shore in relatively shallow waters. Furthermore, available space on these locations is limited, which leads to higher density wind farms (more turbines per square kilometre) to reach the required amount of energy generation for economic efficiency. Shallow waters in combination with limited available space are potential factors for a significant influence on the local seabed, if construction of these initiatives actually takes place. Although the included areas in **Figure 4.3** are not yet confirmed, we include all areas in the further analysis based on **Table 4.2**, and their location in high intensity areas of the NCS.

A different type of human interventions, is the influence of sand extraction from the seafloor. On average 30 Mm^3 of sand and gravel is extracted from the seabed of the NCS annually. This can possibly increase in the future, depending on the land reclamation project Maasvlakte II. Depending on the designed plan for this project, the sand extraction necessary for the realization of this project, can increase to 200-2000 Mm^3 over a time frame of 5 to 10 years. The sand extraction sites are called *sand pits* and their influence on the surrounding seafloor is described by several parameters, which are discussed in detail in *Van der Veen (2008)*. These parameters are more or less similar as presented in **Table 4.2**. As can be read in *Van der Veen (2008)*, the parameter flow velocity has the largest influence on the morphological development. For both sand pits as offshore wind farms, the area of influence is largest in front of the East Anglian coast. For this investigation we limit ourselves to mention the possible relevance in the future. For more details we refer to *Van der Veen (2008)*.

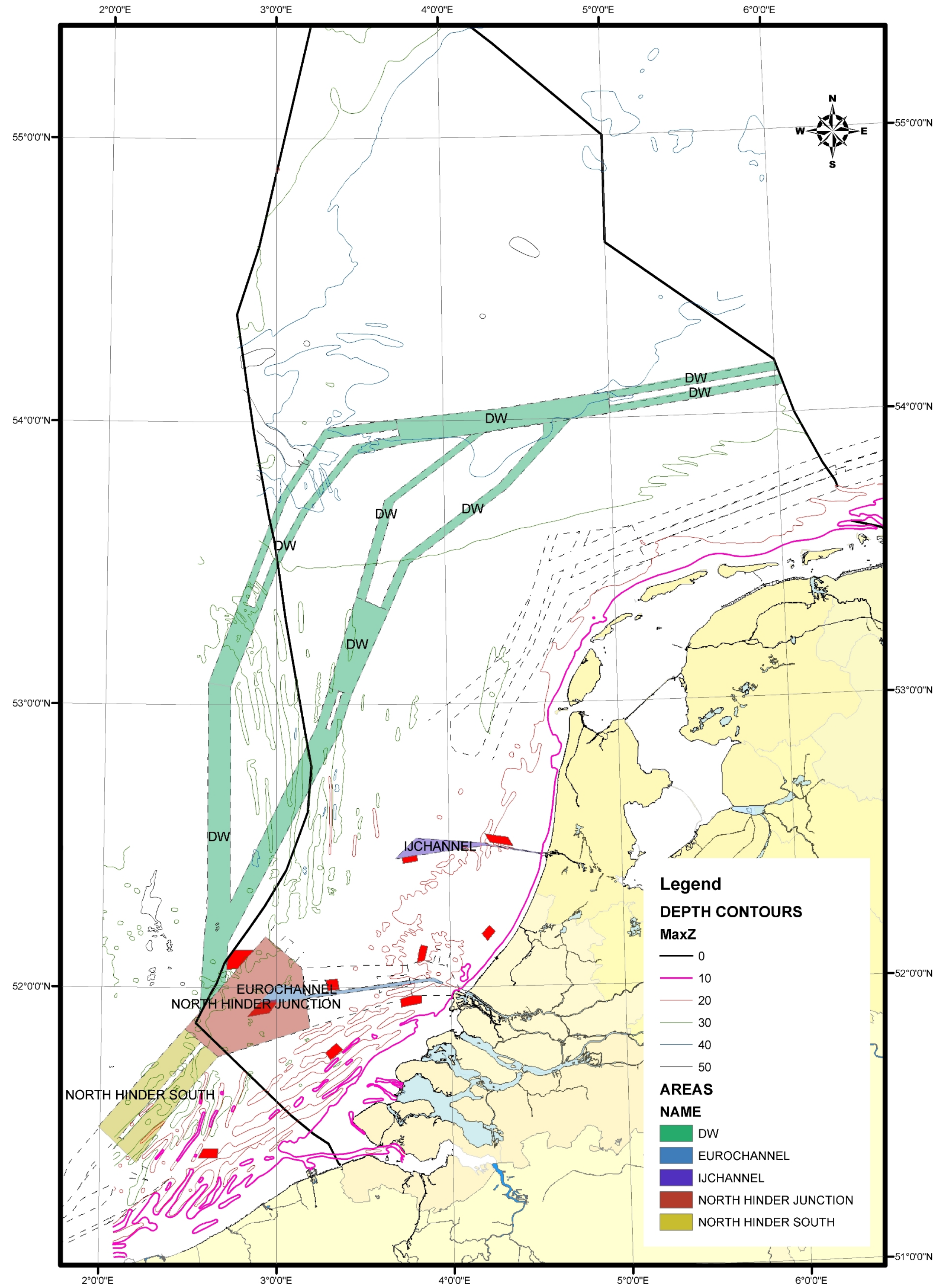

Figure 4.1: A GIS chart of the NCS with all available depth contours and the draught information gathered from the Deep Draught Planning Guide and Rijkswaterstaat. We start the initial prioritization with the exclusion of areas based solely on the available depth contours. The red areas are the anchoring areas near the approach routes to Rotterdam and IJmuiden.

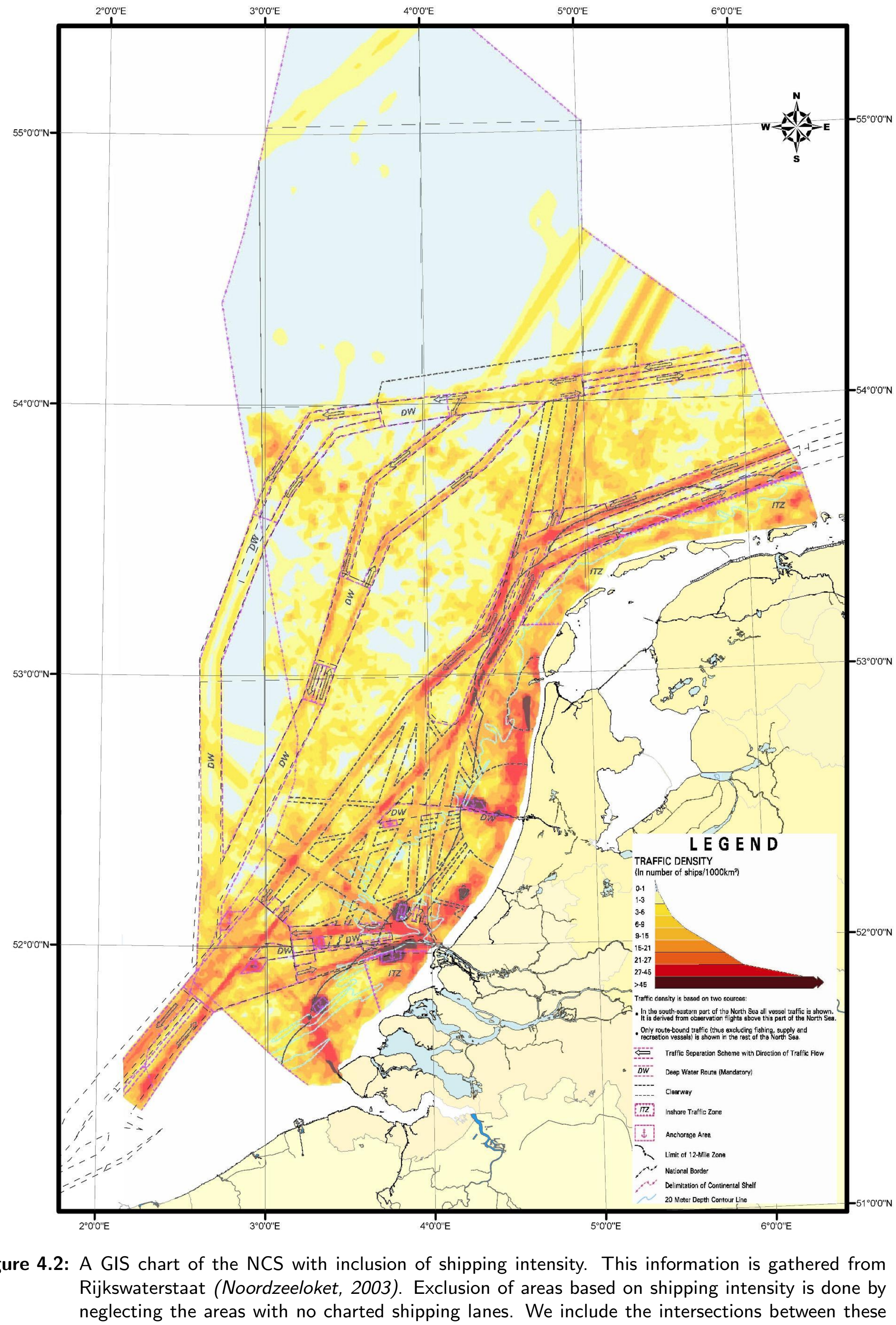

Figure 4.2: A GIS chart of the NCS with inclusion of shipping intensity. This information is gathered from Rijkswaterstaat *(Noordzeeloket, 2003)*. Exclusion of areas based on shipping intensity is done by neglecting the areas with no charted shipping lanes. We include the intersections between these shipping lanes as well.

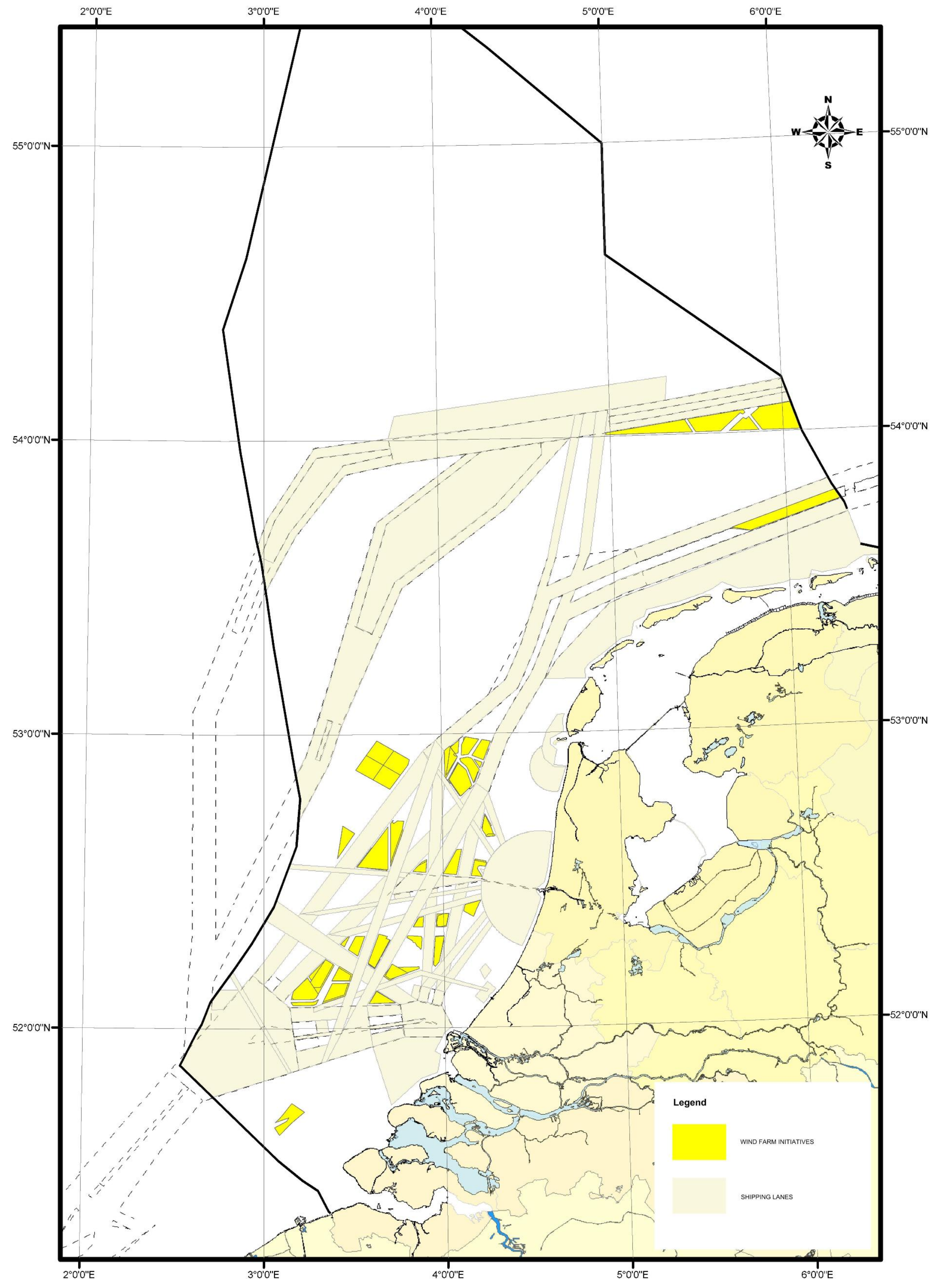

Figure 4.3: A GIS chart of the NCS that shows the most recent situation in wind farm initiatives (updated in October 2007). This information is gathered from Rijkswaterstaat *(Noordzeeloket, 2007)*. We include the locations of these initiatives in the further analysis, due to their influence on the local seafloor and the area of influence around them.

The four factors are now converted into a map of the NCS that shows the remaining areas after exclusion of the areas specified in the three GIS charts presented above. Although it remains difficult to prioritize areas taking all aspects properly into account, the factors above are useful to make an initial prioritization without including seabed dynamics. In **Figure 4.4**, we present the prioritized areas. Again, we emphasize the fact that the excluded areas are relevant in terms of hydrographic surveying, but are less interesting for the purpose of this investigation. The white area enclosed by the blue line, gives the area that is deeper than 40 metres. Although the other white areas are shallower than 40 metres, they are excluded based on the remaining three factors. Only the coloured areas are now prioritized based on the method of this chapter.

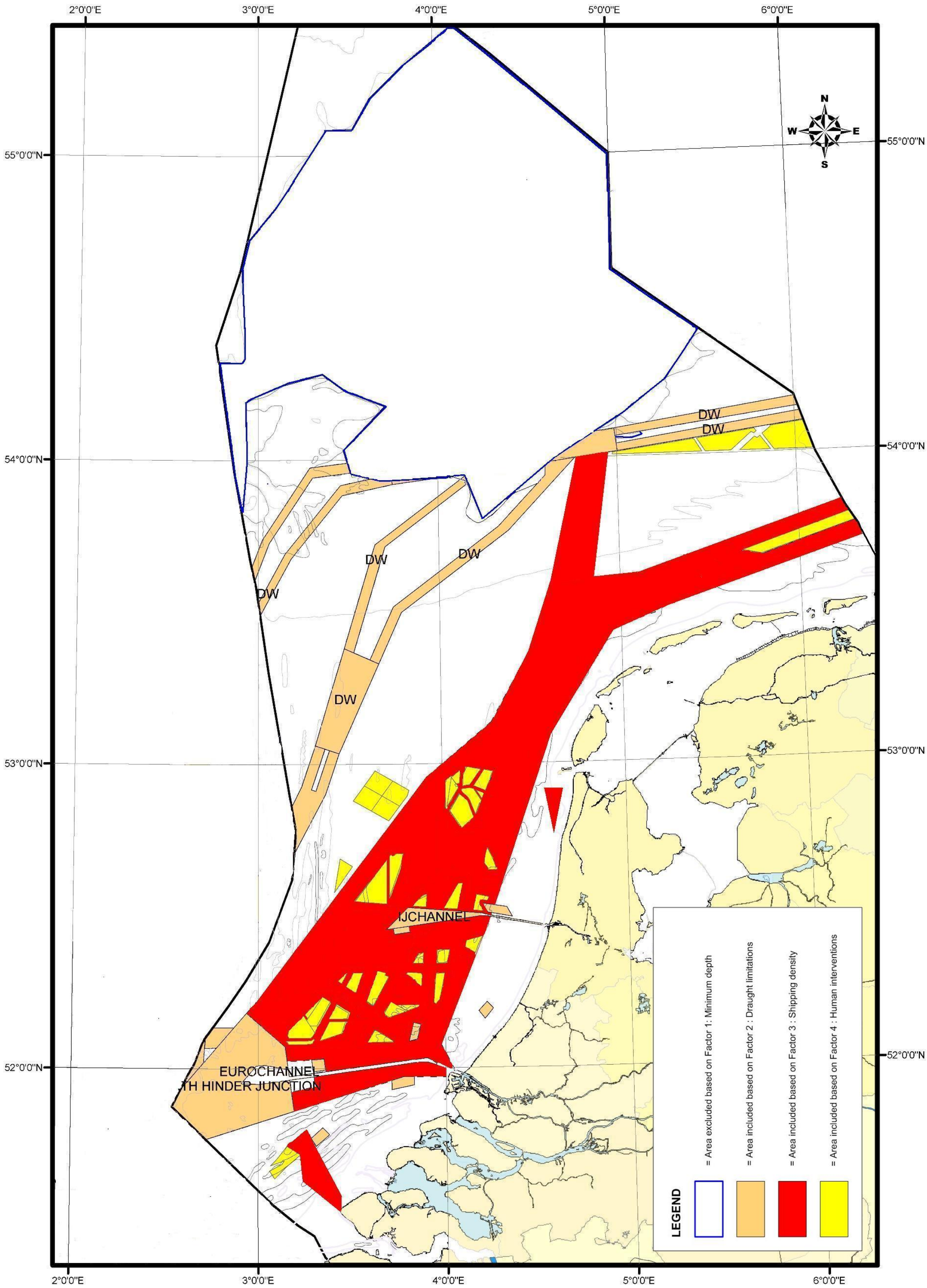

Figure 4.4: This GIS chart is created by performing the initial prioritization discussed in Section 4.3. The blue 40 metre depth line, limits the area that is excluded based on minimal depth only. The prioritized areas are now given by the coloured sections of the NCS. We emphasize the fact that the excluded areas are only excluded for the scope of this project.

Chapter 5

Background: Seafloor monitoring

5.1 Introduction

As discussed in Chapter 4, we discuss the factor *seabed dynamics* separately as it is the main interest of this study. Seabed dynamics is, from the factors discussed previously, the most complicated factor to include in the survey policy, especially for shallow shelf seas like the North Sea. The sandy bottom composition of the North Sea, combined with the relatively shallow depths and currents, causes an dynamic seabed with various patterns. To gain more insight in the behavior of these bed forms, physical models have been designed to calculate migration rate, growth and regeneration rate. At the NLHS, a method for analyzing time series of bathymetric data is initiated, suitable for the study of the behavior of sand waves at the NCS. This method, *deformation analysis*, is covered in more detail in the following sections. The purpose of this chapter is to offer a background in this method, as it is used a basis for the interpretation of seabed dynamics in Chapter 6.

By analyzing time series of bathymetric data, changes over time are detected, which aids the optimization of resurvey frequencies. The method is based on four phases, which are presented in **Figure 5.1**. This chapter gives a step by step description of the phases and their contents, starting with the preparations in Section 5.2 (Phase 0). In Section 5.3 (Phase 1), the spatial analysis is discussed, and in Section 5.4 the time analysis is covered (Phase 2). In Section 5.5 we discuss the possible analysis dimensions (0D, 1D and 2D). Phase 3, is shortly introduced in Section 5.6 and covered, in detail, in Chapter 6.

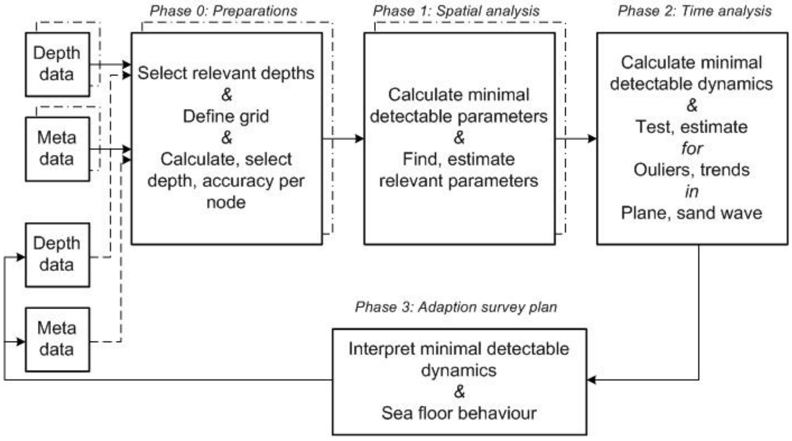

Figure 5.1: The phases in seafloor monitoring according to the method of the NLHO

5.2 Phase 0: Preparations

First, the *variances* (describes the expected error of variable) and the *covariances* (a measure of how much two random variables are varying together) of the measurements have to be calculated. These *measurements* are the depths surveyed with the HOV-s. This is an important step, because a measurement never gives the exact value. When a section of seabed can be described as second order stationary (which means that the spatial covariances do not depend on position) a stochastic model of the seabed is made, which is a covariance function and the variance. The stochastic model is now used for kriging between data points (and for parameter estimation) (see **Figure 5.2**). Kriging is necessary in case of single beam echo sounder measurements, to obtain gridded depth information (discussed in Section 5.2.3). For multi beam echo sounder data, interpolation is not necessary when the data fully cover the seabed. In this context, *fully covers* means that for each grid cell in the Bathymetric Archive System, depth information is available (see Section 2.6).

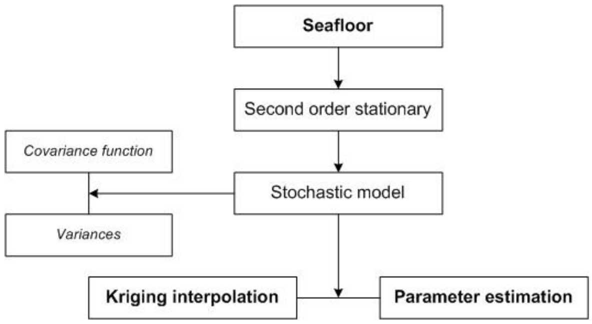

Figure 5.2: The covariance function and the variance are based on the stochastic model. This model is then used for kriging interpolation and parameter estimation

5.2.1 Variance

Heave movement, measurement inaccuracies and tidal reduction, influence the variance of a depth value (Section 2.4). Variance describes the expected error of a depth value. The mathematical notation of variance is given by:

$$Var(\underline{d}) = \sigma^2_{\underline{d}} = E\{(d - E\{\underline{d}\}^2)\}, \tag{5.1}$$

with E denoting the expected value and d the stochastic variable, depth.

5.2.2 The covariance function

Depth is modeled using the assumption that it is the sum of a *deterministic* and a *stochastic* component. The deterministic part is described by a linear function of parameters (for instance a sloping plane), while the covariance function and the variance describe the stochastic model. This two component function is defined as:

$$\underline{d} = E\{\underline{d}\} + \underline{r}, \tag{5.2}$$

with $\underline{d}$ the measured depth based on both components, $E\{\underline{d}\}$ the expected value of $\underline{d}$ and $\underline{r}$ the *residuals*, which are related to interpolation errors, measurement errors and morphological processes. These residuals are presented in mathematical notation as:

$$\underline{r} = r + e_k + e_m, \tag{5.3}$$

with r, e_k and e_m, respectively the residuals of morphological processes, interpolation and measurements.

By calculating the covariance at several locations at specified distance intervals, an empirical covariance function can be obtained. Because the covariance is only calculated at specified space intervals, the covariance function consists of a limited number of covariance values only. In **Figure 5.3** the sampled covariance function is drawn for the direction of *highest variability*, which is defined as the direction perpendicular to the sand wave crests, and for the direction of *lowest variability*, which is assumed to be perpendicular to the direction of highest variability.

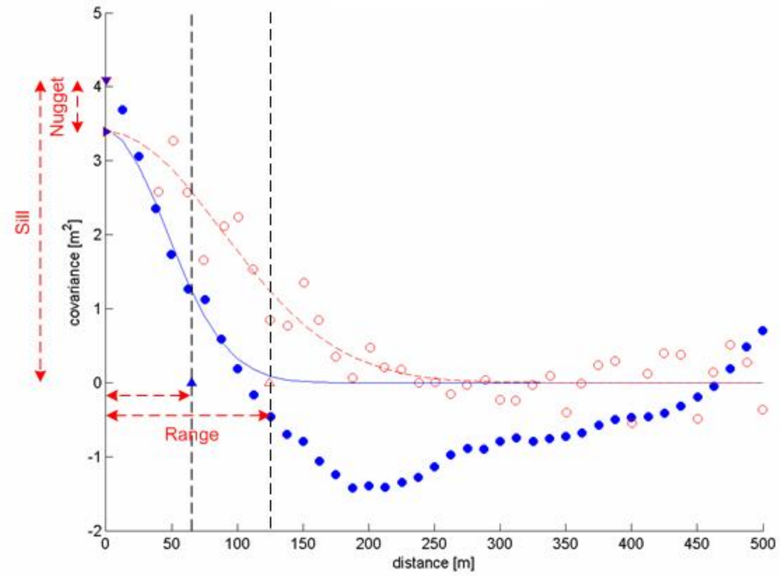

Figure 5.3: Covariance function for two directions - highest variability (blue) and lowest variability. The circles are representing the sampled covariance function, while the lines are the fitted functions (described by Equation (5.4)). The range of the functions is given by the fitted horizontal lines, the nugget effect and the sill are represented by the fitted vertical lines. The variance is given by the top triangle.

In **Figure 5.3**, three unknown parameters are introduced: *Nugget*, *range* and *sill*. These parameters are defined as:

- *Nugget*: the discontinuity at the origin of the covariance function. The nugget represents the micro-scale variations (equals the variance).
- *Range*: the point beyond which the covariance is assumed to be negligible (constant).
- *Sill*: the covariance at distance zero (including the nugget).

The covariance function is composed from the residuals mentioned in Equation (5.2). In this figure, a sand wave pattern is detected in the direction of highest variability (negative autocovariances). The sampled covariance function is fitted for both directions with the same type of function (Equation (5.4)). This is possible because the hole effect, which is found in the direction of highest variability, is located outside the range of the covariance function. The resulting continuous covariance function is *positive definite*, meaning that the variances calculated from such a function are guaranteed to be positive. The Gaussian function is defined as *(Chiles and Delfiner, 1999)*:

$$C(s) = b \cdot \exp\left(-\left(\frac{s}{a}\right)^2\right), \tag{5.4}$$

with b the sill minus the nugget, s the distance and a the range.

5.2.3 Kriging interpolation

To obtain gridded depth data, interpolation is a necessary step, especially for single beam surveys, which are not positioned on a regular grid. Various approaches are possible in interpolating the surveyed tracks to a regular grid (of which the nearest neighbor method is the most simple). At the NLHO, a method called *Universal kriging* is used, which is based on interpolating weights obtained from the covariance function. Universal kriging treats a non-stationary variable as though it is the sum of two components. The *drift* (identical to a trend surface) is the average or expected value of variable and is the slowly varying, non-stationary component of the surface. The residuals are the differences between the observations and the drift. Universal kriging performs in fact three steps *(Davis, 2002)*:

1. The drift is estimated and removed to form stationary residuals at the grid points;
2. The stationary residuals are kriged to obtain estimated residuals at unknown locations;
3. The estimated residuals are combined with the drift to obtain estimates of the actual situation.

Because it is a statistically based method, kriging produces variances of the interpolated data. Kriging is defined as a *BLUE*, or Best Linear Unbiased Estimator. *Best* means that it aims to minimize the variance of the errors, *Linear* means that the estimates are linear combinations of the available data, and *Unbiased* means that the expectation equals the mean value. To use Universal Kriging on the data, a sloping plane is fitted which gives the required residuals (see Section 5.2.2). From the covariance function, interpolation weights are obtained using the matrix **C** and the vector **b**, which are given by:

$$\mathbf{C} = \begin{bmatrix} C_{x_1,x_1} & C_{x_1,x_2} & \cdots & C_{x_1,x_k} & 1 & x_{1,1} & x_{2,1} \\ C_{x_2,x_1} & C_{x_2,x_2} & \cdots & C_{x_2,x_k} & 1 & x_{1,2} & x_{2,2} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ C_{x_k,x_1} & C_{x_k,x_2} & \cdots & C_{x_k,x_k} & 1 & x_{1,k} & x_{2,k} \\ 1 & 1 & \cdots & 1 & 0 & 0 & 0 \\ x_{1,1} & x_{1,2} & \cdots & x_{1,k} & 0 & 0 & 0 \\ x_{2,1} & x_{2,2} & \cdots & x_{2,k} & 0 & 0 & 0 \end{bmatrix} \text{ and } \mathbf{b} = \begin{bmatrix} C_{x_0,x_1} \\ C_{x_0,x_2} \\ \vdots \\ C_{x_0,x_K} \\ 1 \\ x_{1,p} \\ x_{2,p} \end{bmatrix}, \tag{5.5}$$

with C the covariance values, x_0 the location where an estimate of the depth is to be made, and x_k the position of point k. And finally, $x_{j,k}$ represents the location of point k along coordinate axis j.

The interpolation weights **w** are now calculated as:

$$\mathbf{w} = \mathbf{C}^{-1}\mathbf{b}, \qquad \text{with: } \mathbf{w} = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \vdots \\ \lambda_k \\ \mu_0 \\ \mu_1 \\ \mu_2 \end{bmatrix}, \tag{5.6}$$

with λ_k the kriging interpolation weights and μ_0, μ_1 and μ_2, *Lagrange multipliers* which are introduced to comply to the unbiasedness restriction of a BLUE interpolation method *(Isaaks and Srivastava, 1989)*.

The kriging interpolation method discussed above, introduces a additional variance to the estimation of x_0. This is called the kriging variance, $\sigma^2(x_0)$:

$$\sigma^2(x_0) = C_{x_0,x_0} - \mathbf{b}^{'}\mathbf{w} = C_{x_0,x_0} - \mathbf{b}^{'}\mathbf{C}^{-1}\mathbf{b}, \tag{5.7}$$

In the interpolating phase, the interpolation distance (defined as the distance at which points contribute to the interpolation) is chosen as two times the distance between the survey tracks. With a track spacing of 50 metres, this leads to a distance of 100 metres, which means that the data points further away (low covariances) are receiving zero weight. Thus by applying this range, the number of data points included in the interpolation of a certain *node* (a single point on the interpolated grid) is limited. This speeds up the interpolation process considerably. The grid size must be small enough to detect potential sand waves, but large enough to limit the processing time. A grid of interpolated depths and their standard deviations results from the kriging interpolation. At the edges of the grid, the accuracy is becoming worse due to the limited availability of surrounding data points that can contribute to the interpolation of the edge nodes.

5.3 Phase 1: Spatial analysis

This phase will introduce representations of the seabed. For this method, four *levels of complexity* are chosen. These levels of complexity are discussed in Section 5.3.2. The first level of complexity is discussed in the following Section. The results from the spatial analysis of Phase 1 are used as input for Phase 2, to discuss the dynamic behavior of the seabed.

5.3.1 The initial representation

In Phase 1, the interpolated depth data from Phase 0 are used as input. The spatial analysis starts with the initial representation (the H_0- hypothesis) of the seabed, which is a horizontal plane. By performing a statistical testing procedure, this representation is tested to determine the fit of the representation when compared to the actual situation. In **Figure 5.4** this testing procedure is given.

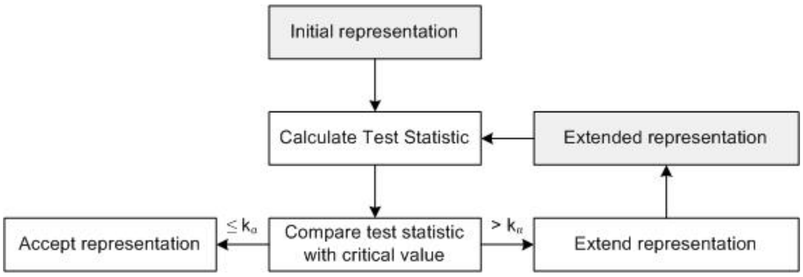

Figure 5.4: Testing of modeled representations. After calculation of the Test Statistic, the hypothesis is compared to a critical value k_α.

The initial model representation (H_0) used for this application is given by:

$$H_0 : E\{\underline{\mathbf{d}}\} = \mathbf{A}\mathbf{x}, \tag{5.8}$$

with $E\{\underline{\mathbf{d}}\}$ the mathematical expectation of the vector $\underline{\mathbf{d}}$, which contains all depth observations on the grid. $\mathbf{A}$ is the model matrix (function model), which describes the relations between the seabed parameters of vector $\mathbf{x}$ and the observed depths of vector $\underline{\mathbf{d}}$. For the H_0 representation a covariance matrix is estimated which describes the residuals of the representation (described in Section 5.2.2). The estimation of vector $\mathbf{x}$ is calculated as the least squares solution $\hat{\underline{\mathbf{x}}}$ and is given by (more detailed in *Verhoef (1997)*):

$$\hat{\underline{\mathbf{x}}} = (\mathbf{A}^T \mathbf{C}_\mathbf{d}^{-1} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{C}_\mathbf{d}^{-1} \underline{\mathbf{d}}, \tag{5.9}$$

with $\mathbf{C}_\mathbf{d}$ the covariance matrix of the observations $\mathbf{d}$. The superscripts -1 and T denote an *inverse* and a *transpose* respectively. As can be seen in **Figure 5.4**, the hypothetical representation is accepted when the calculated test statistic is smaller or equal to the pre-determined critical value k_α. This critical value is defined using α as (see also **Figure 5.6**) the *level of significance*, which is the probability that the initial hypothesis is rejected while it is in fact true. The test statistic for the initial representation is calculated by:

$$\underline{T}_0 = \hat{\underline{\mathbf{r}}}^T \mathbf{C}_\mathbf{d}^{-1} \hat{\underline{\mathbf{r}}}, \tag{5.10}$$

with $\hat{\underline{\mathbf{r}}}$ the residuals.

5.3.2 Alternative hypotheses

When the initial representation does not fit well, alternative hypotheses are selected to test whether an extended representation fits significantly better. In Phase 1, three alternative hypotheses, or *levels of complexity*, are tested:

1. H_{a1}: First alternative hypothesis. Fitting of a sloping plane with the parameters: depth d, slope in x-direction Φ_x and slope in y-direction Φ_y;
2. H_{a2}: Second alternative hypothesis. Fitting of a sine wave with the extra parameters: Amplitude A and phase φ;
3. H_{a12}: Third alternative hypothesis. A sloping plane superimposed by a sine wave with wavelength L. For this hypothesis, all extra parameters specified in H_{a1} and H_{a2} are possible. This hypothesis is composed using the other two alternative hypotheses.

These hypothetical seabed representations can be seen in **Figure 5.5**.

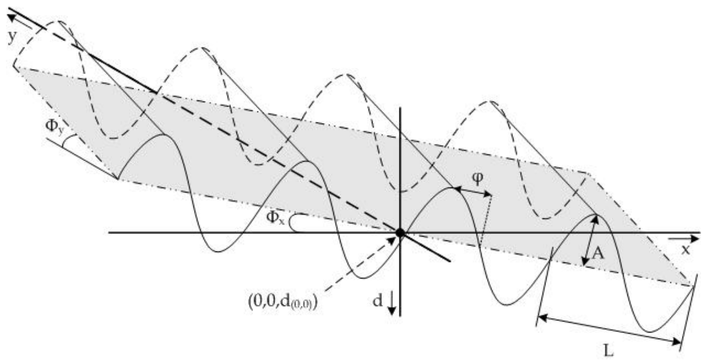

Figure 5.5: Spatial parameters of the seabed representations. First a horizontal plane is tested, which is, in the case of rejection, extended by a sloping plane with angles Φ_x and Φ_y. The second extension is modeled by a sine wave with wavelength L. The additional parameters for this representation are amplitude A and phase φ. The final representation in this example combines hypotheses H_{a1} and H_{a2}

In **Figure 5.5**, the model extensions are depicted with the additional parameters of each representation. The representation of H_0 is drawn as a horizontal plane. The hypothetical extensions of the alternative hypotheses are resulting in a new definition of the model representation as:

$$H_a : E\{\underline{\mathbf{d}}\} = \mathbf{A}\mathbf{x} + \mathbf{B_a}\nabla_\mathbf{a}, \tag{5.11}$$

with $\mathbf{B_a}$ the matrix specification of the coefficients of the new seabed parameters, and $\nabla_\mathbf{a}$ a vector that contains the new seabed parameters. First, two alternative hypotheses are tested simultaneously: a sloping plane, and a sine wave. If one of these alternative hypotheses statistically fits the gridded area according to the testing procedure, this alternative hypothesis is used as the new spatial representation of the seabed.

When, after one iteration, H_{a1} and H_{a2} are both still insufficient, a second iteration is performed which combines the H_{a1} and H_{a2} hypothesis into H_{a12}. The test of a hypothesis is performed by calculating the new test statistic, $\underline{T}_a$ (with a the alternative hypothesis), for each hypothesis. The new test statistic is also compared to a critical value to check if the extension of the model is significant. The test statistics for the alternative hypotheses are calculated by:

$$\underline{T}_a = \underline{\hat{\mathbf{r}}}^T \mathbf{C_d}^{-1} \mathbf{B_a} (\mathbf{B_a}^T \mathbf{C_d}^{-1} C_{\hat{\mathbf{r}}} \mathbf{C_d}^{-1} \mathbf{B_a})^{-1} \mathbf{B_a}^T \mathbf{C_d}^{-1} \underline{\hat{\mathbf{r}}}, \tag{5.12}$$

with $\underline{T}_a$ the test statistic, and $\mathbf{C_{\hat{r}}}$ the covariance matrix of the residuals, given by:

$$\mathbf{C_{\hat{r}}} = \mathbf{C_d} - \mathbf{A}(\mathbf{A}^T \mathbf{C_d}^{-1} \mathbf{A})^{-1} \mathbf{A}^T \tag{5.13}$$

During the testing procedure, the initial hypothesis is characterized by a central χ^2-distribution *(Verhoef, 1997)* with Q *degrees of freedom.* The alternative hypothesis however, is not centrally distributed, but follows a non-central χ^2-distribution with a non-centrality parameter λ:

$$\lambda = \nabla_{\mathbf{a}}^T \mathbf{B}_{\mathbf{a}}^T \mathbf{C}_{\mathbf{d}}^{-1} \mathbf{C}_{\hat{\mathbf{r}}} \mathbf{C}_{\mathbf{d}}^{-1} \mathbf{B}_{\mathbf{a}} \nabla_{\mathbf{a}} \tag{5.14}$$

This non-centrality parameter is used when we compare more alternative hypotheses simultaneously. Each hypothesis could be tested with its own critical value, when the tested hypotheses have a different number of *degrees of freedom.* Also a difference in dimension of the hypotheses can lead to a different number of degrees of freedom. In **Table 5.1** the possible hypotheses and their properties are presented:

Table 5.1: Degrees of freedom of statistical hypotheses in Phase 1

Dimension	Hypothesis	Parameters	Degrees of freedom (d.o.f.)
1-D	Sloping plane	Φ	1
	Sand wave	A ; φ	2
	Sloping plane and sand wave	Φ ; A ; φ	3
2-D	Sloping plane	Φ_x ; Φ_y	2
	Sand wave	A ; φ	2
	Sloping plane and sand wave	Φ_x ; Φ_y ; A ; φ	4

To compare two hypotheses with different degrees of freedom, the test statistic $\underline{T}_a$ of each hypothesis must be confronted with its own critical value. For each hypothesis, the test statistic is divided by its matching critical value to generate the test quotient:

$$\underline{T}_a / k_\alpha, \tag{5.15}$$

with k_α the critical value with Q_a degrees of freedom and a χ^2-distribution. With multiple hypotheses, the most probable representation is now the hypothesis for which is valid (adapted from *Verhoef (1997)*):

$$\underline{T}_{a_i} / k_{\alpha, a_i} > \underline{T}_{a_j} / k_{\alpha, a_j} \;\; \forall \;\; j \neq i, \tag{5.16}$$

with i and j denoting the different alternative hypotheses. To apply this method, it is demanded that the levels of significance for each alternative hypothesis are connected, to ensure that the probability that a hypothesis is rejected due to a model misspecification, is equally large for all tested representations, independent on the number of degrees of freedom *(Baarda, 1967, 1968).*

The test quotient of Equation (5.15) is also used in determining the most appropriate wavelength for the sand wave extension. By maximizing the test quotient for a given critical value k_α, while changing the wavelength, the most probable wavelength is found.

When studying hypotheses, three possible errors are identified when choosing a representation:

1. H_0 is valid, H_a is accepted;
2. H_a is valid, H_0 is accepted;
3. H_{a1} is valid, H_{a2} is accepted (only in case of more than one alternative hypothesis).

These errors are related to the choice of the critical value k_α. Graphically, this situation can be sketched as presented in **Figure 5.6**.

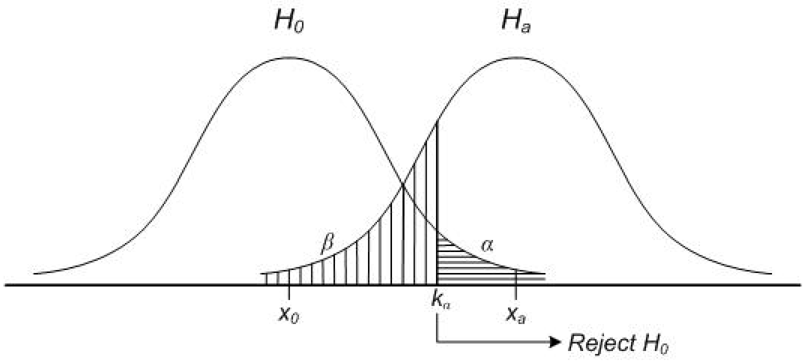

Figure 5.6: Relation between H_0 and H_a. H_0 is rejected when the critical value k_α is exceeded *(Verhoef, 1997)*

In this figure, α is the probability that H_0 is rejected while it is in fact true (error of the first kind), β is the chance that H_0 is accepted while H_a is true (error of the second kind). The first error type, acceptation of H_a while H_0 is true, is the level of significance α (as discussed in Section 5.3.1). In general, it is said that a small α is desirable *(Dorst, 2004)*, but this implies a large β which increases the probability of a missed alert (or acceptation of H_0 while in fact H_a is true). An error of the third kind can not be identified in **Figure 5.6**. The probability of this error increases when the alternative hypotheses are more alike.

5.3.3 The overall model test

After the calculation of the test statistics of the chosen hypotheses, a new spatial representation is chosen. This new representation is then tested in the *Overall model test*, which determines whether the representation needs extension in the form of an adaption of the stochastic model by extending the (co)variance matrix $\mathbf{C_d}$ of the observations. In schematic form, this phase in statistical testing can be presented as illustrated in **Figure 5.7**.

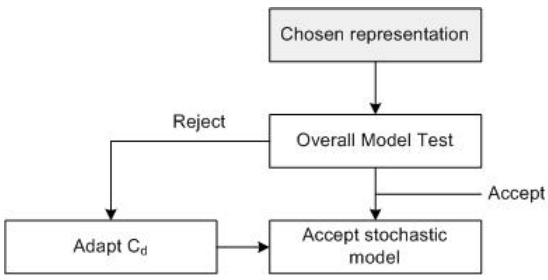

Figure 5.7: After determining the most likely representation, the Overall model test is performed which determines whether the representation needs extension in the form of an adaption of the stochastic model

The overall model test is performed by calculating a new test statistic given by:

$$\underline{T}_O = \underline{\hat{\mathbf{r}}}^T \mathbf{C_d}^{-1} \underline{\hat{\mathbf{r}}}, \tag{5.17}$$

which is used for the quotient $\underline{\hat{\sigma}}^2$ (the variance factor), given by:

$$\underline{\hat{\sigma}}^2 = \underline{T}_O/(m-n), \tag{5.18}$$

with m the number of observations and n the number of unknowns. If the value of the variance factor is smaller or equal than 1, the stochastic model of the representation is accepted. When $\underline{\hat{\sigma}}^2 > 1$, the representation needs extension of the covariance matrix $\mathbf{C_d}$. This covariance matrix is written in the notation of a variance component model:

$$\mathbf{C_d} = \sum_{k=1}^{p} \underline{\hat{\sigma}}_k^2 \mathbf{C_k}, \tag{5.19}$$

in which $\mathbf{C_k}$ are the p independent cofactor matrices. If $p = 1$, $\underline{\hat{\sigma}}_k^2 = \underline{\hat{\sigma}}^2$ is valid, Equation (5.18) is used to calculate the quotient $\underline{\hat{\sigma}}^2$. After extending the covariance matrix with new components to comply to the overall model test, the stochastic model is accepted and the representation is now used for Phase 2 (discussed in Section 5.4).

The testing procedure described in this section, can be illustrated with an example generated with a MATLAB Toolbox. **Figure 5.8** shows an example of the spatial test quotients of different levels of complexity (slope and sand wave extension). The larger the calculated test quotient, the greater the need for this specific extension. After more iterations, with extended spatial representations, the test quotients will decrease. This means that the spatial representation becomes more accurate and further extension does not lead to a significant improvement of the representation. When a spatial representation is chosen, the overall test statistic is calculated, which decreases after more iterations.

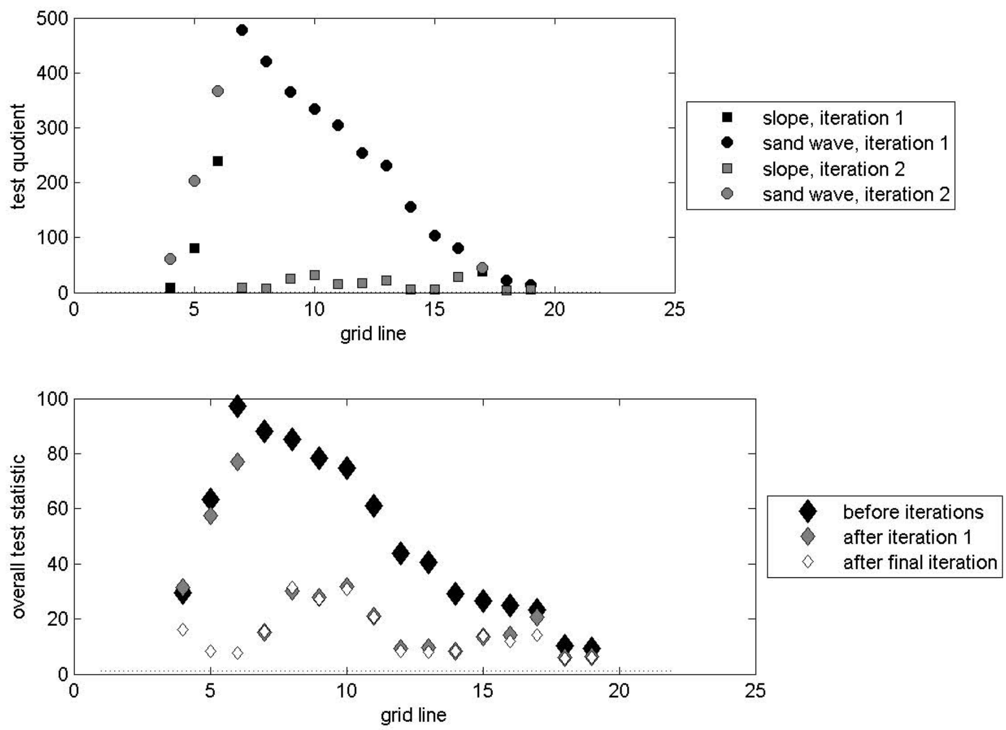

Figure 5.8: Spatial test quotients for different levels of complexity. After choosing a representation, the overall test statistic is calculated to determine the need for an extension of the stochastic model. The value one in the lower figure is represented by a dotted line and gives the required overall test result.

5.4 Phase 2: Time analysis

In this phase, time analysis, the seabed representation is tested statistically on dynamics. In comparison with Phase 1, Phase 2 repeats the procedure of statistical testing, but instead of adding extensions in a spatial way, temporal extensions are chosen. Two kinds of extensions are specified: a linear trend in all surveys, and a single outlying survey. In this context, outlying means that the survey differs significantly from the other surveys to which it is compared. The same steps of **Figure 5.4** are executed for the statistical hypotheses designed for these extensions. The input is now a representation with a chosen level of complexity, which depends on the number of spatial parameters as specified in Section 5.3. For each extension a test statistic and a critical value are calculated. The number of alternative hypotheses is dependent on the number of surveys available. In case H_{a1} or H_{a2} is accepted, the hypotheses in Phase 2 can be specified as:

- H_0 : Static (no dynamics);
- $H_{tr,pl}$: First alternative hypothesis. Trend in plane;
- $H_{tr,sw}$: Second alternative hypothesis. Trend in sand wave;
- $H_{out,pl,n}$: n alternative hypotheses for an outlier in plane (with n the number of surveys);
- $H_{out,sw,n}$: n alternative hypotheses for an outlier in sand wave (with n the number of surveys).

These temporal extensions are presented schematically by **Figure 5.9**.

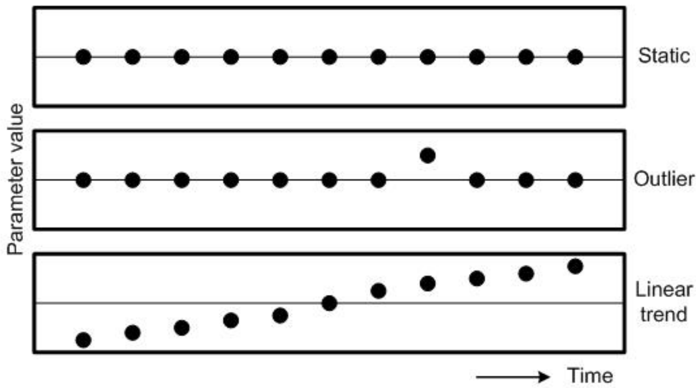

Figure 5.9: Temporal extensions for seabed dynamics

As already discussed in Section 5.3, the possibly different number of degrees of freedom are important when comparing more alternative hypotheses simultaneously. As illustrated in **Table 5.1** and **Table 5.2** the dimension of the hypothesis influences the number of degrees of freedom. The possible different dynamic parameters in Phase 2 are given in **Table 5.2** for trends. For outliers a comparable table could be set up:

Table 5.2: Degrees of freedom of statistical hypotheses in Phase 2

Dimension	Hypothesis	Trend parameters	Degrees of freedom
1D	Trend in horizontal plane	$\Delta d/\Delta t$	1
	Trend in sloping plane	$\Delta d/\Delta t$; $\Delta\Phi/\Delta t$	2
	Trend in sand wave	$\Delta A/\Delta t$; $\Delta\varphi/\Delta t$	2
2D	Trend in horizontal plane	$\Delta d/\Delta t$	1
	Trend in sloping plane	$\Delta d/\Delta t$; $\Delta\Phi_x/\Delta t$; $\Delta\Phi_y/\Delta t$	3
	Trend in sand wave	$\Delta A/\Delta t$; $\Delta\varphi/\Delta t$	2

When applying Phase 2 of the method to a data set, the temporal test quotients and overall test statistics are calculated. For this application, a MATLAB Toolbox *(Dorst, 2007)* is written to interpolate the depths obtained from the database, and to apply Phase 1 and Phase 2 of the statistical procedure. To method is illustrated by a test case, based on an actual survey of an area in the southern North Sea in 2003. The values for the 2003 survey are now assigned for all surveys in the test case (six surveys spread over 12 years). We now add simulated dynamics to each of the six surveys. In this specific example, the input parameters used are presented in **Table 5.3**.

Table 5.3: Input parameters for the example in the MATLAB Toolbox

Parameter	Value	Unit
Grid resolution	280	Nodes
Wavelength	720	[m]
Slope	Yes	[-]
Migration speed	4	[m/s]
Maximum outlier	1.5	[m]

The application of this toolbox generates results in the form of temporal test quotients and overall test statistics. We can now analyse the results in three dimensions: 0D, 1D and 2D. The advantages and disadvantages of these dimensions are further discussed in Section 5.5. We use a 0D analysis for the description of grid node behavior. The toolbox generates an image of the grid and describes each grid node, independent of the surrounding nodes. This nodal analysis can be seen in **Figure 5.10**.

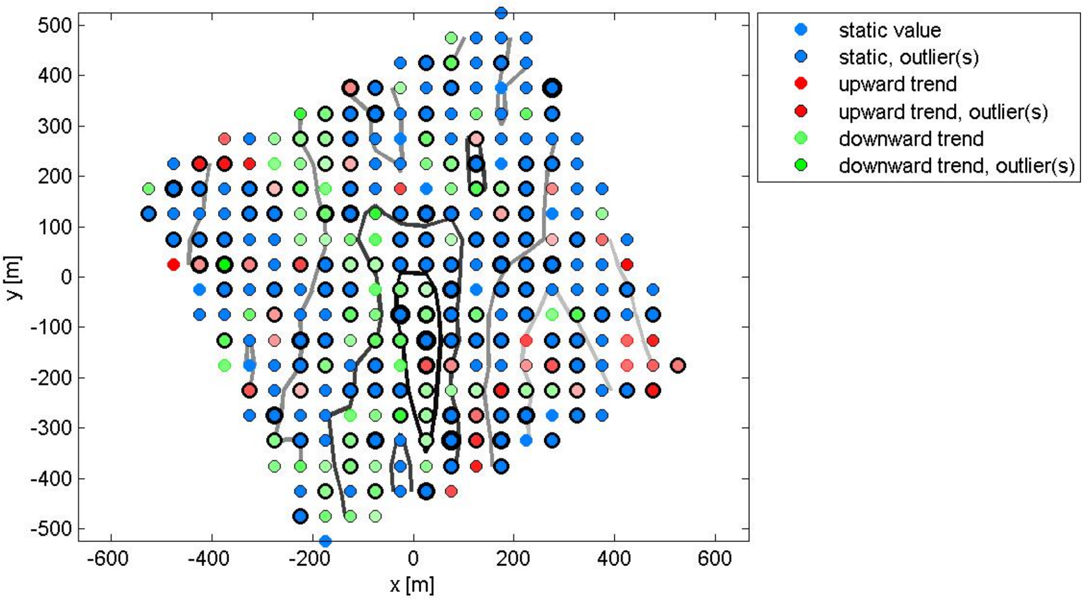

Figure 5.10: Behavior of the individual grid nodes. The intensity of the different colors describes the height of the trend (darker colors mean larger trends). The black circles around the colored dots represent the maximum outlier for each node. The thicker the line, the larger the number of outliers is. The contours illustrate the depth, where the darkest lines are the shallowest.

The temporal extensions discussed above are designed for 1-D and 2-D dimensions. If we want to discuss grid nodes individually, 0D analysis is a valuable method.

In **Figure 5.11** the results are presented for 1-D visualization in x-direction. For the analysis of a grid node, a 0-D visualization is used, while a 1-D y-direction is chosen for detecting changes in the direction of lowest variability (see Section 5.2.2). Finally a 2-D visualization is used for analyzing the grid as a whole. These different options are further discussed in Chapter 6

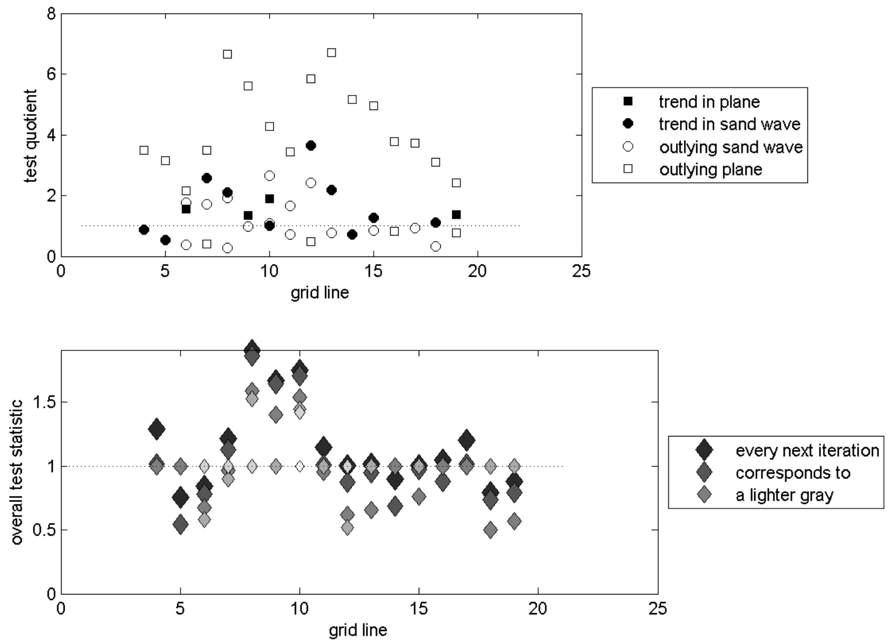

Figure 5.11: The temporal test quotients (top) and overall test statistics for the example data sets for 1D analysis in x-direction. When a test quotient is larger than one, an extension should be made. The larger the test quotient, the greater the need for this specific extension. The overall test statistics are calculated for each iteration. After the second iteration, overall test statistics are set to one, because of the estimation of additional covariance components for $\mathbf{C_d}$.

As can be seen in **Figure 5.11**, a relatively large part of the test quotients for each grid line are above one. This means that an extension of this type is a relevant extension of the temporal characteristics for that specific grid line. A value smaller or equal than one, means that this specific extension does not improve the representation significantly. When analyzing a trend in plane, it can be seen that a temporal extension of this type does not give a significant improvement when compared to for example, an outlying plane.

The overall test statistic for the chosen extension(s) for each grid line is one in the final iteration, because an adaption of the stochastic model is made (see Section 5.3.3). Now after calculation of the test quotients and the overall test statistics, an estimation is made of the dynamic parameters. In **Table 5.4**, the parameters for a sloping plane and a sand wave are pictured for as well Phase 1 as Phase 2.

Table 5.4: Potential parameters in Phase 1 and Phase 2

Pattern	Phase 1 potential parameters	Phase 2 potential parameters
Sloping plane	Depth (n times)	Bed level trend and (n-2) outliers
	Slope in x-direction (n times)	Trend in slope in x-direction and (n-2) outliers
	Slope in y-direction (n times)	Trend in slope y-direction and (n-2) outliers
Sand wave	Amplitude (n times)	Amplitude trend and (n-2) outliers
	Phase (n times)	Migration speed trend and (n-2) outliers

For this specific test run, the following results for the x-direction grid line (1D) analysis are obtained.

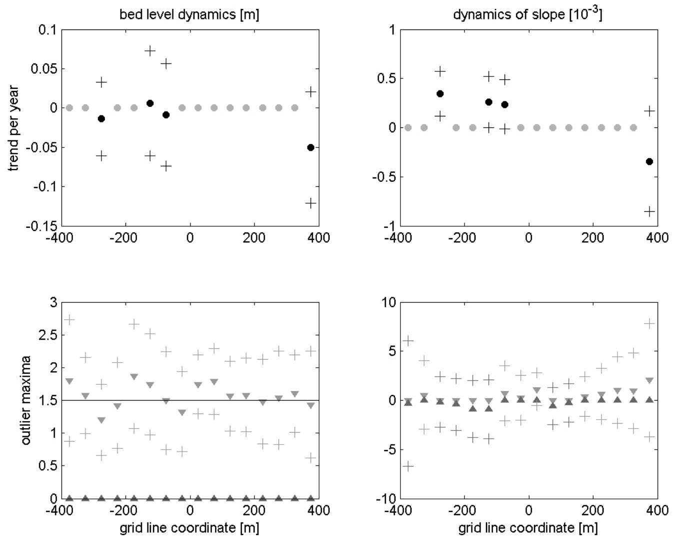

Figure 5.12: Results for the dynamics of the parameters bed level and slope. Both parameters are used in the alterative hypothesis H_{a1}. The black circles mean trends and grey circles represent no dynamics. For each circle the 95 % confidence interval is included. The triangles indicate the largest outliers in positive and negative direction, with their confidence intervals (presented by the '+'-symbols). The true dynamics as specified in the test case are represented by the horizontal line (see **Table 5.3**).

In **Figure 5.12** the dynamic behavior of the parameters bed level and slope are presented. When comparing the sub figures on the left and right side, it can be seen that the same grid line coordinates are estimated for each parameter. This is done because in each tested representation a combination of the spatial parameters bed level and slope is modeled. This implies that when dynamic behavior is found on for example grid line coordinates -220 and 390 for bed level changes, the second spatial parameter slope must be checked on dynamics too for the same coordinates. The same situation occurs for the analysis of a sand wave in **Figure 5.13**. For each parameter, an estimate of the dynamics for that specific grid line is made with inclusion of the 95 % confidence interval (presented in both figures by the '+'-symbol). When looking at the outlier maxima for the bed level dynamics, it is apparent that for some coordinates an outlier is not likely because the pre-determined maximum outlier of 1.5 metres lies at the edge of the 95 % confidence interval.

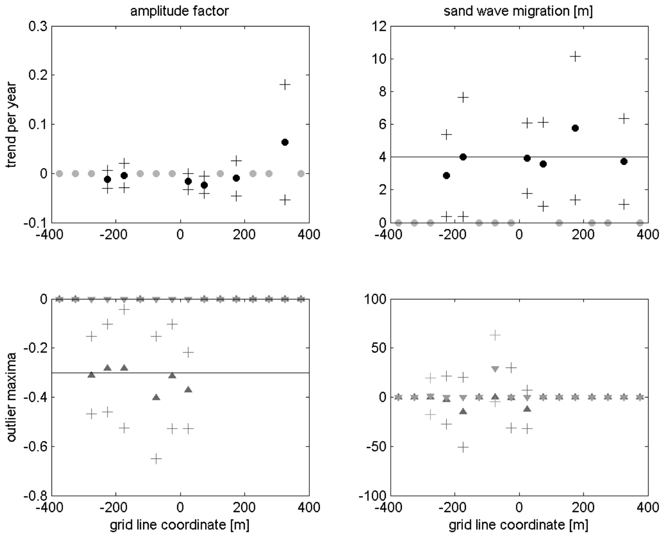

Figure 5.13: Results for the dynamics of the parameters amplitude factor and sand wave migration. These parameters are used in the hypothesis H_{a2}. The symbols used in this figure are equal to the symbols of Figure 5.12.

The figures presented above are all based on 1D results. Instead of analyzing each grid line individually, we can also analyse a grid at once, describing the behavior of the entire grid over a determined time frame. The temporal behavior of a grid is than resulting in a figure as for example **Figure 5.14**.

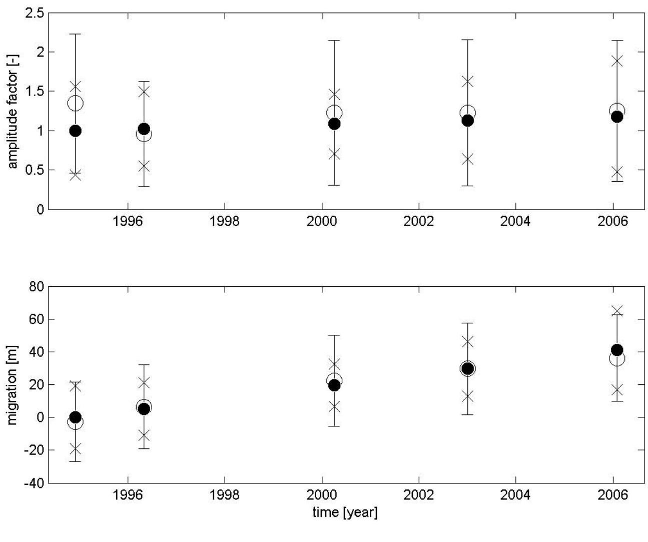

Figure 5.14: Temporal behavior of a grid. In this figure a trend is found for the amplitude factor and the migration. The white circles are the results after Phase 1, while the black circles give the results after Phase 2. The 95 % confidence interval is given by the horizontal lines for Phase 1 and the crosses for Phase 2.

5.5 Dimensions

As already partly discussed in the previous sections, we can use three different dimensions for the analysis of a grid. In this section, we discuss the advantages and disadvantages of each dimension. The dimensions are summarized as:

- 0D : Analysis of a grid node.
- 1D : Analysis of a grid line (in x- or y-direction).
- 2D : Analysis of a full grid.

The dimensions itemized above are pictured in **Figure 5.15**:

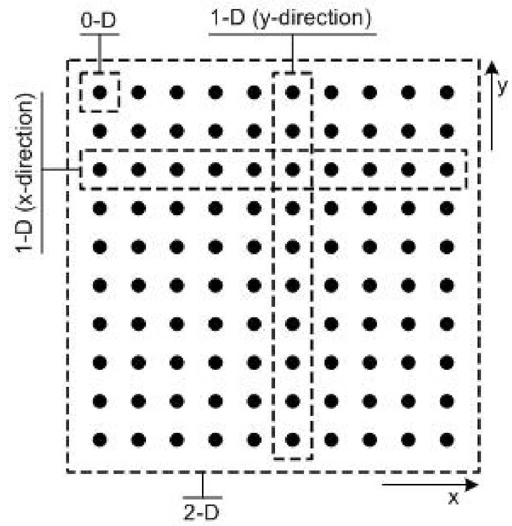

Figure 5.15: Interpretation dimensions of gridded depth information. The black dots represent the grid nodes.

The advantage of a 0D analysis is its simplicity; each grid node can be analysed individually on its movements. Furthermore, for 0D analysis no fixed area definition is required, which removes a restriction in the analysis of the NCS. 0D is also valuable for detecting spatial variation within a specific grid area. The downsides of this approach are that 0D is unable to detect dynamic behavior of bed patterns and second, small but constant variations are not found. In conclusion, 0D analysis is simple but difficult to interpret.

1D analysis is more suitable for detecting a sand wave pattern. Instead of a single node, a grid line of a specified grid is analysed. The advantage is that a sand wave can be identified, including its temporal behavior (growth and migration). Furthermore, the precision of the parameters is significantly higher than in the 0D approach. When compared to 2D analysis, 1D generates more precise parameters in case of an irregular seabed because the extension of the covariance matrix C_d in the LSVCE for a 1D analysis is smaller. The downside of a 1-D analysis is that the results are too complicated for a straight forward interpretation.

In case of a very regular seabed, the parameters of a 2D analysis are more precise than in a 1D analysis because a 1D approach delivers more unknown parameters leading to less precision of parameters with a regular seabed. The advantage of this approach is that a complete grid is analysed at once, simplifying the interpretation of the results. The downside of 2D analysis is that we are not able to adapt the wavelength per grid line, which means that the residuals increase if the seabed is less regular.

Purely based on the characteristics of each type of analysis, we conclude that 0D is not directly suitable for interpreting seabed dynamics on the NCS. Although this project does give a nodal analysis, proper interpretation of the seabed must be done with a regional approach or a combination of both. Further research is necessary to test the performance of the regional approaches. By determining the most appropriate spatial dimensions, the interpretation of seabed dynamics can be done more accurately. The differences between the dimensions are summarized in **Table 5.5**:

Table 5.5: The three dimensions for detecting seabed dynamics. For each alternative the advantages and disadvantages are included.

Dimension	**Type of analysis**	**Advantages**	**Disadvantages**
$0D$	Grid node	- Simplicity - No fixed area definition - Suitable for detecting spatial variation	- Not suitable for detecting pattern dynamics - Large output
$1D$	Grid line	- Suitable for detecting sand waves - More precise parameters in case of a less regular seabed	- Less precise parameters in case of a highly regular seabed - Fixed area definition
$2D$	Planar (Grid)	- Analyses a complete grid - More precise parameters in case of a highly regular seabed	- Less precise parameters in case of a less regular seabed - Fixed area definition

5.6 Phase 3: Adaptation Survey policy

After completing the previous phases, the interpretation of the results following from this procedure, is the logical consecutive step. Both the spatial analysis as the time analysis will shed light on the seabed characterization of a specific area, but the translation of this knowledge into improved survey planning and more efficiency within the Hydrographic community, is not yet completed. Chapter 6 will offer an approach in the interpretation of seabed dynamics in the analysed areas.

Chapter 6

Interpretation of seabed dynamics

6.1 Introduction

The Seafloor Monitoring method discussed in Chapter 5 forms the basis for the interpretation of seabed dynamics on the Netherlands Continental Shelf. In this chapter we introduce a method for the analysis of dynamics on a 0-dimensional level. This analysis is then used for the interpretation of different scenarios of dynamics on a test area. We discuss the results of the introduced method and how this can aid the optimization of the survey efforts of the NLHS in Chapter 7. In Section 6.3 we shortly introduce two other analysis methods that can be used for the interpretation of seabed dynamics. These methods are not further elaborated in this study.

As discussed in Section 2.2, the current survey policy is based on four *factors*: minimum depth, shipping density, draught and seabed dynamics. With these factors in mind there are several areas on the NCS that can be identified as *critical*; or in other words, areas that require special attention. Especially areas with a shallow depth in combination with high traffic intensity and high levels of seabed dynamics are most likely to be labeled as critical. These critical areas are the prime interest for hydrographic surveying, and are therefore categorized in the higher resurvey categories. The question remains however, how each sub-area of the NCS can be categorized into resurvey categories with respect to these four factors. In Chapter 4, we already selected the most relevant areas. These areas are now selected for the discussion of seabed dynamics.

Although several processes influence the shape of bed patterns , the *aspects* listed below (starting with the most relevant) are the most important for justifying frequent hydrographic surveying:

1. Natural pattern growth
2. Change in bed level
3. Migration
4. Pattern growth after human interventions

We introduce this order of relevance to emphasize the influence of seabed dynamics on the optimization of resurvey frequencies. Pattern growth is most relevant because this phenomenon directly influences the depth and thus the safety of the passing vessels. The second aspect is also highly relevant because relatively sudden changes in bed level affect the navigation depth directly. Migration is interesting but does not directly influences the minimum water depth (except in situations where sand waves migrate into an area that is otherwise relatively flat). The last aspect involves pattern growth (regeneration) after human interventions. Although relevant, bed patterns that are influenced by human interventions are regenerating to lower amplitude bed forms than patterns affected by natural pattern growth.

Aspects 1 and 2 are present on several scales, which can interfere when more than one pattern is present. The behavior of bed forms after human intervention is important in areas where dredging activities take place. In general, it can be said that in areas where human intervention takes place, a relatively sudden change in morphology is possible. Dredging, sand suppletion, offshore wind farm construction, and similar projects can have a significant influence on the characteristics and behavior of the seabed. Amplitude of the bed pattern is relevant in the shallow areas of the NCS in terms of UKC for passing vessels. High amplitude sand waves, which are capable of migrating across the seabed, are a problem if they migrate through navigation channels and reduce UKC to critical levels. As discussed in Chapter 1, sand waves are the primary interest of this project, due to the combination of significant amplitude growth and relatively high migration rates. The other patterns are neglected because of either their immobility compared to sand waves or their less significant amplitude.

6.2 Approach

In the following sections, the approach for interpreting seabed dynamics is discussed. In this approach we start with the introduction of three options for analyzing seabed dynamics in Section 6.3. We then proceed with nodal (0D) analysis in Section 6.3.1. The regional approaches (grid lines or a full grid) are shortly discussed in Section 6.3.2 and Section 6.3.3. In this study, the emphasis is laid on the nodal analysis of a test area. This test analysis is based on an actual survey of a area in the southern North Sea in 2003. The depths surveyed in this year are called the reference depths. We now use these reference depths for the other surveys (six in total). After this, we add simulated dynamics to the surveys. The results of the nodal analysis of this test area are presented in Chapter 7. In this chapter we suffice with the elaboration of the chosen approach.

6.3 Options for analyzing seabed dynamics

For all three options We now define the most critical node, as the node with the highest depth variation at 95 % C.I. on the upward (shallow) boundary. Each option is elaborated below:

1. **Nodal:** Nodal analysis. This method is based on the selection of the most critical node.
2. **Regional:** Grid line or grid analysis. We estimate the seabed dynamics with a regional approach. We then select the most critical node.
3. **Regional combined with nodal:** For this option we compare the most critical node of the nodal analysis and the most critical node of the regional analysis.

6.3.1 Option 1: Nodal

To investigate the behavior of each grid node, we describe each depth as function of several components. These components are: reference depth, trends and outliers for each survey year. We now use an **A**-model for a general description of all grid nodes. Although already discussed in Section 5.3, we provide the **A**-model for the test area used in Chapter 7. Equation (6.2) and Equation (6.3) are strictly valid for the discussed test area.

$$\mathbf{d}_n = \mathbf{A}\mathbf{x}, \;\; \mathbf{C}_{\mathbf{d}_n} = \mathbf{A}\mathbf{C}_{\mathbf{x}}\mathbf{A}^T, \tag{6.1}$$

with $\mathbf{d}_n$ the vector which contains the nodal depth for each survey, $\mathbf{A}$ is the model matrix, and $\mathbf{x}$ contains the dynamic parameters (the seabed parameters).

We start with composing the model matrix $\mathbf{A}$:

$$\mathbf{A} = \begin{bmatrix} 1 & t_1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & t_2 & 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & t_4 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & t_5 & 0 & 0 & 0 & 0 & 1 & 0 \\ 1 & t_6 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \tag{6.2}$$

The vector containing the seabed parameters, $\mathbf{x}$, is given as:

$$\mathbf{x} = \begin{bmatrix} d_{ref} \\ \Delta d/\Delta t \\ ol_1 \\ \vdots \\ ol_6 \end{bmatrix}, \tag{6.3}$$

with d_{ref} the reference depth in the third survey (2003), $\Delta d/\Delta t$ the trend (upward or downward), and ol_n the outlier in survey n (for the test area, $n = [1 \ldots 6]$).

We repeat this procedure for each node, to generate an array that consists of six values for each node. We now calculate the mean of these values to obtain d_m. Furthermore, we calculate the minimum value (the shallowest) at 95 % C.I. of $\mathbf{d}_n$ to obtain the maximum upward boundary in the array. The measure for dynamics is now the maximum possible depth variation at 95 % C.I., d_{dyn}. We repeat this procedure for each node. The result is a time-averaged depth with the maximum upper boundary for each available grid node. The maximum depth variation **Figure 6.1**.

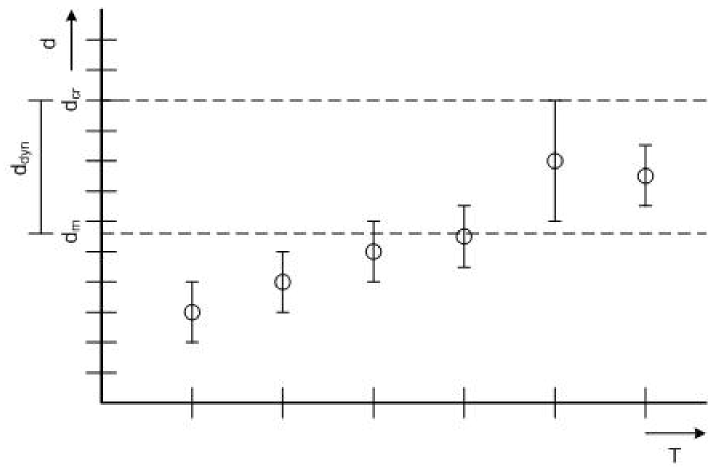

Figure 6.1: This graph presents the mean depth, d_m, the most critical depth, d_{cr} and the maximum depth variation, d_{dyn} for this particular node over timescale T. The vertical lines for each depth value represent the 95 % confidence limits.

We use MATLAB to run the analysis described above. Before we extend the current MATLAB Toolbox with this method, we sketch a flowchart that describes the procedure of the analysis. The flowchart for Option 1 is given in **Figure 6.2**.

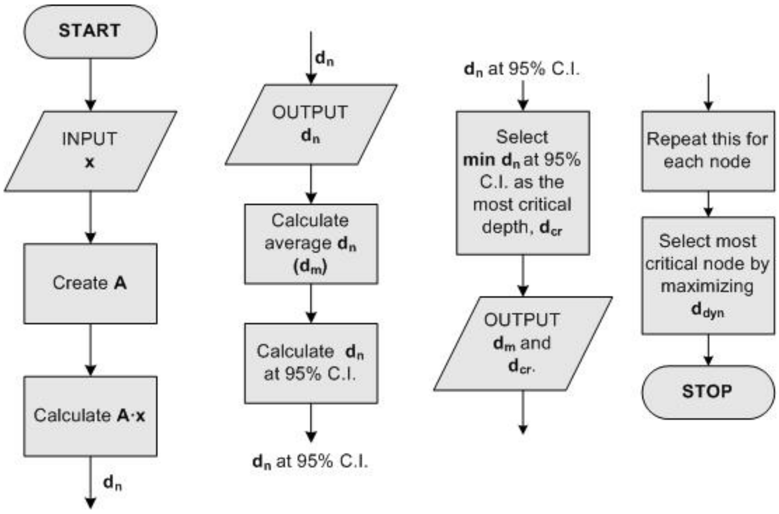

Figure 6.2: The MATLAB flowchart for 0D- analysis. The result delivered with this procedure is a mean depth, d_m, and a most critical depth, d_{cr}, for each node. We now select the most critical node within the selected grid by maximizing the depth variation d_{dyn}.

By implementing the 0D analysis on a test area in MATLAB, we can discuss the influence of parameters on the dynamics of the seabed. As output we define two aspects for the characterization of the seabed:

1. The most critical node.
2. The location of the most critical node.

The most critical node is now representative for the whole grid, if the maximum depth variation for other nodes across the grid shows a similar magnitude. We can now prioritize areas based on the presence of a significant depth variation. Furthermore we specify the height and location of the most critical node for each test run, to discuss the influence of dynamic parameters on the seabed character.

6.3.2 Option 2: Regional

In case we decide to follow a regional approach we make a choice for 1D or 2D analysis of the seabed with the help of the **2D Overall Model Test** (2D OMT) of the spatial representation (discussed in Section 5.3.3). When a spatial representation is chosen in Phase 1, an 2D overall model test statistic (2D OMTS) smaller than one implies a regular seabed. An 2D overall test statistic larger than one implies a irregular seabed. Thus, based on this property only, we can distinguish the character of the seabed and the most appropriate dimension for interpreting the dynamics. This decision process is modeled in Figure 6.3.

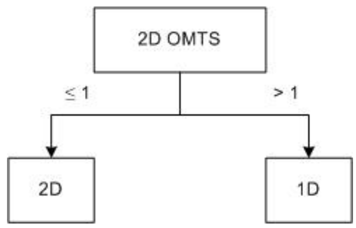

Figure 6.3: In Step 2 we choose for 1D or 2D analysis, purely based on the 2D Overall Model Test Statistic (2D OMTS). A value smaller than one implies a regular seabed and 2D is chosen. If the statistic is larger than one, the seabed is irregular and we choose for 1D.

As discussed, the benefits of regional approach in comparison with a nodal approach are significant. In this section, we first discuss a 2D approach which is essentially the same as the 1D approach (except that for 1D we have a set of dynamic parameters for each available grid line).

We start with the construction of a vector for each available dynamic parameter containing the initial value, the trend and the outliers for each survey. For example we choose the slope in x-direction, Φ_x, which leads to vector $\hat{\mathbf{h}}$ given as:

$$\hat{\mathbf{h}} = \begin{bmatrix} \Phi_x^{ref} \\ \Delta\Phi_x/\Delta t \\ ol_{\Phi_x^1} \\ \vdots \\ ol_{\Phi_x^6} \end{bmatrix}, \tag{6.4}$$

For the other dynamic parameters, slope in y-direction (Φ_y), amplitude of sand wave A, and phase φ (see Section 5.3.2), a similar vector is made. The vectors described above are multiplied by the model matrix $\mathbf{A}$ to obtain a new set of vectors that contain the properties of the parameter in question for each available survey. For both 1D and 2D we must continue to calculate the *morphological characterization*, $\hat{\mathbf{m}}_{x,y}$. For the 2D situation, we both have a slope in x-direction, and a slope in y-direction. To obtain a linear expression for $\hat{\mathbf{m}}_{x,y}$, we replace the original sand wave parameters for the linear parameters $A_s^{(c)}$ and $A_s^{(s)}$ defined by:

$$A_s^{(c)} = A_s cos(\kappa\xi_s), \;\; A_s^{(s)} = A_s sin(\kappa\xi_s), \tag{6.5}$$

with s the survey number, κ the wave number, and ξ_s the position of the first crest at the positive side of the origin (the origin of **Figure 5.5**). κ is given by:

$$\kappa = 2\pi/L, \tag{6.6}$$

with L the wavelength. We now define $\hat{\mathbf{m}}_{x,y}$ as:

$$\hat{\mathbf{m}}_{x,y} = d_s^b + \Phi_s x + \Phi_s y - A_s^{(c)} cos(\kappa x) - A_s^{(s)} sin(\kappa x), \tag{6.7}$$

with d_s^b the bed level (depth) at survey s. We calculate $\hat{\mathbf{m}}_{x,y}$ for each available survey so that we obtain six m-values for each node. The further procedure is largely the same as for 0D analysis;

we select the most critical node by calculating the maximum d_{dyn} for each node. In most cases the differences between the morphological characterization and the observed depths can be quite large in case of a less regular seabed. This implies larger residuals. The performance of this method is thus dependent on the character of the seabed. The more regular the analyzed section becomes, the more precise the results are, which benefits the interpretation of the depth variations.

For the 1D analysis, we use the same approach as presented above. The difference is now that we have more dynamic parameters available. Although we have the same *type* of parameters, the quantity increases because we have four parameters for each available grid line. The benefit of a 1D approach is that in case of a less regular seabed, we can minimize the residuals because we can estimate the dynamics per grid line individually, leading to higher precision. The method is the same as for 2D analysis, but now we obtain six m-values for each node along the grid line they are located on. Then we select the most critical node based on maximizing the depth variation d_{dyn}.

6.3.3 Option 3: Regional in combination with nodal

The third option is a combination of the methods described above. Although 0D analysis is suitable for discussing the individual grid node behavior, it fails to detect dynamic bed forms like sand waves. However, it is useful to use include 0D analysis to detect spatial variation. Especially in less regular seabeds, spatial variation can be significant. By combining the 0D approach with the regional approach (1D or 2D), we first detect dynamic bed forms, while on the other hand, spatial variation is discussed.

For this option we thus start with the regional analysis. Based on **Figure 6.3**, we choose for a 1D or a 2D analysis for estimating seabed dynamics. As described under Option 2, we then select the most critical node with the highest depth variation, d_{dyn}. We then proceed with 0D analysis to select a second most critical node. Then we compare both selected nodes on magnitude and location. Based on the higher accuracy of a regional approach, the first most critical node is representative if the differences between both nodes are significant.

In this investigation, only the 0D approach is included in the results presented in Chapter 7. The other two options are more or less similar, but the input for calculating the most critical node is different. For the actual interpretation of the found dynamics, we now discuss an interpretation method in Section 7.4.

Chapter 7

Results

7.1 Introduction

In this Chapter, we test the procedure presented in the previous chapter and we discuss the performance of the 0D analysis on a test area. Although we zoom in on the most critical section of the NCS in Chapter 4, further analysis of the selected areas for these areas is mandatory. In the test case, we introduce several scenarios of seabed dynamics that can occur under realistic circumstances. By studying the maximum depth variation d_{dyn}, we interpret the influence of the scenarios on a hypothetical section of the seabed. The resulting figures of each scenario are presented in Appendix C. In Section 7.2, we introduce the scenarios and the parameters that can be adjusted for different levels of dynamics. Section 7.3, will discuss the results of the test case and finally Section 7.4 discusses the interpretation of the results.

7.2 Dynamic scenarios

To test the performance of the described 0D approach of Chapter 6, several scenarios are calculated to determine how suitable the approach is for detecting seabed dynamics by means of isolating the most critical node. The scenarios that are tested are composed from four manually adjustable parameters: migration speed, gale coefficient, outliers and the standard deviation of the measurements. Each parameter is now scaled for typical North Sea conditions (based on literature). As can already be read in **Table 1.1**, the regular migration speed of sand waves in the North Sea is in the order of 10 metres per year. Lower migration speeds are also present, but these are more difficult to detect because these bed patterns are often smaller than the standard deviation of the measurements.

For the test case we start with a static representation with no migration, which is then changed in 5 metres per year and 10 metres per year respectively (simulated dynamics). The gale coefficient determines the effect of gales on the reduction of the amplitude of the present bed forms. A factor of 0.80 means that the amplitude of the present dynamics are reduced with 20 % . With the maximum amplitude of sand waves in the North Sea being around 10 metres (see **Table 1.1**), this implies a reduction of 2 metres due to gale influences. The third parameter that can be adjusted for the test area, is the presence of an outlier. Outliers can occur due to errors in the use of the measuring equipment or incorrect processing of raw data. The size of this outlier is set at 0.5 metres, which is based on information presented in *Dorst (2004)*. This value is expected to be realistic, but depends on the type of error made. The effect of these type of errors are minimized due to the quality control performed at the section POM (see Appendix A.3). The final parameter is standard deviation. According to IHO specifications *(International Hydrographic Organization, 1998)*, the standard deviation of measurements for Order 1 areas is set at 0.36 metres. We assume that the measurements that are used for the test runs are according to this specification. As an extra scenario, we introduce a standard deviation of 0.72 to include possible effects of rough measuring conditions, a larger track spacing or less accurate equipment.

The scenarios in this investigation and their settings are summarized in **Table 7.1**. As can be seen, we start with the static situation, with all parameters set to: *no dynamics*. Scenario two, introduces a migration speed of 5 metres per year with all other parameters unchanged. The third scenario uses the same migration speed, but incorporates a gale coefficient of 0.80 in the fourth survey (which reduces the bed patterns in this survey with 20 %), an outlier in the third survey of 0.5 metres, and an increased standard deviation for the fifth survey of 0.72. Scenario four repeats the second scenario, but increases the migration speed to 10 metres per year (the typical migration speed for North Sea conditions). The final scenario, uses a migration speed of 10 metres per year, a gale coefficient of 0.80 in the fourth survey, an outlier in the third survey of 0.5 metres, and a higher standard deviation of 0.72 in the fifth survey.

Table 7.1: The scenarios used to test the performance of the designed 0D approach. For each migration speed, we test the minimal and maximal dynamic situation. We start the test sequence with all parameters set to 'no dynamics'.

Scenario	No. of samples	Migration	Gale coefficient	Outlier	Standard deviation
1	5	0	1	0	0.36
2	5	5	1	0	0.36
3	5	5	0.80	0.5	0.72
4	5	10	1	0	0.36
5	5	10	0.80	0.5	0.72

7.3 Test results

We now use the MATLAB flowchart presented in Section 6.3.1 to develop a script that is capable of calculating the most critical node within a grid. Resulting from this script (included in Appendix H), is the parameter d_{dyn} which describes the difference between the mean depth over all surveys and the upward 95 % C.I. boundary. We now present the results of the 0D analysis by drawing an image of the mean depth for each node across the number of surveys. The second image represents the 95 % C.I. of the upward boundary (as illustrated in Section 6.1). The mean depth and the 95 % C.I. are illustrated in **Figure 7.1**. The third image gives the maximum depth variation d_{dyn} which is illustrated in **Figure 7.2**. For each run we obtain these three images by running the written MATLAB scipt. For the benefit of this investigation we only include the images of the depth variation, which are indirectly used for the interpretation of seabed dynamics and its influences. These depth variation images together with a table containing the size of the input parameters, are included in Appendix C. In this chapter we include an example of all three images discussed above.

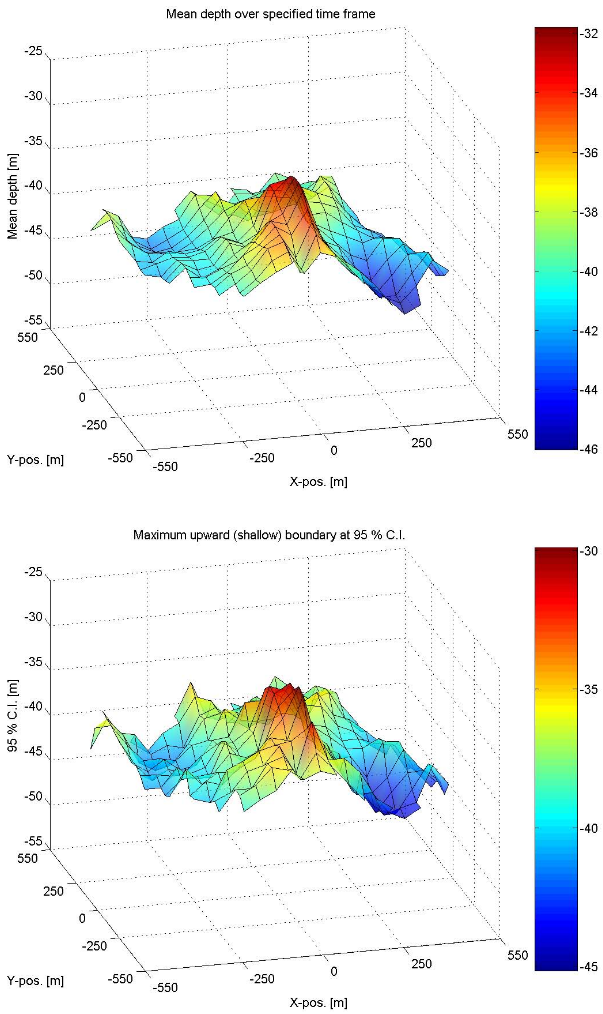

Figure 7.1: The top image shows the mean depth for each grid node along the specified survey period. The second image shows the 95 % C.I. of the upper boundary within the six available surveys for each node.

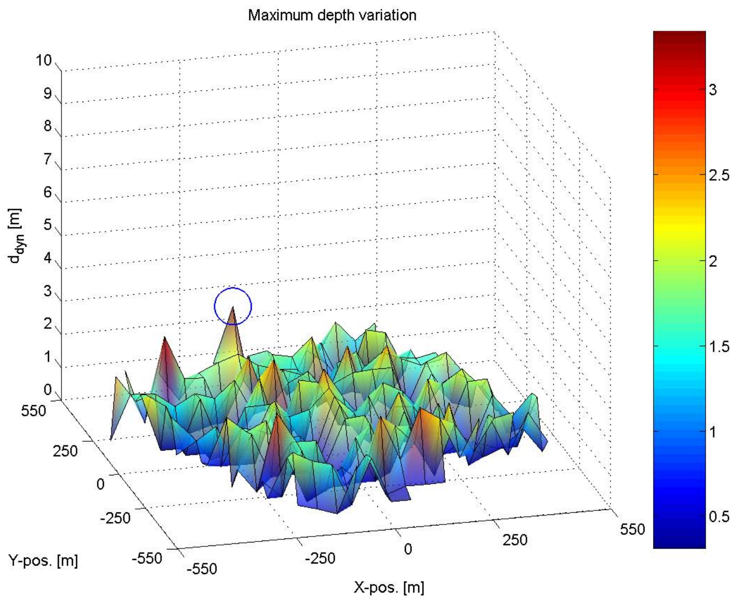

Figure 7.2: This image shows a maximum depth variation of 3.362 metres, located at X=-175 m, Y=325 m. The blue circle represents the location with the maximum depth variation.

As can be seen in the figures above, the most critical node (the node with the highest d_{dyn} is located on the top edge of the grid (we call this the North side. The three other sides are named analogously). When comparing the depth variation image with the mean depth and the 95 % C.I. graph it is concluded that the spike in this graph for location (X=-175, Y=325) is not likely to be very realistic. This is mainly due to the fact that on the edges of the grid, the limited availability of surrounding data points leads to less accuracy in the estimation. A lower accuracy means that the variance for this location increases, leading to a higher upper (shallow) boundary at 95 % confidence interval (see also Section 5.2.3). Thus we can conclude that the assignation of 'most critical node' to this specific grid node location is pessimistic. When looking at the other grid coordinates, we see that majority of the other spikes in this particular grid are around 2 to 2.5 metres. Next to this rather stable depth variation, the grid nodes for which specification is valid, are distributed over the full grid, meaning that the found depth variation is representative for the entire grid. The given range for maximum depth variation is expected to be more realistic than the value presented for the most critical node.

The example discussed above is off course based on just one set of data. We must run each scenario discussed in **Table 7.1**, more than one time to decrease the effect of randomization errors. For the 0D analysis discussed here, we choose for five repetitions for each scenario. These five repetitions are executed after two test runs (undocumented) for each scenario. We now discuss each scenario individually based on the plots presented in Appendix C to H.

7.3.1 Scenario 1

For run 1, 3, 4 and 5 we see that the maximum depth variation is located on the edges of the analysed grid. Due to the effect described above, these nodes are not likely to be representative for the entire grid. For run 2, the most critical node is located more in the middle of the grid. Although we do find some high peaks on the edges of the grid, the highest peak occurs at (X=275, Y=-75). The other peaks in this graph are in the gradation of 2 to 2.5 metres. The other runs show a similar maximum depth variation across the grid when we exclude the peaks on the edges. Based on the five samples for the first scenario we estimate that the depth variation in a situation with no dynamics is in the order of 2 to 2.5 metres with a maximum of around 3.3 metres (run 2). We use this initial depth variation as a basis for discussing the other scenarios.

7.3.2 Scenario 2

In scenario 2, we include a migration speed of 5 metres per year, with all other factors unchanged. We directly see in the figures in Appendix D, that the peaks for depth variation become more elongated and varying across the grid. As can be seen in Figure 7.1 (which is the initial situation with no dynamics), a sand wave can be identified in the X-direction (the direction of highest variability) with its crest located at approximately X=0. The majority of the peaks in depth variation for all runs of scenario 2 are concentrated around the crest of the sand wave. This can be explained by the fact that the modeled sand wave migrates in positive X-direction, which means that the estimation of the nodes that change in depth becomes less accurate. This is caused by the fact that the difference between the mean depth over all surveys and the maximum value available in the surveys increases. This implies automatically that the maximum depth variation increases. The limitation of this method in case of 0D analysis quickly becomes clear. When we apply dynamics on a grid, the depth variation increases due to the effect of averaging the depth over the specified time frame. Using only 0D analysis we thus cannot define the character of the dynamics. In other words we fail to describe the actual pattern behavior.

7.3.3 Scenario 3

The situation for scenario 3 is similar to scenario 2, but instead of only migration, we now add a gale coefficient, an outlier and an increased standard deviation for the fifth survey. With respect to magnitude of the maximum depth variation, we can say that there is not much difference when compared to the second scenario. And again we find a concentration of peaks around the crest of the modeled sand wave, although this is not as clearly visible as for scenario 2. The influence of the gale coefficient, the outlier and the increased standard deviation can not be seen in the figures presented in Appendix E.

7.3.4 Scenario 4

For scenario 4 we increase the pattern migration to 10 metres per year. All other parameters are the same as for scenario 2. From the five runs executed, three runs show the exact same coordinates for the most critical node (see Appendix F). The location of this node (X=-75, Y=-75) is located on the crest of the migrating sand wave. The most critical nodes of the other two runs are located not far from this point. We thus assume that the depth variation for these particular nodes of the grid is the highest.

7.3.5 Scenario 5

The final scenario is equal to scenario 4, but is extended with a gale coefficient, an outlier and an increased standard deviation for the fifth survey. The location of the most critical node in this scenario is much more spatially distributed than the most critical nodes in scenario 4. Although the inclusion of more dynamic parameters does seem to influence the location of the most critical node, the magnitude of maximum depth variation is not significantly higher than for scenario 4 (one exception for run 4).

The procedure used above to perform 0D analysis can be a useful addition in describing seabed dynamics and spatial variations, but as a stand alone solution it is not very suitable. To offer more useful results, a regional approach or a combination of both is mandatory.

7.4 Discussion

7.4.1 Introduction

To results of the test area are now used for a discussion on how the results can be used for the interpretation of seabed dynamics. The method used on the test area is based on 0D analysis, and we therefore are limited when it comes to the actual estimation of long term seabed behavior. The 0D analysis performed above is more suitable to detect spatial variations in the data, and it is therefore recommended to combine the results presented above with a regional approach (based on 1D or 2D analysis). However, the results presented above are useful when it comes to the interpretation of seabed dynamics and we therefore discuss an interpretation method in Section 7.4.2.

7.4.2 Interpretation

In this section we discuss the interpretation of the results. Because Option 2 and Option 3 of Section 6.3 are not yet implemented on a test area, the actual interpretation of pattern dynamics with the approach discussed below can not be shown. However, we do offer a method that can be applied in further investigation in this field. The interpretation phase is elaborated below.

We define a categorization method for the NCS, which takes all factors into account. The procedure steps discussed in the sections above are translated to a interpretation method which prioritizes areas into five categories. The five categories are presented in **Table 7.2**.

Table 7.2: Five categories for the interpretation of seabed dynamics are elaborated in this Table. The highest priority is given to Subcategory 2a. (High dynamics within the analyzed area)

Category	Definition	Priority	Priority number
1.	Prioritized areas	Normal	2
2a.	Analyzed areas - High dynamics	High	1
2b.	Analyzed areas - Moderate dynamics	Normal	2
2c.	Analyzed areas - Low dynamics	Low	3
3.	Excluded areas	Low	3

The interpretation by means of the categories discussed in **Table 7.2**, can be drawn as presented in **Figure 7.3**. This figure is an example, and the highlighted analysis areas are not true locations.

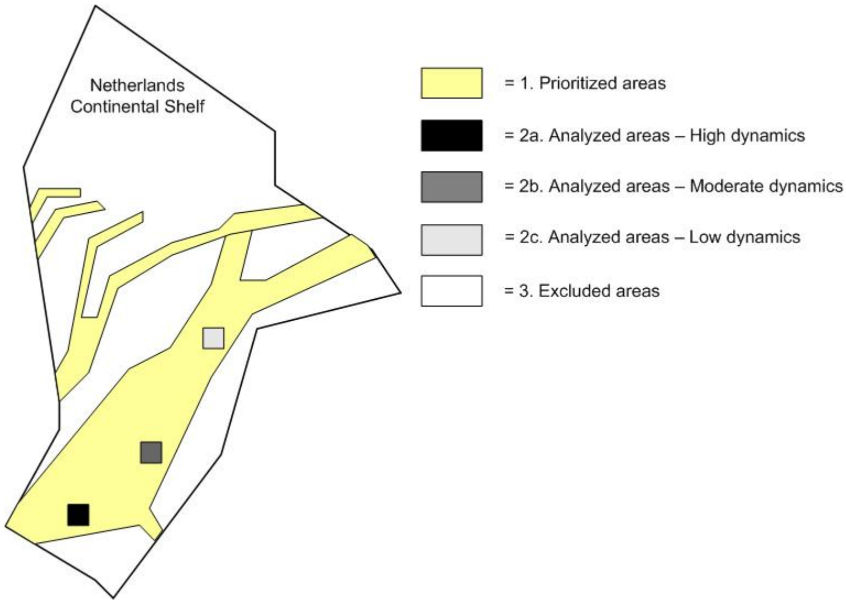

Figure 7.3: This figure shows the specified categories as discussed in **Table 7.2**. The yellow areas are prioritized based on the procedure of Chapter 4. The three highlighted analysis areas are hypothetical.

As can be seen in the procedure described above, we assign the labels *high*, *moderate*, and *low* dynamics. To quantify these labels, seabed dynamics must be scaled according to the potential risk for navigation. By determining the most dynamic node within an analyzed grid, we can estimate the character of the grid. As read in Chapter 6, the most dynamic node is based on the difference between the average depth over a certain time frame, and the highest upward trend or outlier at 95 % confidence interval. This maximum depth variation is now matched to the mean depth of the grid, the location and the navigation requirements for that location. If the minimum depth plus the maximum depth variation found in the grid becomes critical with respect to the navigation requirements, the found dynamics are labeled as *high*. If the grid is not yet critical, and is not expected to be so in the near future, we label the grid as *moderate*. If no, or low dynamics are found, the grid is not critical and is expected to be within safety margins for the following years, and we assign the label *low*. For the grids that are labeled as *moderate*, we use the resurvey frequencies of the current survey policy. If the grid is labeled *high*, we first check the current resurvey frequency. If this frequency is not suitable, an adaptation of the frequency is required.

The downside of this method is that we use 0D analysis in this study. As discussed in Chapter 6, we expect to gain better results with a regional analysis or a combination of regional and nodal. As can be seen in the procedure described above, we only quantify seabed dynamics for specified analysed areas. The remaining section of the prioritized area is given a normal priority (current frequencies), that is extended with recommendations issued on basis of a generalization of the results from the analysis areas.

7.4.3 Generalization in space and time

In this section it is discussed whether the interpretation can be used for a generalization in space and time. This generalization is beneficial because it means that the results of the chosen analysis areas can be used to generate information on seabed dynamics in future situations and on other locations in the prioritized areas. To make this possible, the interpretation of seabed dynamics must be universal to some extent.

With respect to pattern dynamics it can be said that when sand waves reach their final saturated form, they become stable. Migration speed for example, only decreases slightly in the evolution process of a sand wave. Thus, to estimate the long term migration speed of fully grown sand waves, we can use linear stability analysis *(Németh et al., 2007).* For the amplitude of the sand wave, it can be said that the evolution is not linear. In the initial phase of the development, the growth rate is relatively small, while with increasing saturation this speed increases. In the final phase (to reach the fully grown state), the growth rate diminishes again *(Németh et al., 2007).* In relation to this subject this means that when a trend in amplitude factor is found after deformation analysis, it is likely to change when the sand wave is reaching the final phase of its evolution. For typical North Sea conditions sand waves reach their fully saturated (evolved) state at $\sim$ 20 % of the water depth *(Németh and Hulscher, 2003).* If we want to use the results of the analysis of a small area for describing other locations (spatial), we need similar conditions on those locations. For example, if we find a pattern with a specific amplitude that migrates into one direction, we expect to find a similar pattern on locations with similar flow conditions, depth and seabed composition. Although this is a very rough approach, it does help us to locate the more critical areas that require a higher priority.

Chapter 8

Conclusions and recommendations

The goal of this study is to interpret seabed dynamics as a factor for determining the most appropriate resurvey frequency for a specific research area. Over the last years, continuous research has been done in this field by estimating seabed dynamics with a statistical methodology called deformation analysis. The research goal described in Chapter 1 is summarized below to highlight the most important aspects of this study.

> *The goal of this study is to offer a method for interpretation of seabed dynamics on the Netherlands Continental Shelf. By pointing out the step between the data analysis process and the actual choice for a resurvey moment, we can indicate a simplified approach to describe the dynamics as a factor for planning purposes.*

The problem originating from this goal is that the translation of estimated seabed patterns and their characteristics, to more efficient and reliable resurvey frequencies, is complex and prone to interpretation errors. These interpretation errors can not be accepted in the nautical world, because all bathymetric surveying is limited by requirements of the International Hydrographic Office, and must guarantee safe passage of vessels. Misinterpretation can thus lead to an increased risk for navigation on the shelf. It is therefore required to offer an approach based on previous research and scientific knowledge, to guarantee the safety. Based on the research goal and the problem description, we offer a set of research questions to aid the optimization of the survey efforts. Each question is discussed individually and includes the results obtained during the duration of this study. Furthermore, we include recommendations after each research question, which can be used for further investigation.

Question 1

What is the current method for the construction of the survey plan, and how is the method of deformation analysis used as a tool for the involved data analysis process?

Conclusions

The current survey plan of the Royal Netherlands Navy is based on four factors: Minimum depth, draught, shipping density and seabed dynamics. This last factor, seabed dynamics, is difficult to quantify and is therefore not easily interpreted as a factor for designing resurvey frequencies. In the 2003 survey policy, seabed dynamics is included in a deterministic way. Based on this deterministic approach, areas with high levels of seabed dynamics are, depending on its location, prioritized above less dynamic areas (see Appendix A). On basis of this 2003 survey policy, yearly survey instructions are issued that present the areas that are to surveyed for that hydrographic year.

Over the last years, first steps have been taken in the inclusion of deformation analysis as a tool for estimating seabed dynamics. As described in Chapter 5, this method is able to estimate trends and outliers in seabed patterns. Deformation analysis has been applied on several areas, which are largely located in the approach route to Rotterdam. These shallow areas are characterized by a high shipping intensity and small UKC margins. Analysis of these areas showed that for some areas, seabed dynamics forms a significant factor for navigational safety. Depending on the actual character of the seabed on these locations, and the chosen statistical representation, the estimated dynamics can be accurate enough to be used for optimizing resurvey frequencies. However, the interpretation of these results and their accuracies is complex and not yet implemented.

The optimization of the survey policy is however not only dependent on the inclusion of seabed dynamics. As a result from the interviews at the Hydrographic Office, it has appeared that the efficiency of the HOV-s is lower than anticipated in advance. To optimize the survey policy, we thus need a two-way solution. On the one hand the reliability of the HOV-s must increase, and on the other hand, a proper interpretation of detected seabed dynamics is required.

Recommendations

To include seabed dynamics as a quantifiable factor for the optimization of the survey policy, it is required to complete the last phase in the Seafloor Monitoring project: the interpretation of the present dynamics within an analysed area. To include this interpretation in a new survey policy, a method must be designed that is capable of categorizing areas of the NCS according to the detected and expected dynamic behavior. Because seabed dynamics remains susceptible to variations (the statistical analysis also includes variances), the categories must be wide enough to make a reliable assumption. If the categories are to narrow, areas can possibly be classified in the wrong category. In this study, a first step in this field is set, but further research is mandatory.

Question 2

Can we use the proposed method for the interpretation of seabed dynamics for the benefit of improving the survey policy, and what results can we expect from this method?

Conclusions

As already mentioned above, a proper interpretation is required to include seabed dynamics as a true factor in designing resurvey frequencies. In this study we approach the interpretation of seabed dynamics as a step by step procedure. The first step is the initial prioritization which excludes areas that are less relevant on the factors: minimum depth, draught, shipping density and human interventions. This last factor is added to incorporate the effects of possible area planning in the coming years.

After the initial prioritization, we select an analysis area within the prioritized area that is analysed on seabed dynamics with the approach discussed in Chapter 6. This analysis is based on the selection of the most critical node as the measure for dynamics of a particular section of seabed. The most critical node is selected by maximizing the highest depth variation. Due to time limitations, we were only able to execute 0D analysis. Resulting from this procedure is a description of the investigated grid in terms of peak dispersion of depth variations, the maximum depth variation and its location.

To offer a more complete analysis of the designed approach and the impact on the interpretation of seabed dynamics, we must include a regional approach and a combination of the regional and the nodal approach. Both approaches are still based on the selection of the most critical node, but they a more capable in describing the actual behavior of the seabed in terms of dynamic parameters like sand wave amplitude and phase. The result from the analysis of a grid is thus a most critical node which is representative for that grid.

We now go to the next phase in the method, which discusses the interpretation of the most critical node as a measure for seabed dynamics. As already mentioned under Question 1 on the previous page, seabed dynamics is prone to relatively large variations and the statistical method used in this study introduces variances when it comes to the spatial approximation of the seabed. Based solely on the 0D approach, it is impossible to detect pattern dynamics. The method described in Chapter 6 is thus not suitable for interpreting *pattern* dynamics. However, we do offer the possibility to perform a quick analysis of a specific grid within an analysis area, to obtain a general idea of the possible depth variations within this area.

Recommendations

To improve the method discussed in Chapter 6 it is required to extend the 0D analysis with a regional analysis. Another possibility is to ignore 0D, and solely base the analysis on a regional approach. The advantage of this regional analysis is that the spatial approximation of the seabed is more accurate. Instead of looking at individual nodes within a grid, we analyse grid lines or a full grid at once. Depending on the character of the seabed, we choose for a one dimensional or a two dimensional analysis (possible with 0D extension). If the seabed can be described accurately with this regional approach, the results will become more precise, leading to an improved description of the dynamics. We thus recommend to execute a regional analysis (possibly in combination with the nodal analysis) on selected analysis areas within the prioritized areas of Chapter 4.

Question 3

How performs the proposed method on a small test area, and how can we generalize this in a spatial and temporal way?

Conclusions

As already mentioned, 0D analysis is not suitable for detecting pattern dynamics. However, we can specify the maximum variation in depth with relation to navigational safety. This depth variation is defined by the variation between the mean depth and the maximum upward boundary at 95 % confidence interval for each grid node. By maximizing this variation, the most critical node can be selected. To test the 0D analysis, a test area has been analysed with five different scenarios of sumlated dynamics. For each scenario five test runs are executed, and for each run a maximum depth variation is calculated. Based on the location of the maximum variation, and the size of the variable across the whole grid, a general idea of the present dynamics can be formed.

In the test grid a single sand wave can be identified. In scenario 1 we assume that this sand wave is static. If we now calculate the depth variations in the grid we see that the values for each node are rather uniform at around 2 to 2.5 metres. The maximum depth variation is found, in most cases, at the edges of the grid. This is caused by the limited availability of surrounding data points, which results in lower accuracy.

For scenario 2 to 5, we add simulated dynamics. We now see that the distribution of the depth variations is more concentrated on the crest of the modeled sand wave. This is due to the fact that the difference between the mean depth for these nodes and the maximum upward boundary is larger, because the crest of the sand wave migrates to the right. This migration causes a lowering of the mean depth for the nodes on the left side of the crest of the sand wave.

After the analysis, the interpretation of the results is the next phase. Based on scientific literature, sand wave migration assumed to be linear. We also find that sand waves reach their evolved state at approximately 20 % of the water depth. This linear and stable behavior of sand waves is however affected by multiple processes. For instance, the dredging of navigation channels, and weather influences, can have an effect on the shape, amplitude and migration rate of the bed forms. Thus we assume that in areas which are located in deeper waters and where no (relevant) human interventions take place, sand waves are stable and can rather easily be included in the survey policy. For areas like the southeastern section of the NCS, the interpretation is less straightforward. For instance, dredging activities in the Rotterdam approach channel affects the local sediment balance.

The method elaborated in this study focusses initially on the selection of the most critical areas based solely on the factors depth, draught, shipping intensity and human interventions. After this initial prioritization the method analyses small selected areas within the prioritized area, which are analysed for maximum depth variation. We now define three categories in which we can categorize the selected analysis areas: *high dynamics*, *moderate dynamics*, and *low dynamics*. For this categorization we need to connect the found maximum depth variation with the requirements in the field of navigational safety. If we find a maximum depth variation that is, when combined with the minimum depth within the area, critical or expected to be in the near future, we label this area with *high dynamics*. For these areas it is recommended to increase the resurvey frequency. If we find a maximum depth variation that is not critical (and not expected to be so in the near future), we label the area with *moderate dynamics*. The resurvey frequency for these areas then remain unchanged. We assign the label *low dynamics* to areas with uniform depth variations (stable over the entire analysed grid). For these areas we recommend to decrease the current resurvey frequency.

Recommendations

The current method is based on a sample of five years. For further research it is recommended to check if the assumption of characterizing an area with the maximum depth variation still holds for longer time scales. For this purpose we need data for specific analysis areas from the database, which are then analysed with the method described in this study. If we compare the differences in the maximum depth variation over different time scales we can check if the current resurvey frequency is optimal for this area. In other words: if we find a maximum depth variation of approximately four metres in a time frame of five years, and a value of also four metres for the same area but over a larger time frame, we can possibly reduce the current frequency. Further analysis in this field will show if this assumption holds. This only describes the temporal generalization of the results.

For a spatial generalization, we need to locate areas with approximately equal characteristics. If we find for example two areas with approximately the same flow properties, depth, and bed composition, we can assume that (under equal weather circumstances), the maximum amplitude and migration rate have the same order of magnitude. To study this, the method described in this document must be implemented on several areas with equal characteristics. If comparison of the results shows that this assumption is safe, we can estimate seabed dynamics of a random area with comparable characteristics, based on a spatial generalization of an analysed area.

Appendix A

Interviewing at the Hydrographic Office

This Appendix will include the used methodology for performing the interviews at the Hydrographic Office of the Royal Netherlands Navy. Based on this methodology and the formulated questions, three interviews are performed at the Hydrographic Office. The results from these interviews can also be found in this appendix.

A.1 Methodology

Although an interview is sometimes described simply as a conversation with a purpose, the actual definition of an interview can be given in many forms. As presented in *Millar et al. (1992)*, a definition is:

> *"A face-to-face dyadic interaction in which one individual plays the role of interviewer and the other takes on the role of the interviewee, and both of these roles carry clear expectations concerning behavioral and attitudinal approach. The interview is requested by one of the participants for a specific purpose and both participants are willing contributors."*

In this definition six aspects are identified that are important for a successful interview:

1. *Face-to-face*: an interview takes place as a face-to-face conversation, for the benefit of at least one of the participants.
2. *Dyadic*: the interview takes place between two people at a time. More persons often have a negative influence on the proceedings of the conversation.
3. *Roles*: both participants are expected to play an individual role, one as the interviewer and the other as the interviewee. It is important to maintain these roles to reach the interview objective.
4. *Requesting the interview*: a research interview is usually requested by the interviewer, who gives a projected sequence of the interview as a part of the request.
5. *Purpose*: there is clear purpose of the interview, meaning that the questions are on-topic and stated to reach a previously formulated research objective.
6. *Voluntarily*: both parties should undertake the interview voluntarily. If not, the obtained results are most likely not reliable.

A somewhat different definition for a *research interview* is now formulated as: a two-person conversation initiated by the interviewer to obtain research-relevant information, focussed on the content specified by the research objectives.

There are four approaches of a research interview. The first is highly structured with predetermined answer options and a fixed asking sequence. The second approach is also structured but a degree of flexibility in the answers of the interviewed persons is allowed. When, as a third option, question sequence is not specified in advance, we speak of a moderately structured interview. This type allows for a more conversational style of interviewing. The fourth type is non-structured *(Emans, 2002)* and only some guidelines (main-themes) are specified before the interview. For this investigation the choice is made to follow the third approach, because it gives the interviewee considerable freedom in his or her answers and, at the same time, remains sufficiently structured to obtain the required response.

The interview must be structured with structuring criteria. In *Millar et al. (1992)*, several of these criteria are mentioned, of which the most important are given in **Table A.1**:

Table A.1: Structuring criteria

Criteria	**Highly structured**	**Highly unstructured**
Topic control	High	Low
Question content	Fixed wording	Variable wording
Question type	Closed	Open
Number of questions	Fixed	Variable
Sequence of questions	Fixed	Variable
Response alternatives	Fixed	Variable

The structuring criteria of **Table A.1** are adapted to the required specifications:

Table A.2: Structuring criteria for the NLHO interviews. The used terminology is elaborated below

Criteria	**Moderately structured**
Topic control	High
Question content	Fixed wording
Question type	Both (Including probing questions)
Number of questions	Fixed
Sequence of questions	Semi-variable
Response alternatives	Variable

The topics that are listed in Section 3.3 are fixed (determined in advance). For each topic, a number of questions are formulated, which are also fixed. As is read in Section A.2, the character of the questions is variable and includes both open as closed questions. Next to these, a third category is included: probing questions. The three question types used are:

- *Closed questions*: This type involves restricted questions. In *Hargie et al. (1987)* three types of closed questions are identified:
    1. Yes / no
    2. Identification
    3. Selection questions
- *Open questions*: These questions allow the interviewee considerable freedom in determining the amount of information given. This type of questioning can give more background information than closed questioning.

- *Probing questions*: This type consists of questions that encourage further expansion of an interviewee response, which therefore gives interviewees most freedom to continue with the selected topic. In *Brenner et al. (1985)* this type of questions are described as follow-up questions. Logically, probing questions are preceded by open questions.

The number of questions is also fixed to remain within an acceptable time frame. To obtain a fluent interview, it can be necessary to adapt the question sequence to the interviewee's responses. The questions used are included in Section A.2.

A.2 Questions

This section will cover the formulated questions and its specific type, noted between brackets at the end of the question (according to Section A.1). The questions formulated per category are listed below:

1. (a) What input is used for the design of the survey policy? (*Open*)
   (b) What is the current way of using depth information in a survey policy? (*Open*)
   (c) How is seabed dynamics a factor in the survey policy? (*Open*)
   (d) How does shipping intensity influence the design of the survey policy? (*Open*)
   (e) What are the problems related to the current resurvey frequencies at the NCS? (*Probing*)
   (f) What are the benefits of a higher survey frequency for the safety at sea? (*Open*)
   (g) Why are the areas deeper than for example 40 meters included in the survey policy, when they are not critical? (Shouldn't we pay more attention to the critical areas?)(*Probing*)

2. (a) What knowledge is the basis for the current frequencies? (*Open*)
   (b) In what way is the current survey policy (2003) different than the previous one? (*Open*)
   (c) How are seabed dynamics accounted for in the current way of designing the survey policy? (*Open*)
   (d) How was this dynamic behavior applied to the practical survey policy in the recent history? (*Open*)

3. (a) To what level is the NCS covered with MBES data? (*Closed*)
   (b) How does MBES influence the survey frequency at the NCS? (*Open*)
   (c) Should we prioritize areas with single beam data, or should we focus on the critical areas? (*Probing*)
   (d) Are the current HOV-s suitable for the realization of the survey policy? (*Open*)
   (e) Can new and more accurate technologies lead to a further reduction in surveys? (*Probing*)

4. (a) How do external assignments influence the designed year-plan? (*Open*)
   (b) How are unforeseen events (like the Tricolor accident in the Calais Strait) affecting the survey instructions? (*Open*)
   (c) Is there assistance of Rijkswaterstaat in case of material failure or in accomplishing the year plan? (*Open*)

5. (a) How are the survey data (on board the survey vessels) analyzed and by whom? (*Open*)
   (b) Is there feedback from the Production department back to POM? If yes, how is this done and can you give an example? ((*Probing*)
   (c) What are the main benefits of the change from SHIP1 to SHIP2 (System for Hydrographic Information Processes)? (*Open*)

6. (a) How are Directorate-General of Public Works and Water Management and NLHO cooperating in the planning of their survey activities? (*Open*)
   (b) How are other activities (like bottom sampling) coordinated and what is done with the acquired information? (*Open*)
   (c) In what way are the resurvey frequencies limited by the Government and economical measures? (And does this have any effect on the safety at the North Sea?) (*Probing*)

7. (a) How does the RNLN cooperate with foreign countries in formulating their survey policies? (*Open*)
   (b) Is there international survey standardization between different hydrographic services? If yes, on what subjects? (*Probing*)
   (c) When looking at the survey policy in foreign countries, are we not too ambitious in our goals? (*Open*)
   (d) What are the international agreements between the Netherlands, England, Belgium, France, Germany, Iceland, Denmark and Scandinavia (NSHC) on the frequencies of bathymetric surveys? (*Open*)
   (e) What are the prominent countries with which the Netherlands are participating in optimizing the survey policy? (*Open*)

8. (a) Is it necessary to survey at all? (Why not let it go?) (*Probing*)
   (b) Is it possible to downgrade to one HOV instead of two or is there need for a third vessel (related to required amount of survey days per year) (*Probing*)?
   (c) What are the expected developments in the coming years on estimating suitable survey frequencies? (*Open*)

9. (a) What are the expected results from the Seafloor monitoring method?
   (b) Do you think that the results from the small research areas can be used for designing a new overall survey policy for the NCS?
   (c) In what what way do you expect the survey policy to change with new knowledge obtained from Seafloor monitoring?

We now present the results from the performed interviews as an integral registration of the conversations. To prevent misinterpretation of the answers, the three registrations are combined to one interview.

A.3 Interview results

1. (a) The yearly NLHS hydrographic survey instructions are delivered on the first of January each year and contain the areas to be surveyed in that specific year and the quality criteria for these surveys. The yearly survey instructions are based on the frequencies of the NLHS survey policy of 2003 and the survey priority assigned to each specific area. The 2003 policy is largely based on experiences with the previous survey policy and can thus be seen as an evolution of this scheme. The survey requirement of the survey policy results from comparing the age of the contents of the source databases and the maximum age allowed by the survey policy. The difference between these two shows the hydrographic survey-arrears[1] at the NCS. All areas which are 'too old' according to the survey policy are prioritized, and included into the yearly Hydrographic survey instructions.

   The formation of the hydrographic survey instructions only depend on the status of each individual area in relation to the 2003 survey policy. Factors like shipping intensity, seabed dynamics, water depth and draught are included in this survey policy and are subsequently not taken into account in the yearly survey instruction. Currently a new survey policy is under development to include recent area planning, deformation analysis results, new developments in shipping intensity, changes of spatial use of the NCS and technological advances in survey techniques.

   (b) The depth information recorded by the survey vessels is transferred to the department POM[2] at the NLHS. At this stage, the data is checked for consistency, completeness w.r.t. the survey instructions and format. The data is covered by a Report of Survey which contains a quantitative description of the executed survey and qualitative assessment. After the initial phase, the approved data is transferred to the other departments of the NLHS. At the department *Acquisition*, the survey deliverables (wrecks, obstructions and other objects on the seabed) are evaluated. The department *Processing* evaluates the quality of the delivered bathymetric data w.r.t. gross errors and quality (spikes and other anomalies) and finally the department Geodesy and Tides evaluates the quality of positioning and tidal reduction. When detecting gross errors, corrupt, incorrect or incomplete data, this is communicated to the survey vessel to correct the data. When the deliverables are accepted by all specialist departments, a letter of acceptation is issued to finalize the survey. At this stage, the survey vessel is allowed to delete the survey data-set in question.

   (c) As discussed, seabed dynamics are included in the design of the survey policy of 2003 in a deterministic way. Thus dynamics, indirectly, influence the design of the yearly survey instructions. Areas which are characterized by high levels of seabed dynamics are, depending on its location, prioritized above less dynamic areas.

   (d) Just like seabed dynamics, shipping density is included in the survey policy and, as such, indirectly in the yearly survey instructions. Information on shipping density is mainly coming from the Directorate-General of Public Works and Water Management (Rijkswaterstaat - RWS). To include shipping density in the survey policy, risk factors must be analyzed. Different risk sources are the UKC of transiting ships (which includes draught, influences of ship movements like squat, roll, pitch and heave), the specific types of shipping cargo and the local sediment composition of the seabed (risk of collision with the bottom, and running aground). For the new design of survey policy (which is scheduled for 2008), recent area planning (for example offshore wind farms)

[1] Also known as backlog
[2] Planning, Operations and METOC. See Section 2.2

is considered. These planned projects are affecting the current location of Traffic Separation Schemes, which results in a necessity for a new survey policy.

(e) The current frequencies are considered sufficient for its purpose. The main problem of the current re-survey frequencies however, is the presumed inefficiency, because re-survey frequencies tend to be too high. The applied re-survey frequencies have not led to accidents to shipping, which might be considered to be a positive confirmation of the present approach. However, also a problem w.r.t. survey capacity does occur. In theory the HOV-s should be able to comply to the survey policy, but due to frequent material failure this has not yet been realized. Furthermore, due to difficulties in estimating dynamic seabed behavior, the current frequencies are partly based on guessing. As a third effect new approaches may also reduce the survey capacity problem.

(f) Safety or risk at sea is difficult to quantify, which means that the benefits of a higher (or lower) re-survey frequency are not directly obvious. When introducing a lower frequency, a sound (scientific) foundation is mandatory, to guarantee safe transits of ships. However, internationally seen the resurvey frequencies of the NLHS are rather ambitious, which means that there might be possibilities for reducing the current frequencies.

(g) The main reason why these areas are included in the 2003 survey policy, is to search the area periodically for obstructions and wrecks. Furthermore, some areas have never been surveyed with modern techniques, which means possibly unknown bottom features and obstructions are present. After covering these low frequency areas with modern surveys, the 15-year frequency can possibly be further reduced. Furthermore, the deeper sections are also included in the IHO specifications for hydrographic surveying, which means that to comply with these regulations, the deeper sections must be resurveyed too. The question remains whether it is necessary to resurvey these areas with the current frequency, when they are surveyed with modern techniques.

2. (a) The re-survey frequencies are based on area-specific features (dynamics, sediment composition, shipping density) and the tendency of greater draughts of the vessels transiting through the NCS. Compared to the previous survey policy, which consisted of 4 categories (with re-survey frequencies of 1,5 and 10 years for the last two categories), the first category frequency is reduced to once per 2 years due to the results of the project Sea bottom Dynamics Monitoring. But instead of 4, there are now 5 main categories (excluding areas surveyed by RWS and the special category of the critical areas in the selected track), with different re- survey frequencies.

   (b) Two things have changed in the survey policy: frequency and the survey areas. This is the result of spatial use of the NCS (the influence of shipping density can be seen when comparing the old and new survey policy) and newly applied survey technologies. The method as such is unchanged, although the inclusion of the first results of the project seabed dynamics analysis are included.

   (c) The first results of the project are included in the present version of the NLHS survey policy in which category 1 re-survey frequencies have been extended to from 1 year to 2 years.

   (d) In recent history, SBES was the dominant technique in bathymetric surveying. Experiments were conducted for interpolation of depths between survey lines. Analysis of the results, showed that interpolation between survey lines with a line spacing of 100 meters did not give a proper image of the seabed (when compared to the actual water depth on site situation). To improve this, so called interlines were surveyed to reduce the interpolation error. In the current situation, MBES delivers full bottom coverage, which makes interpolation between survey lines unnecessary.

3. (a) The use of MBES started with the introduction of the new survey vessels. The first multi beam data set that was fully accepted, dates from 2004, which shows that it is a relative new technology. When looking at the NCS, approximately 10 % is covered with multi beam surveys. The rest is still based on single beam data or is not surveyed at all with modern techniques.

   (b) The introduction of new survey technologies did not result in different survey frequencies. The technological improvements did increase the probability that the planned work for that specific year is completed within the estimated time frame. Instead of making more measurements, the process of surveying becomes more efficient (productive). The new HOV-s, which are capable of higher surveying speeds (10 kts instead of 6 kts), should in theory lead to improved efficiency of hydrographic surveying. However, the introduction of the new survey vessels did not lead to the expected efficiency improvements yet.

   (c) The accent in hydrographic surveying is placed on the navigation safety of the North Sea. Looking at the vessel traffic chart of the North Sea, it can be concluded that the areas in the North are less frequently navigated. Together with the facts that the depth near the coast is much more critical (near the harbor approaches), and that this section is characterized by a higher level of seabed dynamics, these areas are placed higher on the survey priority list. The character of the existing data of that specific area is not a factor in prioritizing the survey areas for the year plan. However, it remains difficult to prioritize areas taking all other aspects properly into account.

   (d) In theory, the HOV-s should be able to comply to the survey policy (they are designed for this purpose). But, due to technological problems (mainly engine failures), the current reliability is too low to reach the stated objective. The ships are currently modified to meet the capacity requirements of the survey policy. The survey techniques used on board are reliable and up to modern standards. However, to realize the yearly survey instructions, and subsequently the survey policy, the reliability of the ships must increase significantly.

   (e) The current technologies used on board are up to date and meet the requirements as stated by the IHO S44 publication for Hydrographic Surveying *(International Hydrographic Organization, 1998)*. MBES systems which are capable of producing higher detailed depth information are available, but have no influence on survey frequency. The only aspect that can be improved at the moment is the survey speed. With higher capacity engines and faster multi beam equipment, this can lead to improved efficiency.

4. (a) External assignments should not affect the designed year plan, because the required amount of Hydrographic Days leaves space for these assignments. In reality however, the frequent technological problems are causing delays, which means that the available days for external activities is less than anticipated in advance. For the 2008 survey year, no large external assignments are planned, to reduce the arrears. Resulting from this, is a year plan with 300 planned Hydrographic Days, significantly more than usual. The Netherlands Antilles Survey Campaign in 2006 is mandatory to cover NL Caribbean waters with modern surveys, and thus is an unavoidable task.

   (b) Accidents or calamities are in general covered by the Coastal directorates of RWS. Thus, this factor has no direct influence on the yearly survey instructions. In some cases however, it is necessary to use the Navy survey vessels for assistance. Exchange of survey efforts is covered by a mutual agreement.

   (c) Both organizations are redundant for each other, meaning that the ships of RWS are used for assistance of the hydrographic survey instructions of the NLHS when there is capacity available. To maintain the priority of safe navigation, the NLHS and the Directorate-General of Public Works and Water Management exchange capacity when necessary. For instance, this year, the RWS survey vessel *MV Arca* assists the NLHS in reaching the stated 2007 objectives.

5. (a) All collected raw data is processed and quality controlled on board of the survey vessels by qualified surveyors. The commanding officer is responsible for the delivery of high quality data. After delivery of the data to NLHO, detailed evaluation of the data is done by the specialist departments. The evaluation of the data is part of the quality circle, which ultimately leads to the letter of acceptance of the specific data set to the commanding officer of the survey vessel.

   (b) Yes there is, for example an error in tidal reduction found by the Geodesy and Tides department, it is communicated towards the POM section. The incorrect data is transferred back to the owner of the problem (in this case the commanding officer of the survey vessel). After correction or re-surveying of the specific area, the data returns into the quality circle until proven to be correct. Small errors are often solved at the bureau.

6. (a) Both have separate areas of responsibility (RWS is responsible for the coastal waters and the areas shallower than ten meters) and are therefore maintaining separate survey policies which are exchanged. Also, the yearly survey instructions are exchanged to remain informed on the proposed coverage. The yearly survey instructions of the RWS however, are not as strict as those of the NLHS. When back-logs occur, this is discussed in the periodical meetings of the NHI (Netherlands Hydrographic Institute) or directly.

   (b) Information on the scheduled areas of the yearly survey instructions is transferred to TNO-NITG. They depict the positions within the survey areas where bottom samples are required for bottom analysis and sediment composition analysis (for geological maps). Furthermore, SSS images are used by NITG for the construction of geological maps and acoustic seabed classification to estimate the sediment composition.

   (c) There is no real budget for surveying activities. A certain amount of Hydrographic Days is required to comply to the designed year plan. These instructions are transferred to the commander of the vessel in question. Resurvey frequencies are not influenced by

Government measures. Economical measures are reflecting in the manning of the survey ships. Capacity problems may be caused by ongoing budget cuts.

7. (a) Survey policies are exchanged between neighboring nations, since they only cover areas of national responsibility. Usually survey policies are also freely available for others. Cooperation on a greater scale is not yet implemented, although the initial steps for this are taken. At the last NSHC conference the harmonization of the survey policies in the wider North Sea area has been initiated. Introducing harmonized survey policies may lead to more efficient survey efforts at the North Sea. Furthermore, the NLHS is cooperating with Belgium, France and the United Kingdom in the survey policy Pas de Calais (bilateral agreement). This survey policy includes agreements on how the Selected Track for deep draught vessels in the Dover strait area is to be surveyed. As discussed at the last NSHC meeting in Rostock, the survey policy Pas de Calais may be included as integral part of a harmonized survey policy for the North Sea.

   (b) The standardization procedure for survey policies is currently in its starting phase, which means that currently each hydrographic service formulates its own survey policy for its area of responsibility. Information on the approach of other countries however, is used in the formation process. It is difficult to standardize survey policy, because each area has different characteristics which lead to different demands in survey approach. The survey techniques have been standardized by the IHO in its Special Publication S44 *(International Hydrographic Organization, 1998).*

   (c) Because the NCS is characterized by high intensity shipping lanes (and large ports), mobile bed forms and shipping with minimal UKC-s, the monitoring of the seabed is more critical than in low intensity areas. When compared to foreign countries, the resurvey frequencies of the NLHS are well justified and will only be reduced on a proper scientific basis.

   The NLHS is especially ambitious in the field of full multi beam coverage of the NCS. This full multi beam ensonification of the NCS is expected to save time in the future.

   (d) The frequency of bathymetric surveys is hard to standardize because of the different seabed characteristics in different areas of the world. The frequencies are partly based on seabed characteristics and the interpretation of these characteristics and their influence on navigation safety. Determining re-survey frequencies is therefore a largely national responsibility. In the Resurvey Policy Working Group however, international agreements on this subject are discussed.

   (e) The prominent countries with whom the NLHS participates are members of the NSHC. There is especially cooperation with Belgium, France and the United Kingdom in de Pas de Calais survey policy. More globally seen, there is consultation between the NLHS and other counties worldwide, but the NLHS-basis for a more standardized survey policy is based in NSHC.

8. (a) A reduction in survey frequency or no surveying at all, is only realistic if there is a proven foundation to do this. National maritime policy does not allow an increase of risks to shipping. The fact remains that IF something happens, the economical damage can enormous.

(b) For this purpose, scenario's must be developed to discuss the possibilities in this field. The advantage of the new HOV-s is that they are multi-purpose ships, which means that they can be employed for different tasks. After the complete coverage of the NCS with up-to-date technologies and proven novel monitoring techniques, it might be possible to reduce survey efforts, but again, only on a proper basis. The stakes are simply too high.

(c) The only way for optimizing the survey policy is to picture the seabed characteristics. New results can be expected from the combination of deformation analysis and the surveying of small representative areas (to make an assumption for the entire area). Furthermore, the task package of the HOV-s is likely to include new activities such as scientific research.

Appendix B

Resurvey categories

As discussed in Section 2.2, the 2003 survey policy is based on five resurvey categories. Although the IHO *(International Hydrographic Organization, 1998)* does specify regulations for hydrographic surveying, the selection of resurvey frequencies is in principle free to choose. The four criteria used for the design of the resurvey policy of the NLHS (section 2.2) are leading to the following categorization *(Dienst der Hydrografie, 2003)*:

- **Cat. 1:** Traffic routes which are restricted by:

$$D + UKC + SM > \text{reduced charted depth}, \tag{B.1}$$

  with D the maximum draught of the expected type of vessels, UKC the Under Keel Clearance, and SM a safety margin of 2 meters. Furthermore, all charted anchor areas are included in this category. Track spacing: 100 meter.

- **Cat. 2:** Traffic routes which do not qualify as category 1, but are important for terminating traffic en transfer vessels. Track spacing: 125 meter.

- **Cat. 3:** Areas enclosed by the 10 meter depth line, and the traffic routes as specified by category 2 which are shallower than 30 meters. Also included are: Deep Water (DW) routes from the Bruine Bank to the 30 meter depth line and from the Skagerrak route to the 30 meter line. Track spacing: 125 meter.

- **Cat. 4:** The remaining areas shallower than 30 meters, the DW route deeper than 30 meters and the Skagerrak route deeper than 30 meters. Track spacing: 150 meter.

- **Cat. 5:** Remaining areas deeper than 30 meters. Track spacing: 250 meter.

Appendix C

Results from the 0D analysis - Scenario 1

Table C.1: Input parameters Scenario 1

Parameter	Input	Unit
Migration speed	0	[m/year]
Gale coefficient (4^{th} survey)	1	[-]
Outlier (3^{rd} survey)	0	[m]
Standard deviation (5^{th} survey)	0.36	[m]

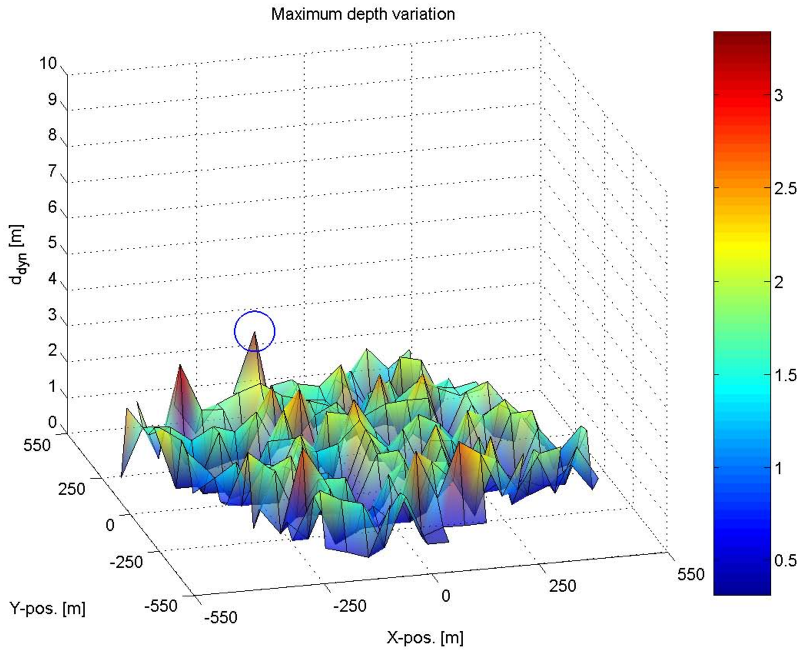

Figure C.1: Scenario 1, Run 1. Maximum depth variation is 3.362 metres located at X=-175 m, Y=325 m.

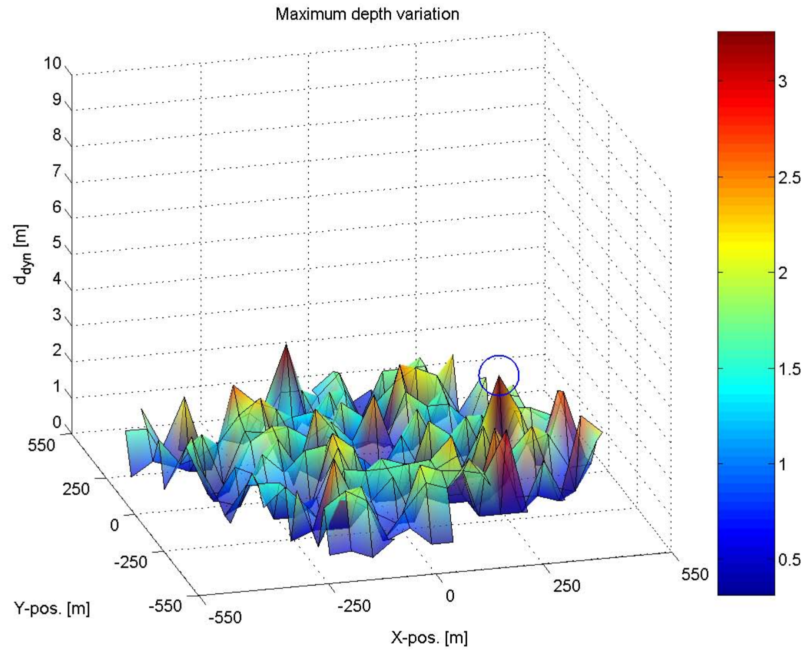

Figure C.2: Scenario 1, Run 2. Maximum depth variation is 3.28 metres located at X=275 m, Y=-75 m.

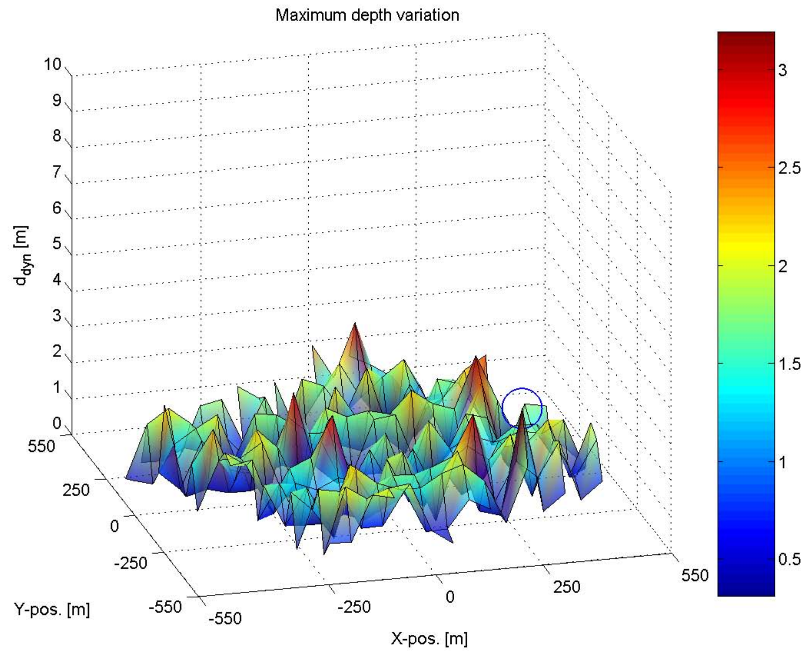

Figure C.3: Scenario 1, Run 3. Maximum depth variation is 3.207 metres located at X=275 m, Y=-275 m.

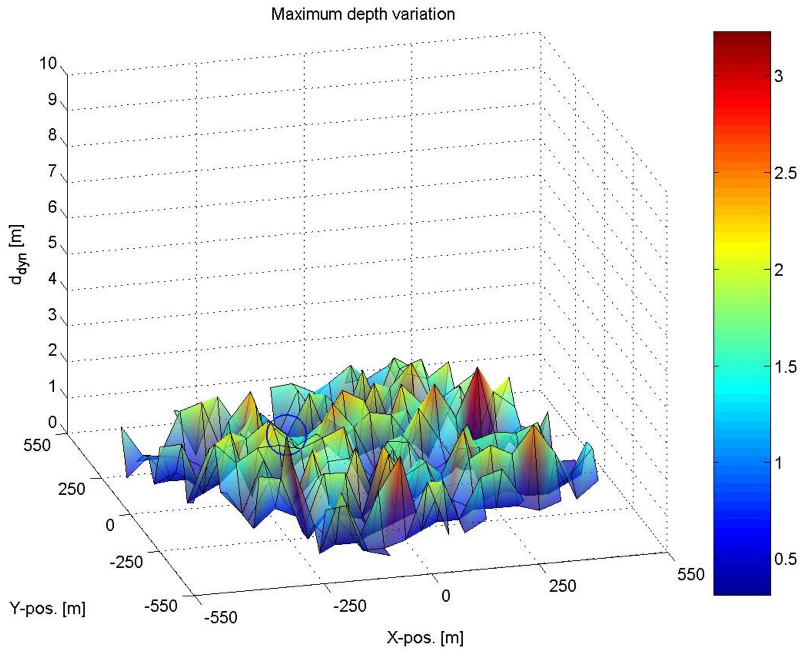

Figure C.4: Scenario 1, Run 4. Maximum depth variation is 3.249 metres located at X=-275 m, Y=-325 m.

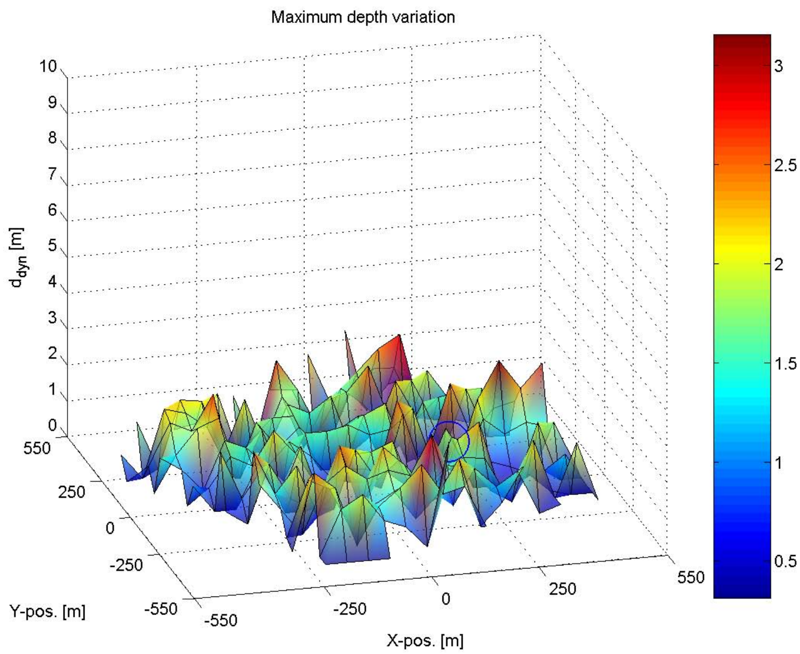

Figure C.5: Scenario 1, Run 5. Maximum depth variation is 3.176 metres located at X=75 m, Y=-425 m.

Appendix D

Results from the 0D analysis - Scenario 2

Table D.1: Input parameters Scenario 2

Parameter	**Input**	**Unit**
Migration speed	5	[m/year]
Gale coefficient (4^{th} survey)	1	[-]
Outlier (3^{rd} survey)	0	[m]
Standard deviation (5^{th} survey)	0.36	[m]

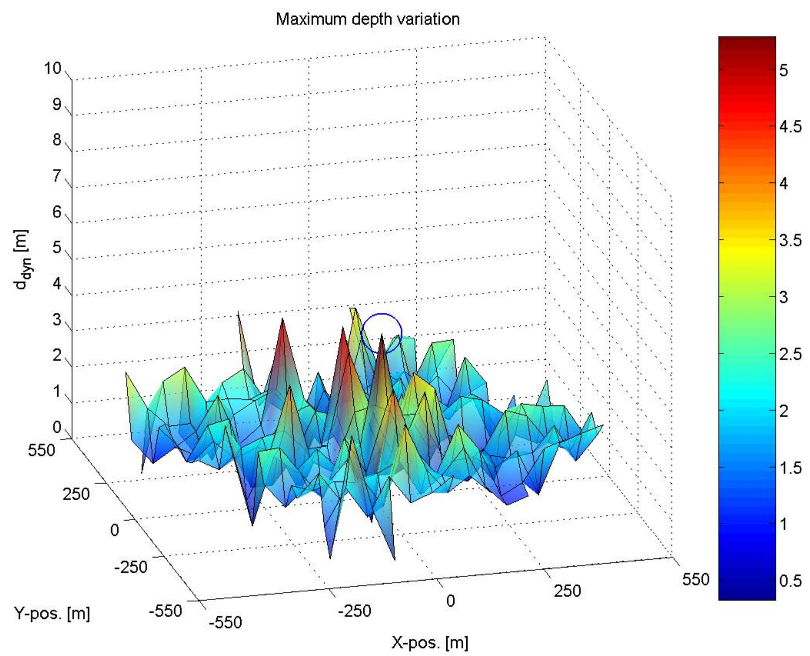

Figure D.1: Scenario 2, Run 1. Maximum depth variation is 5.324 metres located at X=-25 m, Y=-175 m.

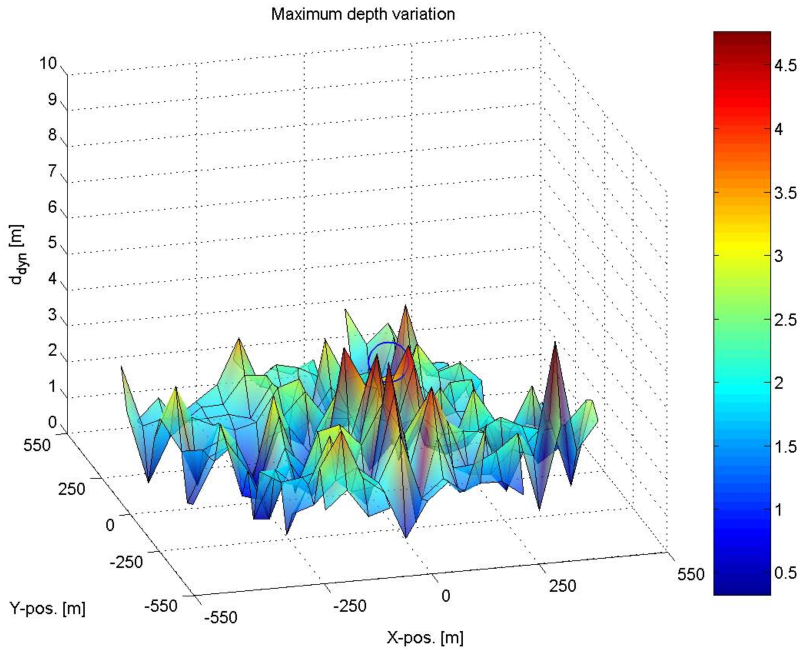

Figure D.2: Scenario 2, Run 2. Maximum depth variation is 4.794 metres located at X=-25 m, Y=-275 m.

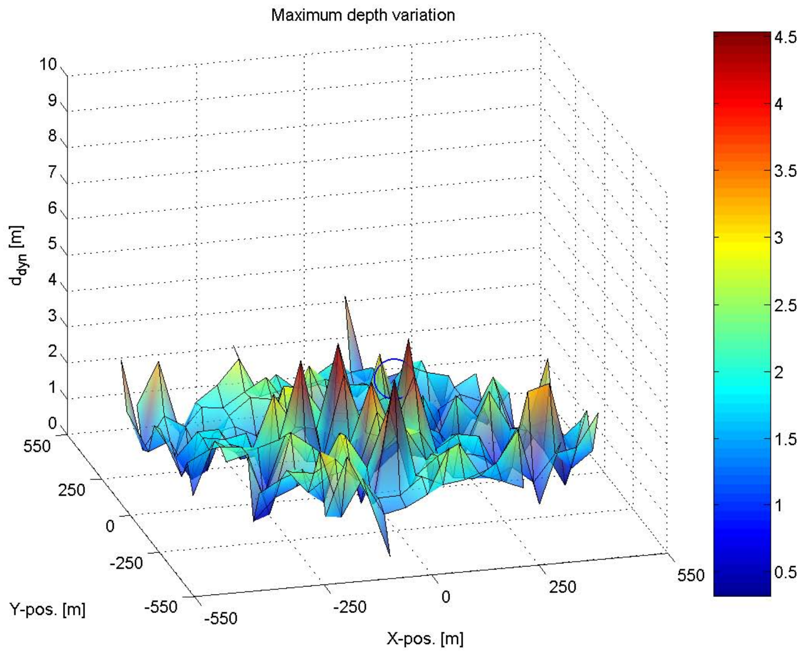

Figure D.3: Scenario 2, Run 3. Maximum depth variation is 4.559 metres located at X=-25 m, Y=-325 m.

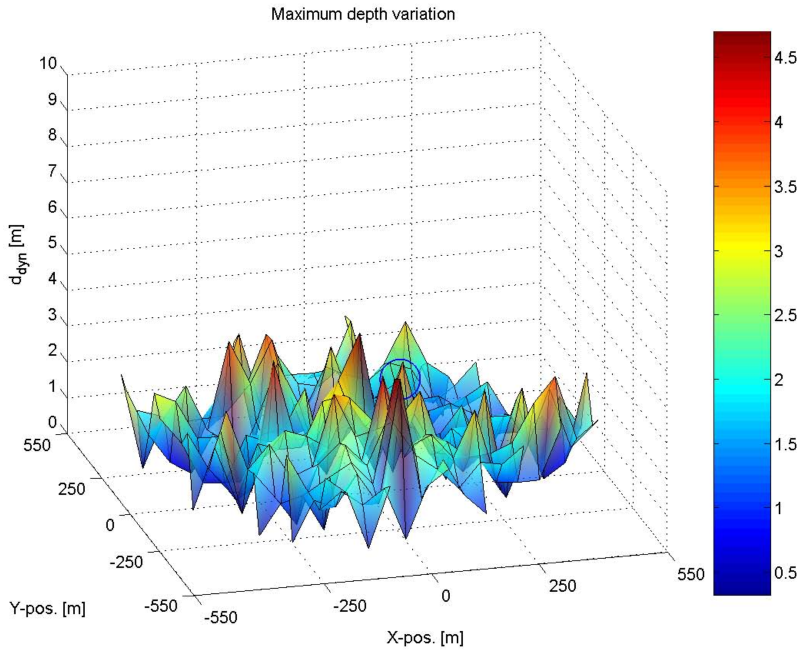

Figure D.4: Scenario 2, Run 4. Maximum depth variation is 4.730 metres located at X=-25 m, Y=-375 m.

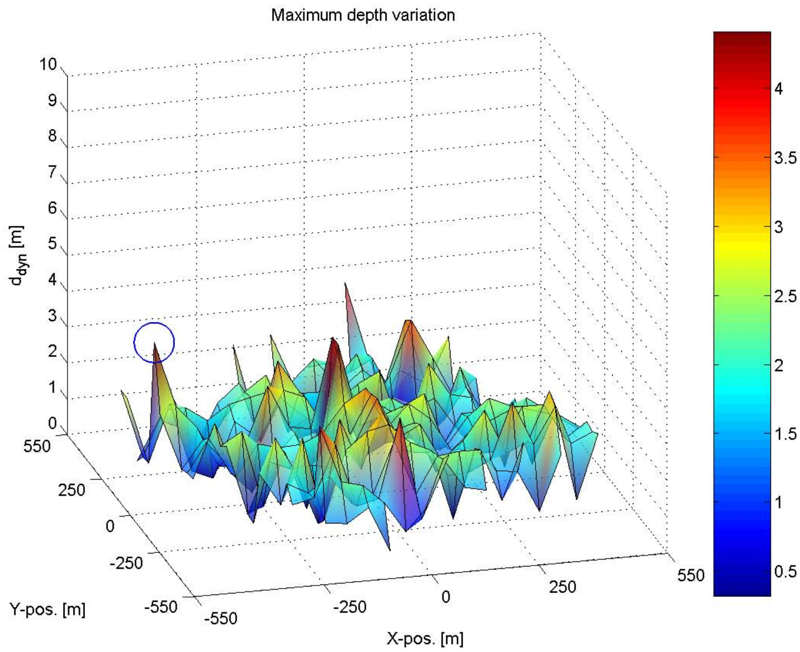

Figure D.5: Scenario 2, Run 5. Maximum depth variation is 4.430 metres located at X=-475 m, Y=75 m.

Appendix E

Results from the 0D analysis - Scenario 3

Table E.1: Input parameters Scenario 3

Parameter	Input	Unit
Migration speed	5	[m/year]
Gale coefficient (4^{th} survey)	0.80	[-]
Outlier (3^{rd} survey)	0.5	[m]
Standard deviation (5^{th} survey)	0.72	[m]

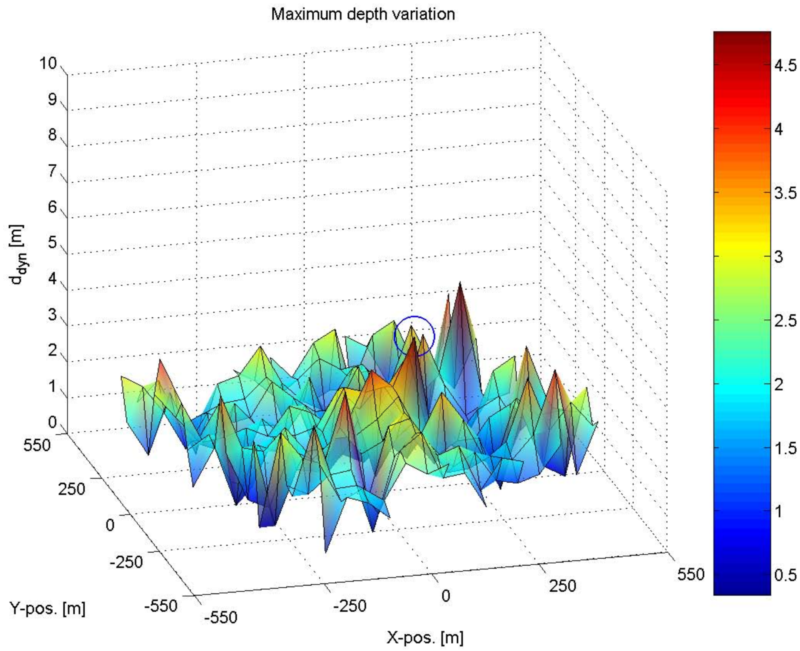

Figure E.1: Scenario 3, Run 1. Maximum depth variation is 4.788 metres located at X=75 m, Y=-125 m.

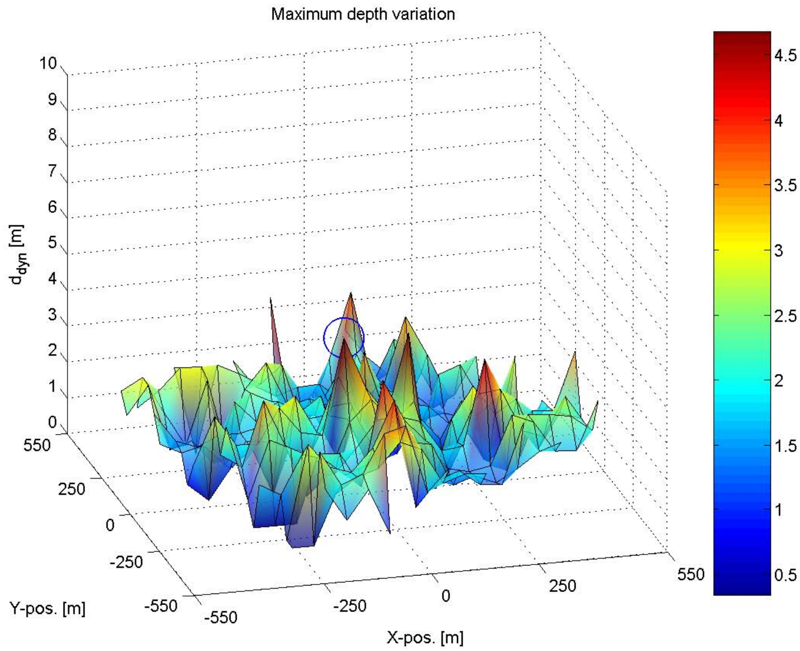

Figure E.2: Scenario 3, Run 2. Maximum depth variation is 4.710 metres located at X=-75 m, Y=-75 m.

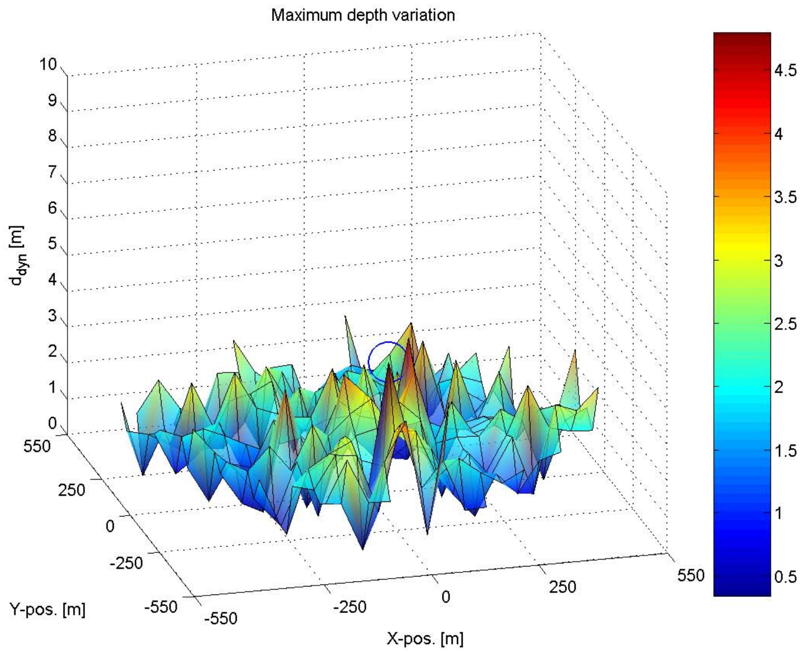

Figure E.3: Scenario 3, Run 3. Maximum depth variation is 4.826 metres located at X=-25 m, Y=-275 m.

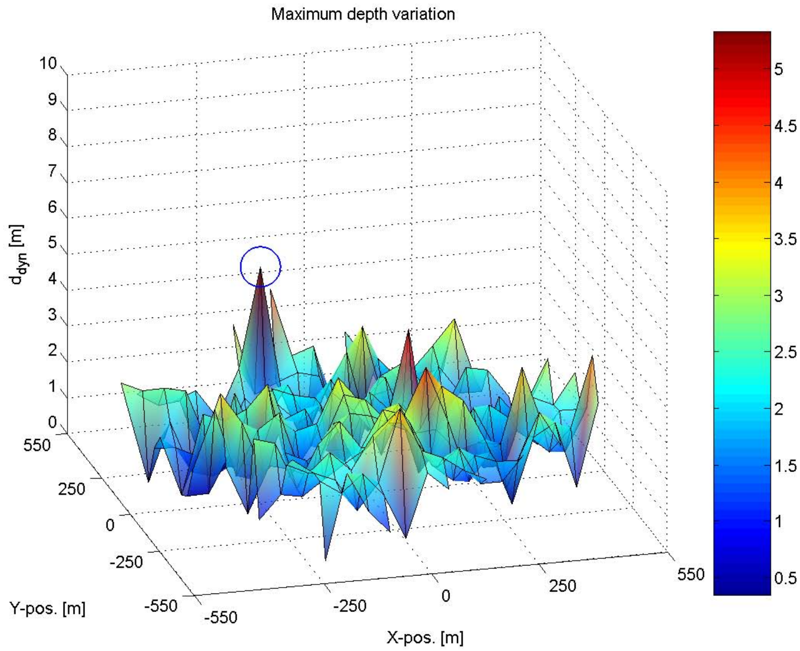

Figure E.4: Scenario 3, Run 4. Maximum depth variation is 5.364 metres located at X=-175 m, Y=275 m.

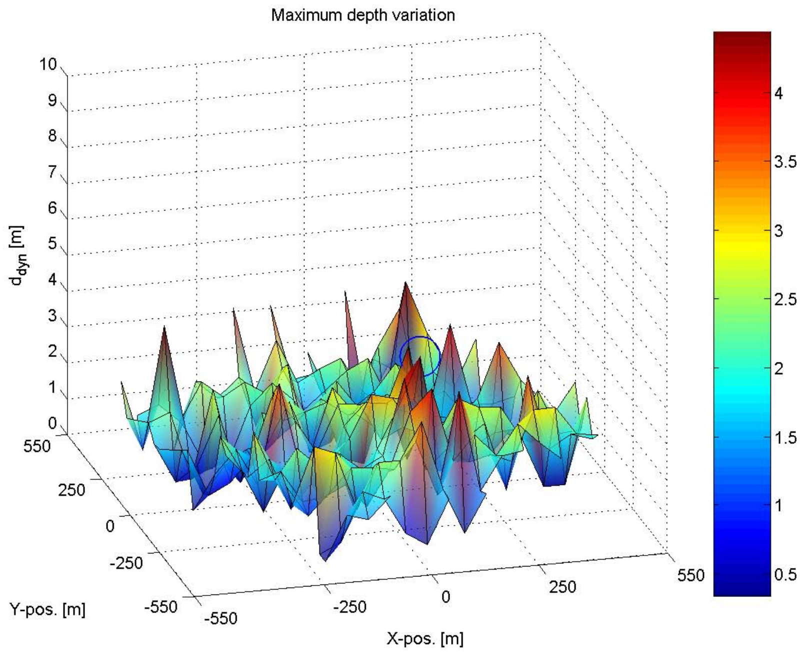

Figure E.5: Scenario 3, Run 5. Maximum depth variation is 4.462 metres located at X=75 m, Y=-175 m.

Appendix F

Results from the 0D analysis - Scenario 4

Table F.1: Input parameters Scenario 4

Parameter	Input	Unit
Migration speed	10	[m/year]
Gale coefficient (4^{th} survey)	1	[-]
Outlier (3^{rd} survey)	0	[m]
Standard deviation (5^{th} survey)	0.36	[m]

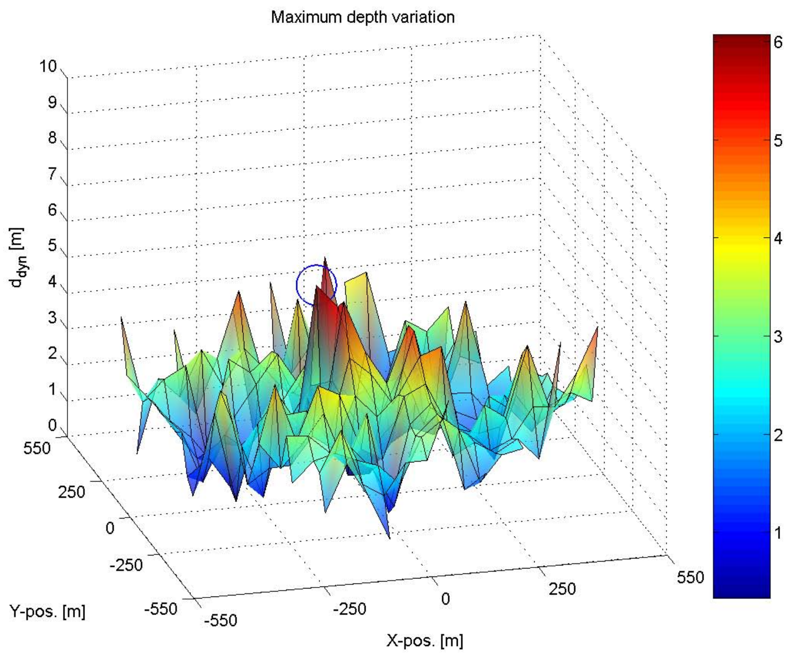

Figure F.1: Scenario 4, Run 1. Maximum depth variation is 6.109 metres located at X=-125 m, Y=-25 m.

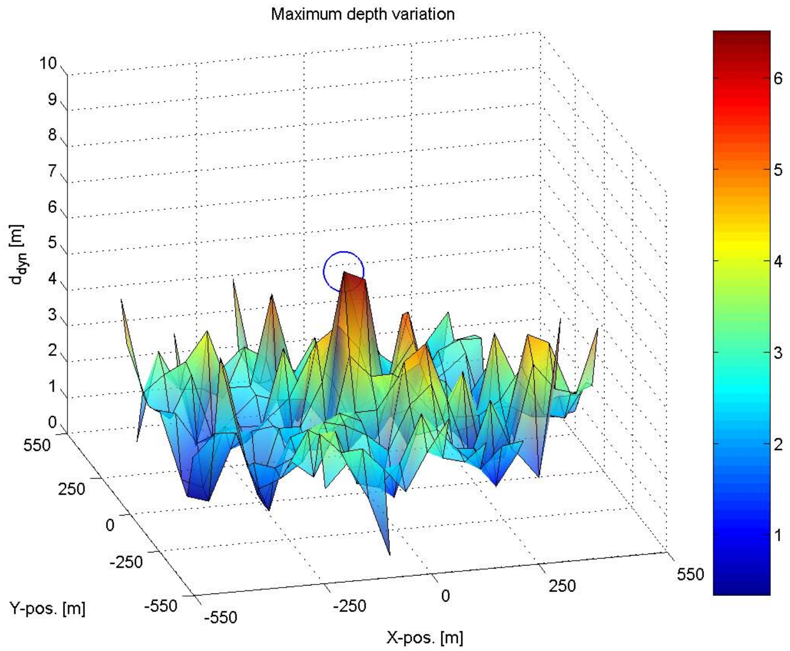

Figure F.2: Scenario 4, Run 2. Maximum depth variation is 6.550 metres located at X=-75 m, Y=-75 m.

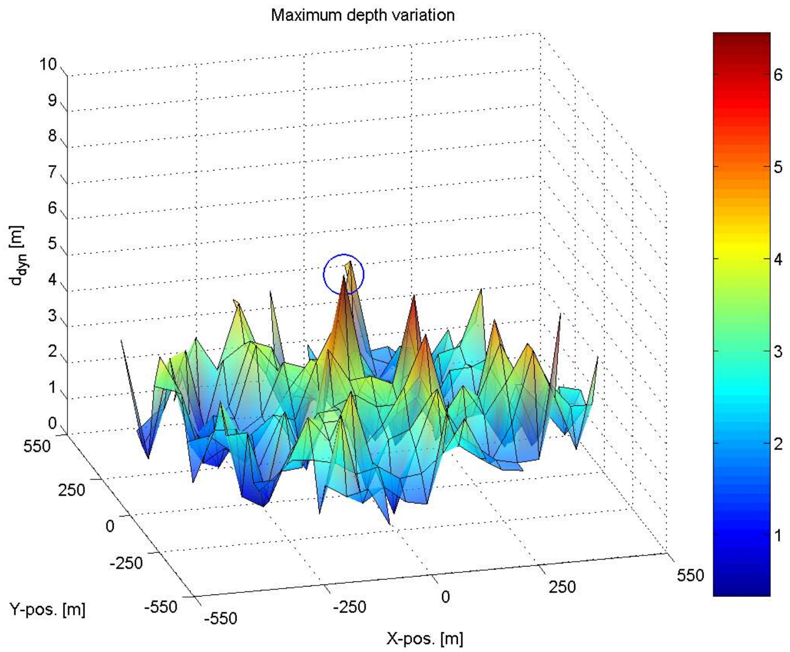

Figure F.3: Scenario 4, Run 3. Maximum depth variation is 6.497 metres located at X=-75 m, Y=-75 m.

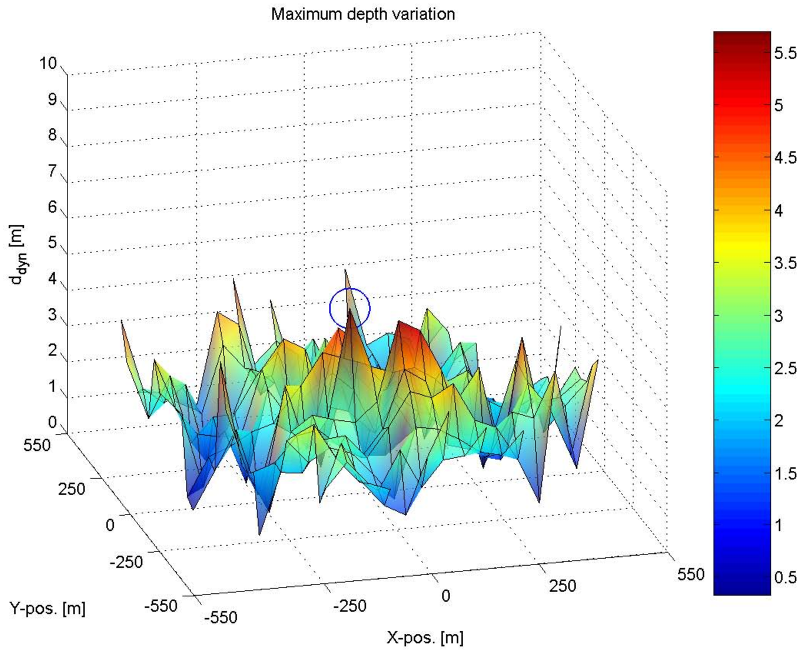

Figure F.4: Scenario 4, Run 4. Maximum depth variation is 5.735 metres located at X=-75 m, Y=-125 m.

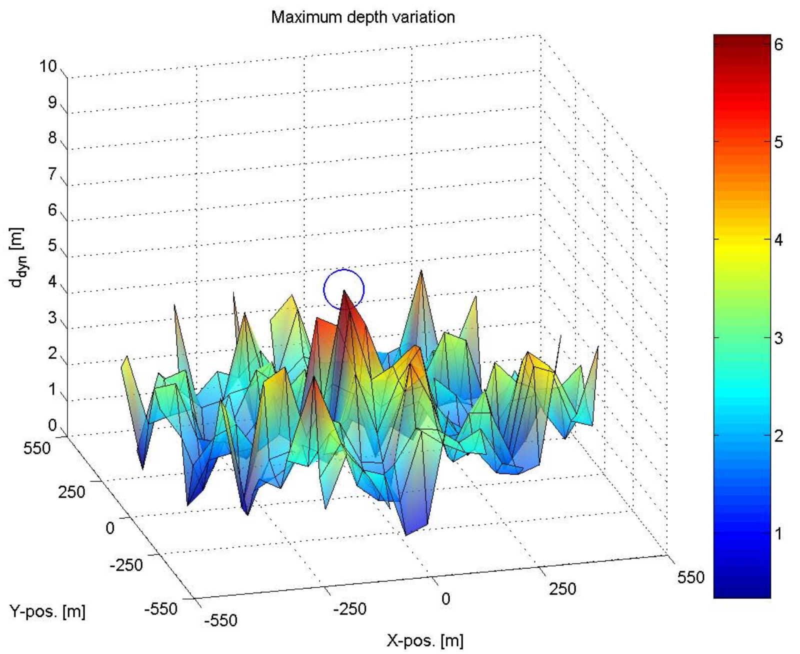

Figure F.5: Scenario 4, Run 5. Maximum depth variation is 6.134 metres located at X=-75 m, Y=-75 m.

Appendix G

Results from the 0D analysis - Scenario 5

Table G.1: Input parameters Scenario 5

Parameter	Input	Unit
Migration speed	10	[m/year]
Gale coefficient (4^{th} survey)	0.80	[-]
Outlier (3^{rd} survey)	0.5	[m]
Standard deviation (5^{th} survey)	0.72	[m]

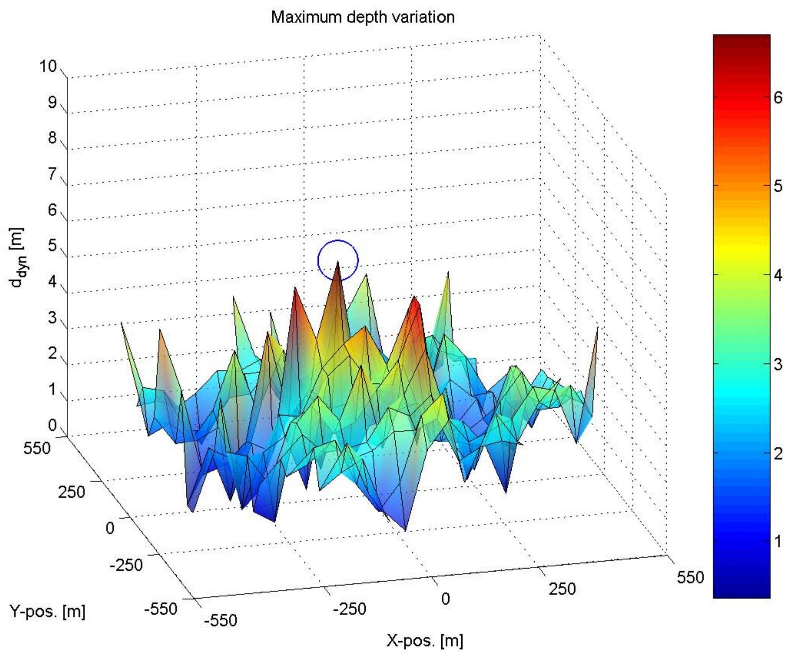

Figure G.1: Scenario 5, Run 1. Maximum depth variation is 6.743 metres located at X=-75 m, Y=-25 m.

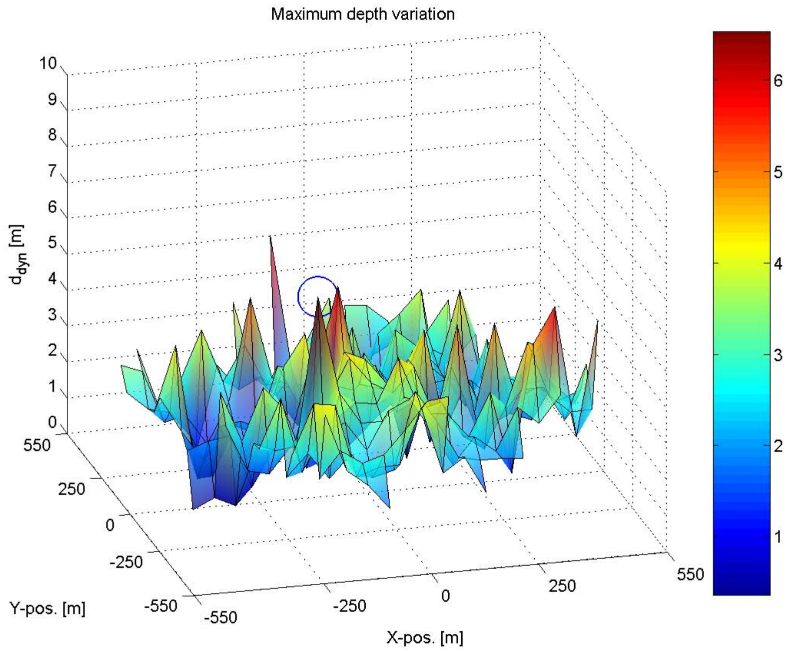

Figure G.2: Scenario 5, Run 2. Maximum depth variation is 6.579 metres located at X=-175 m, Y=-225 m.

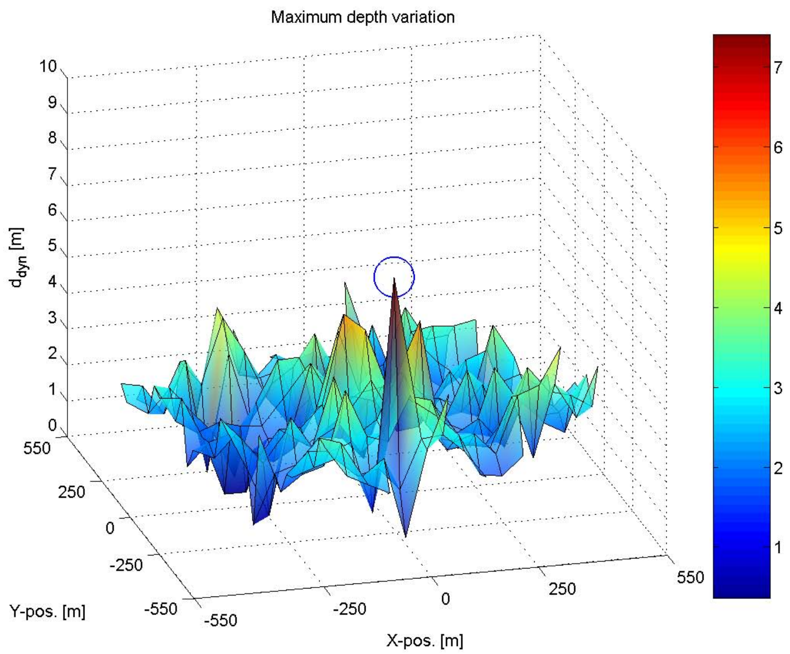

Figure G.3: Scenario 5, Run 3. Maximum depth variation is 7.456 metres located at X=-25 m, Y=-325 m.

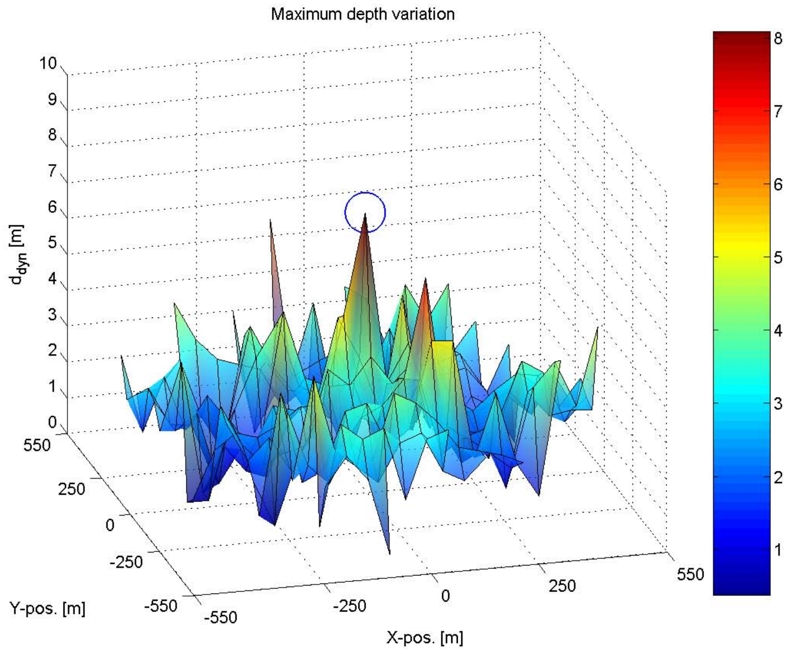

Figure G.4: Scenario 5, Run 4. Maximum depth variation is 8.143 metres located at X=-25 m, Y=-75 m.

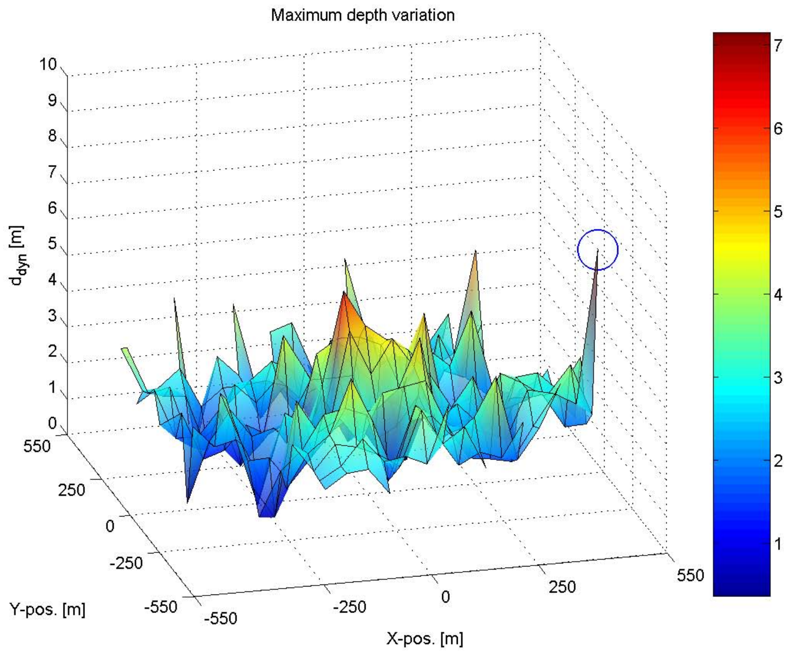

Figure G.5: Scenario 5, Run 5. Maximum depth variation is 7.199 metres located at X=475 m, Y=-225 m.

Appendix H

MATLAB script for 0D analysis

Function for determining the most critical node within a grid, by means of 0D analysis.
Three graphs are drawn:

- The mean depth for all grid node over the six available surveys.
- The 95% C.I. of the upper (shallow) boundary.
- The maximum depth variation given as a function of mean depth and 95% C.I.}

```
clear itr uvec iout Cu
vxytr=[vxydo1; vxydo2; -vxyup1(:,1), vxyup1(:,2:end); -vxyup2(:,1), vxyup2(:,2:end)];
vxyout=[vxyol1;vxyol2];
imat=nan(22);
imat2=nan(22);
imat3=nan(22);
for nn=1:280
    %disp('Node number=');disp(nn);
    uvec=zeros(8,1);
    uvec2=zeros(8,1);
    uvec3=zeros(8,1);
    depthvar=zeros(280,1);
    Cu=zeros(8,8);
    A=[ones(6,1) dt' eye(6)];
    Cu(1,1)=dref(nn,2);
    uvec(1)=dref(nn,1);
    itr=find(vxytr(:,3)==nn);
    if isempty(itr)==0
        uvec(2)=vxytr(itr,1);
        Cu(2,2)=vxytr(itr,2);
    end;
    iout=find(vxyout(:,3)==nn);
    vxyoutnn=vxyout(iout,:);
    for isu=1:6
        iout2=find(vxyoutnn(:,4)==isu);
        if isempty(iout2)==0
            uvec(isu+2)=vxyoutnn(iout2,1);
            Cu(isu+2,isu+2)=vxyoutnn(iout2,2);
        end;
    end;
    cov=A*Cu*transpose(A);
    %disp('uvec='); disp(uvec);
```

```
%     disp('Covariance matrix'); disp(Cu);
%     disp('A-matrix'); disp(A);
%     disp('precision');disp(cov);
    dnode1=A*uvec;
    up95= dnode1+sqrt(diag(cov))*1.96;
    do95= dnode1-sqrt(diag(cov))*1.96;
    dmatrix=[dnode1,up95,do95];
    %disp('Depth with 95% C.I. limits');disp(dmatrix);
    critvec=[mean(dnode1),min(do95)];
    %disp('mean depth and max.95% C.I.');disp(critvec);
    ddyn=mean(dnode1)-min(do95);
    mddyn1=2;
    for irow=((525+dref(nn,4))/50)+1;
        icol=((525+dref(nn,5))/50)+1;
        imat(irow,icol)=-mean(dnode1);
        imat2(irow,icol)=-min(do95);
        imat3(irow,icol)=ddyn;
    end;
end;

[mcol,im]=max(imat3);
[mddyn,im2]=max(mcol);

mddyn1=3;

iirow=im(im2);
iicol=im2;

xvec=[-525,-475,-425,-375,-325,-275,-225,-175,-125,-75,-25,
25,75,125,175,225,275,325,375,425,475,525];

yvec=[-525,-475,-425,-375,-325,-275,-225,-175,-125,-75,-25,
25,75,125,175,225,275,325,375,425,475,525];


figure(24)
h=surf(xvec,yvec,imat');
view([-15 25])
colormap jet
shading interp
set(h,'EdgeColor','k')
alpha(.7)
axis([-550 550 -550 550 -55 -25])
set(gca,'XTick',[-550,-250,0,250,550])
set(gca,'YTick',[-550,-250,0,250,550])
grid on
colorbar
xlabel('X-pos. [m]')
ylabel('Y-pos. [m]')
zlabel('Mean depth [m]')
title('Mean depth over specified time frame')
% print -depsc -tiff -r200 myplot
print('-depsc', 'D:\matlabpics\SelTrack\figures\postscript\meand.eps');
print('-dtiff', 'D:\matlabpics\SelTrack\figures\postscript\meand.tif');
```

```
figure(25)
h=surf(xvec,yvec,imat2');
view([-15 25])
colormap jet
shading interp
set(h,'EdgeColor','k')
alpha(.7)
axis([-550 550 -550 550 -55 -25])
set(gca,'XTick',[-550,-250,0,250,550])
set(gca,'YTick',[-550,-250,0,250,550])
grid on
colorbar
xlabel('X-pos. [m]')
ylabel('Y-pos. [m]')
zlabel('95 % C.I. [m]')
title('Maximum upward (shallow) boundary at 95 % C.I.')
print('-depsc', 'D:\matlabpics\SelTrack\figures\postscript\95up.eps');
print('-dtiff', 'D:\matlabpics\SelTrack\figures\postscript\95up.tif');


figure(26)
h=surf(xvec,yvec,imat3');
view([-15 25])
hold on
plot3(xvec(iirow),yvec(iicol),mddyn,'bo','MarkerSize',25)
hold off
colormap jet
shading interp
set(h,'EdgeColor','k')
alpha(.7)
axis([-550 550 -550 550 0 10])
set(gca,'XTick',[-550,-250,0,250,550])
set(gca,'YTick',[-550,-250,0,250,550])
colorbar
xlabel('X-pos. [m]')
ylabel('Y-pos. [m]')
zlabel('d_{dyn} [m]')
title('Maximum depth variation')
print('-depsc', 'D:\matlabpics\SelTrack\figures\postscript\dvar.eps');
print('-dtiff', 'D:\matlabpics\SelTrack\figures\postscript\dvar.tif');
```

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