Netherlands Enterprise Agency

Site Studies Wind Farm Zone Borssele

Morphodynamics of Borssele Wind Farm Zone

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Zone Borssele Site Data

DNV GL has reviewed the Deltares report '*Morphodynamics of Borssele Wind Farm Zone prediction of potential seabed level changes during the lifetime of offshore wind parks'* draft version 2 issued 2014-12-23

DNV GL has found that

1) the Reference Seabed Levels (RSBLs) presented in figure 4.4 and
2) the Maximum Seabed Level (MSBLs) presented in figure 4.7

obtained by surveys carried out the period from 1999 to 2010, are determined according to best engineering practices. The maps indicate correctly, the respectively potentially lowest and highest seabed levels for future offshore wind farms in the Borssele Wind Farm Zone

DNV GL has noted that in the second phase project, when new bathymetry data become available, the sand wave statistics will be used to define the RSBL and MSBL more accurately and thus less conservatively.

Sincerely
for Det Norske Veritas, Danmark A/S

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Deltares
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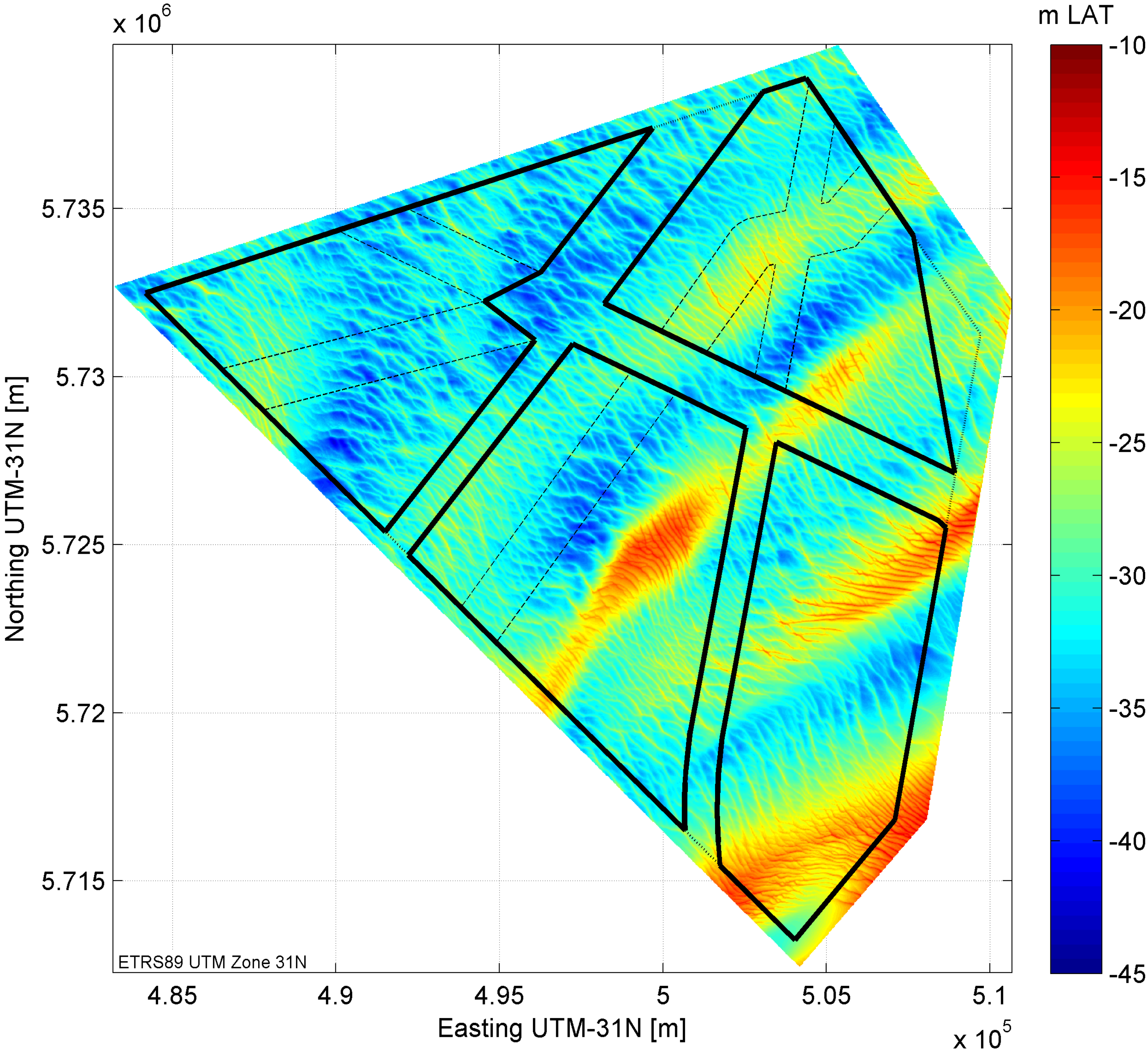
Morphodynamics of Borssele Wind Farm Zone

prediction of potential seabed level changes

during the lifetime of offshore wind parks



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Deltares

Morphodynamics of Borssele Wind Farm Zone

prediction of potential seabed level changes during the lifetime of offshore wind parks

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1210520-000

Title
Morphodynamics of Borssele Wind Farm Zone

Deltares

Client	Project	Reference
Rijksdienst voor Ondernemend Nederland	1210520-000	1210520-000-HYE-0002

Keywords
Seabed morphodynamics, offshore wind, Borssele, sand waves, bed form migration

Summary
This report is the result of the first phase of this project, in which Deltares was asked to determine the morphodynamics of the Borssele Wind Farm Zone (BWFZ). The BWFZ is located just north of the Dutch-Belgian border and is sub-divided into four sites with a combined area of approximately 234km^2. The morphology of the system was classified as highly dynamic, with a complex bathymetry consisting of static (in the timespan between the 2000 and 2010 surveys), shore-parallel sandbanks overlain with dynamic shore-perpendicular sand waves. Within the area, opposing migration directions were found with a governing SW-direction and opposing NE-direction and a variation of up to 30° in both directions.

Sand wave characteristics were determined for the entire BWFZ as well as for the individual sites by means of consistent tracking of crest and trough points of individual sand waves from various transects of 2500 meter equally distributed throughout the BWFZ. The sand waves have a typical average length of 230 meters, height of 4 meters and migration speeds in the order of -1.7m/yr (NE-direction) to 3.2 m/yr (governing SW-direction).

Next, the reference seabed level (RSBL) and maximum seabed level (MSBL) were determined, indicating the predicted lowest and highest seabed level during the lifetime of the wind farms in the Borssele area. Comparison of the RSBL with the most recent bathymetry from 2010 showed a potential maximum lowering of the seabed of approximately 8m.

In the second phase of this study, all findings will be updated and validated using an up-to-date (to be performed), high-resolution bathymetrical dataset. The findings will be complemented by delivery of GIS-files with different "recommendation zones" for foundations and electricity cables.

References
Request for Offer: *RVO, SDE1400015, registration number IUC/201408261500, dated 1 September 2014.*
Proposal: *Deltares, 1210520-000-HYE-0001-o-Quotation for Morphodynamical and Geomorphological Conditions of the Borssele Wind Zone, dated 12 September 2014.*
Contract award: *RVO, SDE1400015, registration number IUC/201408261500, dated 22 September 2014.*

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draft	24 October 2014	Hendrik Jan Riezebos Robert Hasselaar Tim Raaijmakers Tommer Vermaas		Hans de Vroeg		François Clemens Meyer	
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State
draft
This is a draft report, intended for discussion purposes only. No part of this report may be relied upon by either principals or third parties.

Contents

1 Introduction

1.1 Background

The Dutch government has designated three areas in the Dutch part of the North Sea for offshore wind farm development. The first area to be developed is the Borssele Wind Farm Zone (BWFZ). This area is located just north of the Dutch-Belgian border. Several pipelines and telecom cables are crossing the BWFZ, which is sub-divided into four sites with a combined area of approximately 234km^2. A first geological desk study for the Borssele Wind Farm Zone was performed by Crux Engineering BV (2014). In this study, the morphodynamic behaviour of the seabed in the BWFZ was not investigated. The morphodynamics of an offshore wind farm area however determine to a great extent the design of turbine foundations and horizontal and vertical infield and export cable routes. Therefore, RVO requested a proposal from Deltares to determine the morphological conditions of the Borssele Wind Farm Zone by letter dated 1 September 2014 (reference: SDE1400015). On 12 September 2014 the proposal was submitted by Deltares (reference: 1210520-000-HYE-0001). The project was awarded on 22 September 2014. A kick-off meeting by teleconference was organized on 25 September 2014. The contract was signed on 1 October 2014 and latest data delivery to Deltares took place on 2 October 2014.

1.2 Objectives

The study by Deltares will be conducted in two phases. The first phase aims to improve the morphological understanding of the Borssele Wind Farm Zone, based on the currently available (bathymetrical) information. In the second phase, the results of the first phase will be updated based on the results of a field investigation of the BWFZ.

The objectives of the first phase are:
- to improve the understanding of the seabed morphology at the BWFZ
- to improve the understanding of the seabed morphodynamics at the BWFZ over the lifetime of a wind farm
- to define the design reference seabed levels for the BWFZ over the lifetime of a wind farm
- to provide input for field investigation to be carried out

The objectives of the second phase (foreseen in 2015) are:
- to update and validate the findings of the first phase by means of inclusion of a new, high resolution bathymetrical dataset
- To deliver GIS-files with different “recommendation zones” for foundations and electricity cables (e.g. recommended, possible but with some additional measures to be taken, better to be avoided, highly un-recommended, etc.)

1.3 Contents of report

This report provides a general description of the Borssele Wind Farm Zone and the available datasets in Chapter 2. The methodology of the applied analysis techniques is discussed in Chapter 3. The results are discussed in Chapter 4 and the report finishes with conclusions and recommendations in Chapter 5.

2 Description of area and available data

2.1 Description of Borssele Wind Farm Zone

The Borssele Wind Farm Zone is located in the southern part of the Dutch North Sea, near the Dutch-Belgian border (see Figure 2.1). The area is divided into 4 development sites (site I, site II, site III and site IV, named clockwise starting with the north-eastern site), which are subdivided into a total of 10 sub-sites due to the presence of offshore line infrastructure (see Figure 2.2 and Figure 2.3).

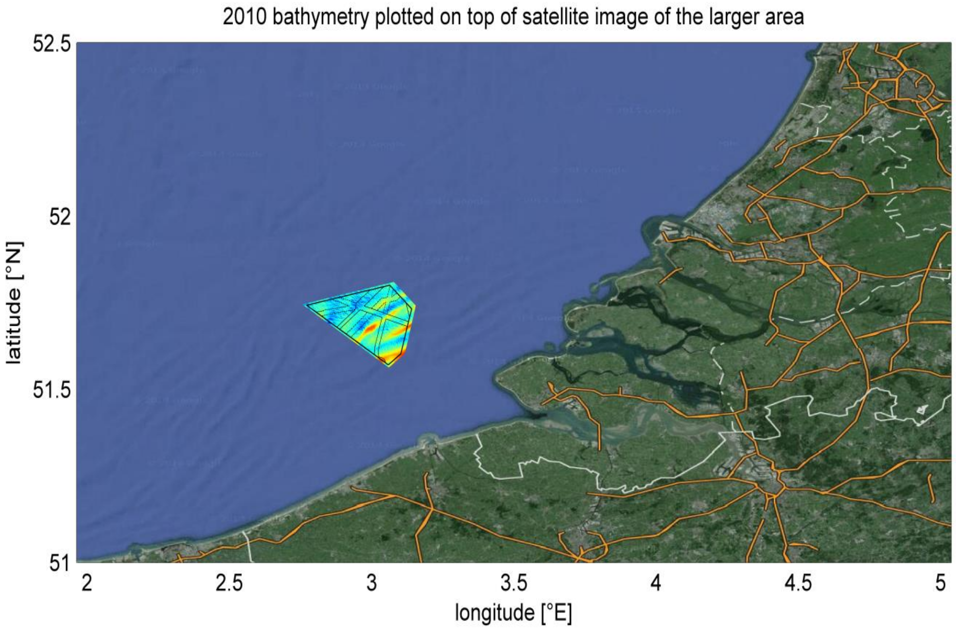

Figure 2.1 Location of the Borssele Wind Farm Zone in the southern part of the Dutch North Sea

Bed levels in the area vary between -12.6m and -42.2m relative to Lowest Astronomical Tide (LAT). The BWFZ has a diverse morphology with shore-perpendicular sand waves on top of shore-parallel sandbanks of over 10m in height (see Figure 2.3). The presence of sand waves is consistent throughout the area, with the exception of a small patch in the southernmost corner of site II. General maps characterizing morphodynamic features at the seabed, such as Figure 2.4, show that in BWFZ sand waves occur with heights between 2-4m around the Rabsbank, with heights between 4-6m around the Schaar Sandbank and with heights larger than 6m in the more offshore located areas.

Close to the BWFZ, in the Belgian part of the North Sea, wind farm development has started some years ago (e.g. Thornton Bank and Belwind are operational with other parks still under development). Studies for these developments indicate complex morphodynamic activity in the area. A study by TNO (this particular department has now merged into Deltares), described in Wiertsema & Partners (2008), on the stability of the Bligh Bank (located just across the border, southwest of site IV), found opposing bed form migration directions, with sand wave lengths in the order of 200m, sand wave heights in the order of 4m and sand wave migration speeds of up to 2.5m/yr. A study by Deltares for the Belwind development found similar morphodynamic behaviour and sand wave dimensions (Deltares, 2008), corroborating the findings for the Borssele Wind Farm Zone in this report (see Section 4.5).

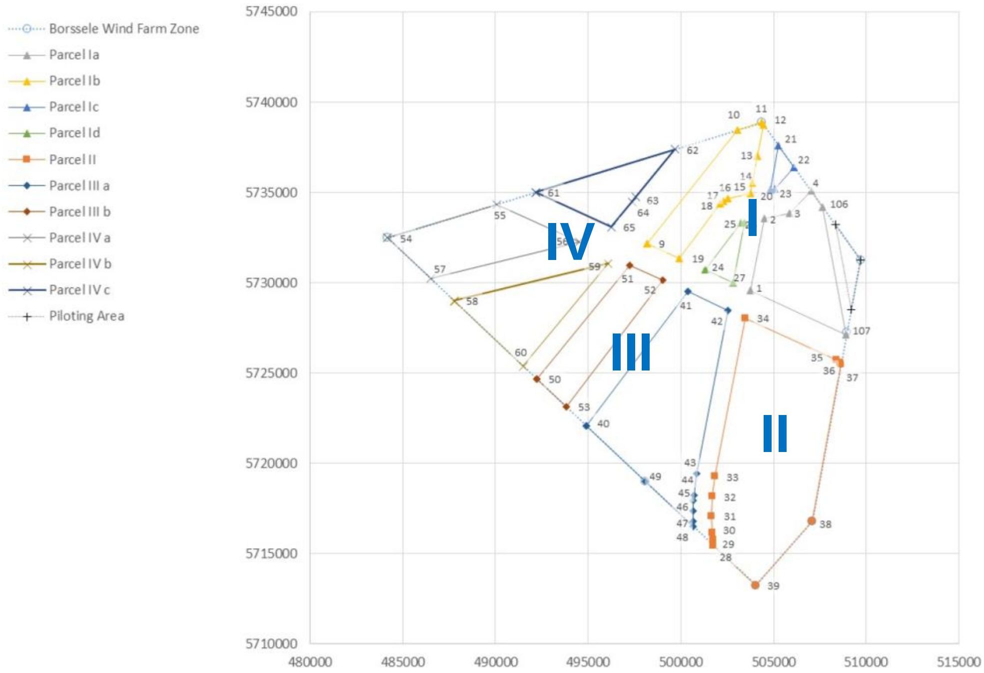

Figure 2.2 Overview of (sub-)plot division in the Borssele Wind Farm Zone and safety zones related to telecommunication and electricity cables [data delivered by RVO]

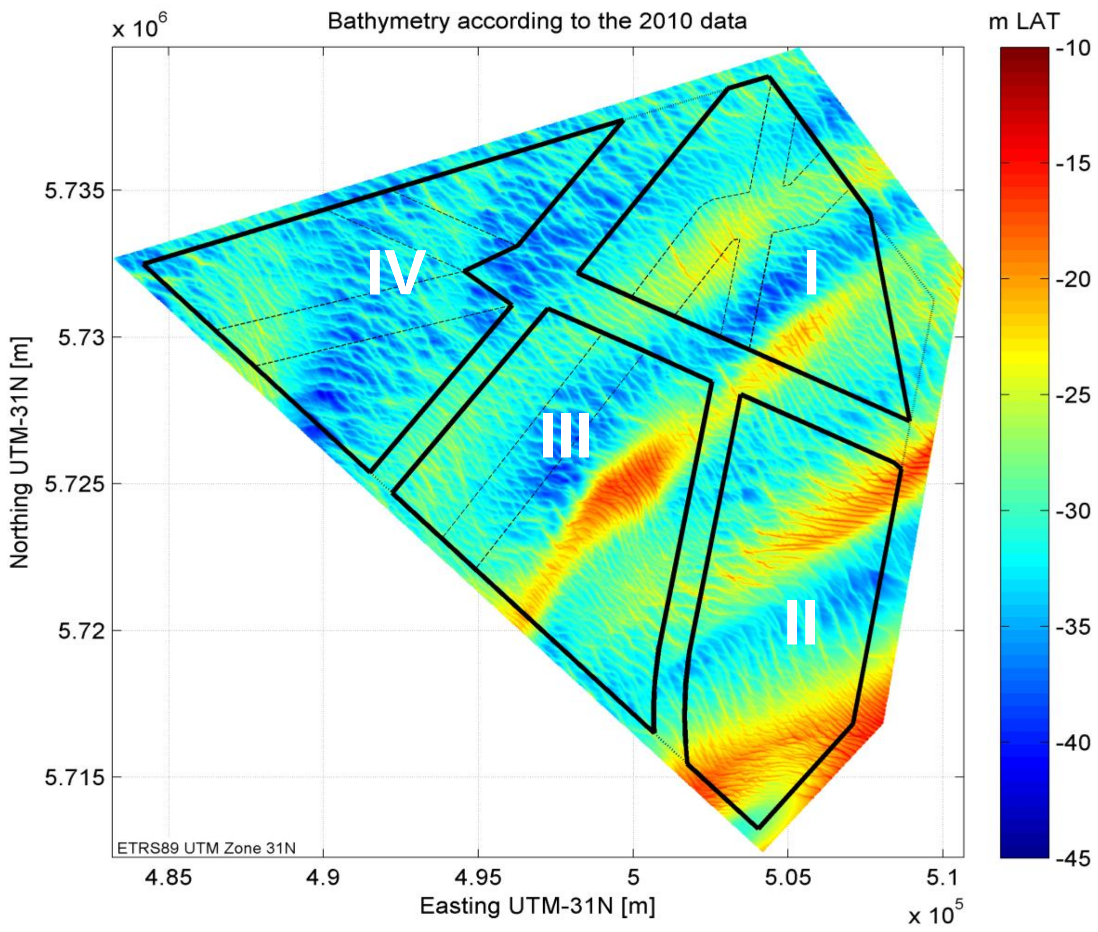

Figure 2.3 Bathymetry according to the 2010 survey. Bed levels are given in m LAT.

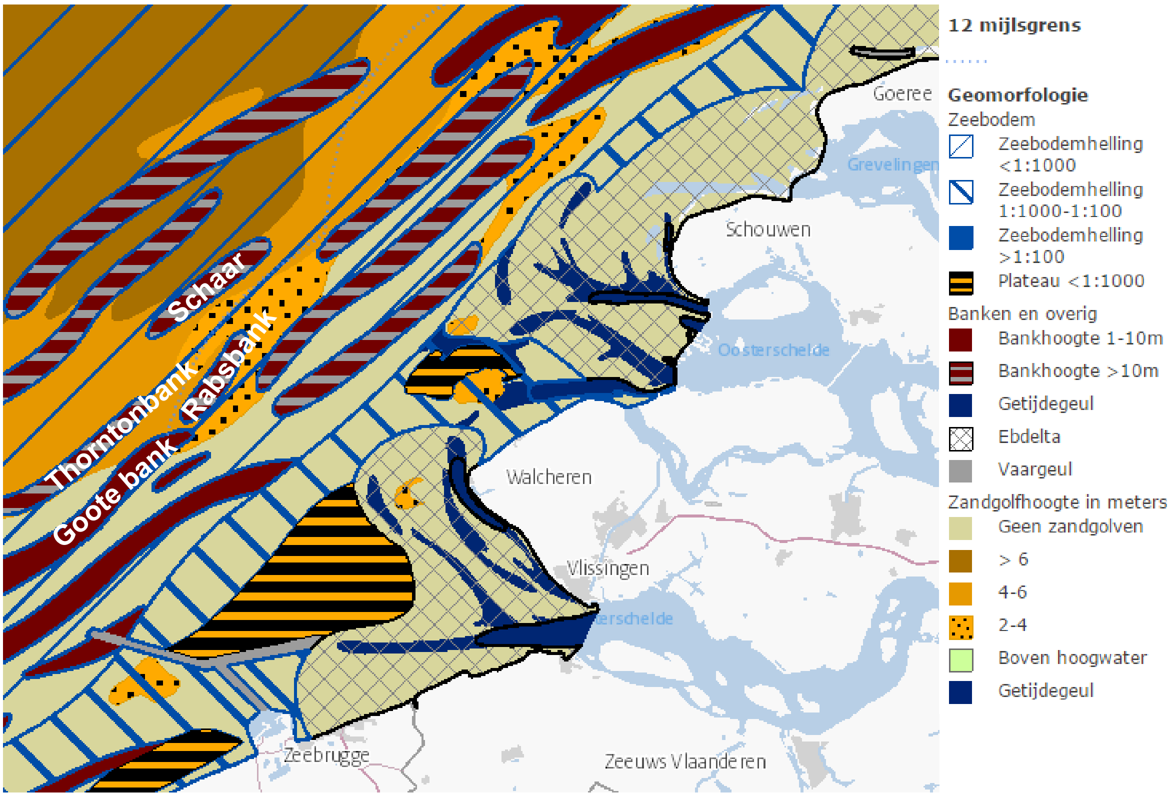

Figure 2.4 Map illustrating seabed morphology in the Borssele Wind Farm Zone [extracted from Noordzeeatlas.nl, underlying data was derived from Van Alphen&Damoiseaux, 1989; names of sandbanks were added in white]

2.2 Available datasets

In the area surrounding the BWFZ, a total of fourteen surveys has been conducted between 1988 and 2014. The project site is located outside the survey boundary of Rijkswaterstaat, therefore, all available historical survey data was collected by the Netherlands Hydrographic Office (NLHO) of the Netherlands Royal Navy (IHO, 1988). The scientific validation of this survey policy was investigated in Deltares (2011). The datasets are summarized in Table 2.1.

A continuous bathymetry, covering the entire project area, is available for the 2010 situation only (see Figure 2.3). The surveys conducted in that year provide an excellent high resolution dataset. For the investigation of the temporal development of the morphology in the area, at least two surveys are required. Therefore, four surveys around the year 2000 are combined into one dataset. The resulting bathymetry is displayed in Figure 2.5. This dataset is combined with the 2010 survey in order to obtain a time series of two datasets. Because the surveys from before 1999 do not cover the entire BWFZ and are of low resolution, these surveys are discarded.

Year	Survey ID	Survey Method	Data density	Coverage	Useful for this study
1988	7727	SBES	Low	Part of plot I	No
1988	7744	SBES	Low	Part of plot IV	No
1988	7745	SBES	Low	Parts of plot III and IV	No
1990	7784	SBES	Low	Parts of plot III and IV	No
1990	7722	SBES	Average	Part of plot I	No
1999	6264	SBES	Average	Part of plot II	Yes
1999	4737	SBES	Average	Part of plot I, II and III	Yes
2000	6104	SBES	High	Part of plot I	Yes
2001	10426	Unknown	High	Part of plot II	No
2001	6544	SBES	High	Parts of plot III and IV	Yes
2004	12644	Unknown	Low	Part of plot II	No
2010	15235	MBES	Excellent	NE part of BWFZ	Yes
2010	15236	MBES	Excellent	Middle part of BWFZ	Yes
2010	15409	MBES	Excellent	SW part of BWFZ	Yes

Table 2.1 Overview of available surveys from the NLHO. SBES means Single Beam Echo Sounder, MBES means Multi Beam Echo Sounder

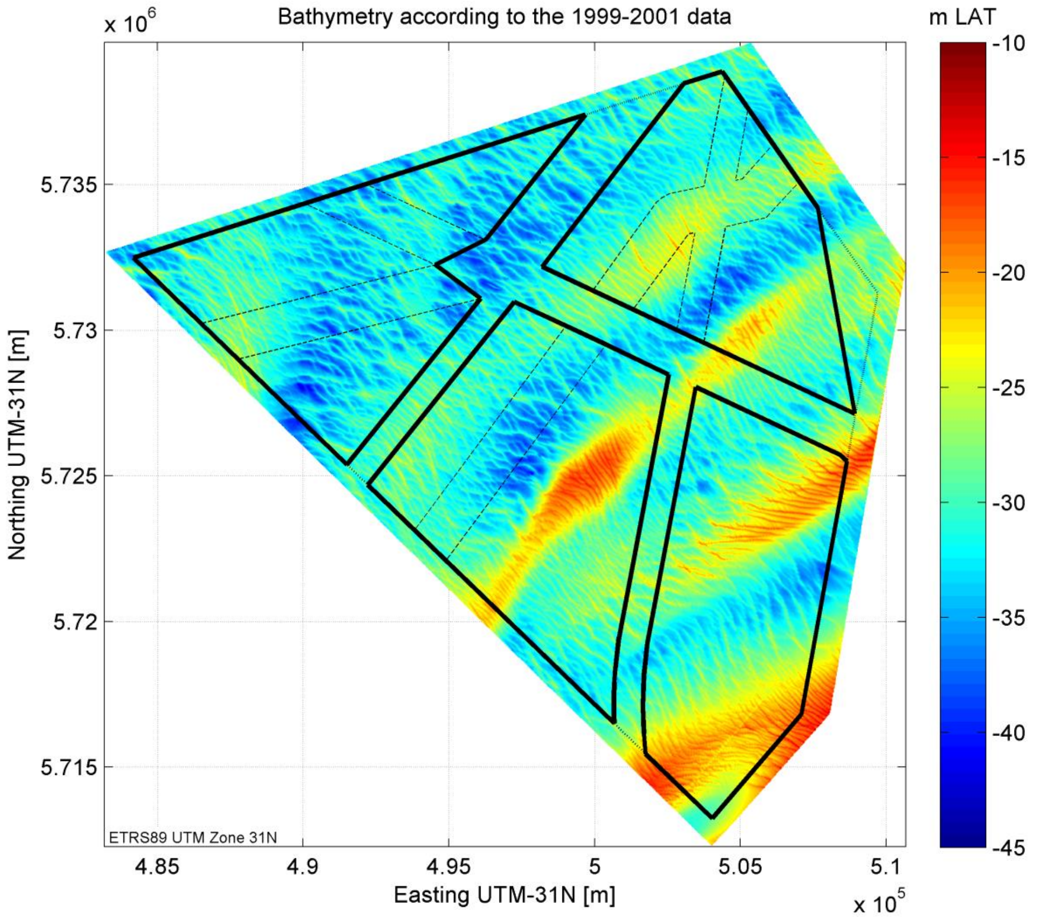

Figure 2.5 Bathymetry consisting of the combined 1999, 2000 and 2001 surveys. Bed levels are given in m LAT.

3 Methodology

3.1 Introduction

In order to determine the morphodynamics at the Borssele Wind Farm Zone, the following techniques were used:

- Large-scale bathymetric filtering and analysis
- Automated detection of bed form migration directions
- Fourier analysis on individual bed forms

In the proposal it was assumed that a cross-correlation technique could be applied to assess the migration direction of bed forms in the Borssele area. However, due to the complex bathymetry and opposing migration directions, a somewhat different technique produced slightly better results. This different technique is discussed in more detail in Section 3.3.

A δz/δt-analysis technique was also mentioned in the proposal. This method is very useful to determine where migrating bed forms are present, as is indicated in Figure 3.1. This figure shows the bed level differences over a period of 9-11 years, dependent on the year of the first survey that was used in this analysis. It can clearly be observed from the difference patterns that bed forms are migrating over the seabed. The length, height and migration directions of the bed forms show significant variation over the BWFZ-area. Note that due to some artificial “stripes” in the survey data (e.g. due to roll misalignment) and small differences in vertical level, this analysis is less suitable to obtain quantitative predictions for bed level variations at future WTG-locations and along cable trajectories.

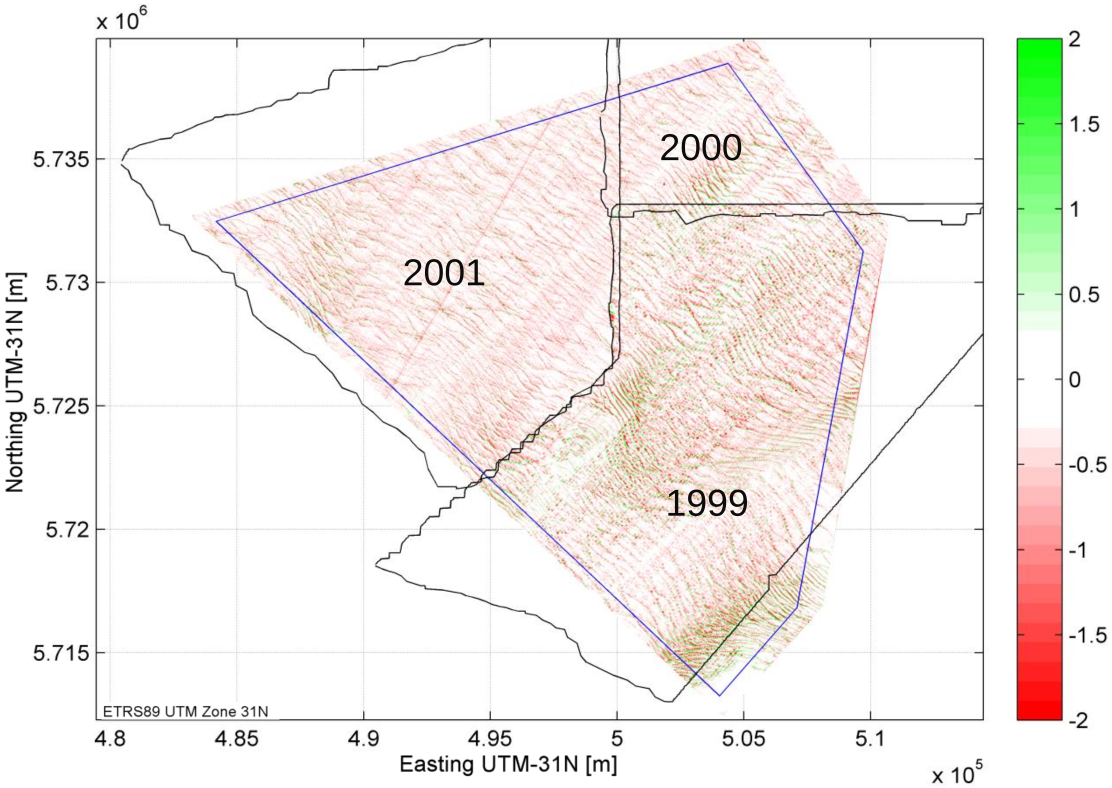

Figure 3.1 Example of δz/δt-analysis: difference plot over 9-11 year period (depending on the surveyed area). The polygons indicate the different years of the first survey that was used in the analysis.

3.2 Large-scale bathymetric filtering and analysis

Two Design Seabed Levels are required as input parameter for many (structural) design aspects:

1. Reference SeaBed Level (RSBL), which is the lowest possible seabed level during the lifetime of the wind parks in the BWFZ;
2. Maximum SeaBed Level (MSBL), which is the highest possible seabed level during the lifetime of the wind parks in the BWFZ.

Both levels can be calculated by artificial shifting of the mobile “components” of the most recent bathymetry (in this case: 2010) with the corresponding migration rate along the corresponding migration direction. In addition, some uncertainty ranges should be added to account for survey inaccuracies and natural variation of the shapes of the considered bed forms.

The lowest bed levels that are found throughout the envisaged lifetime of the wind parks determine the RSBL. Accordingly, the highest levels determine the MSBL. By comparing the predicted bathymetries of each year with the original bathymetry, the minimum and maximum bed level variations during the considered lifetime can be determined.

However, this method works best when the bed form migration speeds and overall migration directions are rather uniform over the considered area and known with sufficient accuracy. As we will see in the remainder of this report, this is not the case for the BWFZ. Therefore, in the first phase of this project an alternative approach was adopted. When new bathymetric data become available in the second phase of this study (expected Q1-2015), the migration directions and speeds can be determined with the required accuracy and the first method will be adopted.

First, in order to isolate the higher frequency migrating bed forms (in the order of sand waves) from the available surveys, a coarse (700m) filtering of the bathymetry was applied. This step splits the bathymetry into a static part (i.e. static within the considered period of 10 years) and an overlying sand wave field superimposed with megaripples. The filter value of 700m was obtained through an iterative process. It includes the vast majority of the sand wave lengths and correlates well with the general statistics described in Section 4.5.2. This value ensures that the migrating bed form information is filtered out while the static bottom features (e.g. sandbanks) retain their form. Comparison of the static bathymetry obtained for both bathymetries (1999/2000/2001-combination and 2010-survey) corroborates this; when subtracting the static bottom features of both surveys, minor spatial differences were found.

In this phase of the project, sandbanks are assumed to be static during the 25-year lifetime of a wind farm (Whether this assumption is valid, will be checked in the second phase of the project, when the new survey data become available). Therefore, only the isolated sand wave field needs to be analysed to determine the extremes in seabed level variation. By adding these extremes to the static bathymetry, the design seabed levels (RSBL and MSBL) are obtained.

Because of the complex bed form migration patterns and observed generation and extinction of individual sand waves, in this first phase of the project the extremes are only determined by identifying the extreme values of the sand wave field by sliding a square block of 2x2km over each point and determining the minimum and maximum sand wave level within that block.

This means that in this phase the actual bed form migration speed is not yet taken into account. Instead a conservative value of potential extremes at each point in the bathymetry is provided. The size of 2km was chosen to ensure that at least two sand waves in all directions are considered for each extreme value, providing additional safety with regard to “spontaneous” generation of new bed forms or natural changes in bed form shapes.

The extreme values of the sand wave field form an outer envelope of minimum and maximum bed levels due to the migrating bed forms. The design levels are then calculated as follows:

RSBL = Static Seabed Level - Max. Negative Surrounding Sand Wave Amplitude
MSBL = Static Seabed Level + Max. Positive Surrounding Sand Wave Amplitude

3.3 Determination of bed form migration directions

Although the sand wave statistics (heights, lengths, migration speeds and migration directions) are not yet taken into account in the calculation of both RSBL and MSBL, these values are already calculated. Nevertheless, the inclusion of a new high resolution bathymetry survey may further increase the accuracy of the results.

In order to obtain correct sand wave transects used in the Fourier analysis (which is introduced in Section 3.4), the migration directions of the sand waves are required. However, as explained in Section 3.1, an alternative technique for the cross-correlation technique was used to determine the migration direction of the bed forms.

The bed form migration direction is determined by looping over the potential migration directions of various transects. For each direction, the sand wave field derived from the oldest of the two surveys is migrated over several distances. Then for each case the RMS-difference between the two datasets was determined. The case with the smallest RMS-difference for the largest migration distance is considered to represent the best estimate for the migration direction. This analysis was performed for directions between 0 and 90°N with both negative and positive migration distances. This means that sand waves migrating with angles between northern and eastern direction (clockwise; 0-90°N) and with angles between southern and western direction (clockwise; 180-270°N) are covered in the analysis, representing migration along the flood and the ebb direction of the tidal current.

Due to the large complexity of the system and the observed extinction and generation of sand waves this is not a fully reliable method. However, by bulk processing a large number of points, reliable statistics can be obtained. The resulting transects and orientations are input for the Fourier analysis, which provides statistics on sand wave characteristics like sand wave height, sand wave length and migration speed (see next section).

3.4 Fourier analysis on individual bed forms

Following the determination of bed form migration directions, a one-dimensional spectral analysis is used to determine individual sand wave dimensions and changes in time. The analysis is performed on transects that have to be drawn in the direction of sand wave migration to prevent that the migration velocity is underestimated. Differences in wavelength when not normal to the orientation of the crests are negligible.

For all transects crest and trough points of the individual sand waves are identified and tracked in time in the 2000 and 2010 surveys. Megaripples, which are superimposed on sand waves, are more dynamic than sand waves and are to be removed in the analysis to ensure consistent tracking of the crest and trough points. By truncating the high and low frequencies from a Fourier series that describes the bathymetric signal, the smaller megaripples and underlying large-scale morphology are separated from the sand wave signal (Van Dijk et al., 2008).

From the sand wave signal, crest and trough points are used to determine the wave lengths and wave heights of individual sand waves. By means of tracking these points in both the 2000 and 2010 surveys, the migration rates of individual sand waves can be estimated. Figure 3.2 and Figure 3.3 below provide examples of two transects in which the sand waves move in opposite directions, illustrating the highly dynamic behaviour of the system:

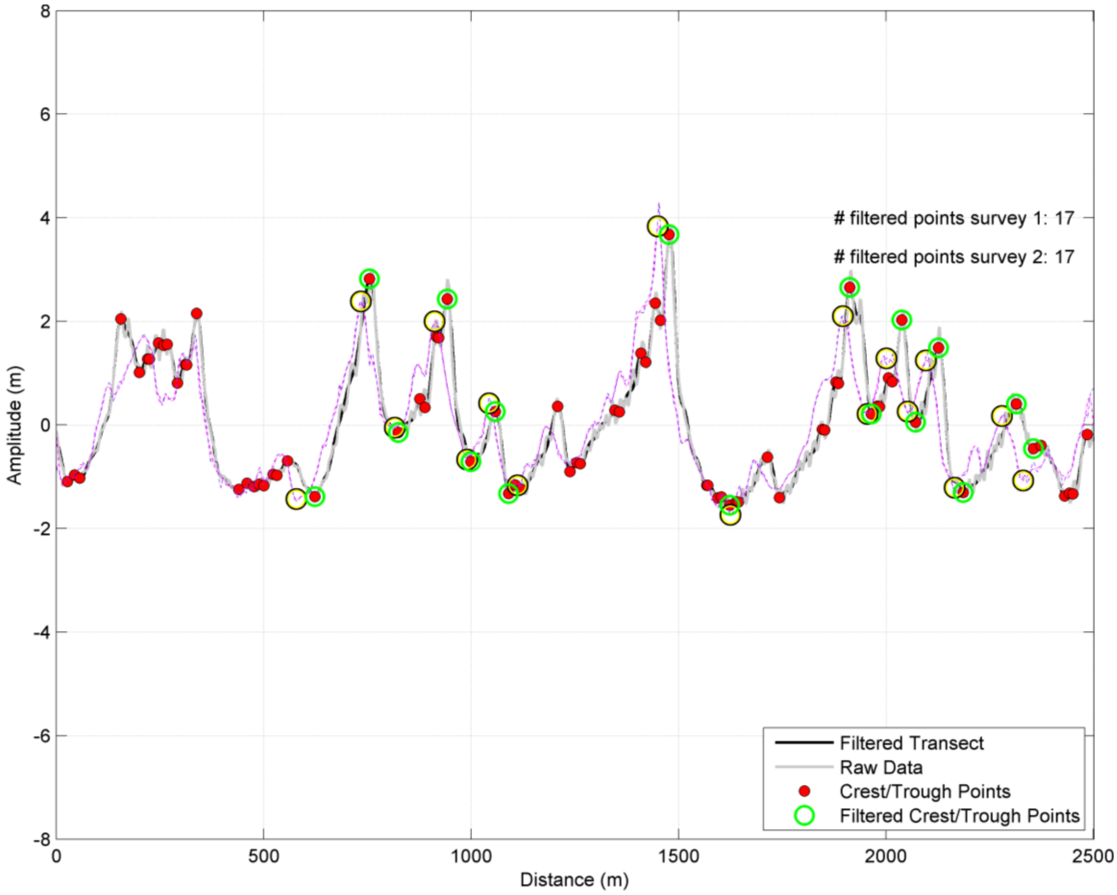

Figure 3.2 Example of Fourier analysis on one of the 2500 meter long transects from NE (left) to SW . Purple dashed line = sand wave signal based on 2000-bathymetrical survey; Pink dashed line = Fourier approximation of 2000 sand wave signal; grey solid line = sand wave signal based on 2010-bathymetrical survey; Black solid line = Fourier approximation of 2010 sand wave signal. The filled red dots indicate all crest/trough points and the green dots indicate which points have been selected for analysis (automatically or manually corrected) in the 2010-signal. Points selected in the 2000-signal are indicated by black circles. The plot shows a clear migration to the right, corresponding to the dominant SW-direction.

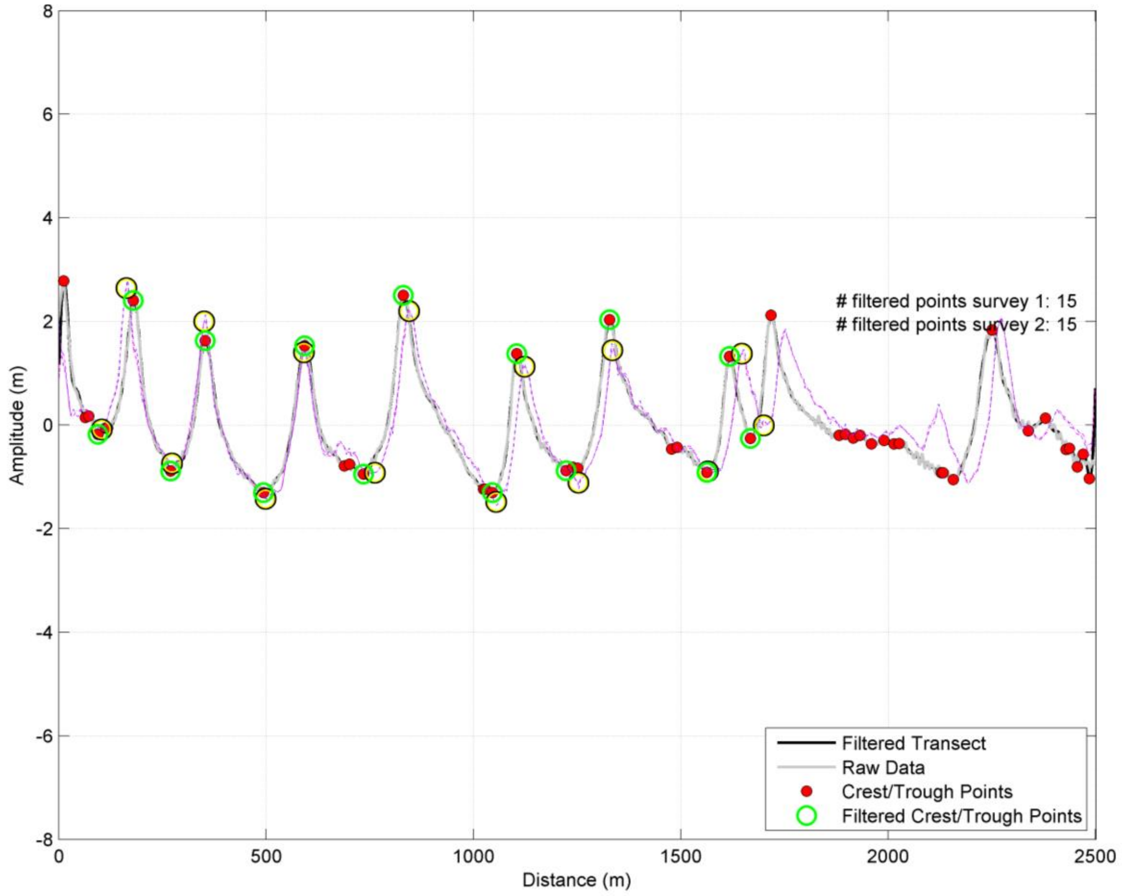

Figure 3.3 Example of Fourier analysis on one of the 2500 meter long transects from NE (left) to SW. Purple dashed line = sand wave signal based on 2000-bathymetrical survey; Pink dashed line = Fourier approximation of 2000 sand wave signal; grey solid line = sand wave signal based on 2010-bathymetrical survey; Black solid line = Fourier approximation of 2010 sand wave signal. The filled red dots indicate all crest/trough points and the green dots indicate which points have been selected (automatically or manually corrected) in the 2010-signal. Points selected in the 2000 survey are indicated by black circles. The plot shows a clear migration to the left, corresponding to the NE-direction.

Over the analysed transects, there is spatial variation in the sand wave displacement between surveys, i.e. not all sand waves and certainly not all selected crest and trough points, shift the same amount between surveys. Additionally, the various bathymetrical datasets of 2000 have been collected over a period of around 3 years in between 1999 and 2001 (see Section 2.2). To arrive at the best estimate migration rates, the migration distances found for all selected points have been divided by the time in between the surveys and within each transect the migration speeds of the individual sand waves have been averaged.

This approach assumes that the seabed is in a state of dynamic equilibrium, which implies that the sand waves will retain their shape and dimensions while they are migrating. However, as stated earlier, the Borssele wind farm zone is highly dynamic with opposing sand wave migration directions and (observed in some transects) generation and extinction of sand waves. Furthermore, event-driven changes of the sand wave shape (e.g. during storms) are also difficult to estimate on the basis of two surveys only. We expect to narrow this source of uncertainties, when the new survey data are included in the analysis. Then these estimated seabed variations on top of the seabed changes originating from sand wave migration will be added to the results as an uncertainty range.

4 Results

4.1 Introduction

In this chapter first the static and dynamic bathymetry are presented in Section 4.2. Then the Reference SeaBed Level (RSBL) and the Maximum SeaBed Level (MSBL) will be determined in Section 4.3 and Section 4.4 respectively. Subsequently, the sand wave statistics will be discussed in Section 4.5. As explained in Chapter 3, in the second phase of this project, when new bathymetry data become available, the sand wave statistics will be used to define the RSBL and MSBL more accurately and thus less conservatively.

Note that the colour scales of all bathymetry plots in this chapter are similar (-10 to -45m LAT) in order to be able to directly visually compare all plots. This means that the limits give no information on the actual minimum and maximum values. These are often presented in the text.

4.2 Static and dynamic bathymetry

As explained in Section 3.2, the bathymetry is split into a static and a dynamic part. For the 2010 bathymetry these two parts are displayed in Figure 4.1 and Figure 4.2 respectively:

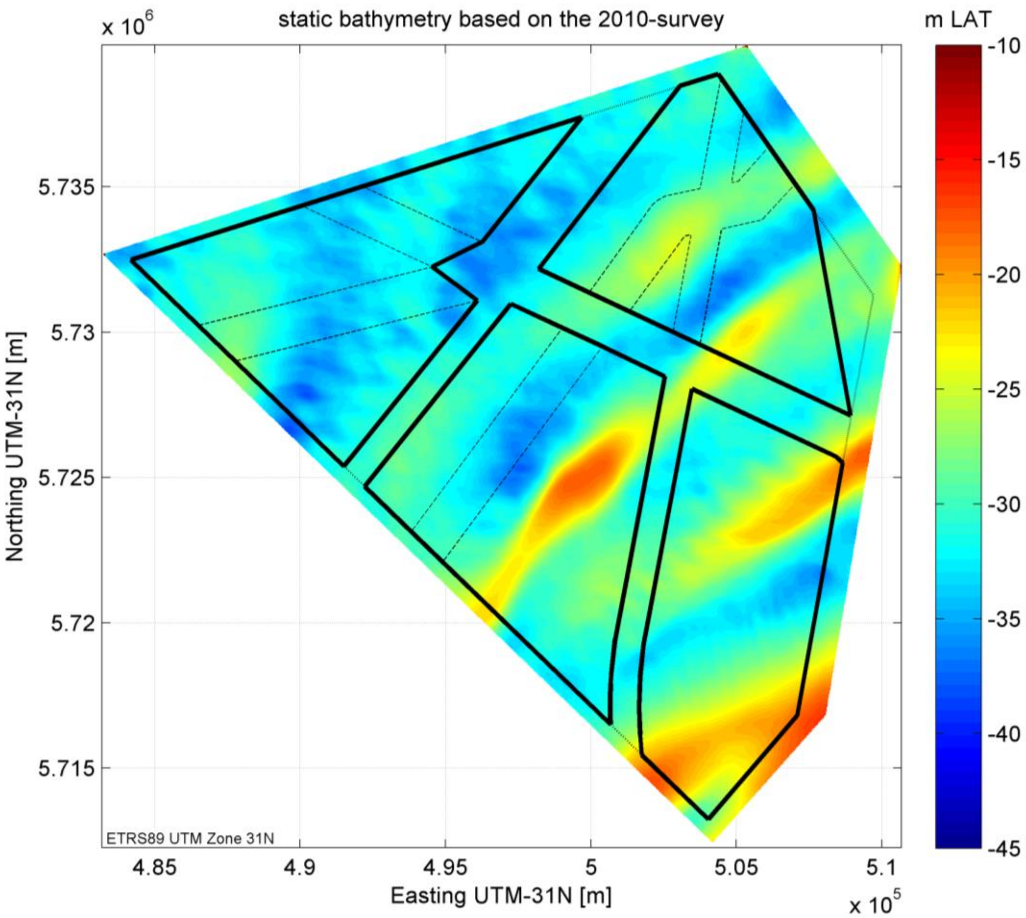

Figure 4.1 Static bathymetry (within the period between the surveys) isolated from the 2010 bathymetry, showing underlying large-scale morphological patterns (sandbanks and swales).

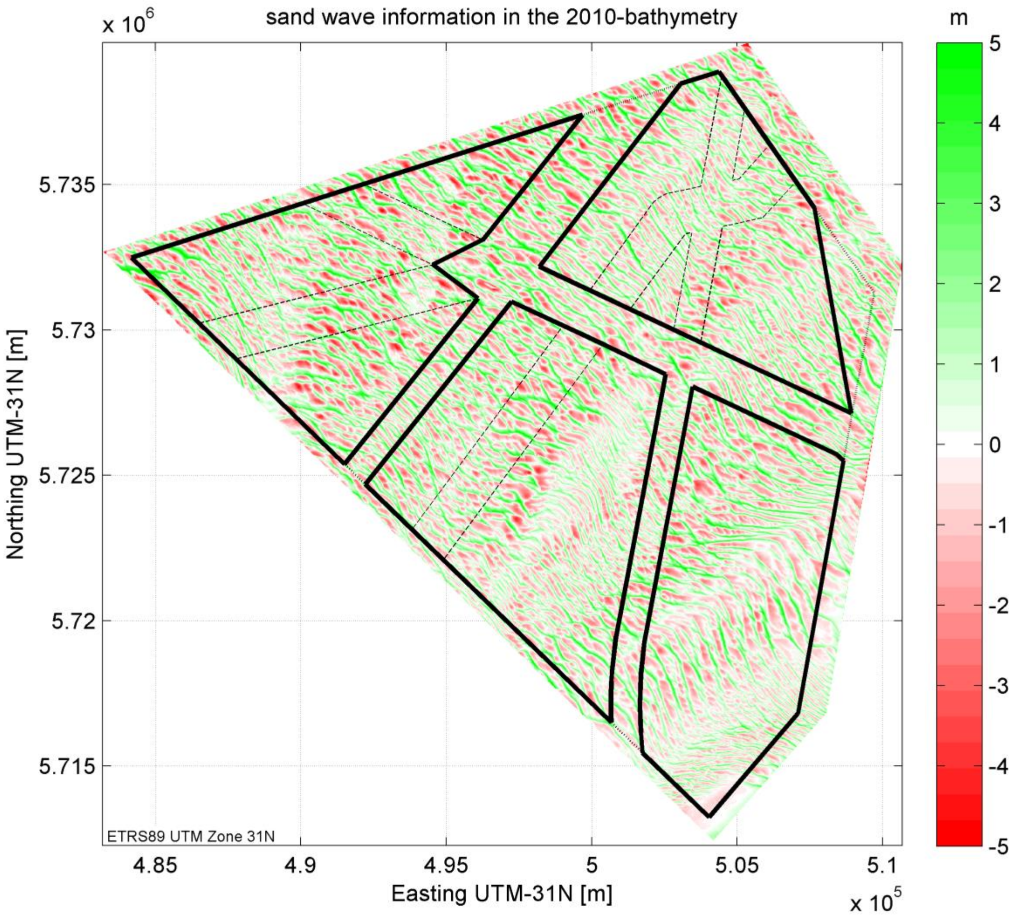

Figure 4.2 Sand wave field isolated from the 2010 bathymetry representing dynamic bathymetry, obtained by extracting the static bathymetry displayed in Figure 4.1 from the 2010 bathymetry displayed in Figure 2.3.

4.3 Reference SeaBed Level (RSBL)

From the sand wave field presented in Figure 4.2 the upper and lower envelopes were determined. The resulting minimum values are plotted in Figure 4.3. The values presented in this figure are based on 99% non-exceedance values of the downward sand wave amplitudes, in an area of 1km around each point in the bathymetry. The largest values (around 4m) are found in the north-western, deeper parts of the BWFZ. On the crests of the underlying sandbanks the values are smaller, in order of 2m.

Next, by combining the minimum values (Figure 4.3) with the static bathymetry (Figure 4.1) the Reference SeaBed Level (RSBL) is obtained. The RSBL is shown in Figure 4.4. The overall bathymetry of the RSBL looks very similar to the static bathymetry, but it is typically a few meters deeper. The RSBL varies between -18.3m LAT and -42.2m LAT. The deepest parts are found in site IV, with 70% of the area below -35m LAT. Such large depths are found in the other sites as well, but more locally.

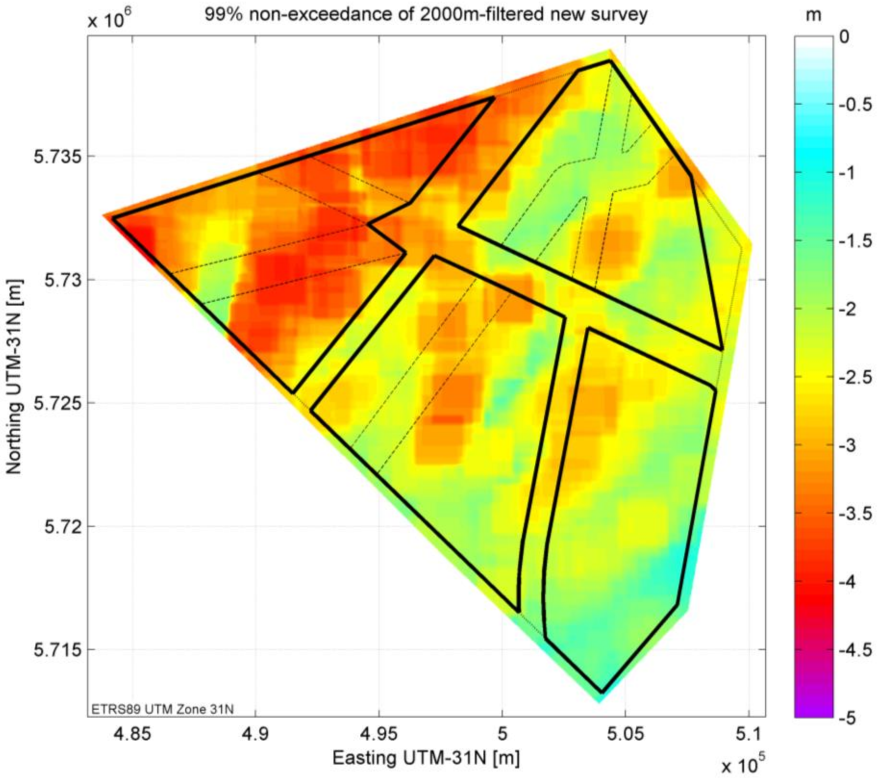

Figure 4.3 The 99% non-exceedance negative values of the sand wave information obtained from the 2010-survey. This plot indicates the lower (negative) envelope of the bed forms plotted in Figure 4.2.

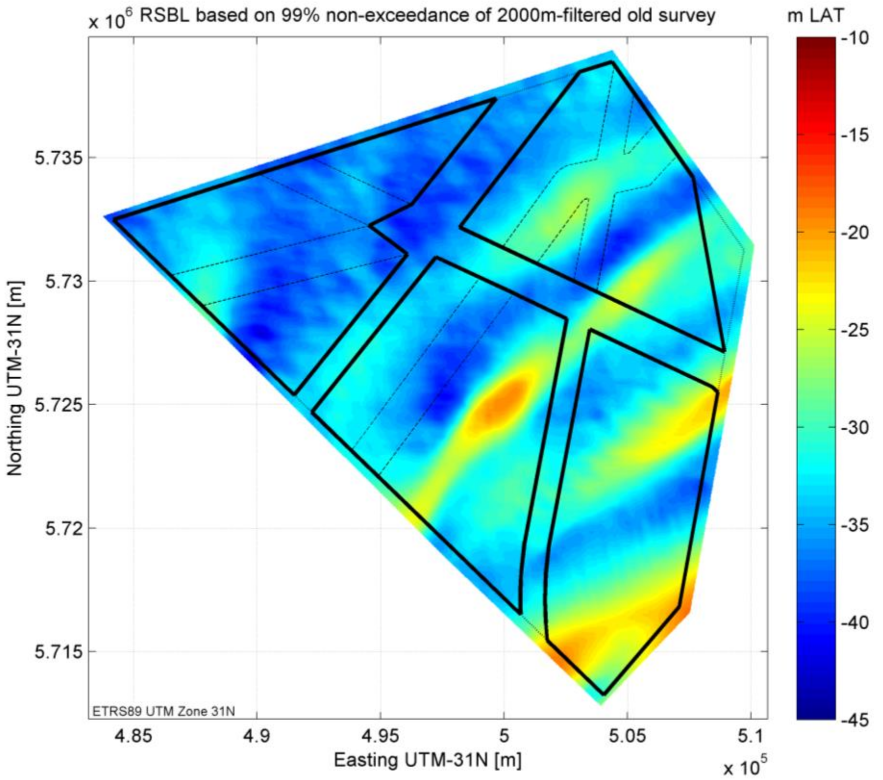

Figure 4.4 The Reference SeaBed Level (RSBL) based on the 99% lower envelope of the sand wave information obtained from the 2010-survey. The RSBL is the summation of the static bathymetry (Figure 4.1) and the lower (negative) envelope (derived from the sand wave field) plotted in Figure 4.3.

By calculating the difference between the RSBL and the most recent bathymetry (2010), the maximum potential seabed level lowering can be predicted, see Figure 4.5. Please note that for design purposes the most recent bathymetry (to be surveyed still) should be compared to the RSBL (Figure 4.4). This will be done in the second phase of this project. The RSBL itself will also be updated on the basis of the new survey data.

The predicted maximum seabed level lowering visualised in Figure 4.5 shows the largest variation in site IV. The other sites show areas with significant lowering as well. It should be noted that the observed pattern follows the large-scale bed form geometry. The current crests of the sand waves have the largest predicted drop in seabed level, while the deepest troughs of the sand waves have a zero predicted drop (i.e. these are already at their lowest and will experience a seabed level rise). This pattern is observed over the entire area, but on top of the underlying sandbanks the height variation between the crests and troughs is typically less, as the wave height typically decreases on these sandbank crests; higher sand waves are found in the swales between the sandbanks. In Section 4.5 the overall BWFZ sand wave statistics, as well as the statistics per site are presented.

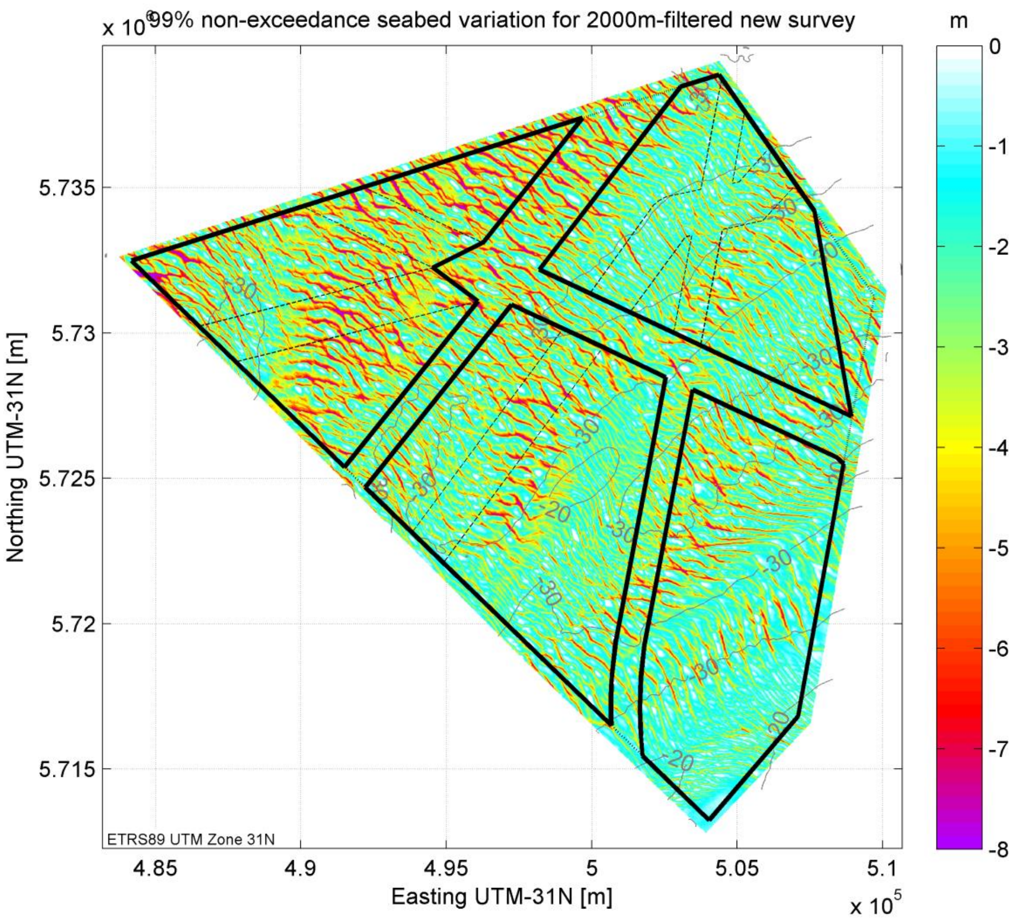

Figure 4.5 The 99% non-exceedance predicted seabed lowering based on the 2010 survey. The values indicate the difference between the 2010 bathymetry (Figure 2.3) and the RSBL (Figure 4.4). Isobaths with 10m intervals are also shown, which illustrate the fact that higher sand waves are found in the swales between the sandbanks.

4.4 Maximum SeaBed Level (MSBL)

Similar to the procedure to determine the RSBL, the Maximum SeaBed Level (MSBL) was determined. Now the upper (positive) envelope of the sand wave field presented in Figure 4.2 was used. The resulting maximum values are plotted in Figure 4.6. The values presented in this figure are based on 99% non-exceedance values of the upward sand wave amplitudes, in an area of 1km around each point in the bathymetry. The largest values (over 5m) are found in the north-western, deeper parts of the BWFZ, similar to where the deeper sand wave troughs are found.

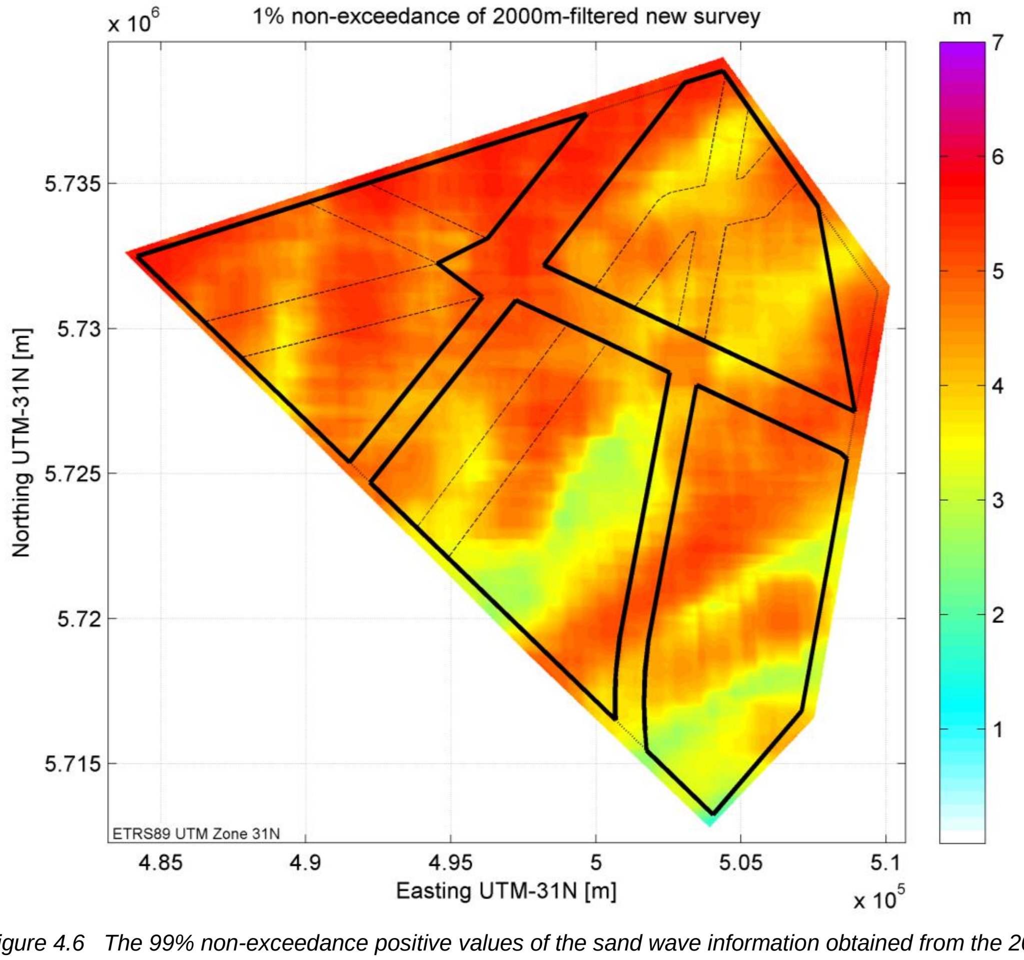

Figure 4.6 The 99% non-exceedance positive values of the sand wave information obtained from the 2010-survey. This plot indicates the upper (positive) envelope of the bed forms plotted in Figure 4.2.

Next, by combining the maximum values (Figure 4.6) with the static bathymetry (Figure 4.1) the Maximum SeaBed Level (MSBL) is obtained. The MSBL is shown in Figure 4.7. The overall bathymetry of the MSBL looks very similar to the static bathymetry, but it is typically a few meters shallower. The MSBL varies between -12.6m and -33.9m LAT. The shallowest parts are found in site II and III.

By calculating the difference between the MSBL and the most recent bathymetry (2010), the maximum potential rise of the seabed can be predicted, see Figure 4.8. Please note that for design purposes the most recent bathymetry (to be surveyed still) should be compared to the MSBL (Figure 4.7).

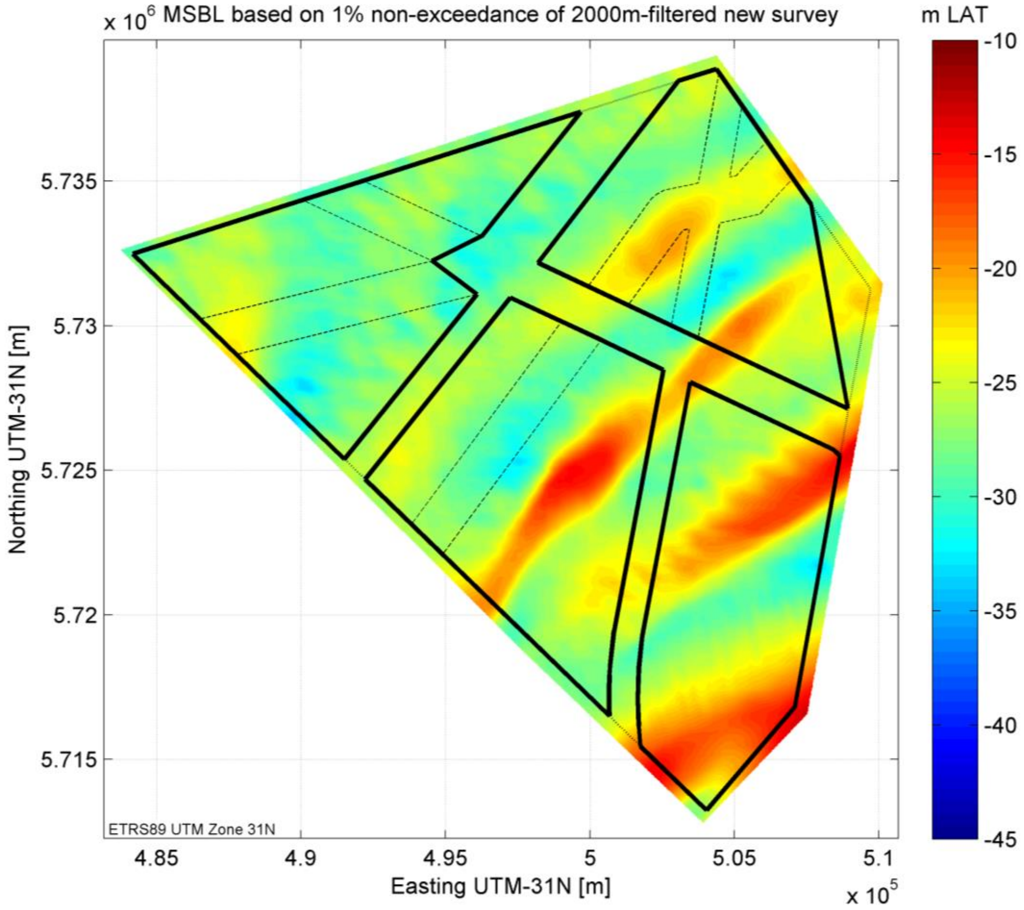

Figure 4.7 The Maximum SeaBed Level (MSBL) based on the 99% upper envelope of the sand wave information obtained from the 2010-survey. The MSBL is the summation of the static bathymetry (Figure 4.1) and the upper (positive) envelope (derived from the sand wave field) plotted in Figure 4.6.

The predicted maximum seabed rise visualised in Figure 4.8 shows the largest variation in site IV, similar to the maximum seabed lowering. The current sand wave troughs of the sand waves have the largest predicted rise in seabed level, while the highest crests of the sand waves have a zero predicted rise. Note that the seabed close to the foundations will most likely not rise significantly, because local scour will prevent this. Buried electricity cables that cause no flow disturbance themselves will obviously not have this “beneficial” scour effect and therefore will experience a rising seabed if a sand wave crest passes over. This might be relevant for the maximum cable temperature (“thermal bottleneck effect”).

4.5 Sand wave statistics

The sand wave statistics are presented for the entire BWFZ and separately for each of the four sites presented in Figure 2.2 and Figure 2.3. Information is provided on the sand wave migration distances, migration speeds, wave lengths and wave heights in the form of maps and non-exceedance plots. The non-exceedance plots display the migration distances and corresponding migration speeds from individual crest and trough points and wave lengths and heights from individual waves. The maps display values averaged per transect. Note that the most southern corner of site II does not contain sand waves and therefore is displayed empty in most of the maps.

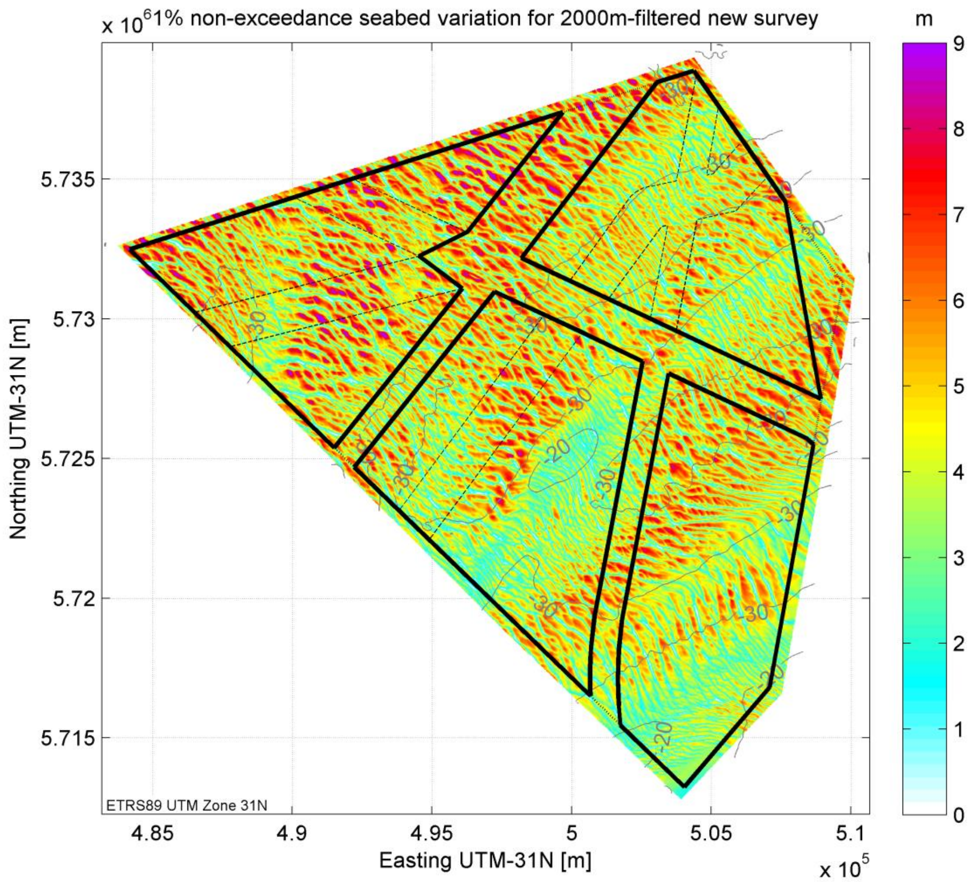

Figure 4.8 The 99% non-exceedance predicted seabed rise based on the 2010 survey. The values indicate the difference between the 2010 bathymetry (Figure 2.3) and the MSBL (Figure 4.4). Isobaths with 10m intervals are also shown, which illustrate the fact that higher sand waves are found in the swales between the sandbanks.

The statistics are based on the tracking in time and space of selected crest and trough points. The selection of the crest and trough points in the 2000- and 2010-surveys has been performed twice; once automatically on the 665 transects displayed in the top plot of Figure 4.9 and once semi-automatically with manual correction wherever necessary on 153 transects spread further apart, displayed in the bottom plot of Figure 4.9 (the background colour of Figure 4.9 shows the difference between the 2010 and 2000 surveys). The manual inspection of the transects of the 2000- and 2010-surveys was required to ensure that an equal amount of consistent crests and troughs were selected in both transects; extinction and generation of sand waves prohibited a fully automated selection of these points. From these manually selected crest and trough points, the migration distances and velocities have been calculated. The statistics of the wave lengths and heights have been derived from the automated tracking of the crest and trough points in the most recent 2010 survey on 665 transects, to ensure a sufficient data coverage.

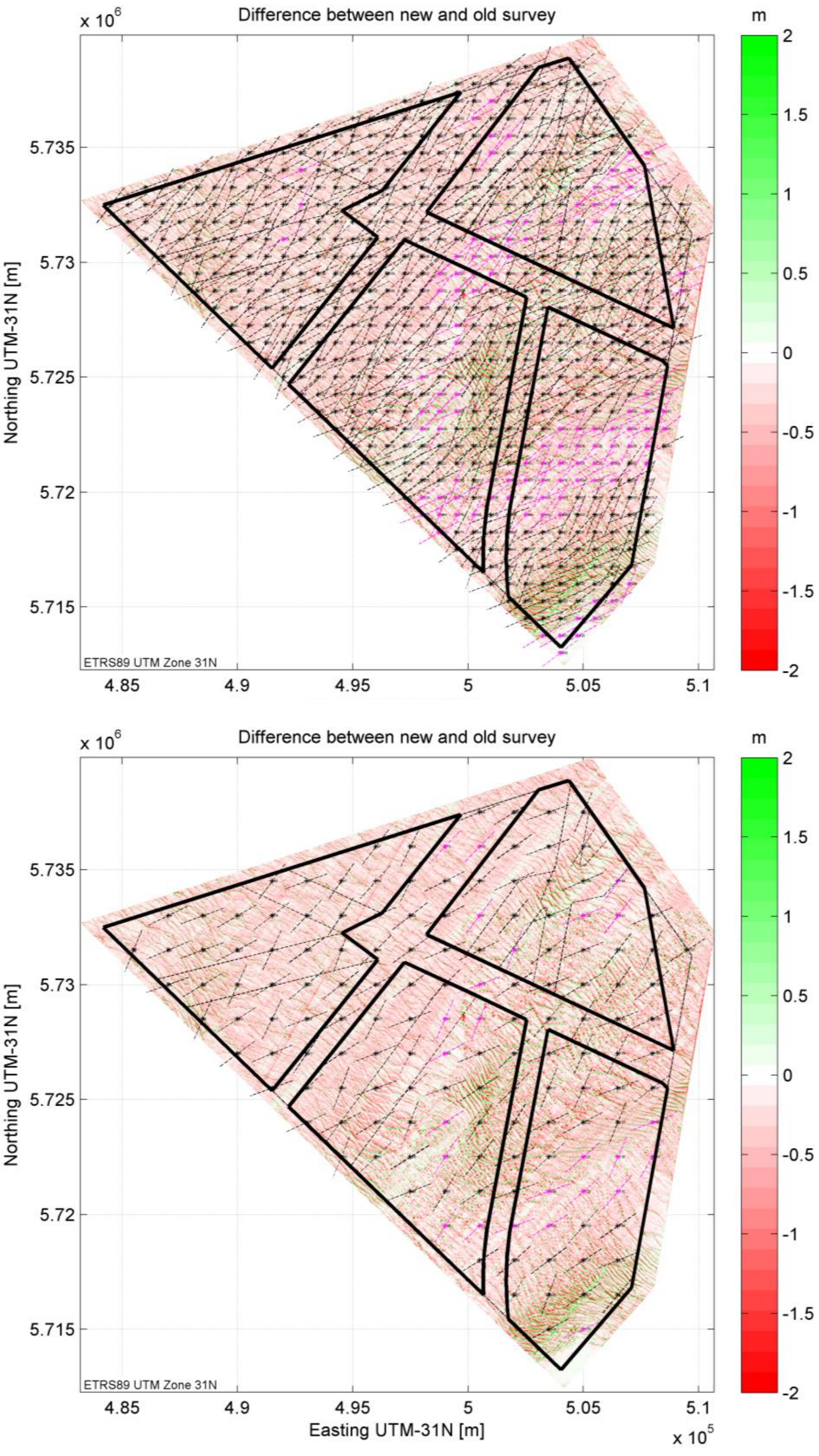

Figure 4.9 Results of the determination of the sand wave migration directions. Top plot is based on 665 transects, bottom plot on 153 transects. Black lines indicate SW-directions, purple lines NE-directions

4.5.1 Sand wave statistics of the Borssele wind farm zone

As illustrated in Figure 4.9, the sand waves in BWFZ are migrating to the southwest (ebb direction) as well as the northeast (flood direction), with a main axis of approximately 230° and 50° respectively (relative to north). This axis varies over the area with a variation of up to 30°. Particularly complex areas are the top of the sandbank in site III and the swales in between the sandbanks in site I, site II and site III. For illustration purposes, the rather complex migration patterns of Figure 4.9 have been schematized in Figure 4.10.

The migration in north-eastern direction in the swale halfway site II and the swale extending all the way through site III and I are most likely related to the flood tidal flow being dominant over the ebb flow, while the swale in between (passing over the south-eastern corner of site I and the north-western corner of site II) is most likely more dominated by the ebb current. The ebb flow is also dominant on top of the crests of the sandbanks. Similar flood- and ebb-dominated patterns were also observed in Van Lancker et al. (2013). More detailed modelling of the tidal flow patterns in this area (preferably over a full spring-neap cycle) will provide a better insight in the relation between sand wave migration and tidal flow.

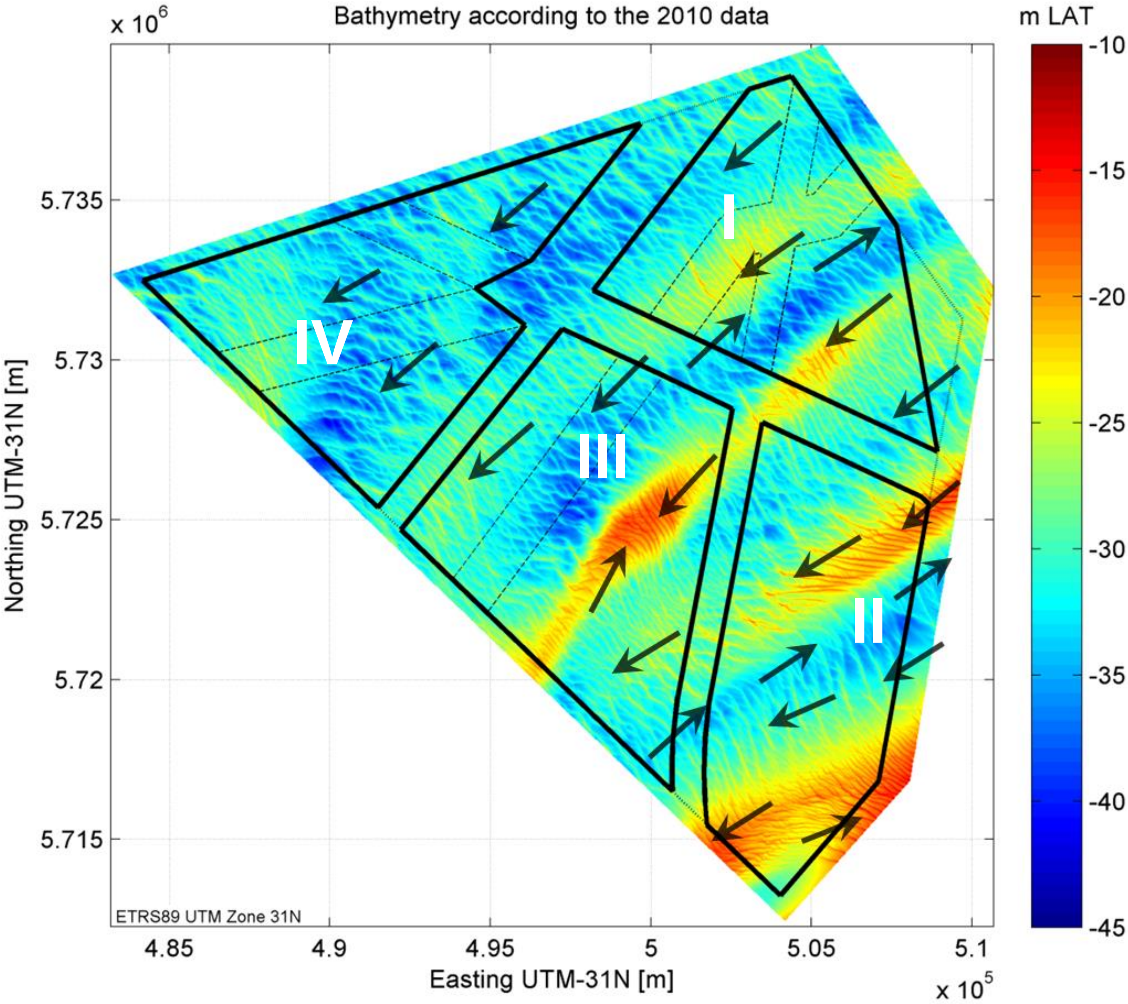

Figure 4.10 A schematized pattern of the sand wave migration directions on top of the BWFZ bathymetry.

Values for the migration distance and migration speed, averaged per transect and estimated using the manually selected crest and trough points of 153 transects, are presented in Figure 4.11 (red = NE, green = SW). Note that some white spaces are plotted near the edges of the sites were no transects were present. The plot of the migration speeds differs spatially from the plot of the migration distances, depending on the relevant survey for each area as the timespan between the 2010 and 1999, 2000 and 2001 surveys varies. The migration directions show a reasonable comparison with Figure 4.9 in which the migration directions are highlighted in black (SW) and purple (NE). Note however, that the algorithm used to determine the migration directions in that figure has been optimized to find the migration directions and not the migration distances and therefore, some differences can occur.

The 5% and 95% non-exceedance values (see Figure 4.12) show migration distances in between 17 meters in NE-direction and 31 meters in the dominant SW-direction with corresponding speeds of 1.7 meters per year in NE-direction and 3.2 meters per year in SW-direction (see Table 4.1). Generally speaking, the highest velocities are found on the crests and the lowest velocities in the troughs of the sandbanks of the underlying static bathymetry (see Figure 4.1).

Parameter	**5% non-exceedance**	**50% non-exceedance**	**95% non-exceedance**
Migration distance [m]	-17	5	31
Migration speed [m/yr]	-1.7	0.6	3.2

Table 4.1 Sand wave migration statistics in the Borssele Wind Farm Zone (- = NE, + = SW)

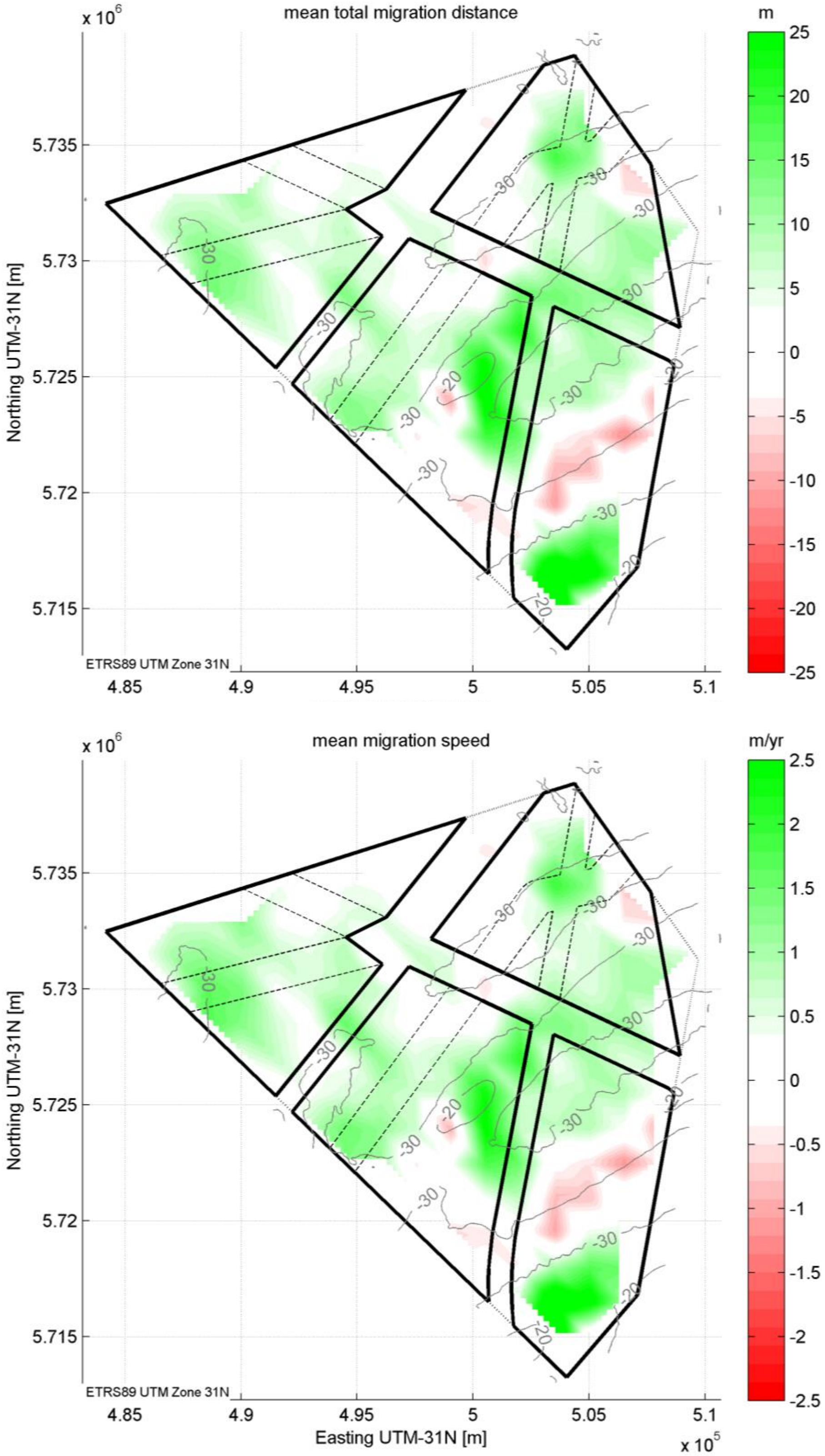

Figure 4.11 Map plots of migration distances (top plot) and migration speeds (bottom plot) estimated using the manual selection of crest and trough points of 153 transects in BWFZ (red = NE, green = SW).

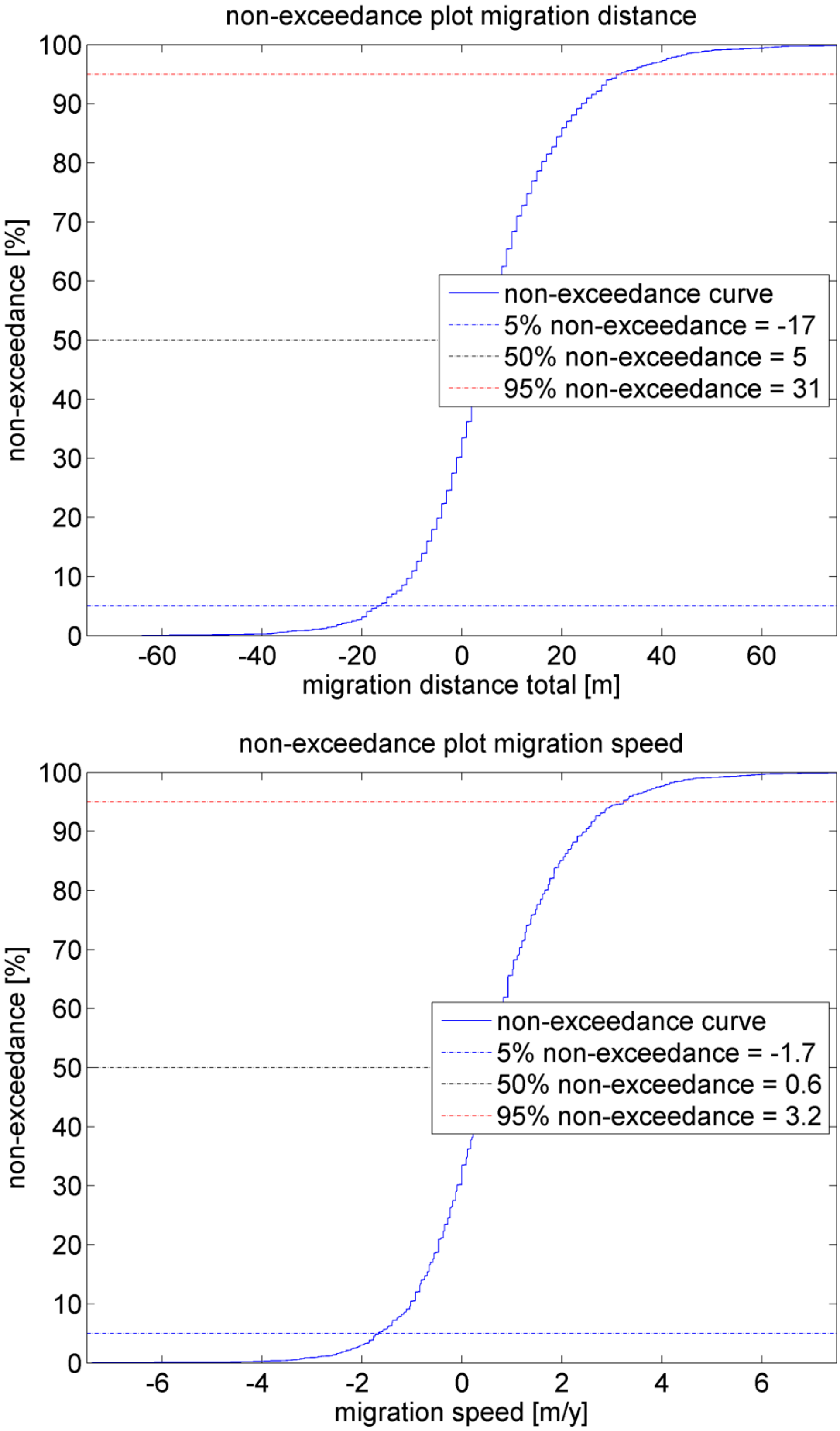

Figure 4.12 Non-exceedance plots of migration distances (top plot) and migration speeds (bottom plot) estimated using the manual selection of crest and trough points of 153 transects in BWFZ.

Figure 4.13 shows map plots of the estimated, transect-averaged, wave lengths (top plot) and wave heights (bottom plot) from the 2010 survey. These values are obtained using the automatically selected crest and trough points from the 665 transects displayed in the top plot of Figure 4.9. Furthermore, the wave height distribution compares reasonably well with the predicted potential seabed lowering, depicted in Figure 4.5, which provides a good indication of the wave height distribution over the Borssele wind farm zone. Overall, low, short waves are found on the crests and longer, higher waves in the troughs of the sandbanks of the underlying static bathymetry (see Figure 4.1). This behaviour is expected since sand waves can only grow to a certain percentage of the water depth (e.g. Yalin, 1964). And although these results show a larger resolution the results are also in line with the results of Van Alphen and Damoiseaux (1989), see Figure 2.4. Figure 4.14 shows the non-exceedance plots of both wave length and wave height. The values of 5%, 50% and 95% non-exceedance are summarized in Table 4.2 below:

Parameter	**5% non-exceedance**	**50% non-exceedance**	**95% non-exceedance**
Sand wave length [m]	114	234	513
Sand wave height [m]	1.4	3.7	7.0

Table 4.2 Sand wave characteristics in the entire BWFZ

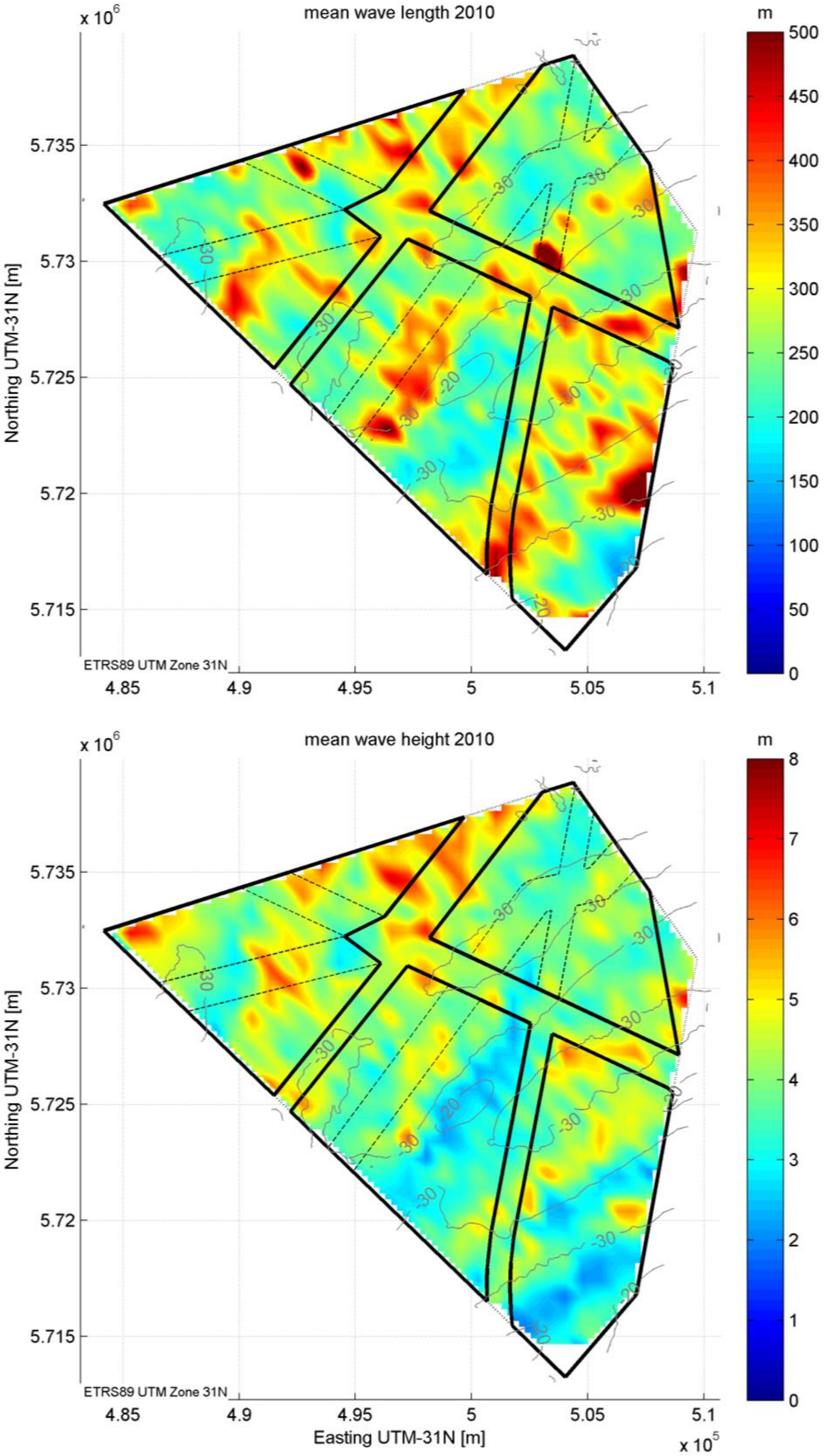

Figure 4.13 Map plots of wave lengths (top plot) and wave heights (bottom plot) estimated using the automatic selection of crest and trough points of 665 transects from the 2010 survey

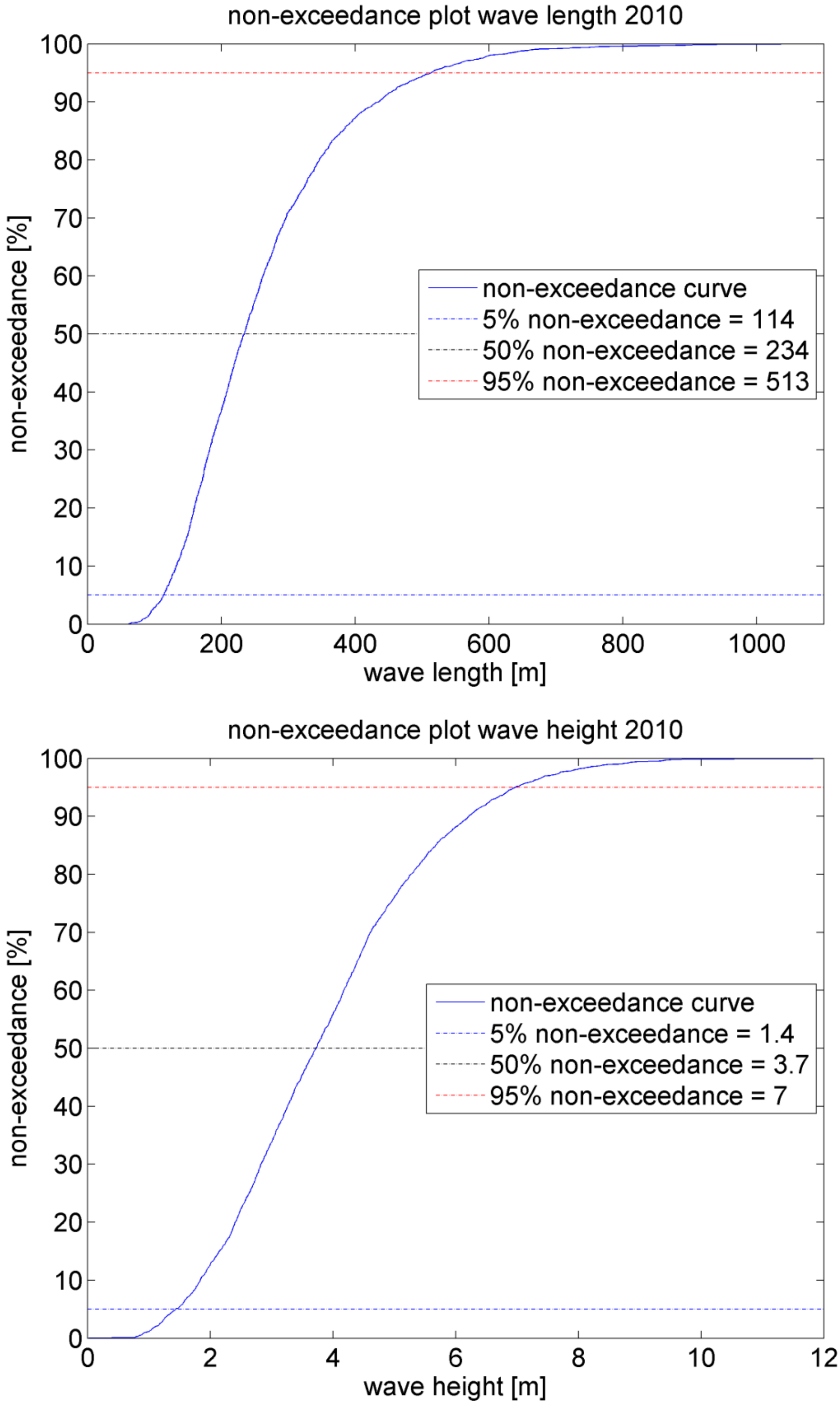

Figure 4.14 Non-exceedance plots of wave lengths (top plot) and wave heights (bottom plot) estimated using the automatic selection of crest and trough points of 665 transects from the 2010 survey; for the entire BWFZ

4.5.2 Sand wave statistics per site

Per site, four non exceedance plots are presented of migration distance, migration speed, sand wave length and sand wave height. Note that, given the 2500 meter long transects used, all waves within the sites, including sand waves in the safety zones have been taken into account.

Statistics of sand waves in site I

In site I, apart from a patch of sand waves in the north-eastern corner, all waves are migrating in south-western direction. The migration speeds are relatively low, reaching a maximum in the crossing of the two safety zones that cross this site. The sand wave characteristics of the site are displayed below in Table 4.3 and Figure 4.15.

Parameter	5% non-exceedance	50% non-exceedance	95% non-exceedance
Migration distance [m]	18	4	32
Migration speed [m/yr]	-1.7	0.4	3.1
Wave length [m]	123	226	427
Wave height [m]	1.6	3.8	6.1

Table 4.3 Sand wave characteristics of site I (migration distance/speed: negative values towards northeast, positive values towards southwest)

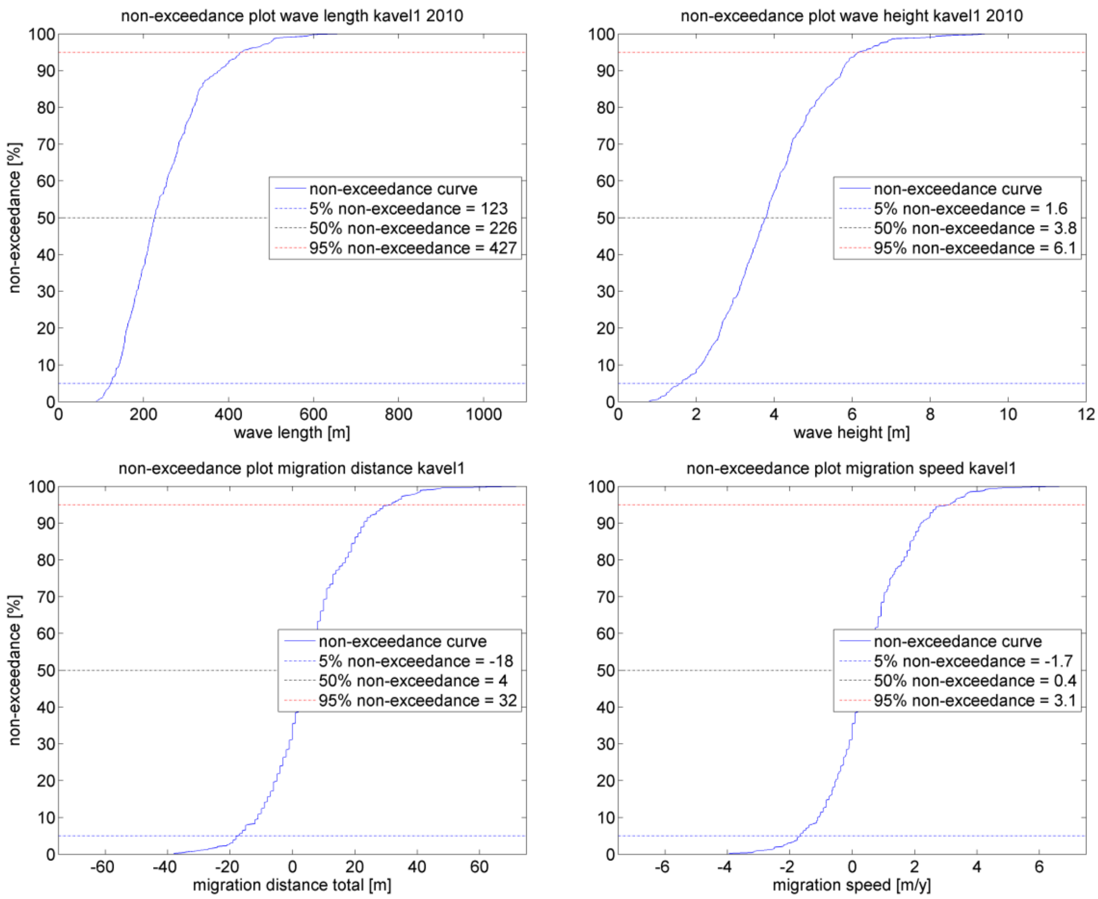

Figure 4.15 Sand wave characteristics of site I

Statistics of sand waves in site II

From Figure 4.11, it becomes clear that site II is divided in three clear parts of alternating sand wave migration direction; the northern top part migrates relatively slowly in the governing south-western direction, the middle part moves relatively fast to the northeast (given that the north-eastern-directed migration is generally slower than the south-western-directed migration) and the southern part moves fast to the southwest. In this last part, located on the crest of an underlying sandbank, the largest migration rates are found of the entire BWFZ. The sand wave characteristics of the site are displayed below in Table 4.4 and Figure 4.16.

Parameter	**5% non-exceedance**	**50% non-exceedance**	**95% non-exceedance**
Migration distance [m]	-21	6	45
Migration speed [m/yr]	-1.9	0.6	4.2
Wave length [m]	102	244	532
Wave height [m]	1.4	3.5	6.7

Table 4.4 Sand wave characteristics of site II (migration distance/speed: negative values towards northeast, positive values towards southwest)

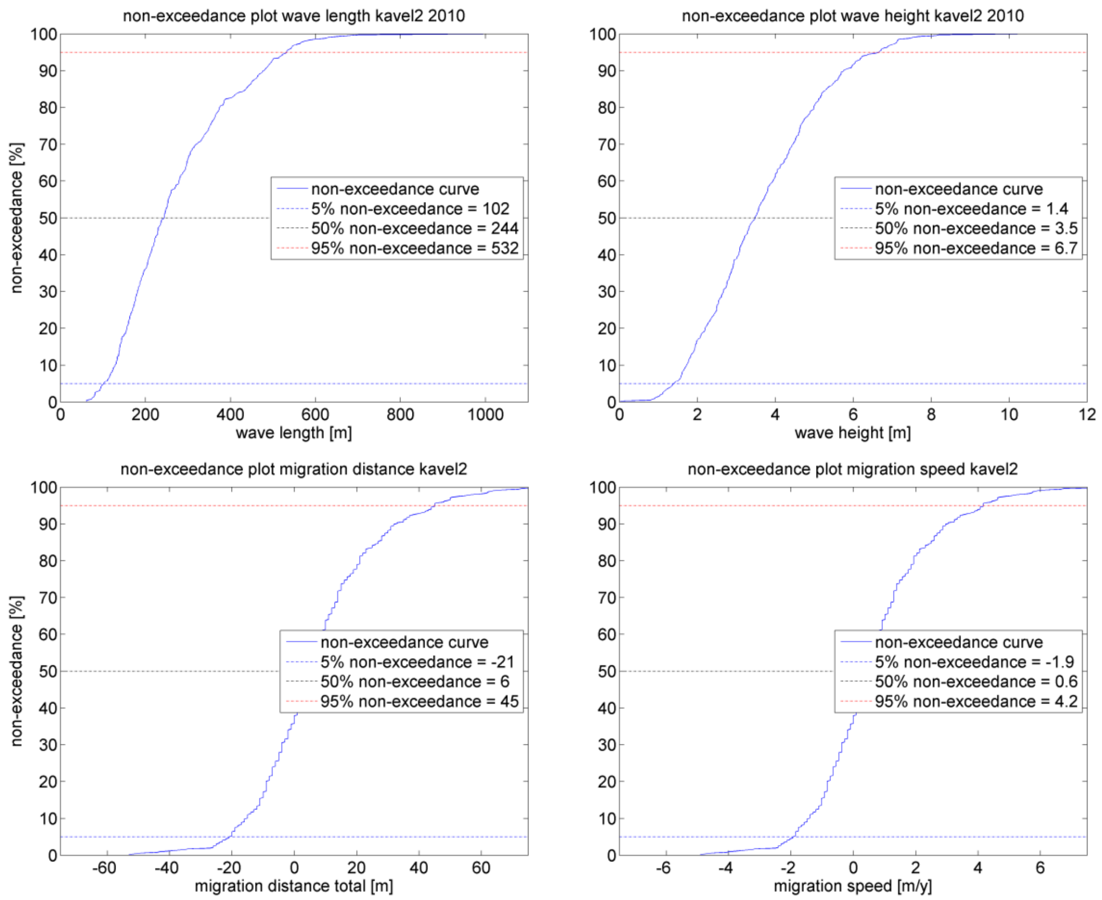

Figure 4.16 Sand wave characteristics of site II

Statistics of sand waves in site III

Figure 4.11 shows that in site III, sand waves are migrating in both south-western and north-eastern direction. The sand waves migrating towards the northeast are mainly found in the bottom right corner of the site. Migration speeds are the largest in the top right corner of the site, in which the sand waves are moving in the governing south-western direction. An interesting point is found in the middle of the site, where the south-western and north-eastern directed sand waves meet at the top of an underlying sandbank. The sand wave characteristics of the site are displayed below in Table 4.5 and Figure 4.17.

Parameter	5% non-exceedance	50% non-exceedance	95% non-exceedance
Migration distance [m]	-17	6	31
Migration speed [m/yr]	-1.7	0.6	3.2
Wave length [m]	115	221	475
Wave height [m]	1.5	3.3	6.4

Table 4.5 Sand wave characteristics of site III (migration distance/speed: negative values towards northeast, positive values towards southwest)

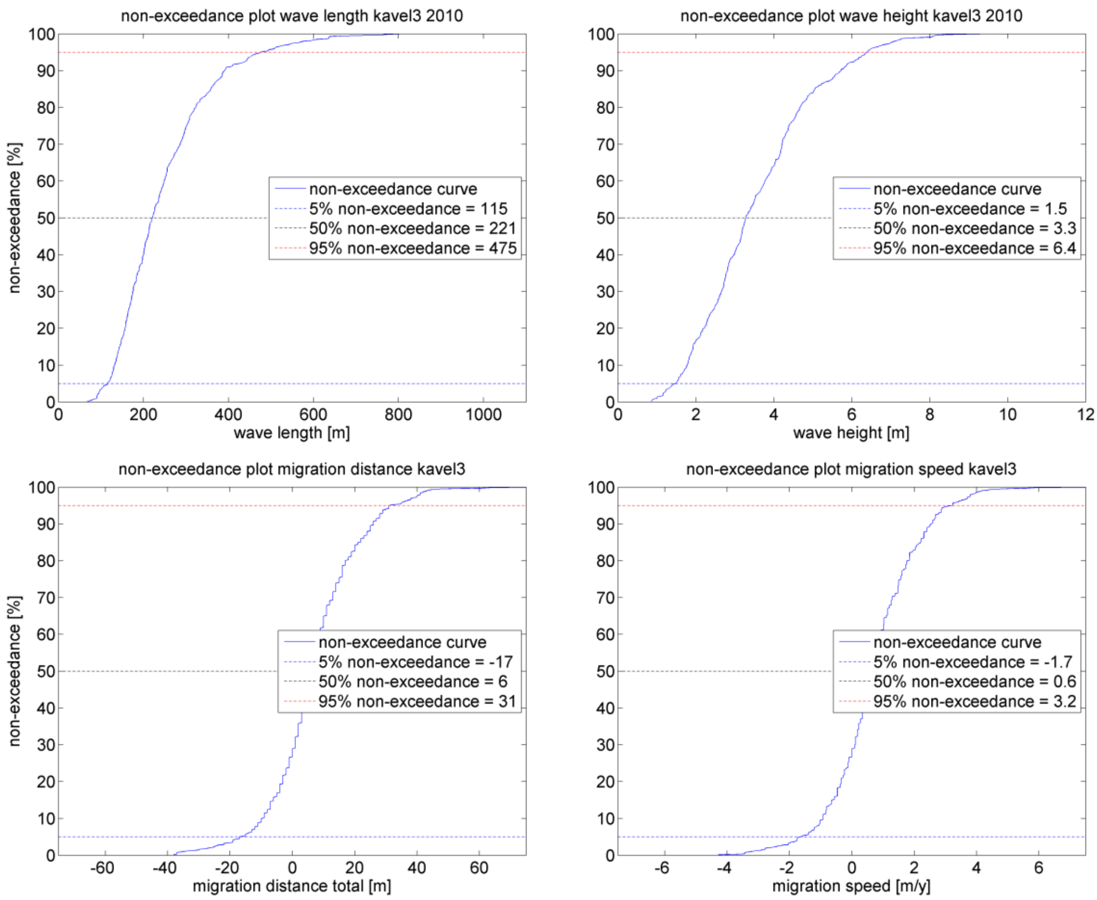

Figure 4.17 Sand wave characteristics of site III

Statistics of sand waves in site IV

Figure 4.11 shows that in site IV, almost all sand waves migrate to the governing south-western direction. Given the underlying static bathymetry, the highest migration velocities are found on the crest of the sandbank in the south-western corner of the site. The sand wave characteristics of the site are displayed below in Table 4.6 and Figure 4.18.

Parameter	**5% non-exceedance**	**50% non-exceedance**	**95% non-exceedance**
Migration distance [m]	-10	5	24
Migration speed [m/yr]	-1.2	0.6	2.8
Wave length [m]	108	231	523
Wave height [m]	1.5	4.2	7.7

Table 4.6 Sand wave characteristics of site IV (migration distance/speed: negative values towards northeast, positive values towards southwest)

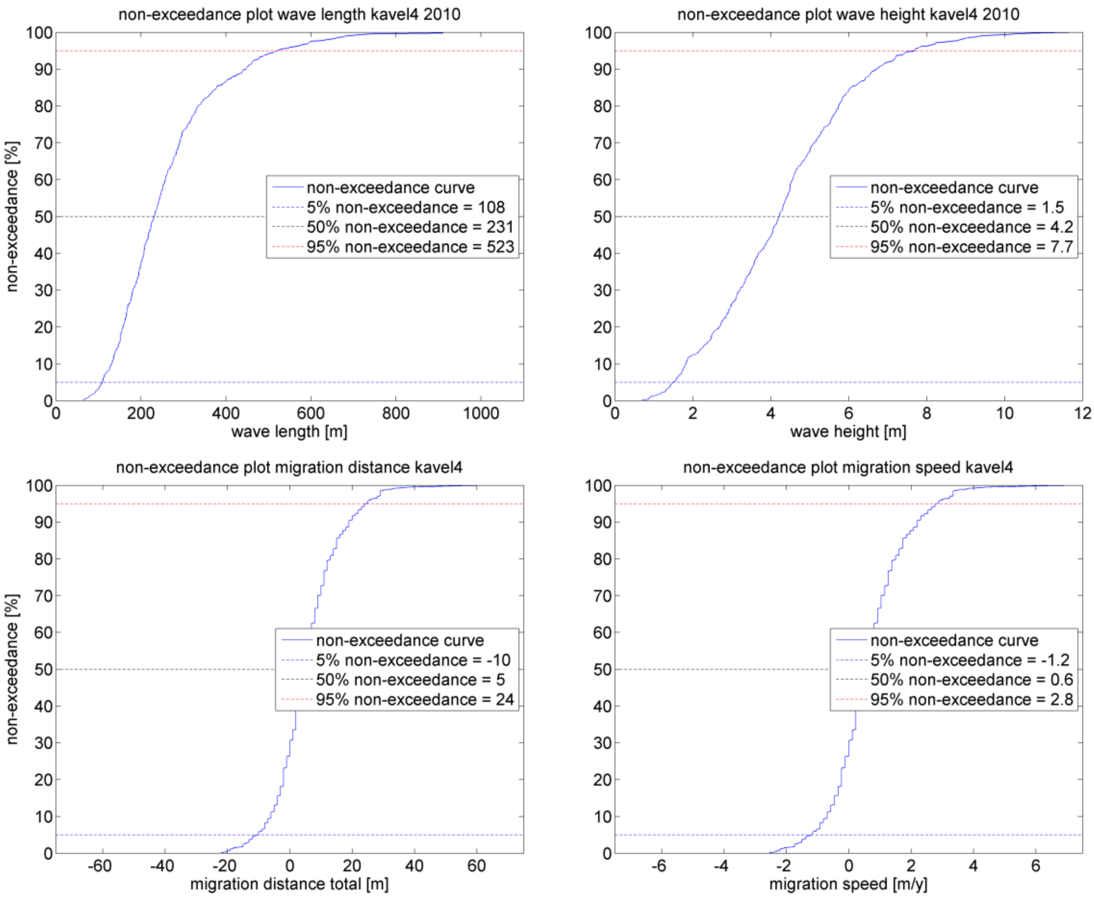

Figure 4.18 Sand wave characteristics of site IV

5 Conclusions and recommendations

5.1 Conclusions

The bathymetry in the Borssele Wind Farm Zone (BWFZ) consists of a complex system of shore-parallel sandbanks covered with shore-perpendicular sand waves. The sandbanks are considered to be static over the lifetime of the wind parks to be developed in the area. This conclusion will be checked in the second phase of this project, when new bathymetry data become available. The sand waves overlying the sandbanks are mobile, have a typical average length of 230 meters, height of 4 meters and typical migration speeds are in the order of -1.7m/yr (north-eastern direction) to 3.2 m/yr (governing south-western direction).

The sand waves in the BWFZ show a complex behaviour, with varying (and in some locations opposing) migration directions. This can result in the extinction of existing sand waves and the generation of new waves in relatively short time periods (less than ten years), which complicates the analysis of the morphodynamics.

The BWFZ is subdivided into 4 sites for offshore wind farm development. Table 5.1 summarizes the overall BWFZ and local sand wave characteristics per site. Although some variation in sand wave dimensions and migration speeds is observed, it is clear that significant morphodynamic activity is present in the entire BWFZ.

Area	Wave height 50% non-exceedance [m]	Wave length 50% non-exceedance [m]	Migration speed 5% non-exceedance [m/yr]	Migration speed 95% non-exceedance [m/yr]
BWFZ	3.7	234	-1.7	3.2
Site I	3.8	226	-1.7	3.1
Site II	3.5	244	-1.9	4.2
Site III	3.3	221	-1.7	3.2
Site IV	4.2	231	-1.2	2.8

Table 5.1 Median sand wave dimensions of the entire BWFZ and per individual plot and lower (5%) and upper (95%) estimates for the migration speeds (negative values towards northeast, positive towards southwest)

For design purposes a Reference SeaBed Level (RSBL) and a Maximum SeaBed Level (MSBL) were obtained, which indicate, respectively, the potentially lowest and highest seabed levels. After splitting the entire bathymetry into a static part (containing the underlying bathymetry including sandbanks) and a dynamic part (containing the sand wave field), the outer envelope of the dynamic sand wave field has been determined. The downward (negative) envelope was subtracted from the static bathymetry to obtain the RSBL; the upward (positive) envelope was added to the static bathymetry to obtain the MSBL.

The resulting RSBL shows a bathymetric shape similar to the existing static part of the bathymetry, but typically about (maximum) 4 meters lower. Comparison of the RSBL with the most recent bathymetry from 2010 shows a predicted maximum seabed level lowering of approximately 8m. As expected, the largest lowering is found at the location of the existing sand wave crests, while minimal lowering is found at the location of the sand wave troughs. The most significant seabed level lowering is observed in site IV, which is directly related to the relatively larger sand wave heights found in this site (associated with the larger water depths).

The MSBL shows seabed levels up to over 5m higher than the static part of the bathymetry. Also here the largest potential rise of the seabed level is found in site IV, where the sand wave height is largest. Note that the seabed close to the foundations will most likely not rise significantly, because local scour will prevent this. Buried electricity cables that cause no flow disturbance themselves will obviously not have this “beneficial” scour effect and therefore will experience a rising seabed if a sand wave crest passes over. This might be relevant for the maximum cable temperature (“thermal bottleneck effect”).

In the second phase of this project, when new bathymetry data become available, the sand wave statistics will be used to define the RSBL and MSBL more accurately and thus less conservatively.

5.2 Recommendations

5.2.1 Numerical modelling of hydrodynamics

In order to fully understand the morphodynamic activity in the area and to be able to generate more accurate predictions, it is recommended setting up a hydrodynamic model of the area. Sand wave behaviour is governed by the currents (most prominently by asymmetries in a tidal cycle). By numerical modelling of at least one representative spring-neap cycle at a high spatial and temporal resolution a valuable dataset is generated. The results should be outputted in map-fields of the Borssele wind farm zone, with a temporal resolution of approximately 10 minutes and a spatial resolution of approximately 50 metres. These results can be used to accurately determine relatively small net changes in sediment transport rates and directions over the sandbanks, responsible for the variation in sand wave characteristics. Please note that these model results are not only useful for the second phase of the current study, but also for future in-depth studies (e.g. regarding scour) at the locations of the turbine foundations and electricity cables. Note that it is not proposed to use this model for morphological simulations: for such a large area such simulations would be very computationally expensive (too time-consuming).

5.2.2 Geophysical investigation

Currently, no information is available on the location of non-erodible layers close to the surface. Such layers will limit the maximum seabed lowering to the top of that layer. Information on these layers can be used to improve the accuracy of the predictions, which will lead to a less conservative reference seabed level. It is therefore recommended to expand the current knowledge of the area by means of an additional geophysical investigation.

5.3 Recommendations regarding new field investigations

The main recommendation with regard to new field investigation for the purpose of improving the accuracy of predicted morphodynamic bed level changes is to execute a high resolution bathymetrical survey with a multibeam echosounder (MBES). The current analysis is based on two bathymetries, of which the older one (2000) is of suboptimal quality. This bathymetry was obtained by combining surveys from several years into a single dataset (1999/2000/2001), with interpolation errors and temporal inconsistencies as a consequence. A new, high resolution, continuous bathymetry will be used to update the calculations, validate the assumptions and conclusions from this study, and improve the accuracy of the predictions.

The new survey should have a resolution of at least 5m and should extend at least 500m beyond the boundary of the BWFZ (preferably even more, up to 1km). That way, the bathymetry can artificially be migrated to predict the future seabed level variations. It is also advised to store the raw MBES-data for later reprocessing at a higher resolution. For the current purposes, a 5m grid resolution should be sufficient, but once the exact pile locations and cable trajectories are known, the survey could also be used for more detailed investigations around the pile foundations for which typically a 0.2m resolution is needed.

The field investigation is also recommended to include seismic reflection surveys, core penetration tests (CPTs) and boreholes. A seismic reflection survey can be used to determine the presence of soft layers and identify the presence of in-filled channels. The seismic reflection survey should have sufficient penetration depth (at least 40m below the seabed). The results can be used to identify locations at which CPTs and boreholes should be taken. Based on the size of the Borssele area it is estimated that, as a minimum requirement, in the order of 40-50 CPTs should be executed and in the order of 10-20 boreholes. These should both be taken till at least 50m below seabed.

The geophysical surveys provide information on the stratigraphy in the area. This can be used to identify cohesive layers close to the surface (which is of importance of future seabed level variations and local scour) and areas with consolidated sediments (which impact the driveability of wind turbine foundations). Eventually, a CPT and borehole is required at each foundation location, for this it is recommended to employ piezocone penetration tests.

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