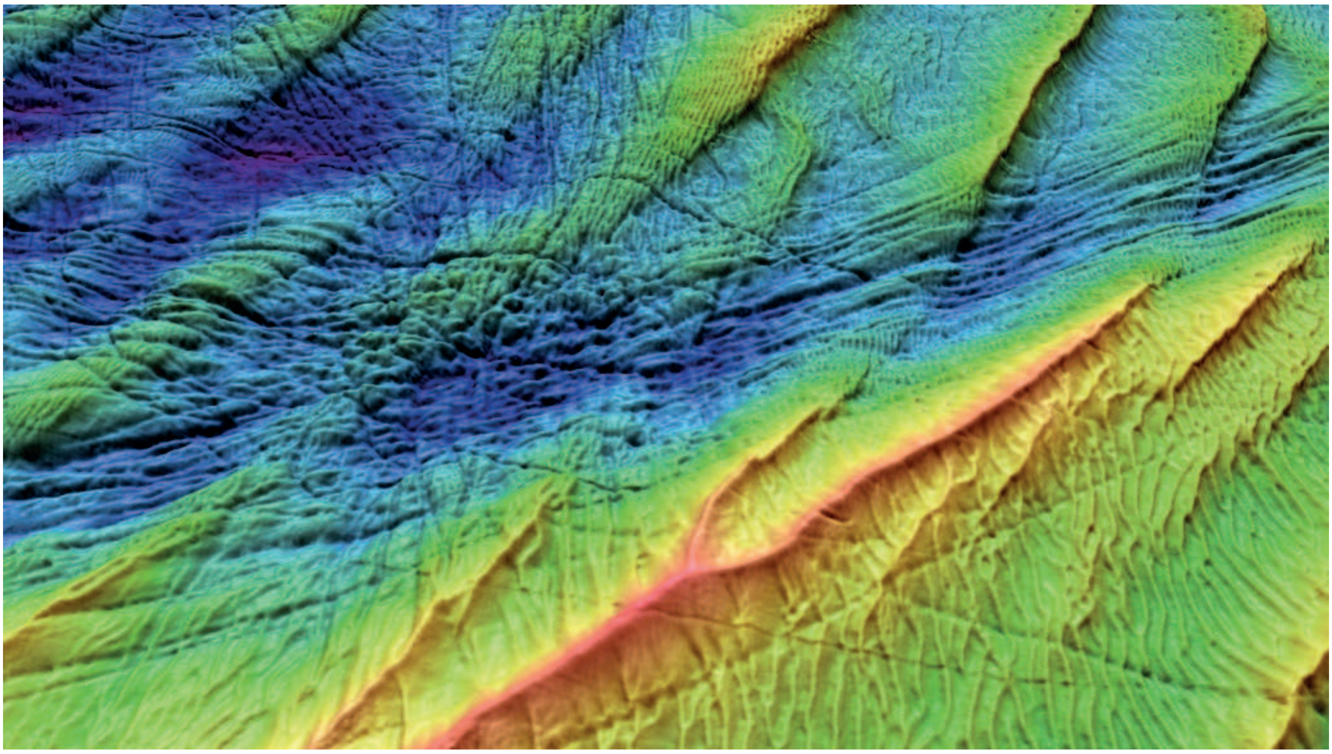
economie

'Which future for the sand extraction in the Belgian part of the North Sea?'



Study day

20 October 2014

Belgium Pier - Blankenberge

Editors: Lies De Mol and Helga Vandenreyken

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Content

Synthesis of the monitoring of the aggregate extraction on the Belgian Continental Shelf from 2011 till 2014

Degrendele Koen[*1], *Roche Marc*[1], *De Mol Lies*[1], *Schotte Patrik*[1], *Vandenreyken Helga*[1]

[*]*Presenting author: koen.degrendele@economie.fgov.be*

[1] *FPS Economy, S.M.E.s, Self-employed and Energy, Directorate-General Quality and Safety, Continental Shelf Service, Koning Albert II-laan 16, 1000 Brussel, Belgium*

Introduction

This contribution presents a summary of the essential facts concerning the control and monitoring of the sand extraction in the Belgian part of the North Sea and the impact of this dredging on the seabed bathymetry, morphology and sedimentary nature, observed since the previous study day in October 2011. Due to the divers target audience of this report – dredging industry, marine scientists and engineers, marine environment managers, economists, etc. – the subject is described as factual and concise as possible. More in-depth information can be found in the other publications from the Continental Shelf Service and the listed references.

In the first part of the contribution an overview is given of the events from the last three years having an important impact on the monitoring program, be it legislative or technical, followed by a summary of the monitoring activities from the Continental Shelf Service from 2011 till present. The second part provides a summary of the statistics of the extraction and monitoring data acquired between 2011 and 2014. The results are combined with the previous data and the conclusions based on the analysis of the entire datasets are compared with earlier findings. This approach allows an extension of our spatial and temporal point of view and leads to more robust and pragmatic conclusions about the real impact of the sand extraction on the marine environment.

Overview of the period 2011-2014

Regulation related to monitoring

Two new regulations have an impact on the monitoring program from the Continental Shelf Service: the Royal Decrees of March 20th 2014 and April 19th 2014. These new legislations change the areas where aggregate extraction is allowed (figure 1). Control zone 2 is subdivided in three sectors corresponding with the three sandbanks in the zone: Kwintebank (2KB), Buiten Ratel (2BR) and Oostdyck (2OD). The areas in between the banks are now outside the control zone and thus closed for extraction. This large diminution in exploitable surface is the consequence of the delineation of the Habitat area, which encompasses the entire control zone 2. Sector 1b of control zone 1, corresponding with the western end of the Gootebank, is eliminated, limiting control zone 1 to the western end of the Thorntonbank (sector 1a). Furthermore, the extractable volume in control zone 2 is reduced by 17.000 m^3 each year (1% of the extractable volume in 2014), again a consequence of the Habitat area.

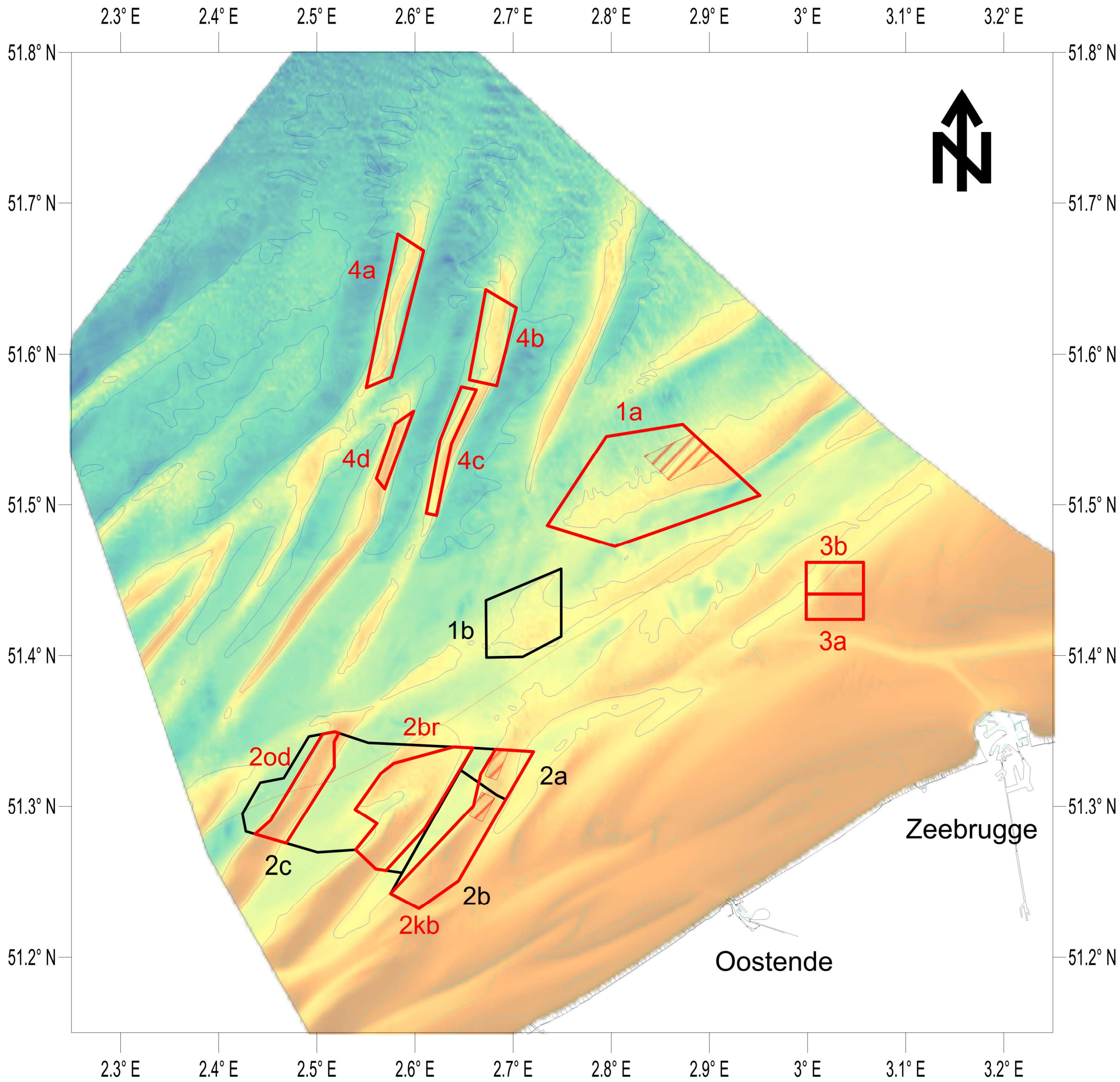

Figure 1: Overview of the current extraction control zones (in red) and former or altered control zones (in black). The hatched areas in red are closed sectors inside the larger control zones.

Technological development

Since 1996, Electronic Monitoring Systems (EMS) are used to control the extraction activities on the Belgian part of the North Sea. It is the responsibility of the Management Unit of the North Sea Mathematical Models (MUMM) to manage the EMS, currently installed aboard 15 dredging vessels and to process the data recorded, on behalf of the FPS Economy. On the basis of the recorded data, it is possible to verify whether the conditions of the concessions are respected. In 2013 the Electronic Monitoring System received an important upgrade (Van den Branden et al., this volume). The new system makes it possible to analyse the data more quickly and frequently, resulting in a closer control on the extraction activity itself.

The monitoring of the impact of the extraction is studied with the EM3002D multibeam echosounder (MBES) from the Continental Shelf Service, installed onboard the research vessel Belgica. In 2009 and 2010 accuracy measurements confirmed the high quality standard (IHO Special Order) of the bathymetric measurements with the EM3002D (Roche and Degrendele, 2011, Roche et al., 2011). To guaranty the stability of the bathymetric system, this evaluation is repeated as often as possible. In 2011, 2012 and 2014 additional measurements in the Vandammesluis (figure 2) were carried out, and the results were compared with previous surveys and the known depths inside the lock. Table 1 summarizes the results of the comparison between the surveys from 2011 till 2014 and the reference depth. Furthermore, longitudinal profiles in the lock are compared with the digitized plan (figure 3). Overall the results remain stable, with the exception of the most recent survey, which shows a shallower profile. An average difference of 8 cm with the reference is observed. This latest survey took place shortly after the installation of a new positioning system aboard RV Belgica and a subsequent new measurement of the geometry of the reference points on the ship. A new survey is planned at the end of 2014 to confirm or correct this result and if necessary to adjust the geometrical parameters in the calculation.

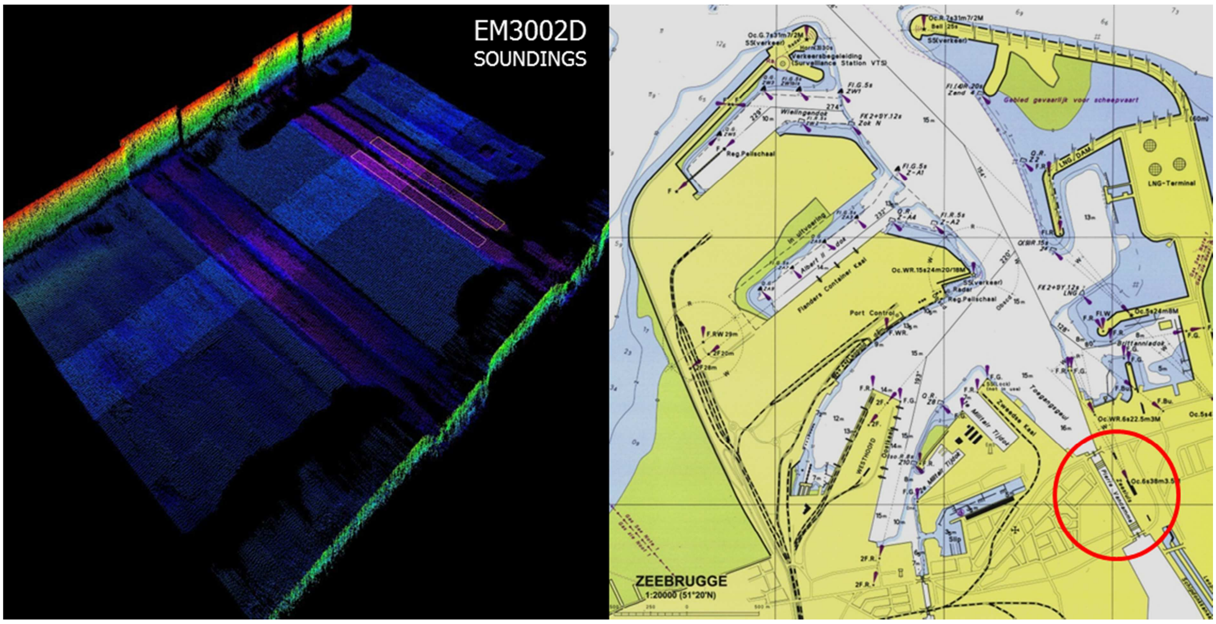

Figure 2: MBES recording of the Vandammesluis with the areas where soundings are compared – location of the Vandammesluis in Zeebrugge (encircled in red).

Belgica EM3002D 09/02/2011					Reference
area	n	mean TAW (m)	stdv (m)	diff (m)	TAW
detail 1	6050	16.54	0.10	-0.03	16.57
detail 2	6060	16.54	0.09	-0.03	16.57
detail 5	52520	15.12	0.05	0.01	15.11
Belgica EM3002D 18/09/2012					Reference
area	n	mean TAW (m)	stdv (m)	diff (m)	TAW
detail 1	6924	16.57	0.11	0.00	16.57
detail 2	6471	16.56	0.13	-0.01	16.57
detail 5	44947	15.13	0.09	0.02	15.11
Belgica EM3002D 28/02/2014					Reference
area	n	mean TAW (m)	stdv (m)	diff (m)	TAW
detail 1	1854	16.47	0.04	-0.10	16.57
detail 2	2343	16.47	0.05	-0.10	16.57
detail 5	25262	15.02	0.05	-0.09	15.11

Table 1: Comparison between the measured depths referenced to TAW in three areas in the lock and the known depths (number of points, mean, standard deviation and difference with the reference for each survey and area).

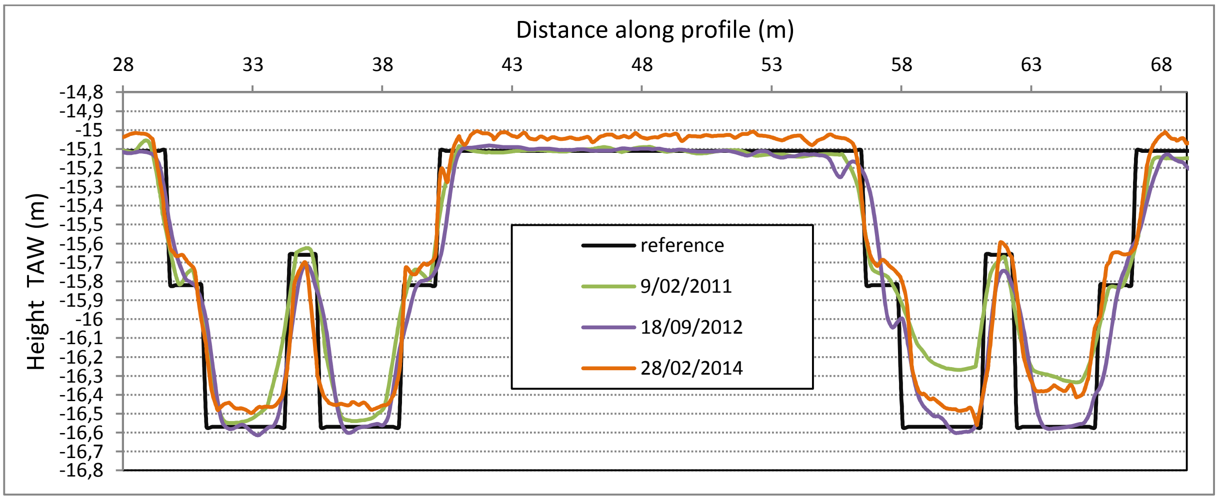

Figure 3: Profile of the quality measurements in 2011, 2012 and 2014 along the Vandammesluis, compared to the profile based on the official plans of the lock.

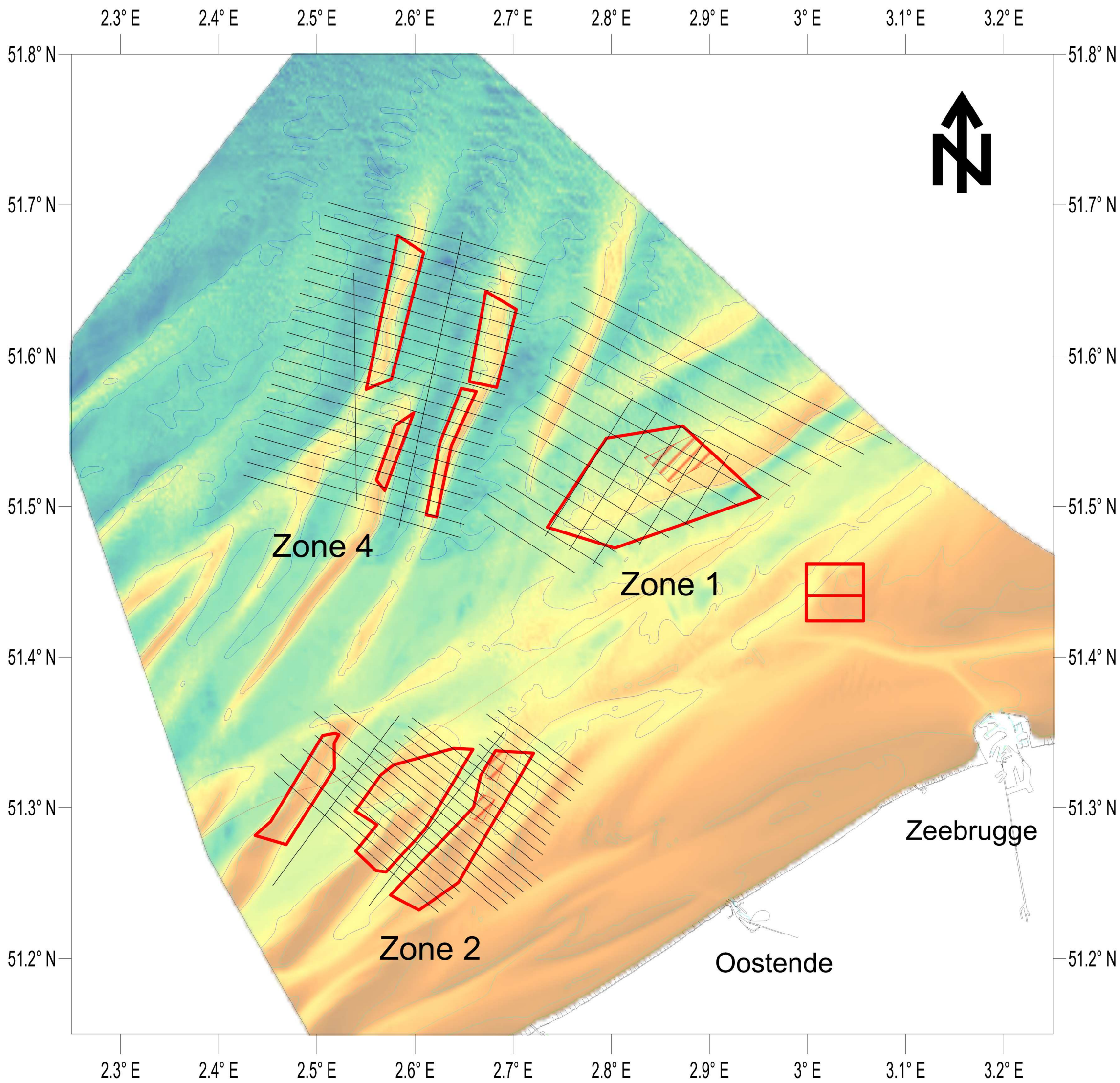

Figure 4: Location of the DECCA lines (in black) across the control zones (in red).

Monitoring activities

The impact of the extraction on the seafloor is studied on two different levels (Roche et al., 2011). Starting in 2007, MBES surveying has been performed along DECCA lines (figure 4) across the Flemish banks in zone 2 (Kwintebank, Buiten Ratel and Oostdyck) and across the Thorntonbank in zone 1. These extensive surveys are repeated yearly in order to evaluate the global evolution of the sandbanks. Since 2011, control zone 4 is studied in the same way. This time series makes it possible to study the differences in evolution between extracted and non-extracted areas and provides a global view on the impact of sand extraction on the seabed morphology and sediments.

Secondly, a number of smaller areas are surveyed more frequently. The delimitation of these monitoring areas is based on the monitoring of the extraction activities with the EMS: they coincide with the most extracted areas at a given time. These zones are studied in detail and provide a good idea of the local impact of the most intense extraction on the seafloor. Based on the recent cartography of the EMS data, a couple of new monitoring areas have been recently defined: HBMC in 2012 and TBMAB in 2013, corresponding with the shift of the most dense extraction activities to these areas. Figure 5 shows their location, together with the earlier defined and regularly surveyed monitoring areas. Note that the areas BRMB and ODMA are now partly outside the new limits of control zone 2, which will result in a new monitoring strategy for these areas.

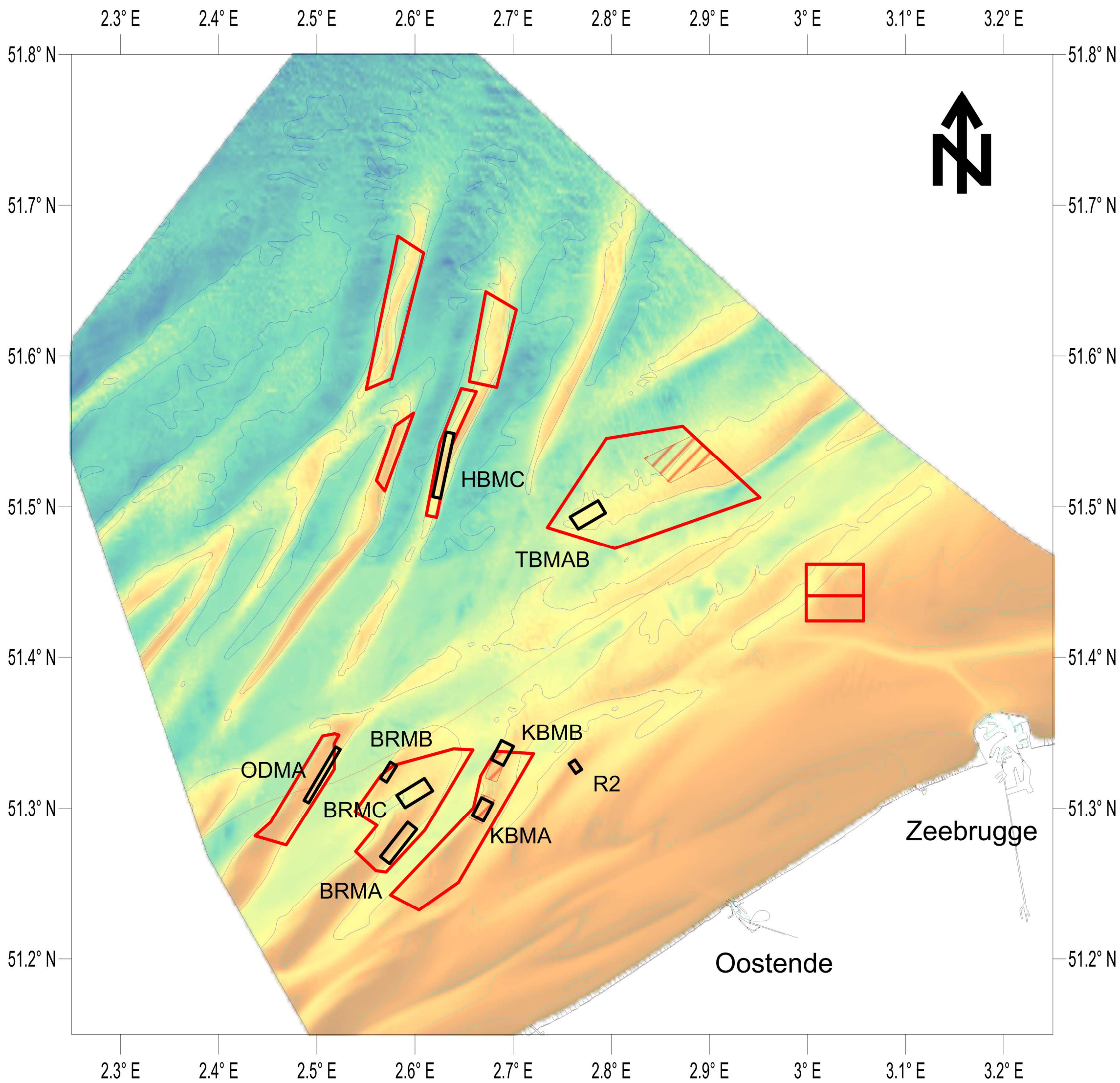

Figure 5: Location of the monitoring areas (in black), in and outside the control zones (in red).

As stated before, the DECCA lines are surveyed only once a year. A more frequent monitoring would be too time-consuming. The frequency of the surveys on the monitoring areas varies and depends on the extraction density. The areas with currently the most extraction and subsequently the highest expected impact on the seabed are monitored more frequent. As figure 6 illustrates, BRMC, which is the area with the most extraction in zone 2, was surveyed 10 times in a three year period, while the areas where the extraction limit of 5 m was exceeded and that have been closed previously (KBMA and KBMB) or that are outside the control zone (R2), were only surveyed half that much. The number of monitoring areas keeps increasing (TBMAB and HBMC) due to changes in extraction patterns and the start of extraction by the Flemish Government in zone 4 (see below).

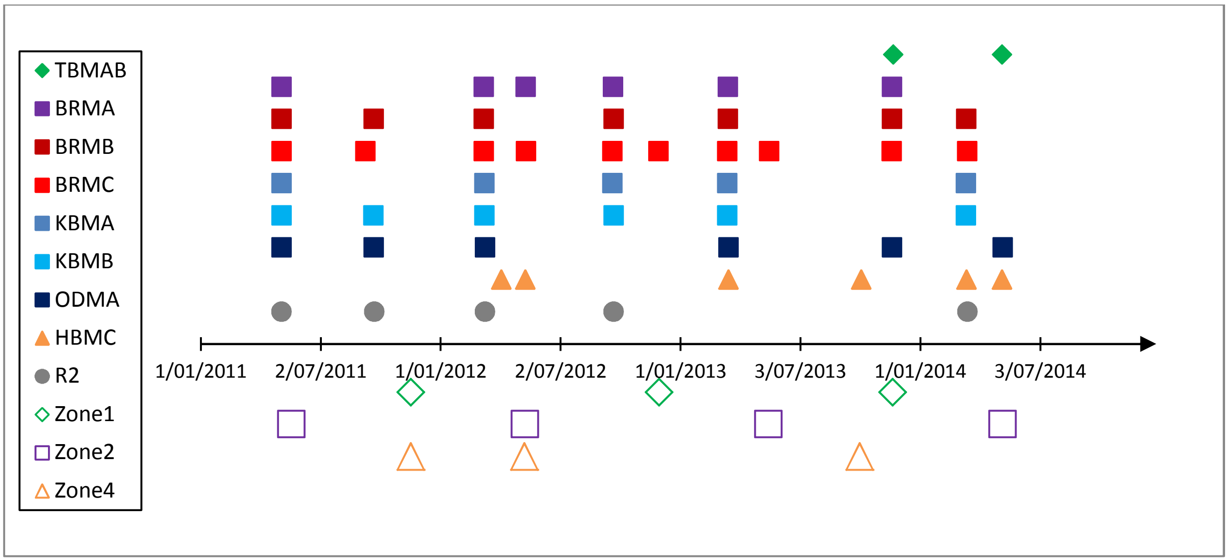

Figure 6: Time line showing the monitoring surveys since 2011. The monitoring areas are displayed above the timeline, the monitoring along DECCA lines beneath.

Monitoring results

Extraction from 2011 till 2014

The EMS is a fundamental tool for the control of the extraction as it allows to calculate for any surface and any time interval the extracted volume. Using the data collected with EMS, the density and geographical pattern of the extraction activities can be mapped and analyzed. Here, an overview of the evolution of the extraction during the period 2011 – 2013 is given. The EMS data for 2014 is not yet complete and will not be included and discussed in this report. The maps of the extracted volumes represent a 100x100 m grid covering the entire Belgian part of the North Sea. The total volume extracted in each grid cell is computed from the EMS data.

The grid of the cumulative volumes from 2003 to 2010 and the successive annual maps (figure 7 till 10) offer a clear view of the spatial evolution of the extraction. Inside zone 2 the extraction is still concentrated on the central part of the Buiten Ratel (monitoring area BRMC), while only small volumes are extracted on the Kwintebank and Oostdyck. The volume extracted on the Thorntonbank in zone 1 remains stable, making this at present, together with the Buiten Ratel and the Oosthinder, the most exploited area. A new monitoring area in zone 1, TBMAB was created and is now measured regularly to supervise the local impact. The extraction in zone 4 started in 2012 and focusses on the southern part of the Oosthinder, in sector 4c. Subsequently the monitoring zone HBMC was created in 2012 and is frequently surveyed to establish the impact from the intensive extraction activities. Another clear observation is the extraction in 2011 and 2013 in zone 3. Figure 11 shows a map of the total volumes from 2003 till the end of 2013, and shows the location of the three currently most supervised monitoring areas, mentioned above.

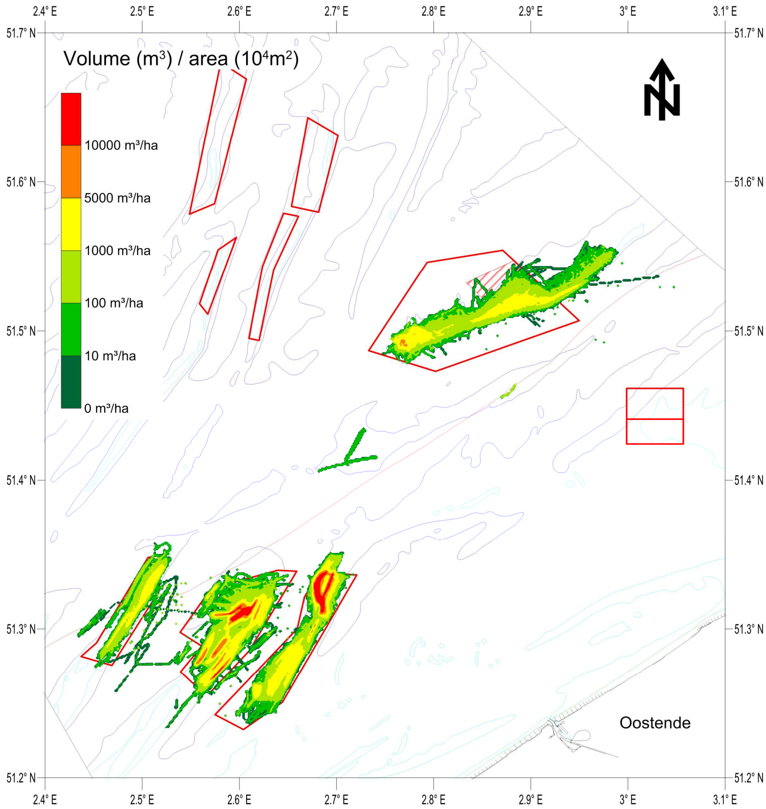

Figure 7: Extraction density in volume/area ($m^3/10^4m^2$ or m^3/ha) from 2003 till 2010.

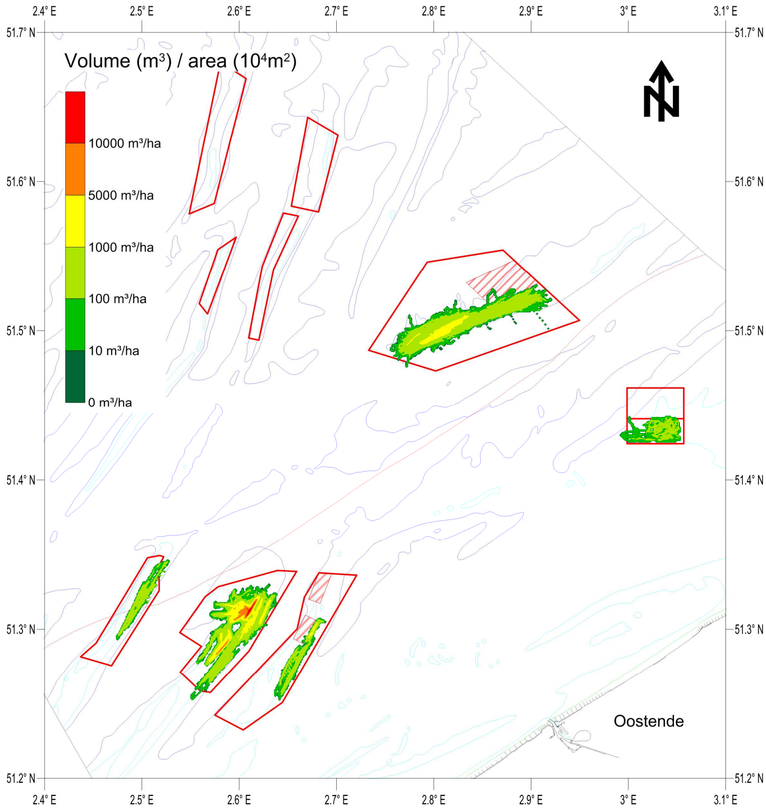

Figure 8: Extraction density in volume/area ($m^3/10^4m^2$ or m^3/ha) in 2011.

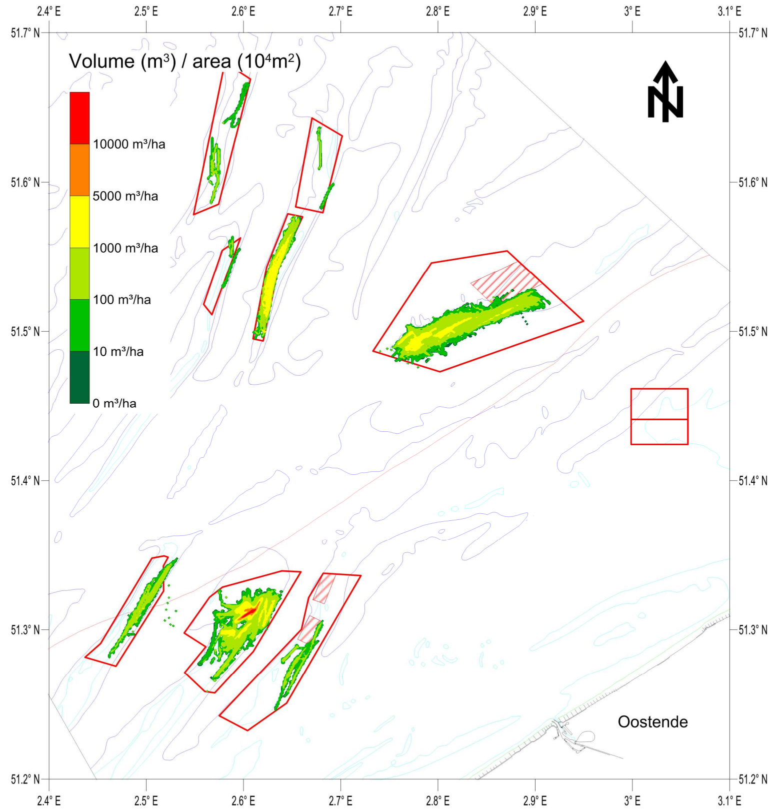

Figure 9: Extraction density in volume/area ($m^3/10^4m^2$ or m^3/ha) in 2012.

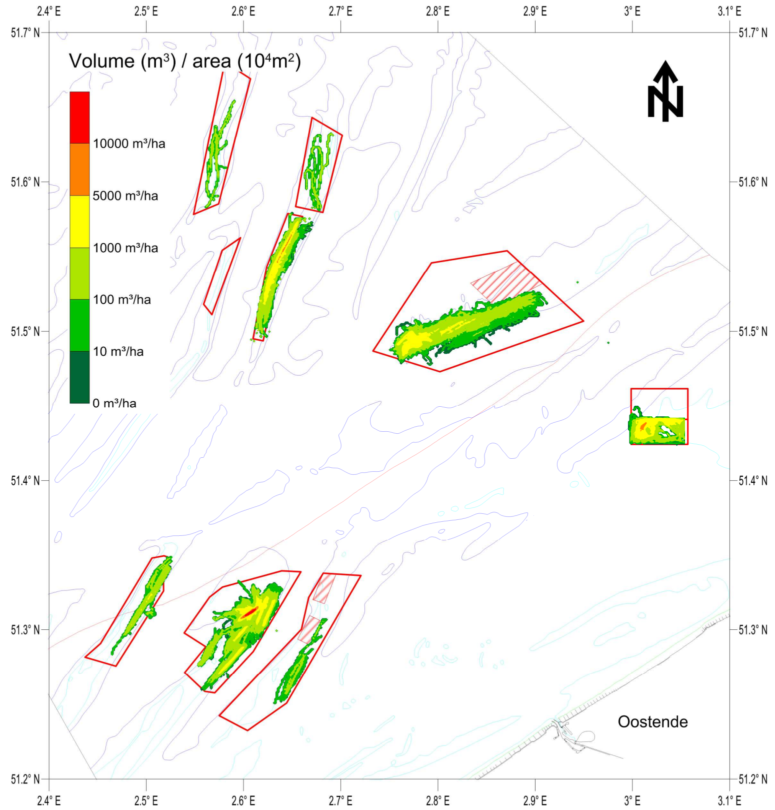

Figure 10: Extraction density in volume/area ($m^3/10^4m^2$ or m^3/ha) in 2013.

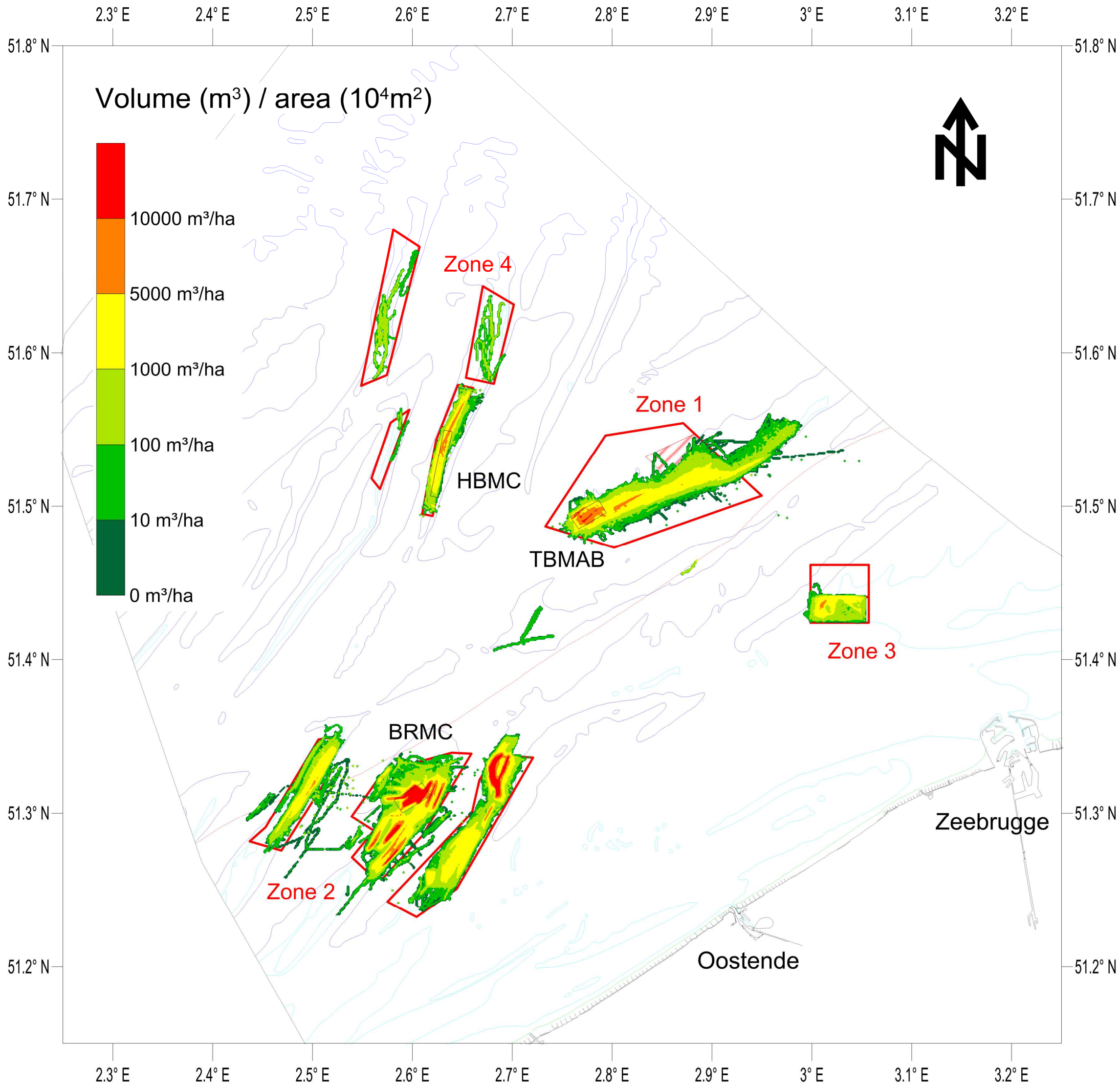

Figure 11: Extraction density in volume/area ($m^3/10^4m^2$ or m^3/ha) from 2003 till 2013 with the most extracted monitoring areas (in black) inside each control zone (in red).

Evolution and impact of the extraction

This report only focusses on the monitoring of the impact of the extraction on the bathymetry, morphology and available sediments, and the physical consequences of the extraction. The ecological impact is studied in depth by the Flemish Institute for Agricultural and Fisheries Research (ILVO) (De Backer et al., this volume). An integrated monitoring of sediment processes focused on zone 4c is organized by OD Nature (Van Lancker et al., this volume). The part of the monitoring program which studies the physical impact is mainly based on the acoustic cartography of the seabed. All data since 2009 were acquired with the EM3002D multibeam echosounder onboard RV Belgica. After the processing of the data (position, tide and draught correction and data cleaning) the soundings were modelled with a resolution, depending of the scale of the investigated area and the density of the available data. To be able to compare with data from before 2009, recorded with an EM1002 multibeam echosounder, these were converted towards the EM3002D reference level (Roche et al., 2011). In the analysis the resulting grids are compared and subtracted to evaluate the bathymetric evolution and the available sediment. A positive difference corresponds with accretion while a negative difference indicates erosion.

The results are discussed for each control zone separately, with the exception of zone 3, where no monitoring is performed up till now.

Control Zone 1

The extraction on the Thorntonbank remains fairly stable (figures 8-10). The cartography of the depth changes along the DECCA lines in 2011 (figure 12) shows no area with a distinct higher impact. It needs to be noted that the area with a higher total extracted volume on the western end of the Thorntonbank (visible on the background layer on figure 12) is not covered by the DECCA lines. The alteration of positive and negative values on the bank is mainly the effect of the shift of the sand dunes. In 2013 (figure 13) the situation looks different. The change is overall more negative and the extreme negative values on the bank correlate with the most extracted areas. Since the difference locally exceeds 2 m, a new monitoring was created (TBMAB) which covers the most affected part of the bank.

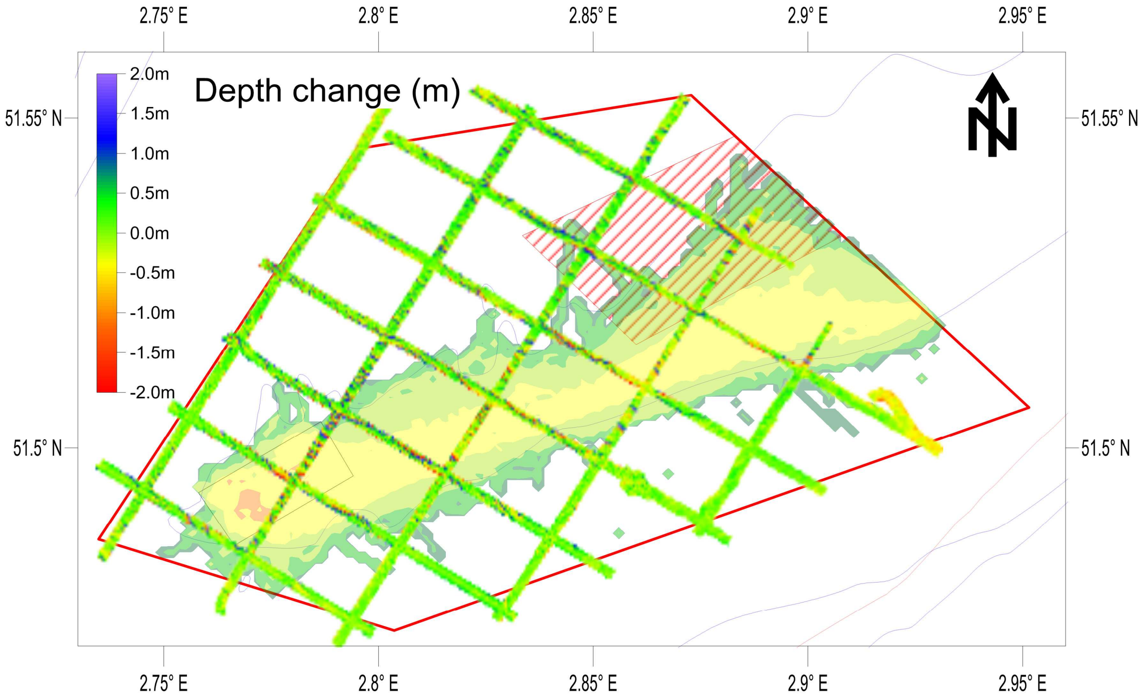

Figure 12: Depth change between the survey along DECCA lines from 17/11/2011 and the reference model. Positive values show an increase in sediment, negative values a decrease. A map showing the extraction density between the survey date and the reference model is used as background.

Both, the last bathymetric survey of TBMAB in 2013 (figure 14) and the difference map between this survey and the reference map for zone 1 from 2003 (figure 15), show a deepening along a corridor with a SW-NE direction. This is also visible on the area to the east of TBMAB, which was mapped during the same RV Belgica measurement campaign.

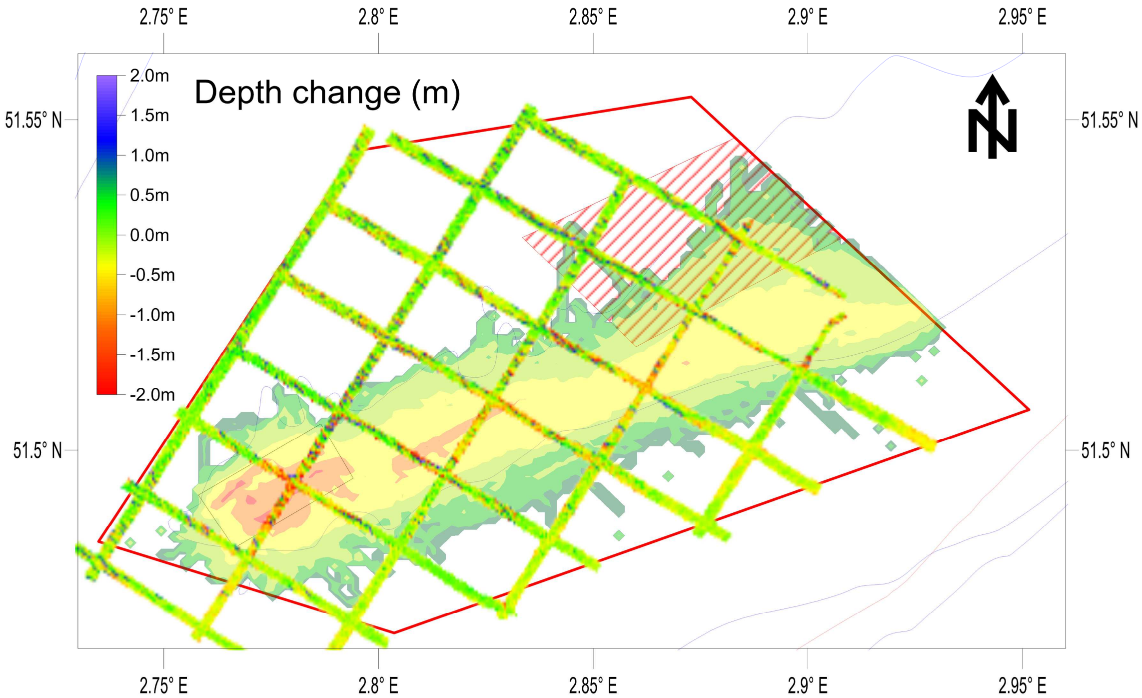

Figure 13: Depth change between the survey along DECCA-lines from 20/11/2013 and the reference model. Positive values show an increase in sediment, negative values a decrease. A map showing the extraction density between the survey date and the reference model is used as background.

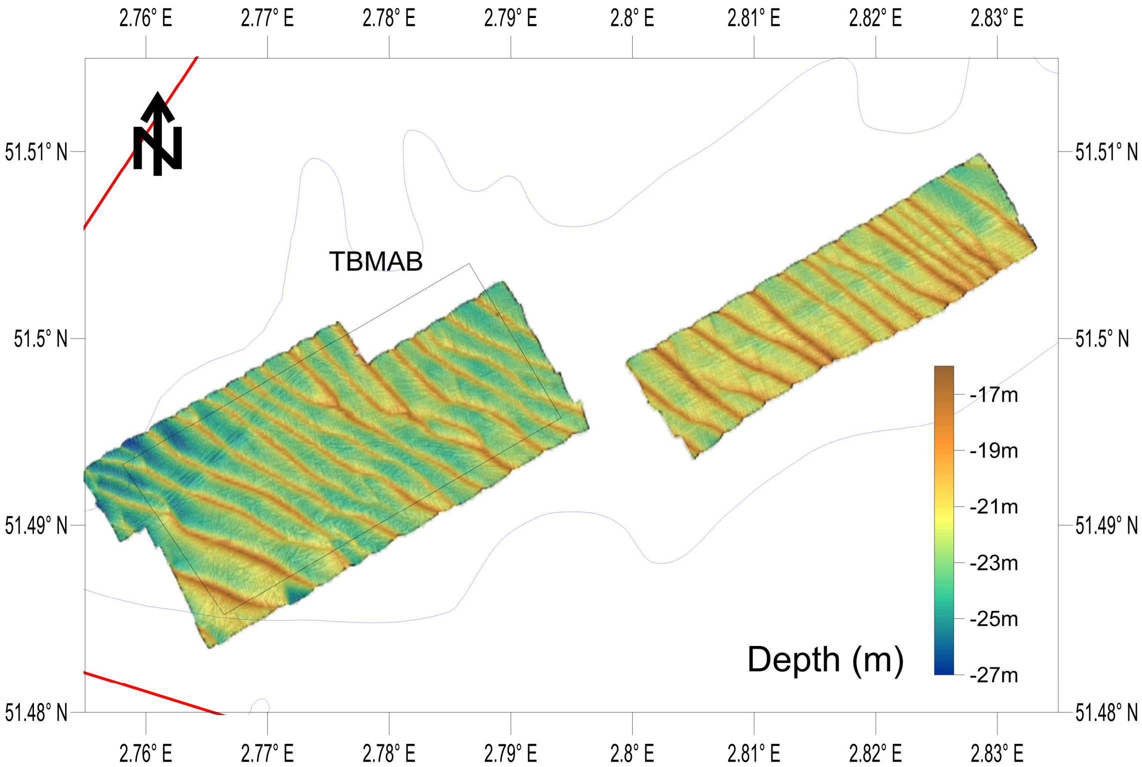

Figure 14: Bathymetry of monitoring area TBMAB, survey 20/11/2013. Depths are referenced to LAT.

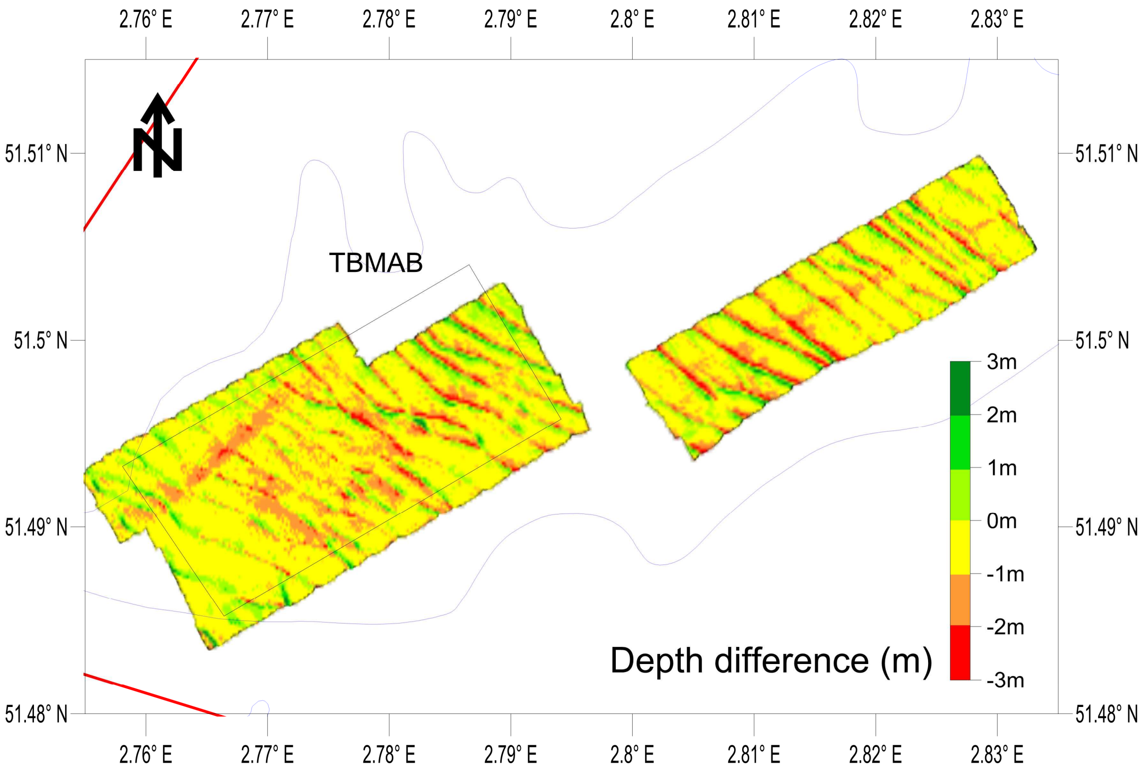

Figure 15: Depth difference between monitoring area TBMAB (survey of 20/11/2013) and the reference model for zone 1. Positive values show an increase in sediment, negative values a decrease.

Control Zone 2

The ongoing monitoring along DECCA lines in zone 2 confirms the results from earlier publications (Degrendele et al., 2010, Roche et al., 2011): The most pronounced differences between the DECCA lines and the 2003 reference model (figure 16) are observed on top of the sandbanks. These high differences are explained by the displacement of the very large dunes covering the sandbanks. The largest decreases of sediment on the Buiten Ratel, Oostdyck and Kwintebank still correspond with the areas with the highest volume of extracted sand. The unexpected negative results in the swale between the Buiten Ratel and Oostdyck fall inside the total combined uncertainty of the reference model and the recent survey (Roche et al., 2011). To avoid the uncertainty due to systematic biases of individual surveys, the quantitative comparison with EMS data, that will be discussed later on, is carried out combining all available data.

To evaluate the local impact six different monitoring areas are surveyed as much as possible (figure 17): the areas on the Kwintebank are formerly heavily extracted but now closed, BRMC is the most extracted since 2008, and the other are on less extracted parts of the Buiten Ratel and Oostdyck. The continuous and frequent measurements provide enough data to allow robust conclusions on the evolution.

The recent results for the “old” monitoring areas KBMA and KBMB (figure 18) seem to confirm the conclusions from the former monitoring reports and articles (Roche et al., 2009, Degrendele et al., 2010). After the closure for extraction the bathymetry and sediments of the areas remain stable, although a slightly negative trend since 2011 is visible. More specific surveys are planned to confirm this trend and verify its significance.

The extraction in ODMA, BRMA and BRMB (figures 19, 20 and 21) varies: from very sporadic in BRMB to recently very high in BRMA and a low constant value for ODMA. This is reflected in the volume decrease for the three zones (figure 22): a small decrease for BRMB and a parallel evolution for BRMA and ODMA.

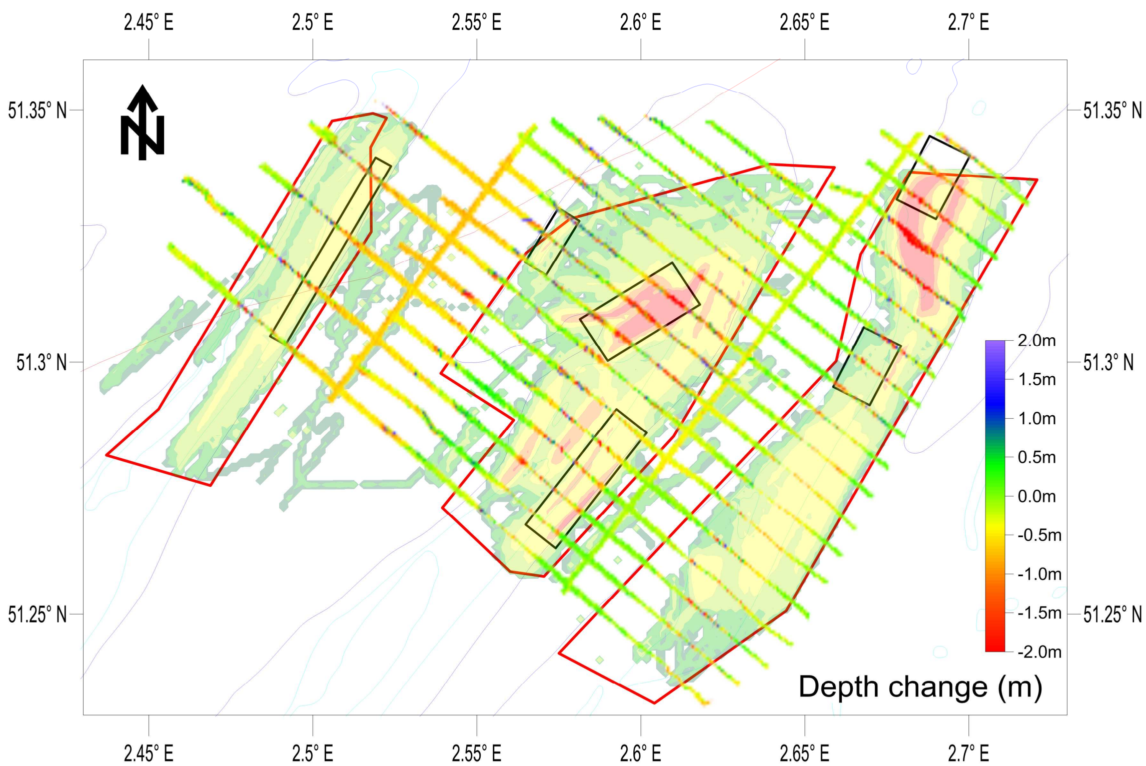

Figure 16: Depth change between the survey along DECCA-lines from 15/05/2013 and the reference model. Positive values show an increase in sediment, negative values a decrease. A map showing the extraction density between the survey date and the reference model is used as background.

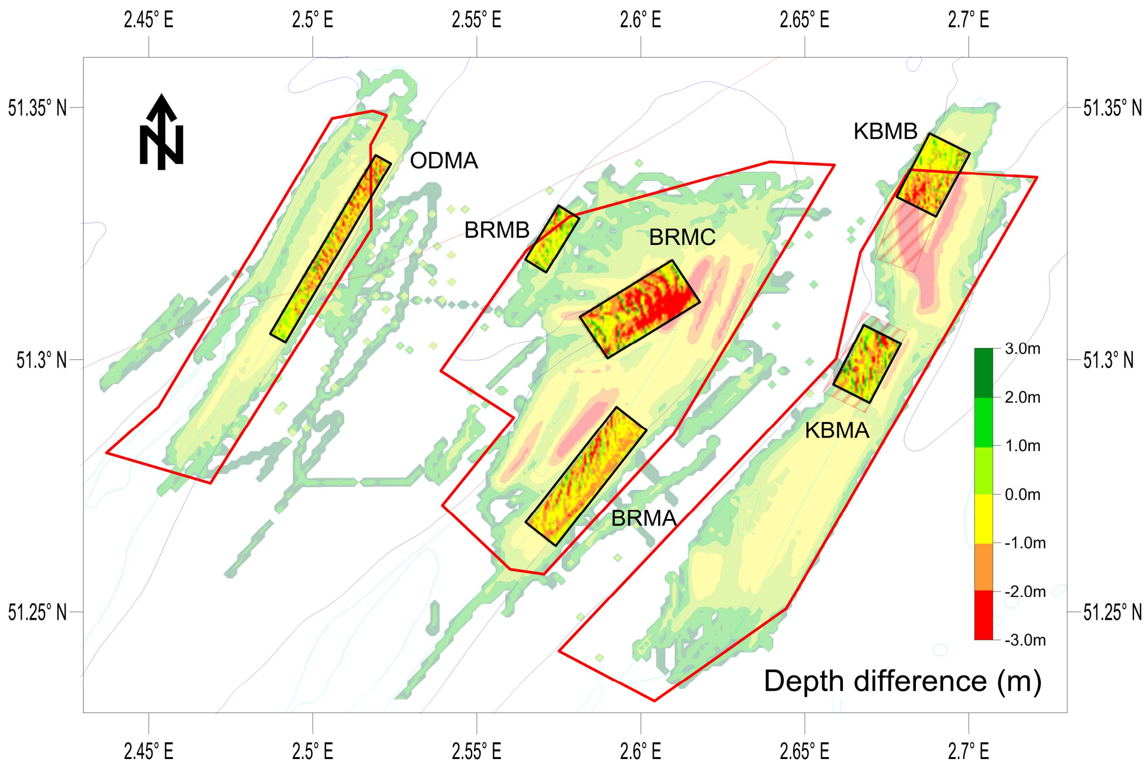

Figure 17: Depth difference between the most recent surveyed monitoring areas (2013 for BRMA, 2014 for BRMB, BRMC, ODMA, KBMA and KBMB) and the reference model for zone 2. Positive values show an increase in sediment, negative values a decrease. A map showing the extraction density between the survey date and the reference model is used as background.

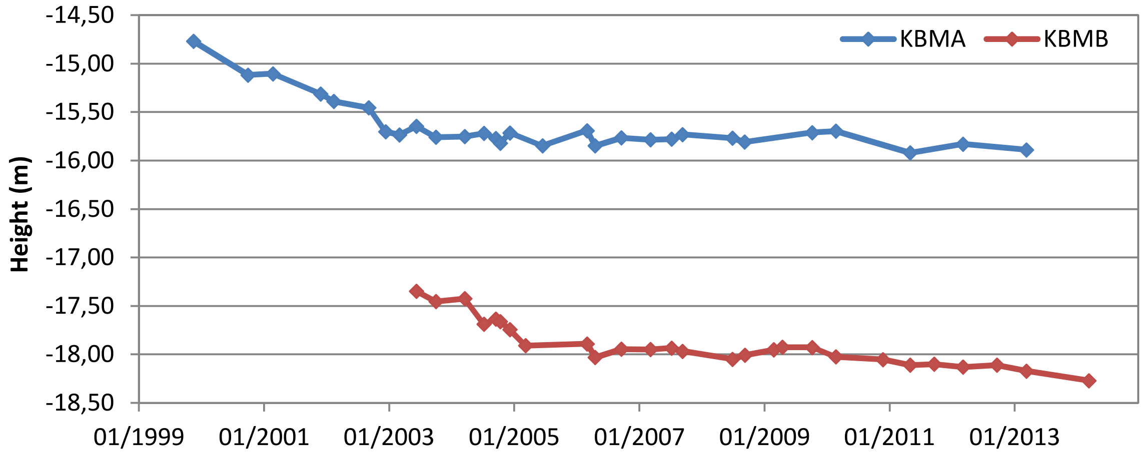

Figure 18: Evolution of the average height referenced to MLLWS of the two monitoring areas on the Kwintebank.

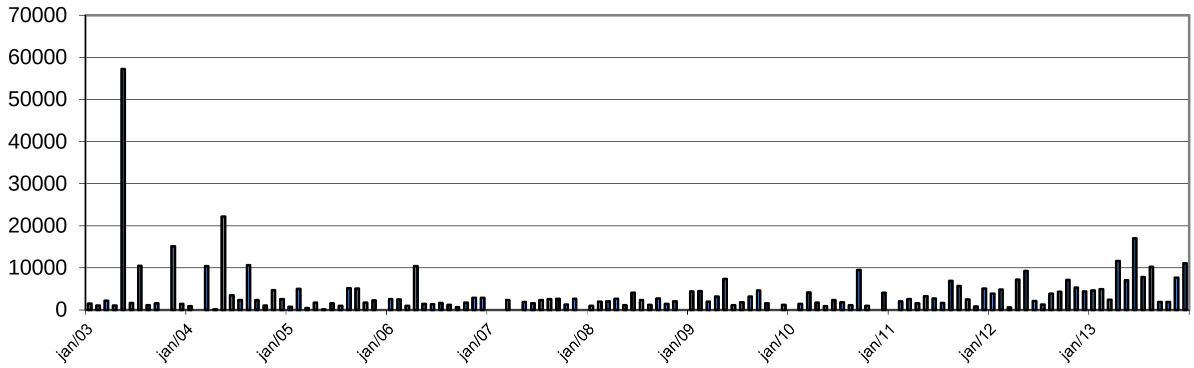

Figure 19: Evolution of the monthly extracted volume (in m^3) in the monitoring area ODMA.

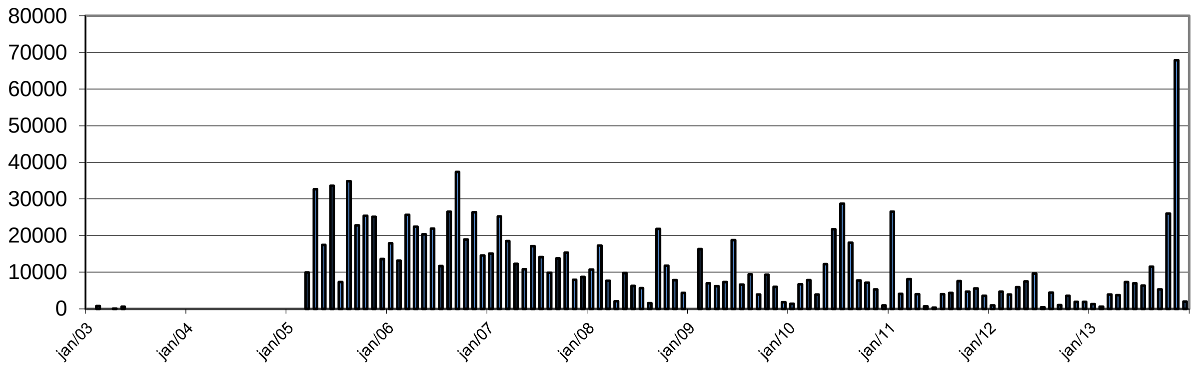

Figure 20: Evolution of the monthly extracted volume (in m^3) in the monitoring area BRMA.

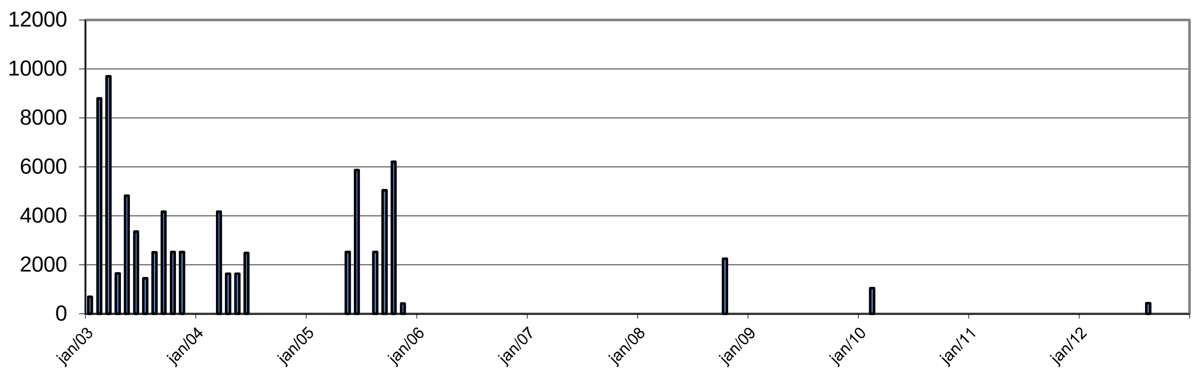

Figure 21: Evolution of the monthly extracted volume (in m^3) in the monitoring area BRMB.

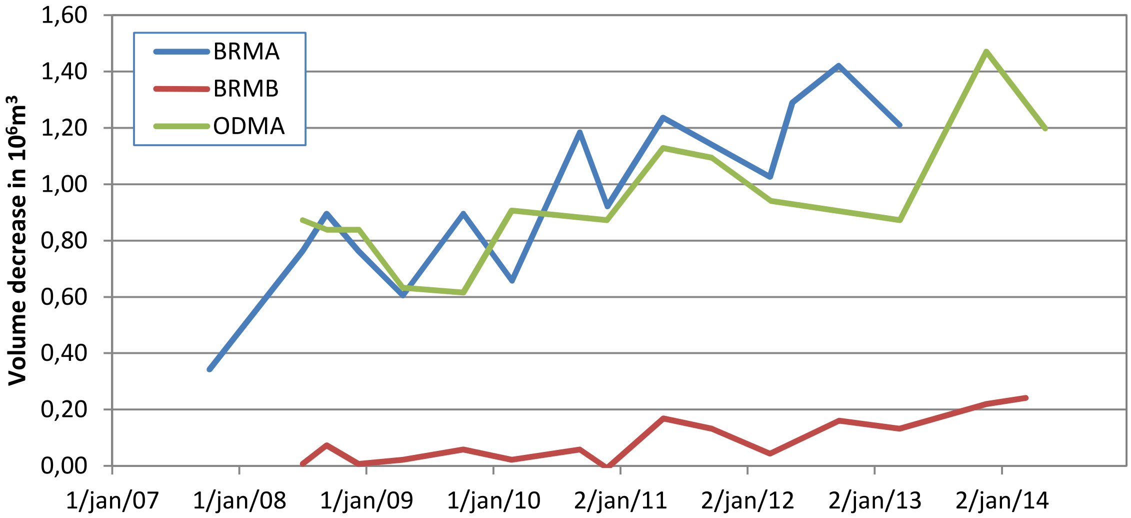

Figure 22: Evolution of the measured volume decrease (in 10^6m^3) inside the monitoring areas on the Buiten Ratel (BRMA and BRMB) and Oostdyck (ODMA).

Since 2008, after the closure of the northern depression on the Kwintebank, the central part of the Buiten Ratel (BRMC) has become the most densely extracted area on the Belgian part of the North Sea (figure 23). The impact is very clear: the initial situation in 2003 (figure 24) dominated by large sand dunes is transformed in a landscape marked by the furrows created by the dredging vessels (figure 25). The difference between both surfaces exceeds 5 meter in the centre of the area (figure 26). The extraction is legally limited to a maximum of 5 meter below the reference surface. A profile across BRMC confirms that this legal boundary has been exceeded (figure 27). The comparison between the volume decrease, calculated from the MBES measurements, and the extracted volume based on EMS demonstrates the relation between both (figure 28).

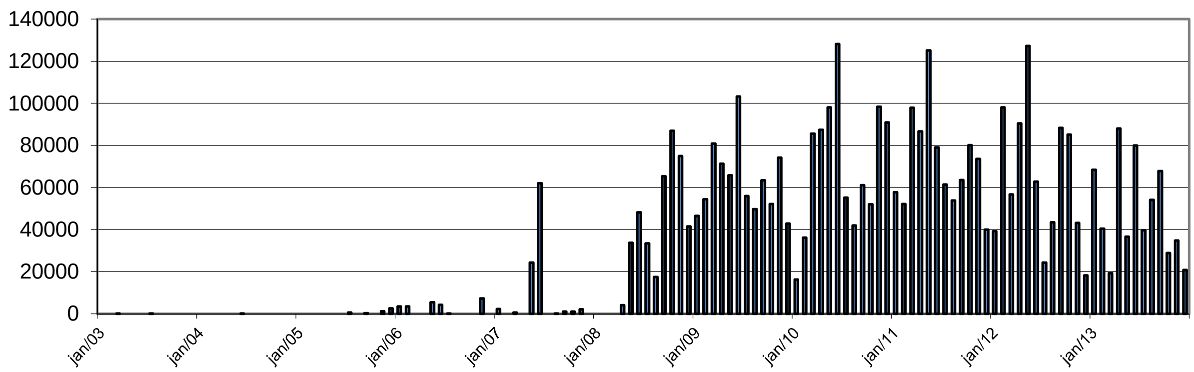

Figure 23: Evolution of the monthly extracted volume (in m^3) in the monitoring area BRMC.

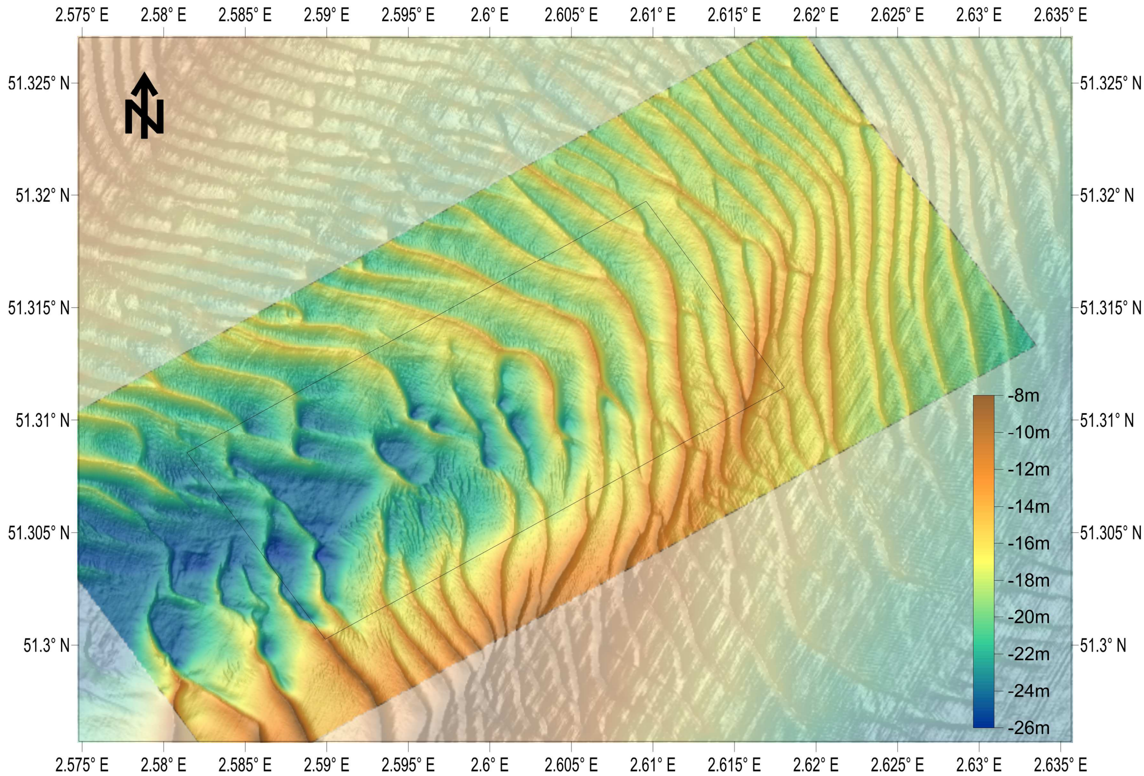

Figure 24: Bathymetry of monitoring area BRMC (limits in black) based on the reference model of zone 2 from 2002. Depths are referenced to MLLWS.

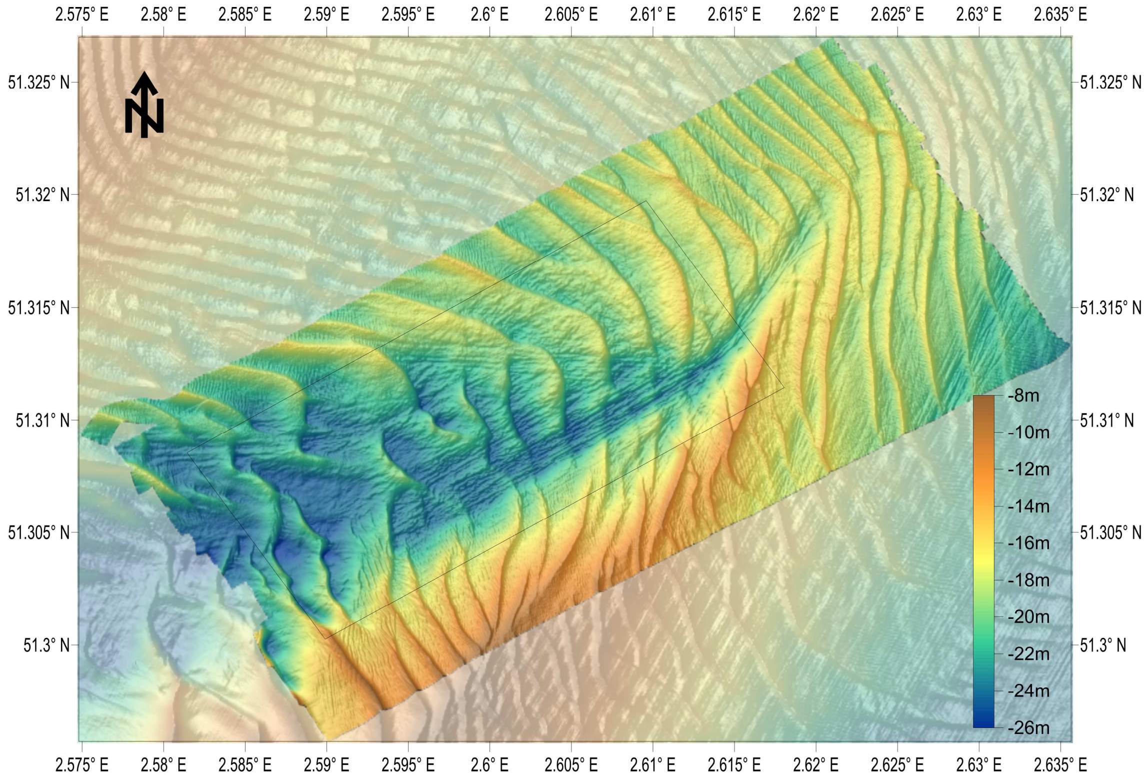

Figure 25: Bathymetry of monitoring area BRMC (limits in black), survey of 13/03/2014. Depths are referenced to MLLWS.

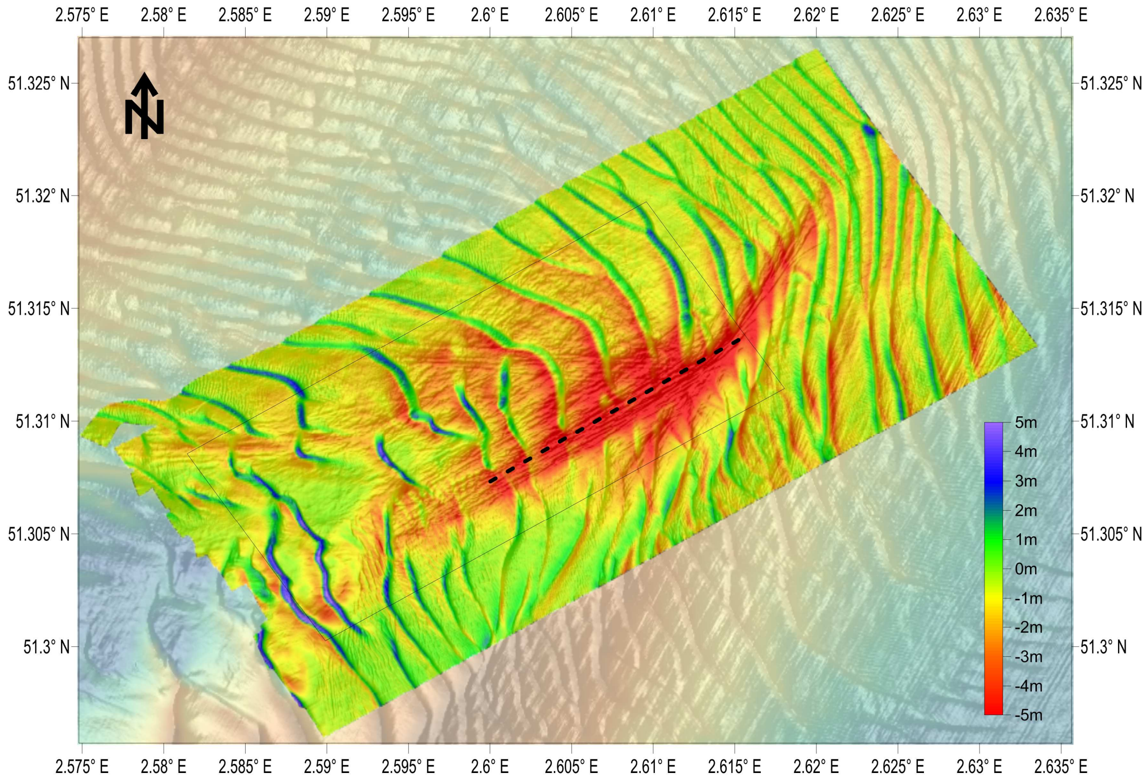

Figure 26: Depth difference between monitoring area BRMC (limits in black), survey of 13/03/2014, and the reference model for zone 2 from 2002. Positive values show an increase in sediment, negative values a decrease. The dashed line is the location of the profile from figure 27.

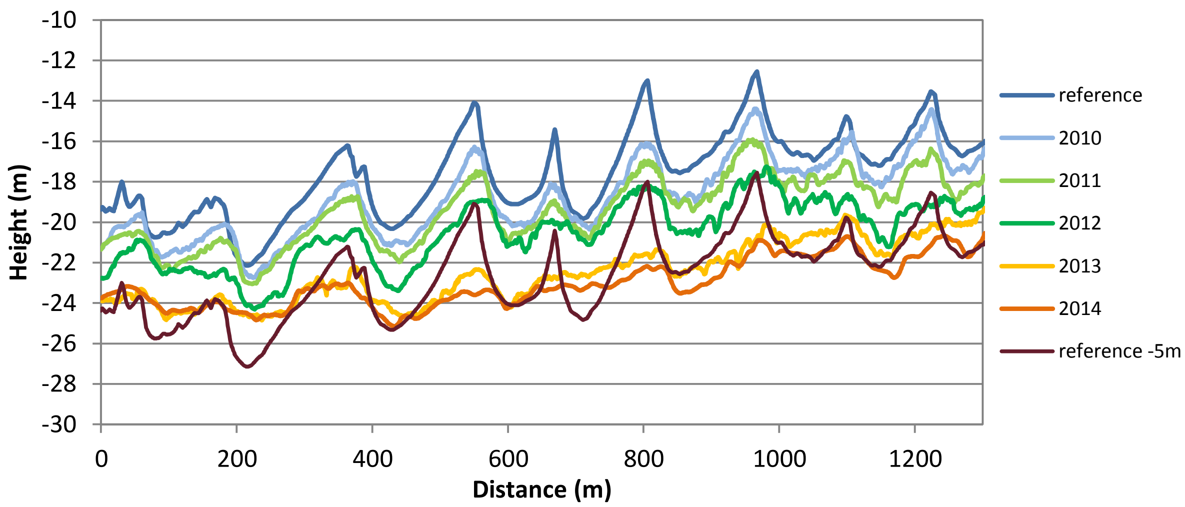

Figure 27: Bathymetric profile across the monitoring area BRMC (dashed line on figure 26). Depths are referenced to MLLWS.

As a result, the Continental Shelf Service advised for a closure in 2015 of an area which encompasses all locations where the limit of 5m is exceeded (figure 29). The coordinates of this area (table 2) and the motivation were published in a report (Degrendele et al., 2014). Based on this report, the consultative commission on the sand extraction at sea unanimously approved the proposal to close the central part of the Buiten Ratel.

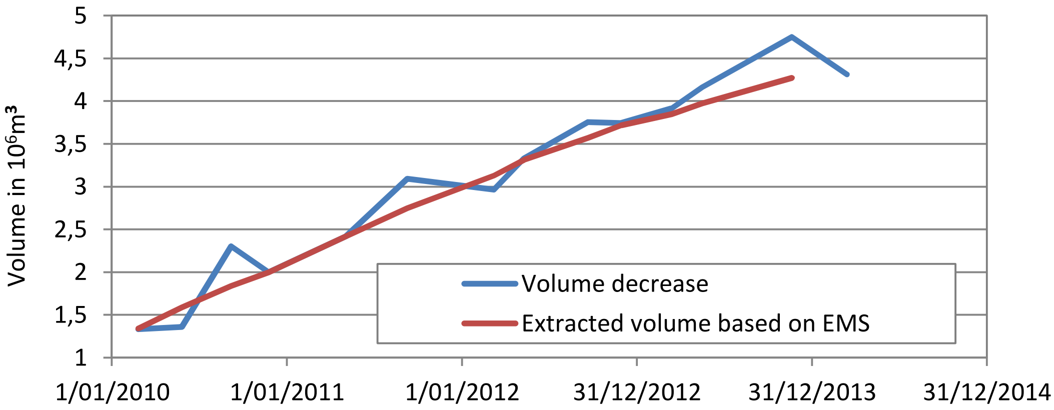

Figure 28: Comparison between the measured volume decrease (in 10^6 m^3) inside the monitoring area BRMC on the Buiten Ratel and the extracted volumes based on EMS calculated for the same surveys. A value of 0.96 is calculated for the Pearson correlation coefficient.

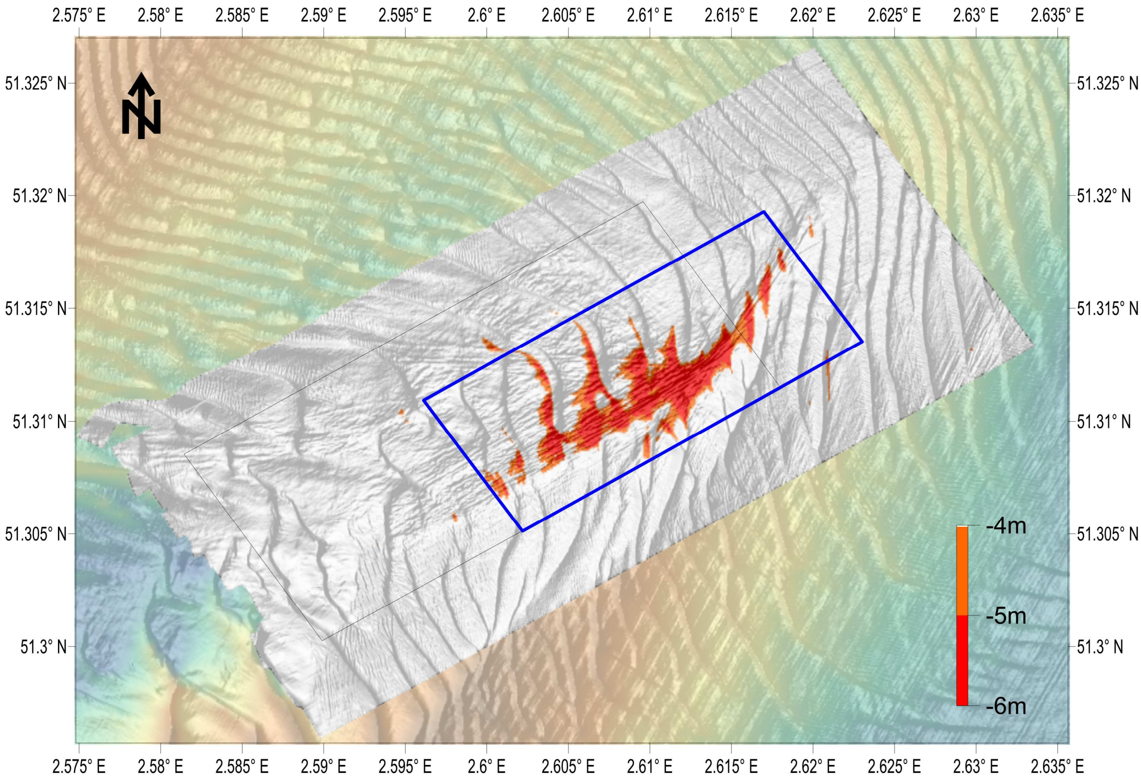

Figure 29: Decrease of depth between the monitoring area BRMC (limits in black), survey of 13/03/2014, and the reference model for zone 2 from 2002. The area that will be closed for extraction in 2015 is indicated in blue.

WGS84 UTM ZONE 31		**LAT LONG**			
Meter		Degrees		Degrees minutes	
X	Y	North	East	North	East
472269	5683832	51.30513	2.60219	51° 18.3075'	2° 36.1314'
471850	5684479	51.31093	2.59612	51° 18.6556'	2° 35.7674'
473308	5685401	51.31928	2.61699	51° 19.1570'	2° 37.0192'
473726	5684757	51.31351	2.62302	51° 18.8108'	2° 37.3811'

Table 2: Coordinates of the area on the Buiten Ratel that will be closed for extraction in 2015.

Control Zone 4

The extraction in zone 4 started in 2012, so the overall impact is still limited. The surveys along the DECCA lines across the banks in 2012 and 2013 (figure 30) do not show any significant impact. They only illustrate the very dynamic character of the many large sand dunes on the Hinderbanken (the alteration of blue and red on figure 30).

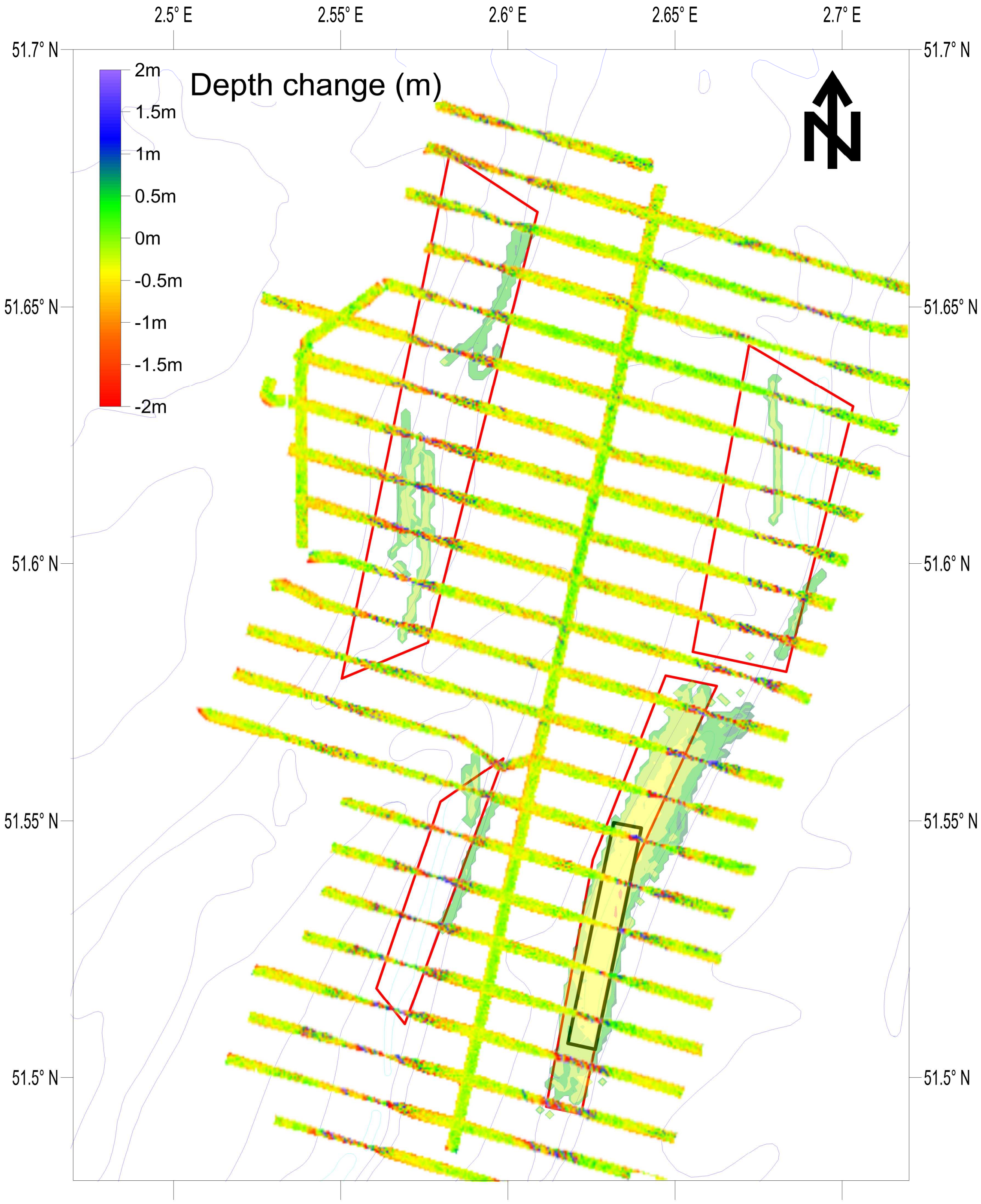

Figure 30: Depth change between the survey along DECCA lines from 15/05/2013 and the reference model. Positive values show an increase in sediment, negative values a decrease. A map showing the extraction density between the survey date and the reference model is used as background.

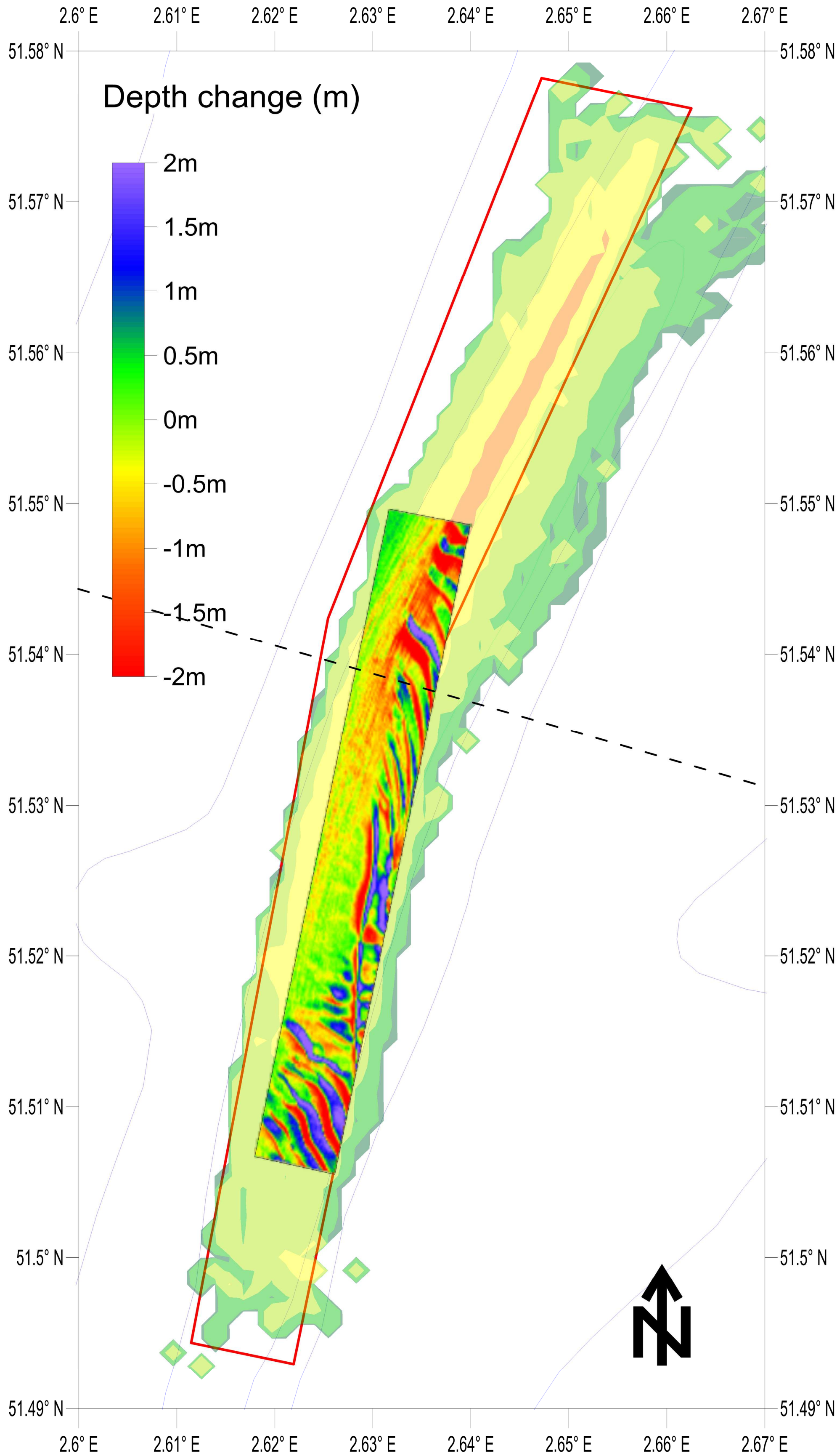

Figure 31: Depth difference between the survey HBMC from 12/03/2014 and the reference model for zone 2. Positive values show an increase in sediment, negative values a decrease. A map showing the extraction density between the survey date and the reference model is used as background.

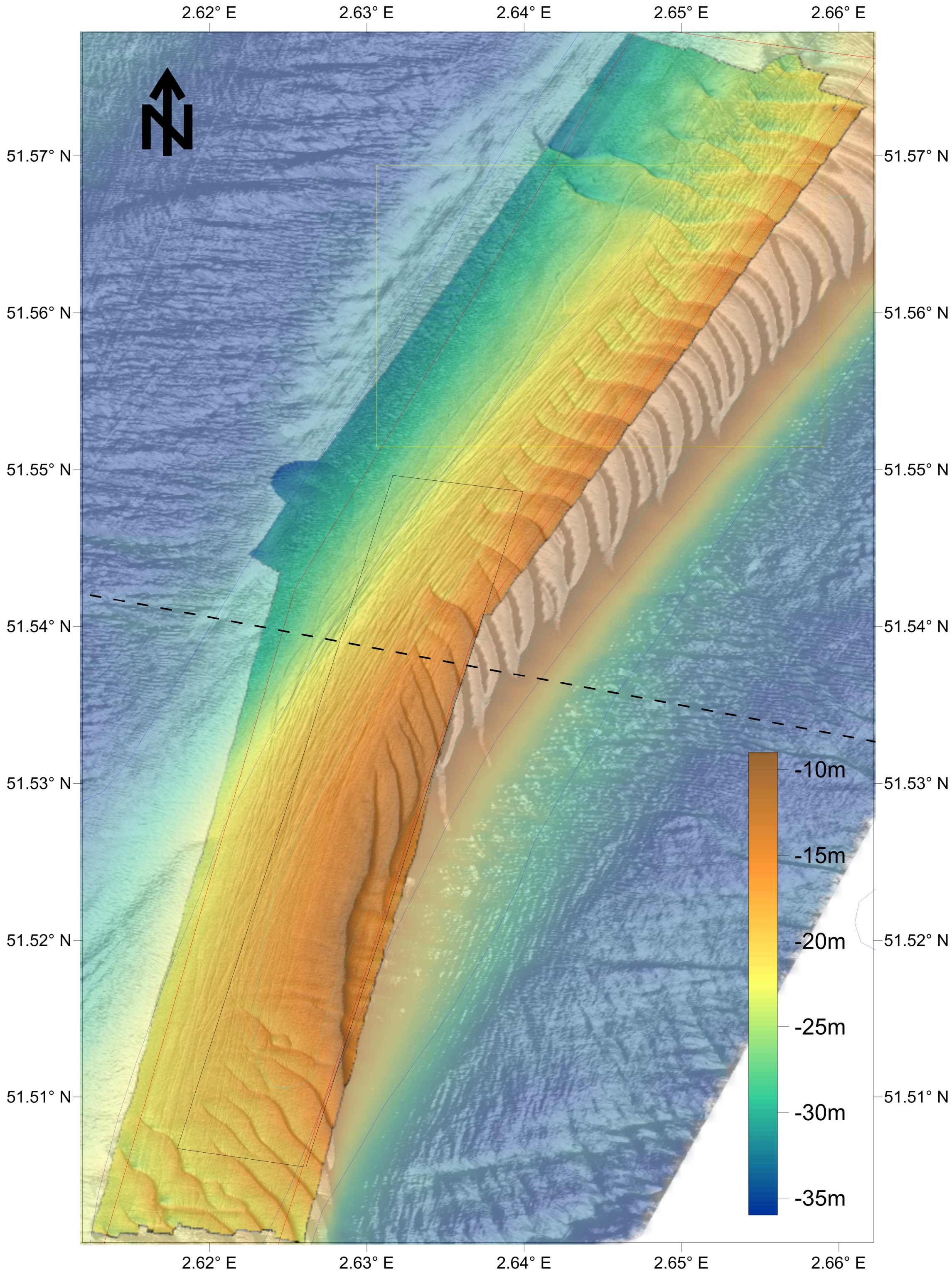

Figure 32: Bathymetry of monitoring area HBMC (limits in black), survey of 12/03/2014. Depths are referenced to LAT. The yellow rectangle is the location of the detailed image in figure 34, the dashed line is the location of the profile from figure 35.

In 2014 the impact is already more obvious. The extraction is concentrated on the central and northern part of sector 4c. Monitoring area HBMC covers only the central and southern part of this sector (figure 31) and thus the monitoring area is occasionally extended to the entire sector (this was the case for the survey on figure 32). The extraction is also very concentrated in time (figure 33). In short intervals, large volumes are excavated for the Master plan Coastal Safety. The bathymetry shows large furrows that are created by the large dredging vessels (figures 33 and 34). The evolution along a profile in sector 4c (figure 35), combining data from the DECCA line surveys and from the HBMC surveys, demonstrates two facts: first, the large sand dunes are very mobile (a shift of 25 m a year) and secondly, the clear impact on the topography from 2014 onwards.

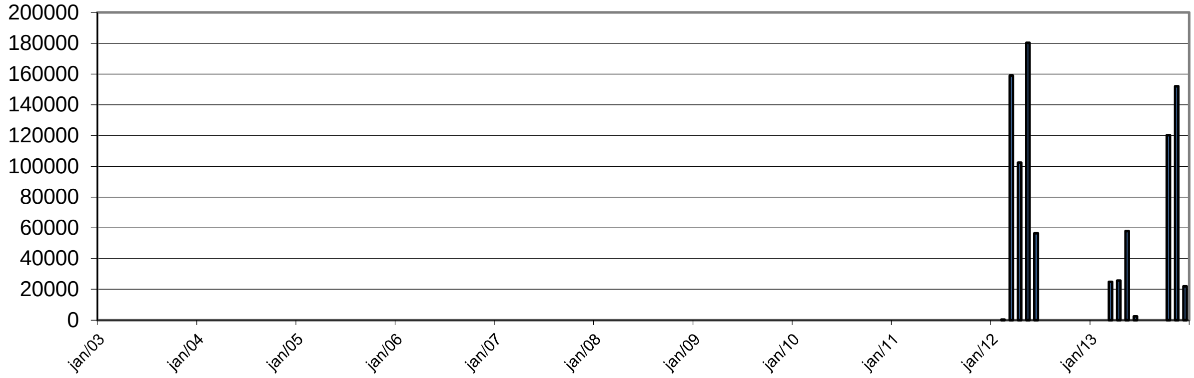

Figure 33: Evolution of the monthly extracted volume (in m^3) in the monitoring area HBMC.

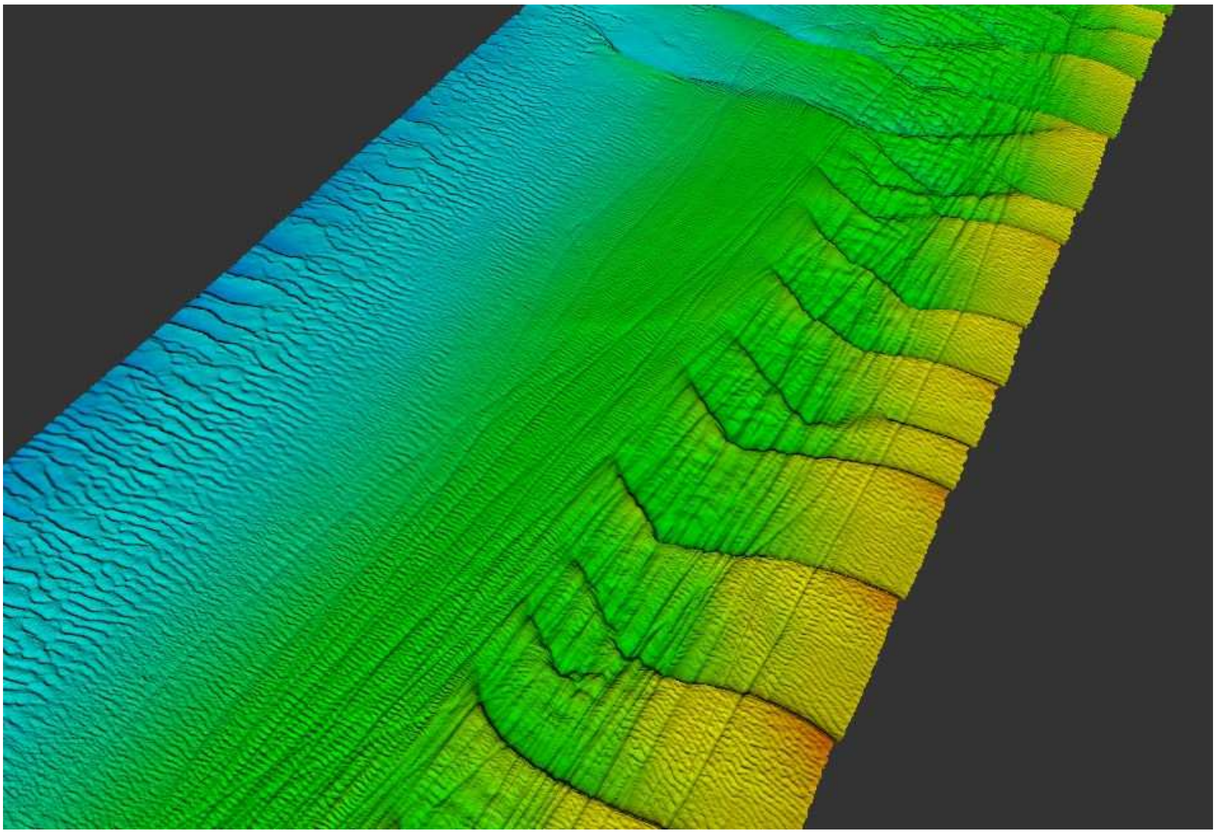

Figure 34: Detail of the northern part of sector 4c, survey of 12/03/2014 (location see figure 33).

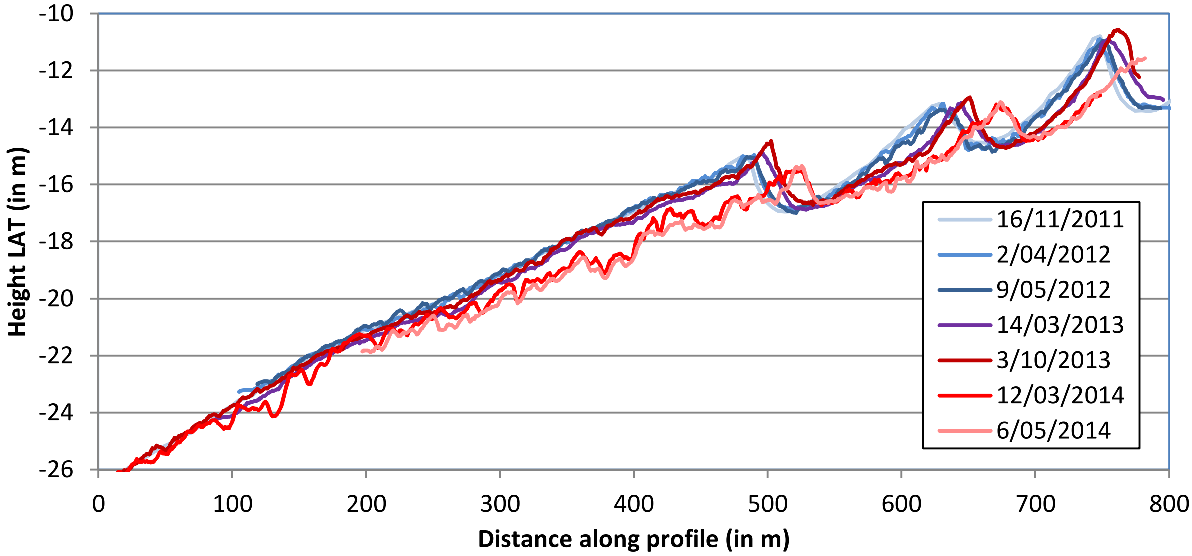

Figure 35: Bathymetric profile across the Oosthinder and the monitoring area HBMC (dashed line on figures 31 and 33). Depths are referenced to LAT.

Correlation MBES – EMS data

The predicted bathymetric differences caused by the extraction activities can be compared with the bathymetric differences measured with the EM3002D along the DECCA lines and in the monitoring areas relatively to the reference models of zones 1, 2 and 4 (figure 36). The methodology has been described previously (Roche et al. 2011 and Roche et al. 2013). A strong correlation is observed between the bathymetric differences measured with the MBES and the bathymetric differences caused by the extraction for both the DECCA data and the monitoring areas data. Globally, considering all the data together, the square of the linear correlation coefficient (Pearson R) between the bathymetric difference measured with the MBES and the bathymetric difference caused by the extraction is almost equal to 0.95. This correlation is statistically highly significant: most of the bathymetric variation observed on the extraction zones can be explained by the extraction itself. Surprisingly, a mean bathymetric variation of -0.3 m is observed in areas where the extracted volume is zero. Such a global decrease of the bathymetry is questionable and must be investigated in detail. It could be related to fluctuations in the accuracy of the reference models due to insufficient corrections of the draft of the ship. Furthermore, our current bathymetric measurements with the MBES EM3002D are themselves subject to errors included in the IHO S44 special order confidence interval which is +/- 0.3 m for 20 m water depth. This confidence interval puts our results into perspective.

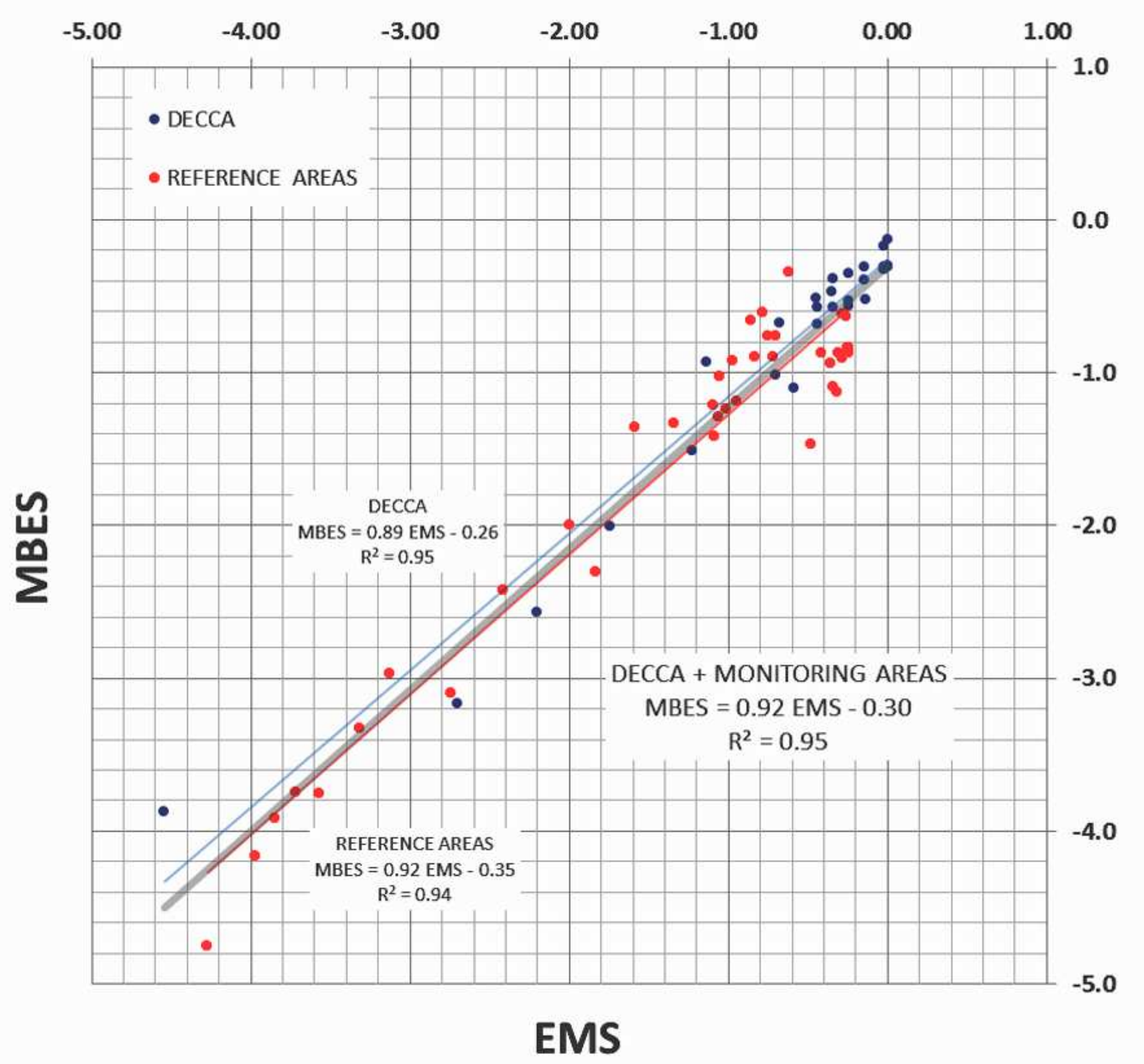

Figure 36: Plot of the bathymetric difference measured with the MBES data versus the bathymetric difference deduced from EMS data; linear regression line based on the DECCA data (blue dots and line) and reference area data (red dots and line) separately and together (grey line).

Conclusions

The main conclusion from the earlier reports and publications (Degrendele *et al.*, 2010, Roche et al., 2011 and Roche et al., 2013) is confirmed: the sand extracted on the Belgian part of the North Sea must be considered as a non-renewable resource whose extraction has a local and non-cumulative impact.

MBES technology remains the most appropriate tool to evaluate with great reliability the impact of the extraction on the seabed topography, morphology and sedimentary nature. But there are a couple of observations that need attention and further investigation: a recent small negative trend is observed in several time series, and although the values fall inside the confidence interval of the MBES data (Lurton et al., 2011 and Roche & Degrendele, 2011), a close follow up is needed. The impact of the accuracy of the reference models on the global trends needs further investigation. In this point of view the annual evaluation of the quality of the measurements on reference sites (the Vandammesluis and a stable area on sea) becomes an invaluable tool and requires more focus and time investment (Roche & Degrendele, 2011).

At this moment, the legal limit for the extraction is still 5 m below the reference surface defined by the Continental Shelf Service. On the central part of the Buiten Ratel this limit has recently been exceeded in a continuous area and subsequently this area will be closed for extraction in 2015 (Degrendele et al, 2014).

The upgrade of the EMS system will allow a faster follow up of the spatial and temporal variations of the extracted volumes. The fast depletion of the legally allowed volumes in certain areas makes a more adaptable monitoring necessary. Due to the closure of the central part of the Buiten Ratel in 2015, the extraction pattern will undoubtedly change.

Acknowledgements

First of all, the excellent navigation by the crew of R/V Belgica during the campaigns was crucial for the monitoring program. The Operational Directorate Natural Environment (former Management Unit of the Mathematical Model of the North Sea and the Scheldt Estuary - BMM) provided the necessary ship time on board the R/V Belgica. The colleagues from ILVO and BMM are thanked for the collaboration in the establishment of a balanced and all-embracing monitoring program.

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Structural and functional biological assessment of aggregate dredging intensity on the Belgian part of the North Sea

*De Backer Annelies[*1], Hillewaert Hans[1], Van Hoey Gert[1], Wittoeck Jan[1], Hostens Kris[1]*

[*]Presenting author: annelies.debacker@ilvo.vlaanderen.be

[1] Institute for Agricultural and Fisheries Research (ILVO), Animal Sciences Unit, Aquatic Environment and Quality, Ankerstraat 1, 8400 Oostende, Belgium

Abstract

Marine aggregate dredging in the Belgian part of the North Sea (BPNS) is restricted to four dedicated concession zones. Within these zones, there are areas under different dredging pressure, but with the advantage that these are situated within a similar habitat (cfr. similar sediment characteristics) . As such, this study assessed how different degrees of dredging pressure executed on a similar sandy habitat affect the benthic ecosystem. Possible responses of the macrobenthos on the dredging pressure were evaluated based on both structural (species number, species composition, abundance and biomass) and functional (e.g. bioturbation potential, BTA) characteristics of the benthic ecosystem. The structural changes in benthic characteristics were summarised by the benthic indicator BEQI.

The most obvious impact of dredging on the benthic community was observed in the most intensely used area (high dredging intensity and frequency) with significant changes in the structural benthic characteristics, and a moderate to poor score for the benthic indicator BEQI. For the benthic functional characteristics, no impact of dredging was measured in any of the areas. Furthermore, the heart-urchin (*Echinocardium cordatum*) was observed to be the most sensitive species to dredging, because it reduced substantially in numbers or even disappeared in all impacted areas.

Our results suggest that the current benthic sandy ecosystem of the BPNS is resilient enough to buffer aggregate dredging when performed at low or at high, but infrequent intensities. However, when dredging focuses on a small surface area, and when it is performed at high and frequent intensities, changes in sediments result in clear biological changes.

Introduction

Aggregate dredging in the Belgian part of the North Sea (BPNS) is restricted to four dedicated zones as cited in RD 19 April 2014. Control on the dredging activities is based on two criteria. The first is the control on the actual dredging by means of an Electronic Monitoring System (the black-box) on board the extraction vessels. This is to supervise whether dedicated extraction zones are respected, and whether extracted volumes do not exceed the granted licences. The second implies an assessment of the impact of dredging on the marine environment by regular monitoring (FOD Economie, 2014a&b). Combination of both control measures offers the opportunity to measure the impact of dredging intensity.

Part of the legal monitoring is of biological nature, to assess the impact of dredging on the soft-bottom benthic ecosystem. Many studies have shown that marine aggregate dredging has the potential to change the composition of seabed sediment habitats (e.g. Foden et al., 2009; Le Bot et al., 2010). Since marine macrobenthic communities are strongly related to sediment habitats (Degraer et al., 2008; Vanaverbeke et al., 2011), they are good indicators to measure potential changes in seabed habitats (Van Hoey et al., 2010). For many years, the impact of aggregate dredging on macrobenthos has been assessed using traditional structural metrics such as abundance, number of species, biomass and species composition (e.g. Boyd et al., 2005; Cooper et al., 2007a; De Backer et al., 2014). However, recently marine conservation focuses more on ecosystem functioning, considering the processes of ecosystems and the individual ecosystem components involved in them (Bremner, 2008). Since one may argue that it might be of even greater importance to consider how dredging affects the way ecosystems function rather than how it affects the species that are present. This can be done by looking at changes in functional diversity through biological traits analysis (BTA). Another way of looking at changes in functioning is to measure changes in bioturbation, because this is a key process in marine systems which influences ecosystem function (Meysman et al., 2006). The community bioturbation potential (BPc) can be used as a metric to estimate the potential of a community to bioturbate (Solan et al., 2004).

Black-box data in the past showed that the different extraction areas were dredged with a different regime (intensity and frequency) (Roche et al., 2011), allowing to define areas under different dredging pressure in the BPNS. Furthermore, the entire BPNS is classified as habitat type 1110 (i.e. sandbanks slightly covered by seawater at all times) under the Habitat Directive. Moreover, the areas with actual dredging in the BPNS are situated in similar sedimentary areas i.e. dominated by medium sands (250-500 µm) and with a median grain size around 300-400 µm (Verfaillie et al., 2006). As such the BPNS can be considered an excellent study area to investigate how different degrees of dredging pressure executed on a similar sandy habitat affect the benthic ecosystem. Further, the objective is to compare structural (using traditional metrics and the BEQI indicator) and functional (BTA, BPc) metrics to evaluate the impact of dredging on the benthic assemblage. Besides, European environmental legislation (e.g. Marine Strategy Framework Directive) demands indicator tools to summarise the status of the marine ecosystem, and the impact upon it by human activities. Therefore, an indicator assessment approach (BEQI) is applied to determine the applicability of BEQI in detecting changes caused by the dredging.

The ultimate aim of this study is to be able to determine the best practice in aggregate dredging to minimise the biological impact on sandy benthic ecosystems.

Methods

Study sites and extraction history

This study focuses on four actual aggregate dredging areas within the restricted extraction zones on the Belgian part of the North Sea (BPNS): Buiten Ratel, Oostdyck, Thornthonbank and Oosthinder (Figure 1). All four locations are dominated by medium sands, but are subject to different dredging regimes. Marine aggregate dredging on the BPNS typically occurs on top of the sandbanks (Figure 1).

The Buiten Ratel is currently the most heavily exploited aggregate dredging area on the BPNS. Dredging steadily increased since 2005 from 0.32 x 10^6 m³ to 1.9 x 10^6 m³ in 2011, since then slightly decreasing towards 1.3 x 10^6 m³ in 2013. Especially, the central part of the Buiten Ratel (an area of 2.5 km²) is the most targeted area with yearly extraction volumes around 8 x 10^5 m³ since 2009. The high intensity of extraction resulted into a 6 m deep depression (Degrendele et al., 2014, this volume). More to the south of the extraction ‘hotspot’ on the Buiten Ratel, extracted volumes are lower, and vary between 7 x 10^4 m³ and 15 x 10^4 m³.

Compared to the other areas, the Oostdyck is the least intensively exploited area, but it has the longest time record of extractions. Yearly volumes since 2003 (start of the black box volume data) are of the same magnitude as in the lower impacted areas of the Buiten Ratel. Extracted volumes varied between 7 x 10^4 m³ in 2007 and 15 x 10^4 m³ in 2013.

The Thorntonbank is increasingly used for aggregate extraction since 2003. Volumes increased tenfold from 0.1 x 10^6 m³ in 2003 to 1 x 10^6 m³ in 2013. The extraction mainly concentrates on the top of the bank and extracted volumes are lower at the edges.

Aggregate dredging on the Oosthinder started only in March 2012. Since then yearly extraction is as high as on the central part of the Buiten Ratel (around 8 x 10^5 m³) but on a larger surface area (approximately 9 km²). Extraction is concentrated to short periods of the year: 4 months intensively dredging with in between periods without dredging (Degrendele et al., 2014, this volume).

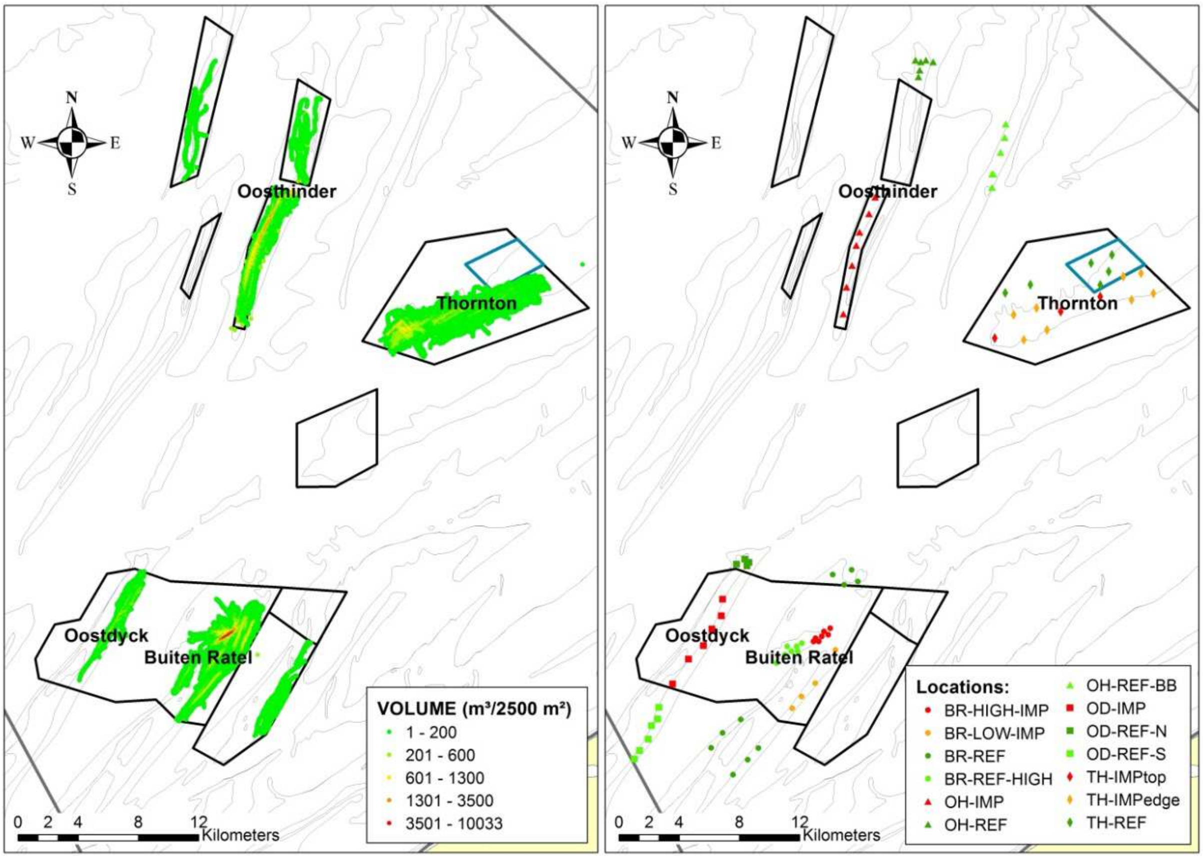

Figure 1: Overview of study sites with black box data extracted volumes in 2013 (left) and sampling locations (right) in the aggregate dredging concession areas on the BPNS. Right panel: sampling locations in the different actual dredging areas, Buiten Ratel (BR, circles), Oostdyck (OD, squares), Thornton (TH, rhombs) and Oosthinder (OH, triangles). Red and yellow symbols indicate impact samples, green symbols indicate reference samples.

Sampling and sample processing

The position of the sampling locations was chosen based on black-box data (a system that keeps track of extraction time and location of the extraction vessels). In all extraction areas, both impact and reference locations were allocated to allow for biological impact assessment (Figure 1). In some areas, a distinction was made between different types of impact samples depending on the dredging pressure, and in reference samples depending on the location of the reference samples. In Table 1 and Figure 1, an overview is given of the different sample groups per area.

In order to avoid any significant seasonal effects in the analyses, all sampling (impact and control) was undertaken at the same time of year. Sampling took place on board the RV Belgica, yearly between 2010 and 2013 in September/October in all extraction areas, except for the Oostdyck in 2012. Furthermore, at the Oosthinder, one extra sampling was done in July 2012 on board the RV Simon Stevin, one month after the first extraction phase had stopped.

Macrobenthos was sampled by means of a Van Veen grab (surface area 0.1 m²), one per location at every sampling occasion. Real-time coordinates of each location were noted. The fauna was sieved alive over a 1-mm sieve, stained with eosin to facilitate further sorting, and preserved in an 8% formaldehyde–seawater solution. All individuals were identified to species level if possible, and counted. For biomass measurements, each species/taxon in every sample was blotted on absorbent paper before being weighed (wet weight) to the nearest 0.00001 g.

A small sediment core (3.6 cm ∅) was taken from each Van Veen sample for granulometric analysis. Grain size fractions up to 1600 µm were analysed using a Malvern Mastersizer 2000G hydro version 5.40 (Malvern, 1999), and determined as volume percentages according to the Wentworth scale. The fraction > 1600 µm was sieved first and as well calculated as volume percentage. The following classes were used: clay/silt (<63 µm), very fine sand (63-125 µm), fine sand (125-250 µm), medium sand (250-500 µm), coarse sand (500-1000 µm), very coarse sand (1000-1600 µm), shells/gravel (> 1600 µm).

Extraction area	Sample groups	Location and description
Buiten Ratel (BR)	HIGH-IMP	Seven impact samples on the central Buiten Ratel, the most impacted dredging area based on the black box data.
	LOW-IMP	Four impact samples on the less impacted area of the Buiten Ratel based on the black box data.
	REF-HIGH	Seven reference samples within the concession area near the high impact area but with no dredging.
	REF	Ten reference samples outside of the concession area both north and south.
Oostdyck (OD)	IMP	Six impact samples in the area under influence of dredging.
	REF-S	Six reference samples on the south-west part of the sandbank.
	REF-N	Four reference samples on the north-east part of the sandbank.
Thorntonbank (TH)	IMPtop	Three impact samples on top of the bank with a higher influence of dredging based on the black-box data.
	IMPedge	Eight impact samples at the edges of the bank with a lower influence of dredging based on the black box data.
	REF	Six reference samples within the concession area but without dredging
Oosthinder (OH)	IMP	Seven impact samples under the influence of dredging since 2012 allocated based on black box data.
	REF	Six reference samples located on the Oosthinder outside of the concession area.
	REF-BB	Five reference samples located on the nearby Bligh Bank.

Table 1: Overview of sample groups in the different extraction areas with indication of the codes used throughout the manuscript.

Data analyses

Table 2 shows an overview of the metrics (structural, functional and benthic indicator) derived from the faunal data (see Sections 0, 0 and 0). These combined with local dredging pressure data provide a profound base for biological impact assessment of aggregate dredging.

	Metric used	No impact if:
Structural	Number of species (No./grab)	at the scale of the 0.1 m² grab, the impact assemblage is as speciose as that of the reference area.
	Number of individuals (No. m^{-2})	total benthic density of the impact assemblage is similar to that of the reference area.
	Biomass (wet weight, g m^{-2})	the biomass of the impact assemblage equals that of the reference area.
	Shannon Wiener diversity (H')	the biodiversity (measured with the metric H') of the impact assemblage is similar to the reference area.
	Assemblage structure	the taxonomic identity and relative abundance of the impact assemblage matches that of the reference area.
Benthic indicator	BEQI (Benthic Ecosystem Quality Index)	the BEQI score of the impact assemblage for the different assessment parameters, is higher than 0.6, which means a comparable benthic habitat condition between impact and reference area.
Functional	Biological traits composition	the numerical composition of the impact assemblage is similar to that of the reference area with respect to life history, behavioural and morphological traits. Implying that the two areas are functionally similar.
	Bioturbation potential (BPc)	the bioturbation potential of the impact assemblage is comparable to that of the reference area.

Table 2: Overview of the biological metrics used throughout the study and how they were interpreted for impact assessment.

Calculating dredging pressure

Different measures of dredging pressure were determined based on the black box data, and the bulk size of the extraction vessel: 1) dredging intensity (total volume extracted in $m^3\ yr^{-1}$), 2) total time dredged (in minutes yr^{-1}) and 3) number of days dredged during one year prior to biological sampling. Furthermore, the interval time (in days) between the last time dredging was taking place and the biological sampling was calculated during one year prior to biological sampling. Spearman rank correlations between all measures were calculated in R 3.0.2 (R Core Team 2013) to check the relationships between the different dredging metrics.

To determine dredging pressure at a biological sampling location, real time coordinates of every sampling location were plotted in ArcMap 10. Around each location, a circular 150 m radius buffer was drawn. The shapefile with buffer locations was imported in R 3.0.2 (R Core Team 2013) to calculate dredging pressure at the biological sampling location within the buffer area (surface area 0.07 km²).

The dredging frequency at each sampling location was visualised by plotting daily extracted volumes between 2010 and 2013.

Assemblage structure

Species richness (S) and Shannon Wiener diversity (H') were calculated for every macrobenthos sample using PRIMER v6 (Clarke & Gorley, 2006). For all univariate measures (S, H', macrobenthos density, biomass and median grain size), a two-way Permanova per aggregate dredging area was performed with factors ‘year’ and ‘location’ on an Euclidean distance resemblance matrix to assess the biological impact (Anderson et al., 2008). If significant differences were detected ($p<0.05$), pairwise tests were conducted.

Further, non-parametric Spearman rank correlations between the univariate measures and the dredging pressure measures were calculated using R3.0.2 (R Core Team 2013) to identify which univariate measures were possibly influenced by the aggregate dredging.

Multivariate analyses were carried out to assess the degree of similarity in species composition between impacted and reference areas across the years. The multivariate analyses were performed on a square root transformed species abundance matrix using the Bray–Curtis similarity index, which is most commonly-used and best suitable for biological community analyses (Clarke & Warwick, 2001). To test for differences between the different sample groups (impact – reference) over the years, two-way crossed ANOSIM tests were performed with factors ‘year’ and ‘location’ at the Buiten Ratel, Oostdyck and Thorntonbank, and with factors ‘location’ and ‘Before/After’ at the Hinderbanken. The output of the ANOSIM test presents a global test with both the ANOSIM test statistic R and the p-value for this test. When the global R is significant ($p<0.05$), pairwise tests indicate where the major differences are situated, again with an R statistic and a significance level. The R statistic has a value between 0 (no differences) and 1 (completely different). For pairwise test, the significance level is very dependent on the number of replicates. Clarke & Gorley, 2006) propose that the R value is the most useful criterion to aid interpretation as it is not a function of the number of replicates. ANOSIM R-values >0.5 indicate clear differences between groups with some degree of overlap (Clarke & Gorley, 2006). To determine the species most responsible for discriminating between sample groups, where significant differences existed, the two-way crossed SIMPER procedure (Clarke & Gorley, 2006) was used with the same factors as for the ANOSIM test.

Relationships between the multivariate data cloud and environmental variables (grain size fractions, median grain size and dredging measures) were investigated through DISTLM (Distance-based linear models) analysis using stepwise selection and AICc criterion. Before running the DISTLM analysis, environmental data were normalised and collinearity among variables was examined using Spearman rank correlation coefficients. If a linear dependency between variables was identified ($r > 0.8$) only one of the variables was retained in the analysis.

Benthic Ecosystem Quality Index (BEQI)

The applicability of BEQI in detecting significant changes in the macrobenthic ecosystem due to dredging was tested on abundance, species number, biomass and species composition. BEQI is proposed as a GES (Good Environmental Status) indicator to measure whether the Belgian environmental targets as set within the Marine Strategy Framework Directive (MSFD) are reached (Belgische Staat, 2012).

The benthic indicator BEQI (www.beqi.eu) evaluates the difference in benthic characteristics (density, biomass, number of species and species composition) between two datasets (e.g. reference versus impact) (Van Hoey et al., 2007; Van Hoey et al., 2014). The outcome is scaled between 0 and 1 and divided into five classes: bad [< 0.2], poor [0.2 - 0.4], moderate [0.4 - 0.6], good [0.6 - 0.8] and high [0.8 - 1]. When the BEQI reaches an EQR (Ecological Quality Ratio) value below 0.6, it is suggested that the difference between the two datasets (reference – impact) is higher than what would be expected without human pressure. When this is the case, a detailed analysis of the outcome is advised. In order to perform a proper indicator assessment of a possible impact, the influence of the natural variability in benthic characteristics on the indicator outcome has to be minimised. Therefore, the datasets used for comparison in the assessment design should have the same habitat characteristics (such as sediment type, depth region, etc.), the same time period (season, year) and contain enough samples to obtain a confident assessment (statistical power) (Van Hoey et al., 2013).

The confidence of the BEQI assessment is based on the variability within the data in three classes (good, moderate and poor). Only the indicator outcomes that scored moderate or good were included in the results. Subsequently, an appropriate selection of the control dataset is advised, as different control data samples will have an influence on the final indicator judgment (Van Hoey et al., 2013).

Assemblage functioning

Biological traits analysis (BTA)

BTA is an ecological approach that looks beyond the mere zoological identity of taxa and the species composition of communities by focusing on the form and function of the biota; that is to say 'what they do' rather than 'who they are'. Essentially, BTA uses a series of life history, morphological and behavioural characteristics of species present in assemblages to indicate aspects of their ecological functioning (Bolam, 2013). Changes in the patterns of trait composition within assemblages can be used to indicate the effects of human impacts on ecosystem functioning (Bremner et al., 2006)

The approach used in this study is adopted from Bolam (2014) and Bolam & Eggleton (2014). To estimate assemblage function, ten biological traits were chosen to describe the life history, morphological and behavioural characteristics of the constituent taxa (genus level or above) (Table 3). Each of the traits was subdivided into various categories chosen to encompass the range of possible values of all the taxa. In total, 46 categories were identified (Table 3). Some of the traits referred to measurable characteristics (e.g. size range, longevity) whose categories presented a 'hierarchical' organisation. Others (e.g. mobility) were wholly qualitative characteristics whose categories represented discrete classes (Bolam, 2014). Information regarding all traits was needed for all taxa, and was accessed through the traits database of the BENTHIS FP7 project. Information on traits within this FP7 project was collected from a variety of sources (see Bolam, 2014). Since taxa can display multi-faceted behaviour depending upon specific conditions and resources available, traits for each taxon were assessed using a 'fuzzy coding' approach (Bolam, 2014 and references herein).

The resulting 'taxon-by-trait' matrix was combined with the 'taxon abundance-by-station' (Ind. m^{-2}) matrix to create the final 'station-by-trait' matrix on which all subsequent trait analyses were based.

The analyses carried out to assess the similarities/differences in traits composition between impact and reference areas were analogous to those performed on the species composition data (see Section 0, ANOSIM and SIMPER procedure).

Trait	Category	Description
Maximum size	<10	Maximum size (length or height) of adult (mm)
	10-20	
	21-100	
	101-200	
	>200	
Morphology	Soft	External tissue soft and not covered by any form of protective casing
	Tunic	Body covered by a protective outer tissue made up of, for example cellulose, e.g., tunicates
	Exoskeleton	Body covered or encased in either a thin chitinous layer or calcium carbonate shell
Longevity	<18	The maximum lifespan of the adult stage (y)
	1-3	
	3-10	
	>10	
Larval development location	Pelagic Planktotrophic	Larvae feed and grow in the water column
	Pelagic Lecitotrophic	Larvae feed on yolk reserves
	Benthic (direct)	Larval stage missing (eggs develop into juvenile forms) or larvae are limited to the seabed

Egg development location	Asexual/budding	Species can reproduce asexually, either by fragmentation, budding, epitoky. Often this is in addition to some form of sexual reproduction
	Sexual-shed eggs (pelagic)	Eggs are released into the water column
	Sexual-shed eggs (benthic)	Eggs are released onto/into the seabed, either free or maintained on seabed by mucous or other means
	Sexual-brood eggs	Eggs are maintained by adult for protection, either within parental tube or within body cavity
Living habit	Tube-dwelling	Tube may be lined with sand, mucus or calcium carbonate
	Burrow-dwelling	Lives within a permanent or temporary burrow
	Free-living	Not limited to any restrictive structure at any time. Able to move freely within and/or on the sediments
	Crevice/hole/under stones	Adults are typically cryptic, predominantly found inhabiting spaces made available by coarse/rock substrate and/or tubes made by biogenic species or algal holdfasts
	Epi/endo zoic/phytic	Live on other organisms
	Attached to substratum	Attached to larger, stable boulders or rock
Sediment position	Surface	Found on or just above the seabed
	Shallow infauna (0-5 cm)	Species whose bodies are found almost exclusively below sediment surface between 0 and 5 cm sediment depth
	Mid-depth infauna (5-10 cm)	Species whose bodies are partly or exclusively found below sediment surface at a depth generally between 5 and 10 cm
	Deep-infauna (> 10 cm)	Species whose bodies are partly or exclusively found below sediment surface at a depth greater than 10 cm
Feeding mode	Suspension	The removal of particulate food from the water column, generally via filter-feeding
	Surface deposit	Active removal of detrital material from the sediment surface. This class includes species which scrape and/or graze algal matter from surfaces
	Sub-surface deposit	Removal of detrital material from within the sediment matrix
	Scavenger/opportunist	Species which feed upon dead animals
	Predator	Species which actively predate upon animals (including the predation on smaller zooplankton)
Mobility	Sessile	Species in which the adults have no, or very limited, mobility either because they are attached or are limited to a (semi-) permanent tube or burrow
	Swim	Species in which the adults actively swim in the water column (many usually return to the seabed when not feeding)
	Crawl/creep/climb	Capable of some, mostly limited, movement along the sediment surface or rocky substrata
	Burrowers	Infaunal species in which adults are capable of active movement within the sediment
Bioturbation	Diffusive mixing	Vertical and/or horizontal movement of sediment and/or particles
	Surface deposition	Deposition of particles on the sediment surface resulting from e.g. defecation or egestion

		(pseudofaeces) by, for example, filter and surface deposit feeding organisms
	Upward conveyor	Translocation of sediment and/or particles from depth within the sediment to the surface during subsurface deposit feeding or burrow excavation
	Downward conveyor	The subduction of particles from the surface to some depth by feeding or defecation
	None	Do not perform any of the above and/or not considered as contributing to any bioturbative capacity

Table 3: Description of traits and categories used in the biological traits analysis. (after Bolam, 2013 & Bolam, 2014).

Bioturbation potential

Bioturbation is the biogenic modification of sediments through particle reworking and burrow ventilation, and a key mediator of many biogeochemical processes in marine systems which in turn have important effects on ecosystem function and structure (Meysman et al., 2006). The bioturbation potential (BPc) is a metric used as a proxy for bioturbation (Solan et al., 2004; Queiros et al., 2013). Furthermore, it is one of the benthic measures incorporated as a GES indicator in the Belgian environmental targets for the MSFD (Belgische Staat, 2012).

BPc is a metric which combines abundance and biomass data with information about life traits of individual species or taxonomic groups. This information describes modes of sediment reworking (R*i*) and mobility (M*i*) of taxa, two traits known to regulate biological sediment mixing, a key component of bioturbation (Queiros et al., 2013 and references herein). The standardised functional classification table as presented in Queiros et al., 2013) was used to assign our taxa to a certain sediment reworking and mobility mode. This allowed us to calculate the BPc for each sample according to the following formula:

$$\text{BPc} = \sum_{i=1}^{n} \sqrt{\frac{Bi}{Ai}} \times Ai \times Mi \times Ri$$

B*i* and A*i* are the biomass and abundance of species/taxon *i* in a sample.

To test for differences in BPc between impact and reference areas, a two-way Permanova with factors 'year' and 'location' was performed on an Euclidean distance resemblance matrix (Anderson et al., 2008). If significant differences were detected ($p<0.05$), pairwise tests were conducted.

Results

Dredging impact at the different sampling locations

Dredging impact was calculated for all biological sampling stations at the different extraction areas. There was a high correlation between the different dredging parameters calculated across all areas. Correlation between the extracted volume and both the total time dredged and the number of days dredged was highly significant with Spearman r-values of resp. 0.93 ($p<0.0001$) and 0.935 ($p<0.0001$) (Figure 2). Similarly, correlation between total time dredged and number of days dredged had a very high significant Spearman r of 0.999 ($p<0.0001$) (Figure 2). A negative significant correlation existed between these three dredging parameters and the interval between last day dredged and biological sampling time with a Spearman r of approximately -0.7.

Because of these high correlations between the different parameters, we chose to continue with extracted volume in our analysis, together with the dredging interval.

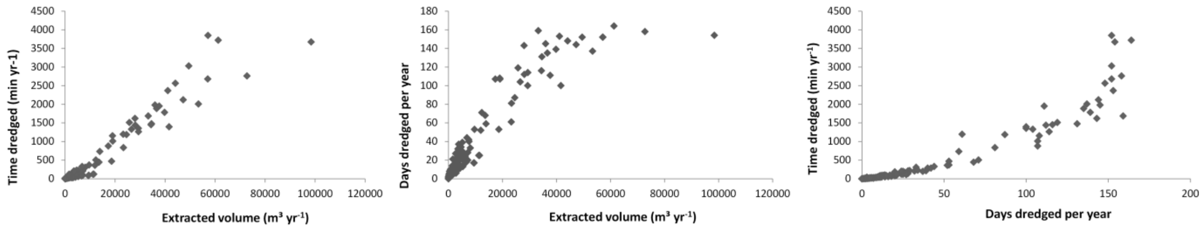

Figure 2: Correlations between the dredging parameters extracted volume (m³), time dredged (min) and days dregded.

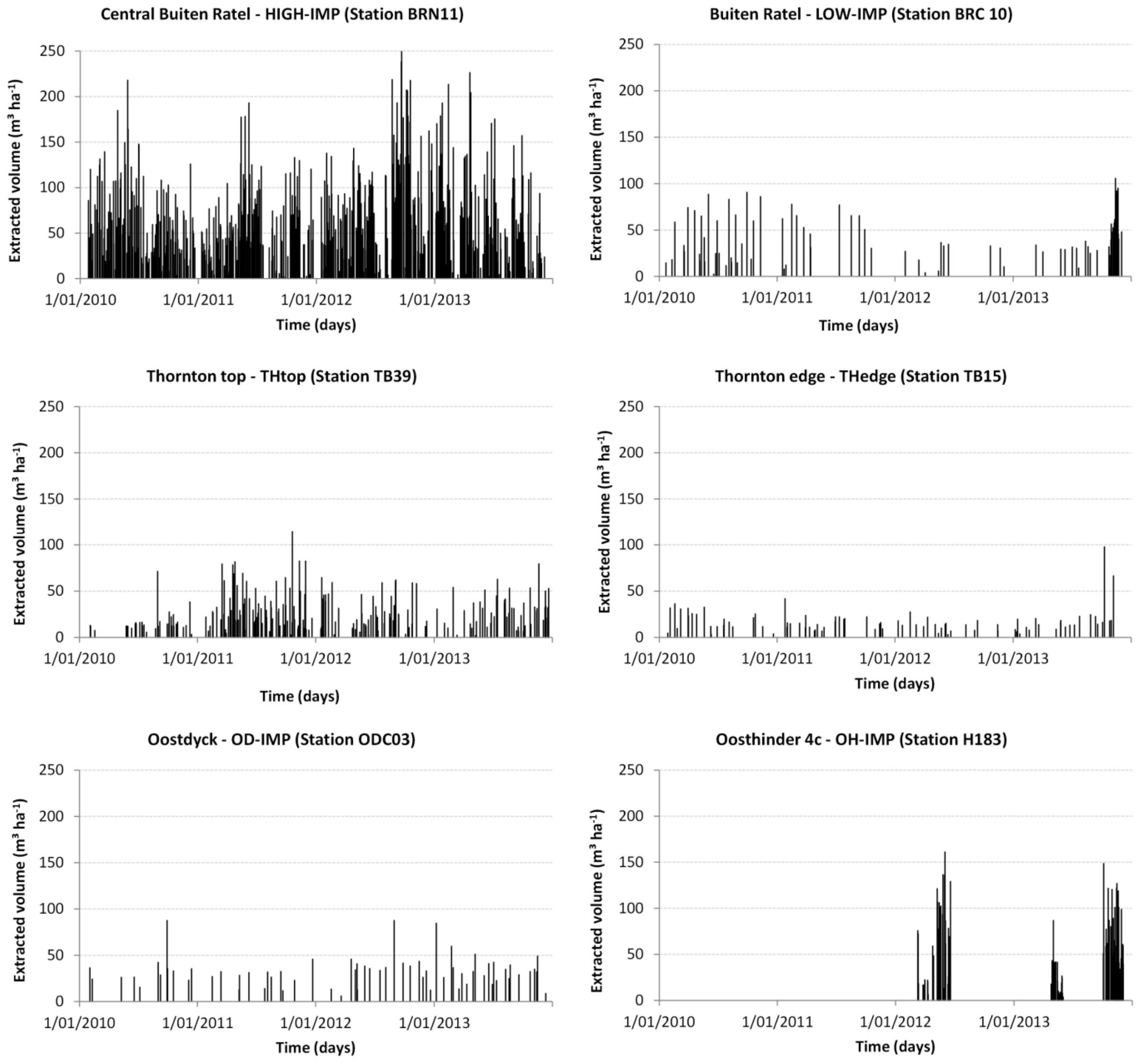

Figure 3: Daily extracted volumes (m³ ha-1) during the period January 2010 - December 2013 at a biological sampling location (buffer of 150 m around the station, 0.07 km² surface area) for the different extraction areas. The visualised biological sampling location (between brackets) is representative for all biological stations and dredging activities occurring in this particular area of the extraction zone.

Extraction volumes at our sampling locations are highest at the central part of the Buiten Ratel (HIGH-IMP) with maximum daily volumes reaching over 280 m³ ha^{-1}. Dredging frequency is very high on the central Buiten Ratel with regular dredging activity during the entire year (Figure 3). A sampling location is on average dredged 112 days per year at an average daily extraction volume of 54 m³ ha^{-1}. At the south of the 'extraction hotspot' on the Buiten Ratel (LOW-IMP) both dredging volume and frequency are much lower. On average, a sampling location is dredged 21 days per year at an average extraction volume of 34 m^3 ha^{-1}. At the end of 2013, extraction frequency is however increasing (Figure 3). Extraction activity at the Thorntonbank is highest at the top with on average 42 days per year extraction activity at the biological sampling location, while at the edge of the bank extraction is low, taking place at on average 10 days per year (Figure 3). Average daily volumes are resp. 24 m^3 and 15 m^3 ha^{-1}. At the Oostdyck, extraction activity is low with on average 11 days dredging per year at an average volume of 33 m^3 ha^{-1}. At zone 4c on the Oosthinder, extraction activity is high and frequent but only in certain periods of the year (Figure 3). Average extraction volume around the biological sampling location is 58 m^3 ha^{-1}. The number of dredging days per year varied between 6 and 50 days (Figure 3) with on average 20 days of dredging per year around the biological sampling locations.

Buiten Ratel

Sediment characteristics

Median grain size was significantly different between the different location groups (pseudo-F=18.297, p=0.0001) with higher median grain size in the HIGH-IMP (avg. 423 µm) and REF-HIGH group (avg. 540 µm) compared to the LOW-IMP (avg. 277 µm) and REF group (avg. 317 µm) (Figure 4 left). Dominant sediment fractions in the HIGH-IMP and REF-HIGH group were medium sand (250-500 µm, resp. avg. 40% and 33%) and coarse sand (500-1000 µm, avg. resp. 24% and 32%), while the dominant sediment fractions in the LOW-IMP and REF group were the fine sand (125-250 µm, avg. resp. 38% and 31%) and medium sand fraction (avg. resp. 58% and 53%) (Figure 4 right).

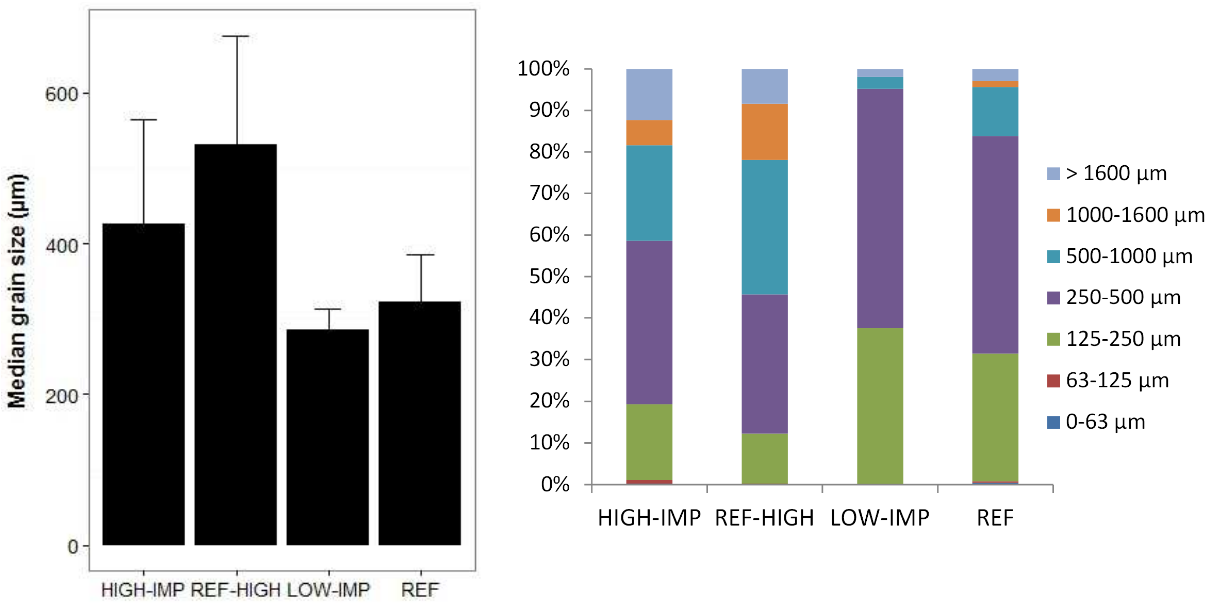

Figure 4: Average median grain size (µm)(left) and average volume percentages of the different sediment fractions (right) for the different sample groups at the Buiten Ratel.

Assemblage structure

Macrobenthic density and biomass were significantly affected by the factor ‘location’ (resp. pseudo-F=6.29, p=0.0026 and pseudo-F=5.75, p=0.0024) but not by ‘year’ or the interaction effect. Pairwise comparisons revealed significantly higher densities at the HIGH-IMP stations compared to the LOW-IMP and REF stations but density at the HIGH-IMP stations was not significantly different from the REF-HIGH stations (Figure 5). For biomass, however, HIGH-IMP stations showed a significantly lower biomass compared to the REF stations (Figure 5). LOW-IMP stations did not differ in density or biomass from the REF stations. Species richness was significantly affected by the factors 'location' (pseudo-F=12.81, p=0.0001) and 'year' (pseudo-F=4.54, p=0.007) but not by the interaction effect. Species richness was significantly higher at the HIGH-IMP stations compared to REF, LOW-IMP and REF-HIGH stations (Figure 5). REF and LOW-IMP stations showed no difference in species richness. For Shannon-Wiener diversity (H') only the 'location' factor was significantly influenced (pseudo-F=5.39, p=0.0027) with both HIGH-IMP and LOW-IMP stations having a significantly higher H' than REF stations (pairwise comparison resp. p=0.0003 and p=0.024).

Dredging intensity was significantly positive correlated with species richness (Spearman r=0.41, p<0.0001), density (Spearman r=0.2, p=0.017) and H' (Spearman r=0.46, p<0.0001). While it was slightly negative correlated with biomass (Spearman r=-0.21, p=0.013).

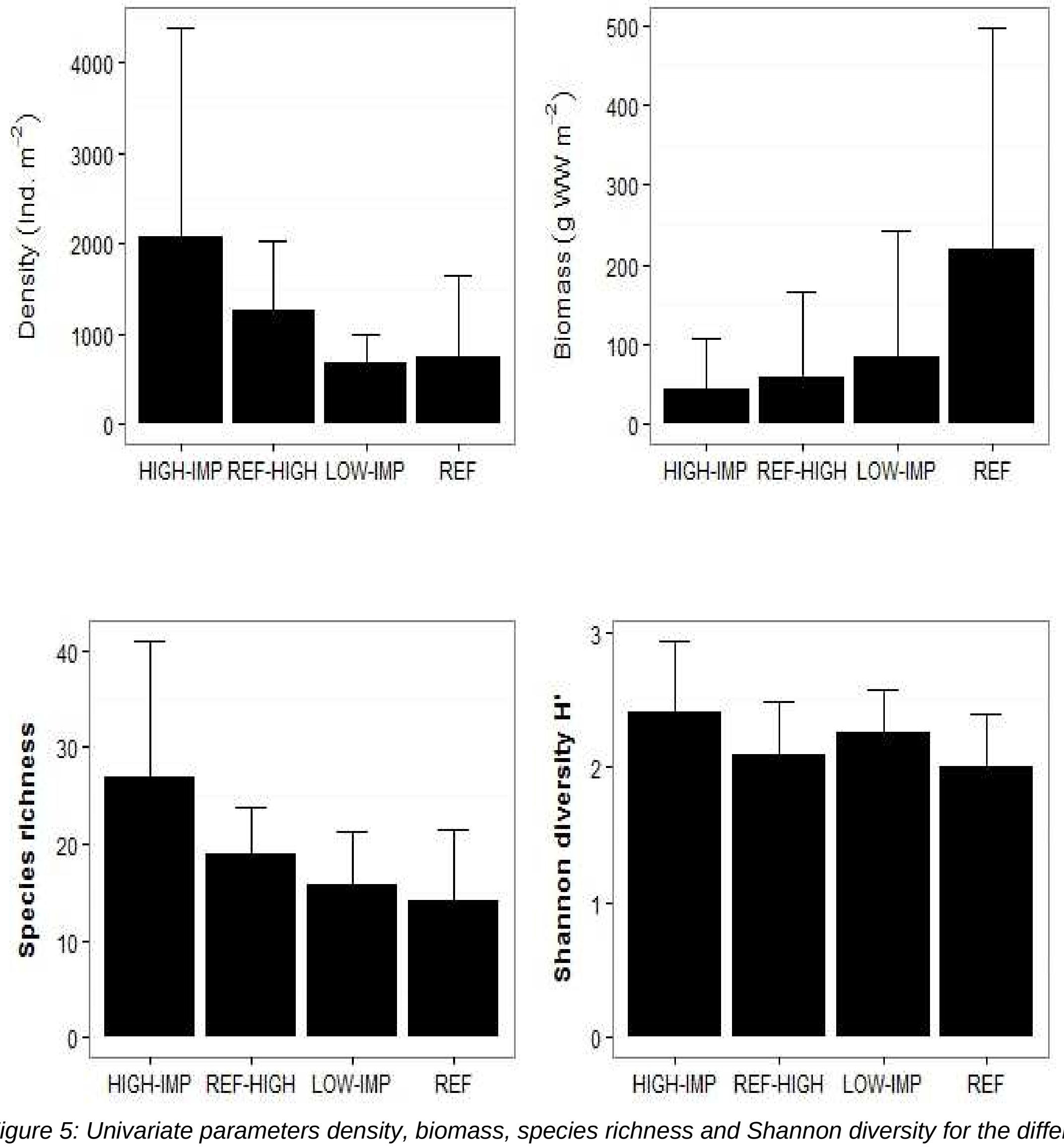

Figure 5: Univariate parameters density, biomass, species richness and Shannon diversity for the different sample groups at the Buiten Ratel.

The multivariate community composition was significantly affected by the factor 'location' across all years (Anosim R=0.423, p=0.0001). Pairwise tests showed that differences were significant between all groups, except between the REF and LOW-IMP group. Differences in community composition were largest between HIGH-IMP and REF (R=0.623), and least different between HIGH-IMP and REF-HIGH (R=0.364) (Table 4 and Figure 6).

The shifts in community composition were confirmed by SIMPER (impact across all years). *Nephtys cirrosa*, *Magelona johnstoni*, *Bathyporeia elegans* and *Urothoe brevicornis* belonged to the 5 most important species with respect to within-group similarity in both the LOW-IMP and REF group. All are typical for clean medium sands. While in the HIGH-IMP group, except for *Urothoe brevicornis*, different species belonged to the top 5 with respect to contributing most to the within-group similarity. Species contributing most to within-group similarity for the HIGH-IMP group were *Lanice conchilega*, *Spio* sp, *Nototropis swammerdamei* and *Eumida sanguinea*. These species were not listed or had a limited contribution (*Spio* sp.) to the within-group similarity of the REF-HIGH group, where *Hesionura elongata*, Oligochaeta sp. and *Nephtys cirrosa* were the 3 species contributing most to within-group similarity. The species for the HIGH-IMP group showed a mixture of species characteristic for medium sands and muddy sands, probably attracted by the increased presence of fine sediments caused by the overflow during dredging. Species in the REF-HIGH samples were more interstitial species, and other species characteristic for coarser sediments e.g. *Ophelia borealis*.

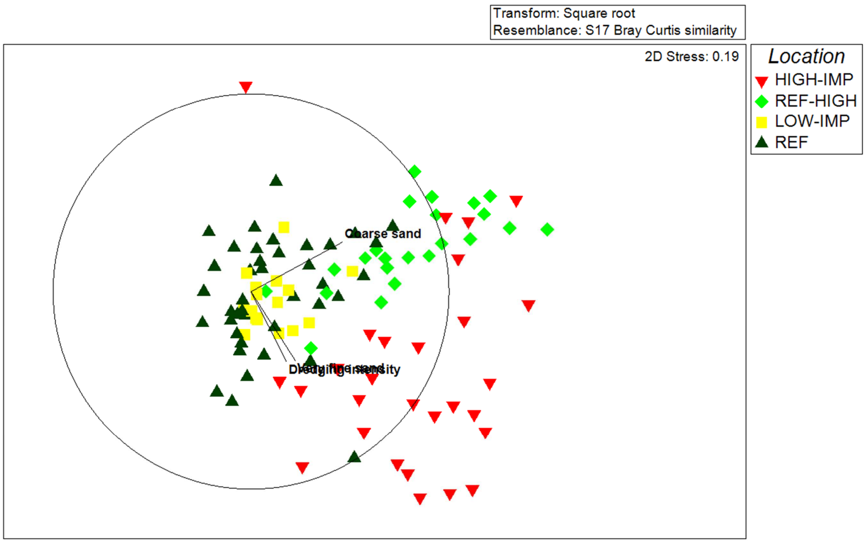

Figure 6: MDS plot based on species abundance data of the Buiten Ratel with indication of the different sample groups.

The environmental variables explaining together 24 % of the multivariate community composition were: dredging intensity (7%), the coarse sand fraction (14%) and the very fine sand fraction (3%). All increased towards the HIGH-IMP samples (Figure 6).

BUITEN RATEL	HIGH-IMP	REF-HIGH	LOW-IMP	REF
HIGH-IMP		**0.364**	**0.469**	**0.623**
REF-HIGH	0.049		**0.619**	**0.467**
LOW-IMP	0.099	**0.239**		-0.171
REF	**0.268**	**0.268**	-0.139	

Table 4: Pairwise ANOSIM R-values between the different sample groups. Values in the upper half (in black) are based on the species composition matrix, values in the lower half (in grey) are based on the traits composition matrix. Significant values are in bold.

BEQI

The BEQI scores for the HIGH-IMP area indicated that there was an impact of dredging on the benthic ecosystem, especially on species composition, density and biomass (Table 5). Densities were higher than expected as based on the variability within the reference locations (Figure 5). Biomass scored bad in comparison with the REF area. This is partly caused by the nearly absence of *Echinocardium cordatum* in the HIGH-IMP area. But even without this species, biomasses in the highly impacted area were much lower than within the REF area. Species composition scored moderate compared with the REF-HIGH area which is in accordance with the multivariate analyses. However, the good status when using the REF area contradicts the MDS plot and the SIMPER analysis. This is probably caused by the high variability within both the HIGH-IMP and the REF area, which causes the indicator not to pick up the signal of change in community composition. Number of species scored high because more species were present in the HIGH-IMP area compared to both reference areas.

For the LOW-IMP area, except for biomass, the status for the different parameters is high, and the overall status is good. The moderate status for biomass was the result of less or smaller *Echinocardium cordatum* in the LOW-IMP area compared to the REF area. The lower dredging intensity in this area of the Buiten Ratel had thus no or a very limited impact on the benthic ecosystem, according to the BEQI indicator.

Area	Control	Similarity EQR	S EQR	Density EQR	Biomass EQR	Final EQR
Central Buiten Ratel (HIGH-IMP)	REF-HIGH	**0.49**	**1**	**0.388**	0.607	**0.621**
Central Buiten Ratel (HIGH-IMP)	REF	**0.61**	**1**	**0.185**	**0.181**	**0.494**
Buiten Ratel flank (LOW-IMP)	REF	**0.807**	**0.83**	0.825	0.535	**0.749**

Table 5: BEQI scores for the parameters similarity, species number (S), density and biomass, and the overall BEQI score for the area. Values in bold indicate that the power to detect changes is good, regular font indicates a moderate power to detect changes. Blue: high status; green: good status; yellow: moderate status; orange: poor status; red: bad status.

Assemblage functioning

Traits composition

The different location groups were more closely grouped when based on traits composition compared to species composition (Figure 7). Nevertheless, the trait composition of the benthic community was significantly affected by the factor 'location' across all years (ANOSIM R=0.158, p=0.001), but the lower R-value indicates the greater similarity in traits composition compared to species composition. Pairwise tests between the 'location' groups revealed significant differences in trait composition between the REF samples on the one hand, and the HIGH and REF-HIGH samples on the other hand, and between the LOW-IMP samples and the REF-HIGH samples but the R-values are very low indicating a large overlap in traits composition between these groups (Table 4). No significant differences were detected between the REF and LOW-IMP samples, and also differences between HIGH and REF-HIGH samples were not significant.

When looking at SIMPER results, trait composition with respect to within-group similarity is highly similar between the different groups which was in accordance with the observed low Anosim R-values. 'Planktotrophic' and 'free living', respectively from traits Larval type and Living habit are in all impact groups amongst the five most important traits with respect to within-group similarity. The small differences between the sample groups result mainly from differences in contribution% with respect to the within-group similarity or from differences in average abundance of the traits between the sample groups.

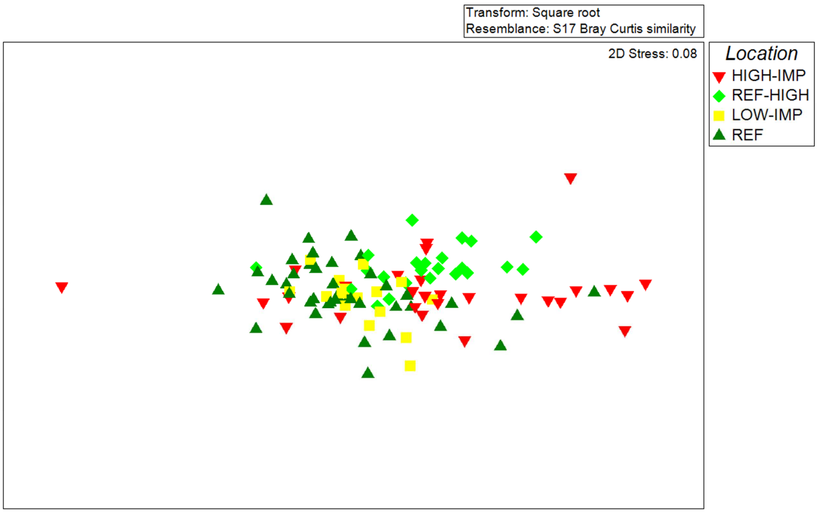

Figure 7:MDS plot based on traits abundance data of the Buiten Ratel with indication of the different sample groups.

BPc

Bioturbation potential of the macrobenthic community was not significantly affected by any of the factors ‘location’, ‘year’ or the interaction factor (Figure 8). Spearman correlation showed as well no significant correlation between BPc and dredging intensity. However, a slightly negative significant correlation was detected with median grain size (Spearman r=-0.27, p=0.0012). Thus, with a lower median grain size, a higher BPc might be expected.

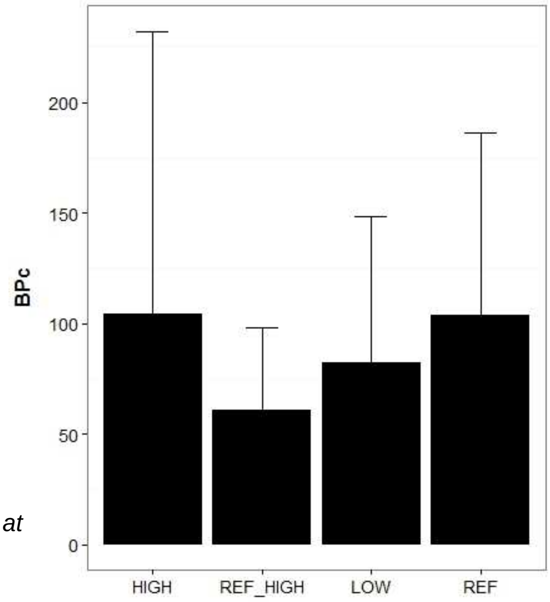

Figure 8: Average BPc for the different sample groups at the Buiten Ratel.

Oostdyck

Sediment characteristics

Median grain size was significantly affected by the factor ‘location’ (Pseudo-F=33.51, p=0.0001), not by ‘year’ or the interaction factor. Pairwise tests showed that median grain size differed significantly between all groups. We observed a decrease in median grain size from north to south, indicating a natural gradient in sediment grain size over the bank: the reference samples in the north of the Oostdyck were the coarsest with an average median grain size of 431 µm, the impact samples had an average median grain size of 346 µm, and the reference samples in the south of the Oostdyck had an average median of 310 µm (Figure 9). The dominant grain size fraction was the medium sand (250-500 µm) in all three sample groups: 64% in REF-N, 79% in IMP and 70% in REF-S. In REF-N, the coarse sand (500-1000 µm) was with average 31% the second biggest fraction, while for REF-S, the fine sand (125-250 µm) with on average 27% was the second biggest fraction. In the IMP samples, fine sand (avg. 12%) and coarse sand (avg. 7%) were the second and third most important fractions (Figure 9).

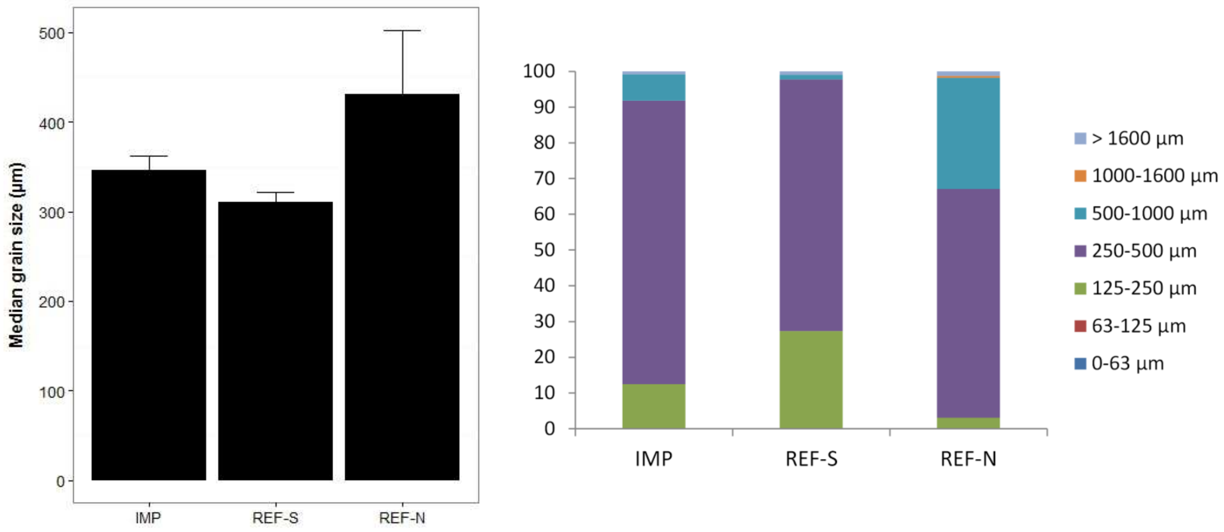

Figure 9: Average median grain size (µm) (left) and average volume percentages of the different sediment fractions (right) for the different sample groups at the Oostdyck.

Assemblage structure

Macrobenthic densities were significantly affected by the factor ‘location’ (pseudo-F=7.86, p=0.0015), but not by ‘year’ or the interaction factor. Macrobenthic densities were significantly lower in the impact area compared to both reference areas REF-N and REF-S (Figure 10). Shannon-Wiener diversity H’ was significantly affected by the factor ‘location’ (pseudo-F=3.48, p=0.04) with a significantly higher H’ in the REF-N samples compared to the REF-S samples (Figure 10). No significant differences were observed between the IMP and the reference samples. The other univariate parameters, biomass and species richness were not affected by the factors ‘location’, ‘year’ or the interaction factor.

A small, negative but significant correlation was detected between both species richness and Shannon-Wiener diversity, and the dredging intensity (resp. Spearman r=-0.29, p=0.014 and r=-0.25, p=0.042). With density, a bigger significant negative correlation with dredging intensity was observed (Spearman r=-0.38, p=0.0012) which might indicate that, although dredging intensity is low at the Oostdyck, it may negatively impact species densities.

Multivariate community composition was significantly influenced by the factor ‘location’ across all years (Anosim R=0.535, p=0.0001). Significant differences were detected between communities at the impact locations (IMP), and communities at both reference locations (REF-S, R= 0.42 and REF-N, R=0.402). But communities were even more different between both reference locations (REF-N and REF-S, R=0.824) (Table 6). The multivariate community pattern visualises the sediment gradient over the Oostdyck sandbank with coarser sediments in the north, gradually changing to finer sediments towards the south (Figure 11).

Oostdyck	IMP	REF-SOUTH	REF-NORTH
IMP		**0.42**	**0.402**
REF-SOUTH	**0.23**		**0.824**
REF-NORTH	0.122	**0.499**	

Table 6: Pairwise ANOSIM R-values between the different sample groups. Values in the upper half (in black) are based on the species composition matrix, values in the lower half (in grey) are based on the traits composition matrix. Significant values are in bold.

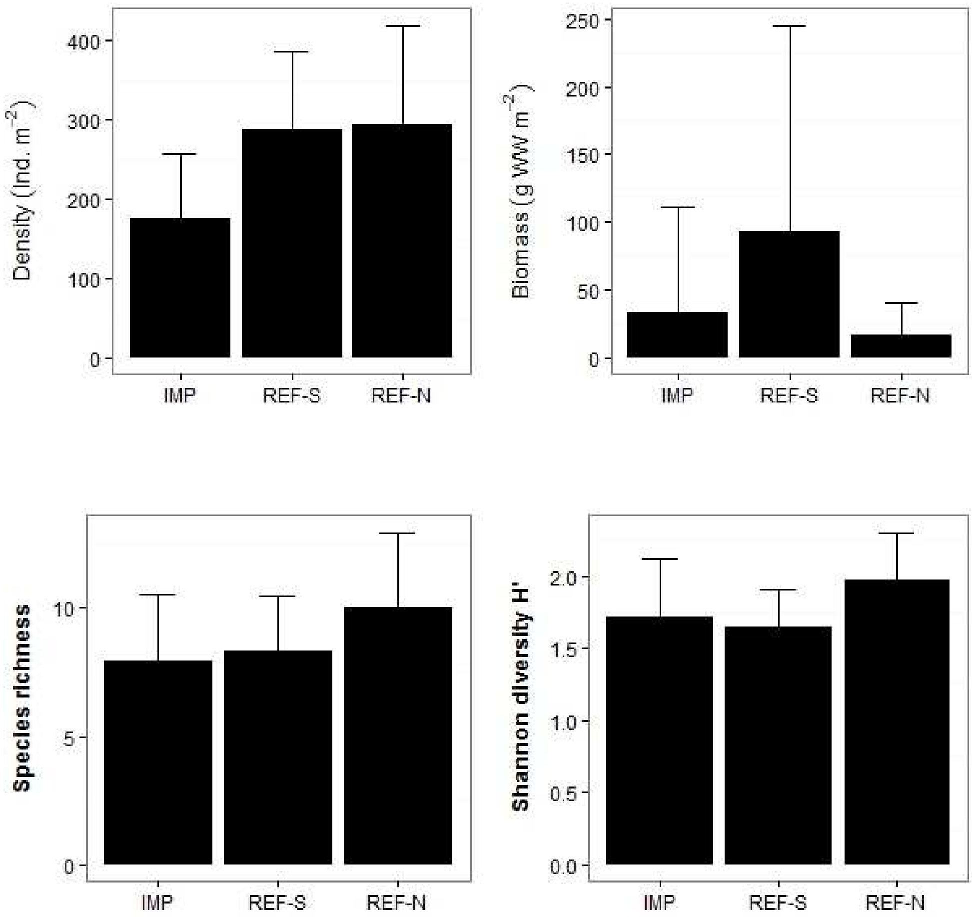

Figure 10: Univariate parameters density, biomass, species richness and Shannon diversity for the different impact and reference groups at the Oostdyck.

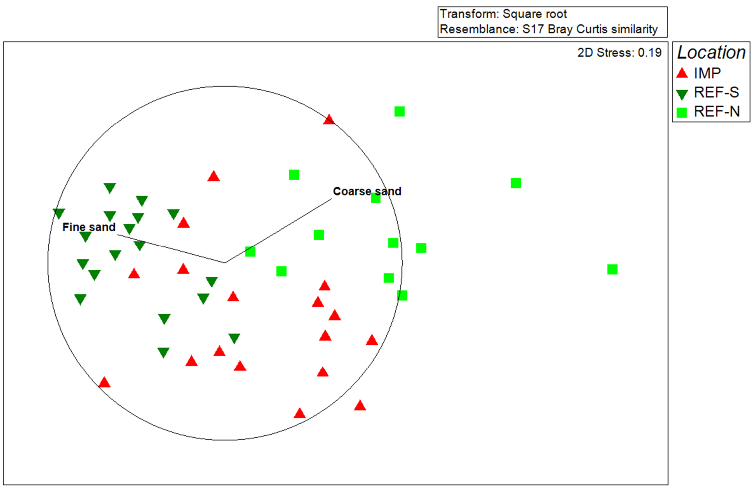

Figure 11: MDS plot of species abundance data of the Oostdyck with indication of the different sample groups.

The shift in community composition was confirmed by SIMPER (impact across all years). *Nephtys cirrosa* was in both the IMP as both reference communities (REF-S and REF-N) an important contributor to within-group similarity. Other species contributing most to the within-group similarity for the REF-SOUTH community, e.g. *Bathyporeia elegans* and *Echinocardium cordatum*, were typical for medium sands. The IMP community reflected the gradient from coarser to finer sediments in its species composition by a mixture of medium and coarser sand species such as resp. *Bathyporeia elegans* and *Ophelia borealis*. While in the REF-N community, interstitial species typical for coarse sands *Hesionura elongata* and *Protodriloides chaetifer* contributed most to within-group similarity.

The observed multivariate pattern based on species composition was best explained by the fine sand (24%) and the coarse sand fraction (8%), together explaining 32% of the observed variation (Figure 11). The dredging had no significant impact on the species composition.

BEQI

The final BEQI score indicated that the impact of the dredging on the Oostdyck was within acceptable limits (> 0.6), since the benthic ecosystem scored overall 'good' independent of the reference area used (Table 7). Thus, the observed variation in the impact area was overall within the boundaries of the variability within the reference area.

Since the natural variability in sediments was high in the area, using only one reference area as control resulted in moderate scores for all parameters except for species number (Table 7). This shows the importance of the use of relevant reference areas.

The moderate score for density was detected regardless of the reference area used. This suggests that the dredging impacted the macrobenthic densities. Because densities in the impact area were lower than expected based on the variability occurring in both reference area (Table 7 and Figure 10).

Area	Control	Similarity EQR	S EQR	Density EQR	Biomass EQR	Final EQR
Oostdyck	REF-SOUTH	**0.597**	**1**	**0.427**	0.499	**0.631**
Oostdyck	REF-NORTH	**0.563**	**1**	**0.473**	0.511	**0.628**
Oostdyck	REF-SOUTH & -NORTH	**0.677**	**0.846**	**0.434**	0.726	**0.671**

Table 7: BEQI scores for the parameters similarity, species number (S), density and biomass, and the final BEQI score for the area (Oostdyck). Values in bold indicate that the power to detect changes is good, regular font indicates a moderate power to detect changes. Blue: high status; green: good status; yellow: moderate status.

Assemblage functioning

Traits composition

The trait composition of the benthic community was significantly affected by the factor 'location' across all years (Anosim R=0.267, p=0.001). The R-value is considerably smaller compared to the R-value based on the species composition matrix, indicating a bigger overlap in traits composition between the different sample groups (Figure 12). Pairwise tests revealed that REF-S differed significantly from both IMP (R=0.23) and REF-N (R=0.499) in trait composition.

SIMPER showed that the traits contributing to the within-group similarity are very similar for the different sample groups and dissimilarity percentages between sample groups are rather small (≤ 25%). 'Free-living', 'diffusive mixing' and 'shallow infauna', respectively from traits Living habit, Bioturbation and Sediment position, were the most important traits in terms of within-group similarity for all three sample groups. Significant differences are mainly based on differences in abundance of the traits between the different sample groups.

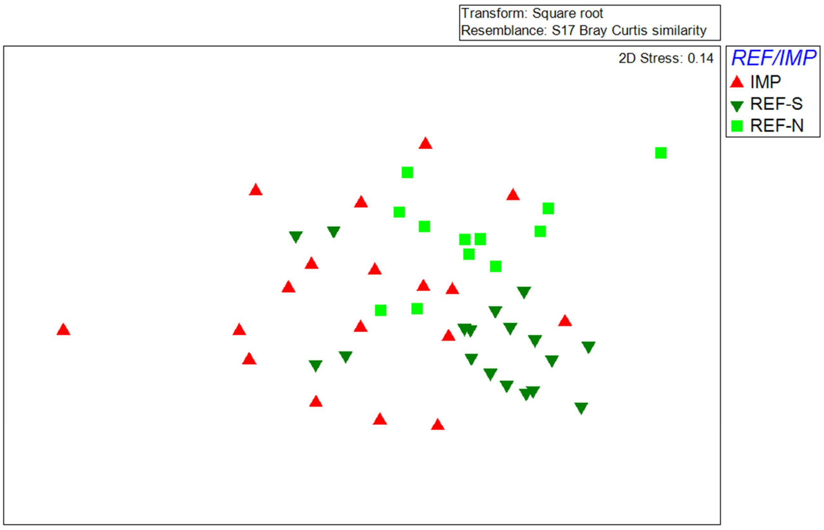

Figure 12: MDS plot based on traits abundance data of the Oostdyck with indication of the different sample groups.

BPc

Bioturbation potential was significantly affected by the factor 'location' (Pseudo-F=5.35, p=0.0065), not by the factor 'year' or the interaction factor. The bioturbation potential was noticeably higher in the REF-S group compared to both the REF-N and IMP group (Figure 13). The higher BPc in the REF-S samples is due to the occurrence of *Echinocardium cordatum* in these samples, which is an important bioturbator and not or less present in the other sample groups.

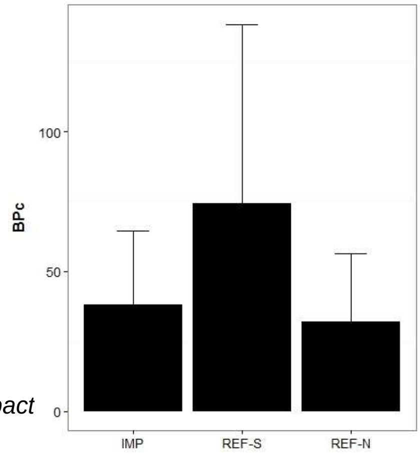

Figure 13: Bioturbation potential for the different impact and reference groups at the Oostdyck.

Thorntonbank

Sediment characteristics

Median grain size is not significantly different between the different sample groups with an average median grain size around 400 µm (Figure 14). The dominant grain size fraction is the medium sand fraction (250 – 500 µm) which constitutes around 60% of the different fractions, followed by the very coarse sand fraction (1000 – 1600 µm) which amounts approximately 20% (Figure 14).

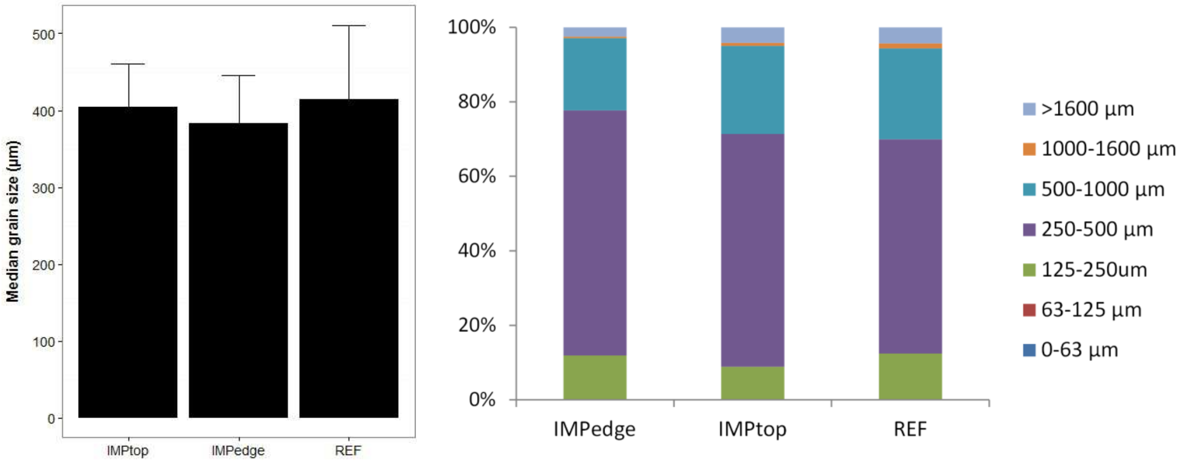

Figure 14: Average median grain size (µm)(left) and average volume percentages of the different sediment fractions (right) for the different sample groups at the Thorntonbank.

Assemblage structure

None of the univariate parameters (density, biomass, species richness and Shannon diversity) were significantly affected by the factor 'location', nor by the interaction factor. This despite the observed lower average biomass (caused by the absence of *E. cordatum*) in the most heavily impacted stations on the top of the Thornton bank (Figure 15). The only significant effect detected within the factor 'year' was for the Shannon-Wiener diversity, but this was both in the impact samples as in the reference samples.

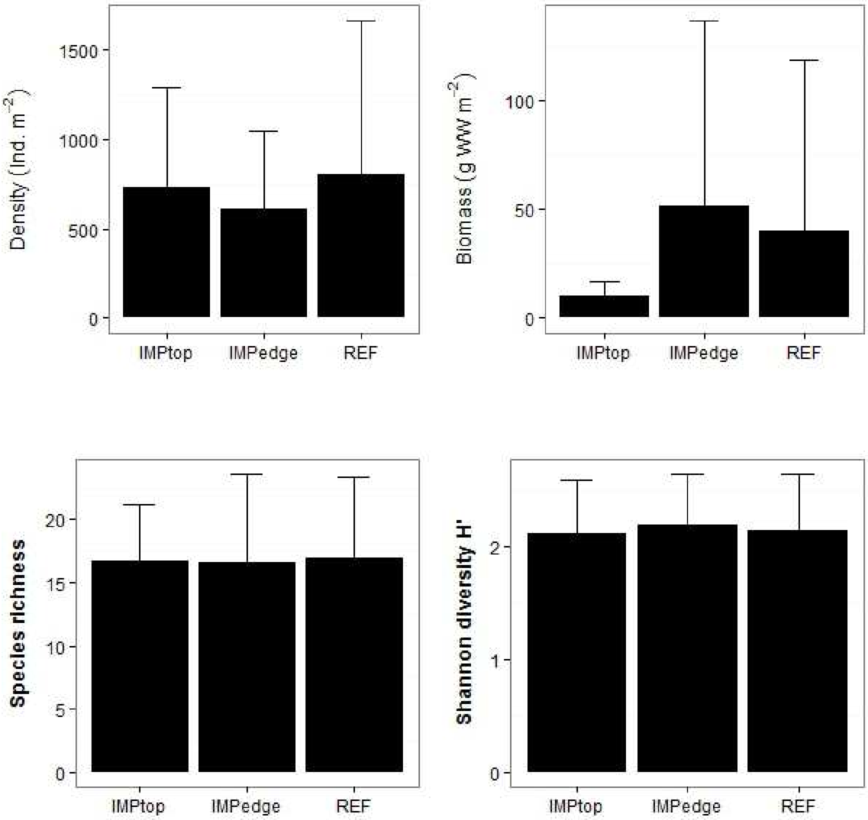

Figure 15: Univariate parameters density, biomass, species richness and Shannon-Wiener diversity for the different sample groups at the Thorntonbank.

No significant correlations were observed between the univariate parameters and dredging intensity, except for biomass. Biomass was slightly negative correlated with dredging intensity (Spearman r=-0.2, p=0.04).

Multivariate community composition was very similar between both impact groups and the reference group (two way crossed ANOSIM R=0.034, p=0.26) (Figure 16). So, the benthic community composition was not influenced by the dredging. The interannual variation was significant, but was very small with an overall R of 0.1.

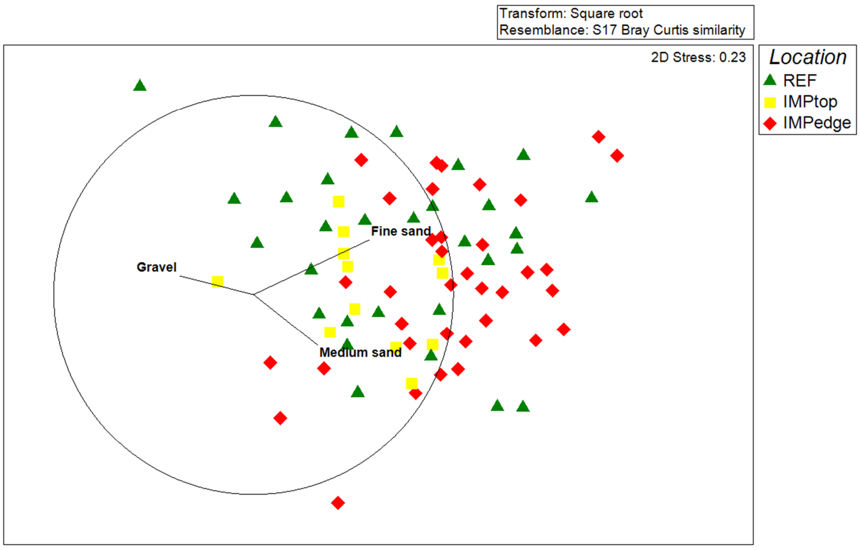

Figure 16: MDS plot of species abundance data of the Thorntonbank with indication of sample groups.

The species listed as contributing most to within-group similarity were very similar for the different groups. *Nephtys cirrosa*, *Spio* sp. and *Hesionura elongata* were among the most important common species in all sample groups.

The observed multivariate pattern was best explained by the sediment. In total 18% of the observed variation was explained by fine sand (10%), medium sand (5.5%) and the gravel fraction (>1600 µm, 2.5%) (Figure 16). Dredging intensity did not affect the species community at the Thortonbank.

BEQI

The BEQI indicator scored overall good for both the more impacted top area and the lower impacted edge area. Only for biomass, the Thorntonbank top area scored moderate, since the biomass in the impacted area was lower than expected of the variability within the reference area. For all other parameters, scores ranged from good to high for both the top and the edge area.

Area	Control	Similarity EQR	S EQR	Density EQR	Biomass EQR	Final EQR
Thornton top (MODERATE impact)	REF	**0.703**	**0.657**	0.834	0.562	**0.689**
Thornton edge (LOW impact)	REF	**0.664**	**0.95**	**0.693**	0.76	**0.767**

Table 8: BEQI scores for the parameters similarity, species number (S), density and biomass, and the final BEQI score for the impact areas at the Thorntonbank. Values in bold indicate that the power to detect changes is good, regular font indicates a moderate power to detect changes. Blue: high status; green: good status; yellow: moderate status.

Assemblage function

Traits composition

The trait composition of the benthic community was not affected by the factor 'location' (Anosim R=0.028, p=0.26), and very little affected by the factor 'year' (R=0.103, p=0.002). Thus, both impact groups and the reference group were functionally similar (Figure 17).

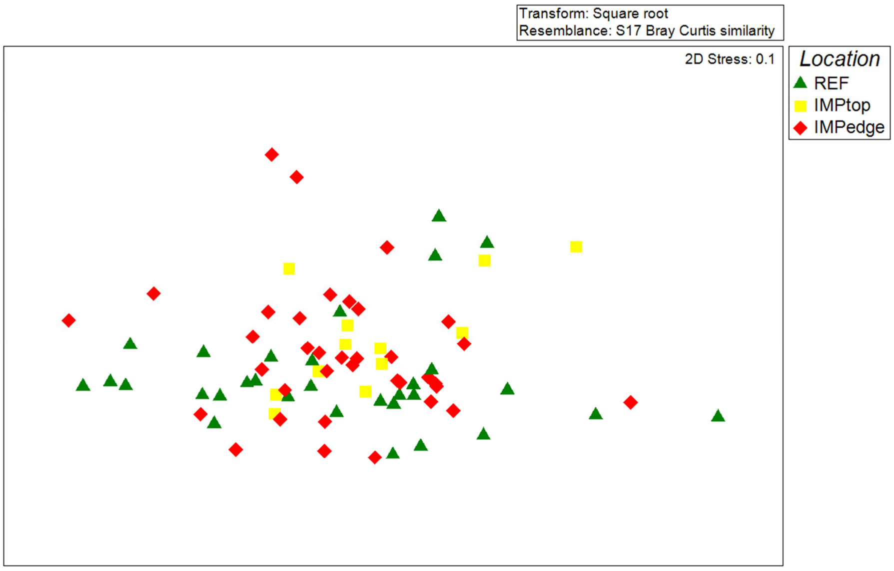

Figure 17: MDS plot of the traits abundance cdata of the Thorntonbank with indication of the different sample groups.

BPc

The bioturbation potential did not differ significantly between the different sample groups, nor between the different sampling years. Although, the bioturbation potential is on average a bit lower at the most impacted top area (42 ± SD 24) compared to the lower impacted edge area (55 ± SD 38) and the reference area (62 ± SD 46) (Figure 18). Furthermore, the BPc was slightly negative correlated with the dredging intensity (Spearman r=-0.21, p=0.04). Again, this is caused by the nearly absence of *Echinocardium cordatum* in the IMP top group.

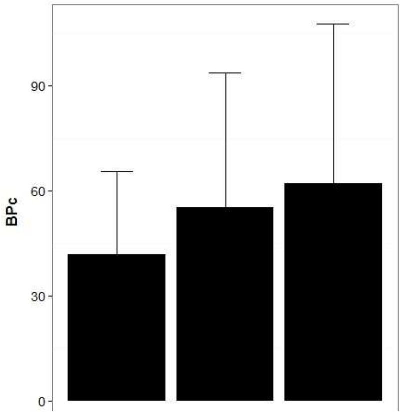

Figure 18: Bioturbation potential for the different impact and reference groups at the Thorntonbank.

Oosthinder

Sediment characteristics

Across all years, median grain size was significantly smaller for the REF-BB group (+/- 350 µm) compared to the IMP and REF group (resp. +/- 370 µm and +/-380 µm). The factor 'year' or the interaction factor did not significantly affect the median grain size (Figure 19). In all three groups, medium sand was the dominant grain size fraction over the years (IMP=62%, REF=74% and REF_BB=76%), followed by 16% coarse sand in both the IMP and REF group, and by fine sand (125-250 µm) in REF-BB (12%) (Figure 19).

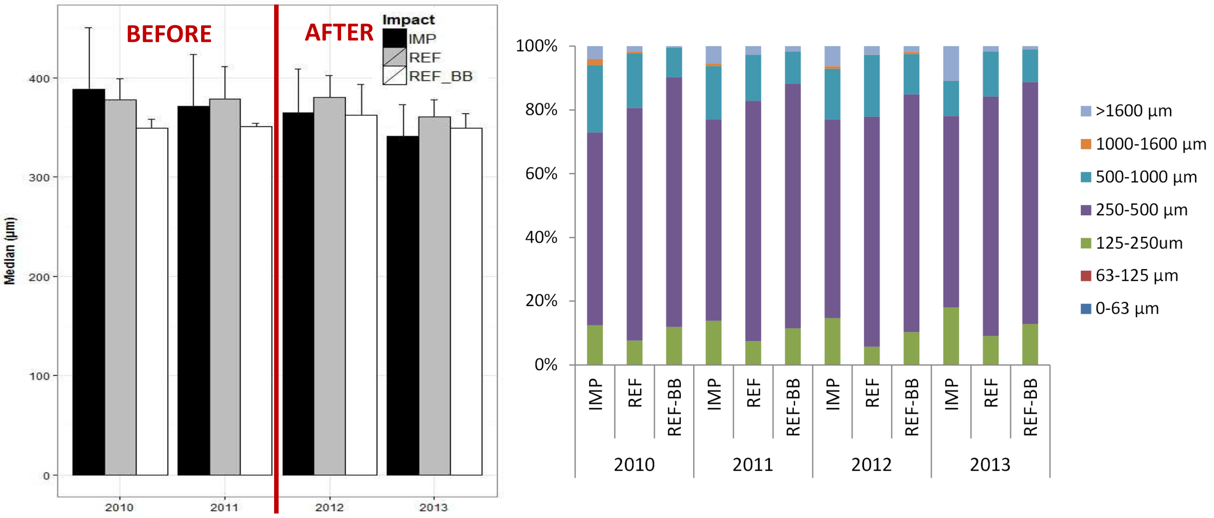

Figure 19: Average median grain size (µm) (left) and average volume percentages of the different sediment fractions (right) for sample groups during the period 2010-2013 with indication before/after dredging.

Assemblage structure

None of the univariate measures was significantly affected by the interaction factor 'location x year'. Thus the dredging, which started in March 2012, had not a measurable impact on macrobenthic density, biomass, species richness and Shannon-Wiener diversity. However, biomass in the impact area was consistently lower after dredging started compared to both reference areas. The only significant effect detected was a lower species richness in the REF-BB group compared to both the IMP and REF group throughout the entire sampling period (2010-2013) (Figure 20). Further, no significant changes between years or sample groups were detected for any of the univariate measures.

None of the univariate parameters were significantly correlated with dredging intensity indicating again that dredging did not affect the structural metrics of the benthic community. Small significant positive correlations were observed between median grain size on the one hand and species number and density on the other hand (resp. Spearman r = 0.21, p=0.012 and r=0.22, p=0.008), which is in accordance with the observed lower species numbers and densities in REF-BB samples compared to IMP and REF samples.

Multivariate community composition was overall significantly different between the different sample groups but with a low overall R-value (ANOSIM R=0.245, p=0.001). Pairwise tests showed that most sample groups differed significantly but R-values were very small indicating a large degree of overlap (Table 9, Figure 21). The only significant changes in community composition were observed between the REF-BB in the period before dredging, and both IMP, REF and REF-BB after dredging (R≥0.45) (Table 9). All other pairwise tests between groups showed no large changes in community composition over time (very small R-values) indicating that the dredging did not influence community composition of the dredging area on the Oosthinder at present.

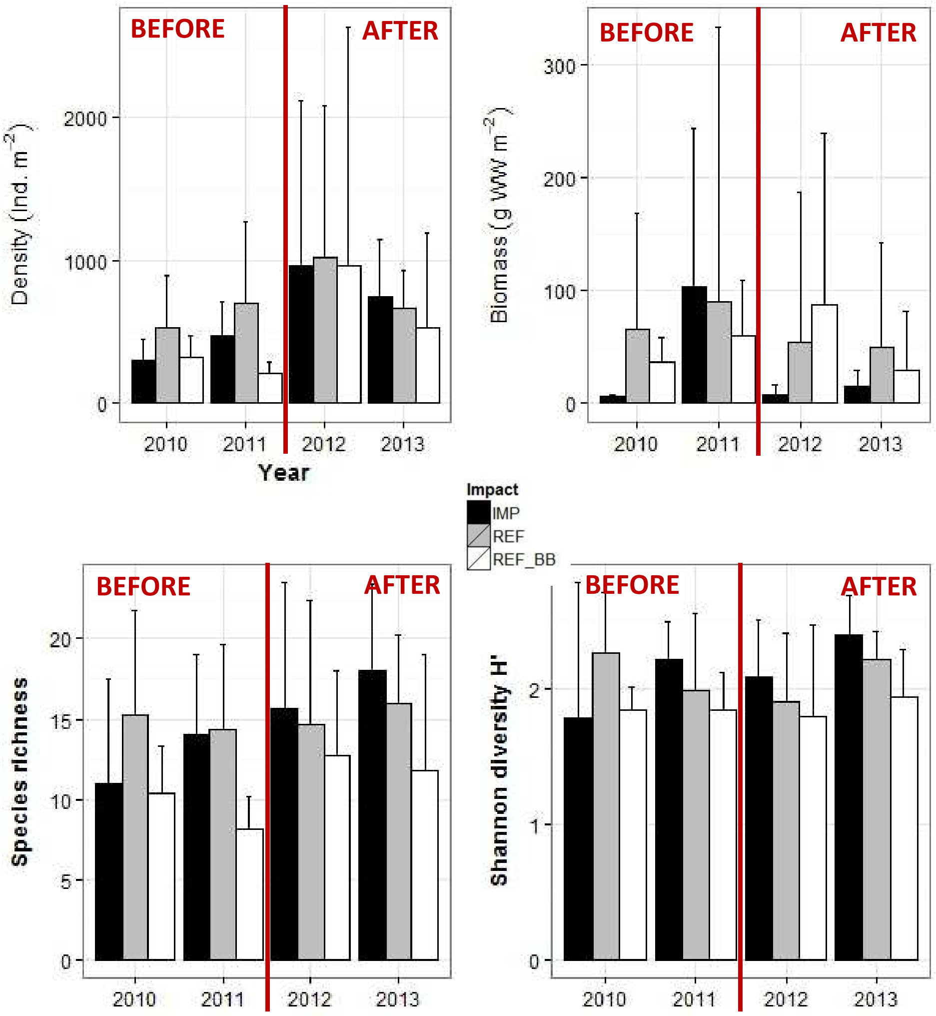

Figure 20: Univariate parameters density, biomass, species richness and Shannon diversity for the impact and both reference groups before dredging started (2010-2011) and after dredging started (2012-2013) at the Oosthinder.

OOSTHINDER	IMP Before	IMP After	REF Before	REF After	REF-BB Before	REF-BB After
IMP-Before		0.127	**0.114**	**0.201**	**0.342**	**0.281**
IMP-After	0.022		**0.231**	**0.175**	**0.511**	**0347**
REF-Before	-0.014	0.004		**0.085**	**0.304**	**0.091**
REF-After	0.075	0.018	0.025		**0.452**	**0.072**
REF-BB-Before	**0.126**	**0.263**	**0.216**	**0.299**		**0.474**
REF-BB-After	0.005	**0.086**	0.019	0.041	0.068	

Table 9: Pairwise ANOSIM R-values between the different sample groups both before and after the start of dredging. Values in the upper half (in black) are based on the species composition matrix, values in the lower half (in grey) are based on the traits composition matrix. Significant values are in bold.

SIMPER showed that the differences in the REF-BB group were caused by the absence of Fabriciidae (different from REF after dredging and REF-BB after dredging), and the high abundance of *Echinocardium cordatum* (absent in IMP after dredging). In general, the community present in all groups resembled the *Ophelia borealis* community as defined by Van Hoey et al. (2004).

Sediment characteristics determined the observed multivariate species composition, and the pattern was not affected by the impact of dredging. In total only 14% of the observed variance in species community is explained by the grain size fractions medium sand (7%), fine sand (5%) and very fine sand (2%) (Figure 21).

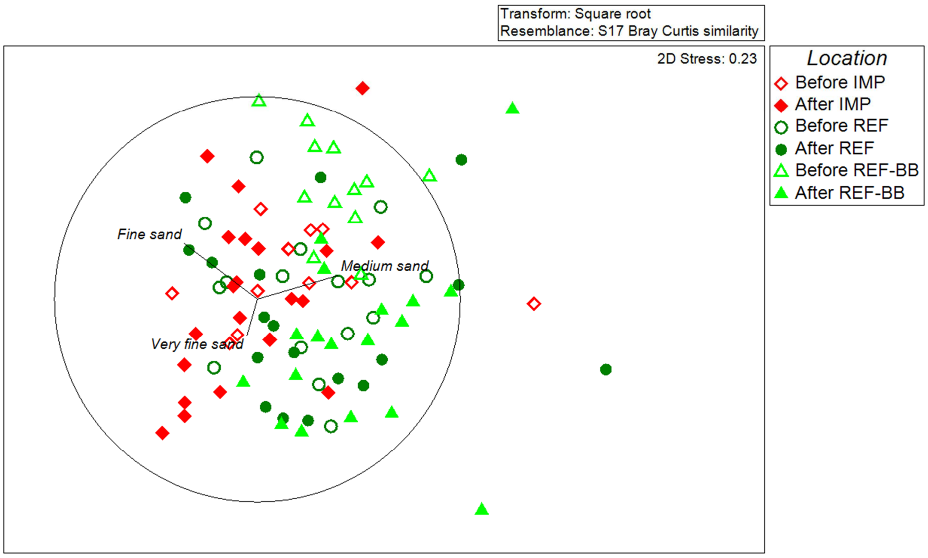

Figure 21: MDS plot of species abundance data of the Oosthinder with indication of sample groups before and after the start of dredging.

BEQI

The BEQI scored overall 'good' for the Oosthinder impact area independent of the reference samples used. The reference samples on the Oosthinder (REF) were most alike with the impact samples (IMP), and scored for all parameters good to high (Table 10).

Area	Control	Similarity EQR	S EQR	Density EQR	Biomass EQR	Final EQR
Oosthinder (Before impact)	REF	**0.72**	**0.822**	**0.644**	n.r.	**0.794**
Oosthinder (After impact)	REF	**0.616**	**1**	**0.979**	n.r.	**0.799**
Oosthinder (Before impact)	REF_BB	**0.757**	**0.968**	**0.776**	0.482	**0.746**
Oosthinder (After impact)	REF_BB	**0.595**	**1**	0.901	0.293	**0.697**

Table 10: BEQI scores for the parameters similarity, species number (S), density and biomass, and the final BEQI score for the impact area at the Oosthinder. Values in bold indicate that the power to detect changes is good, regular font indicates a moderate power to detect changes. (N.r) not reliable: insufficient power to detect changes. Blue: high status; green: good status; yellow: moderate status; orange: poor status.

Sediments in the Bligh Bank reference area (REF-BB) were finer, which gave even before dredging started, a moderate score for biomass caused by a lower abundance of the sea-urchin *E. cordatum* on the Oosthinder. After dredging started the score for biomass was poor, and moderate for similarity both due to the complete absence of *E. cordatum* in the impacted area (Table 10).

Assemblage function

Traits composition

Trait composition of the macrobenthic community was very similar between the different groups (ANOSIM R=0.076, p=0.005). All of the pairwise tests were not significant or had very low R-values, indicating a large degree of overlap in traits composition (Table 9, Figure 21). Thus trait composition was not affected by dredging at the Oosthinder area.

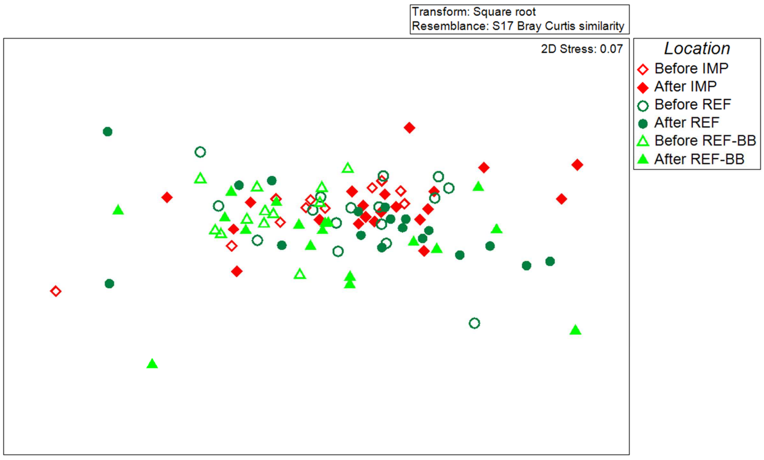

Figure 22: MDS plot of the trait abundance data of the Oosthinder with indication of samples groups before and after the start of dredging.

BPc

No significant changes were detected in bioturbation potential for the factors 'location', 'year' or the interaction factor (Figure 23). Consequently, dredging did thus not affect the bioturbation potential of the benthic community. We did however observe a small negative significant correlation between BPc and median grain size (Spearman r=-0.2, p=0.017).

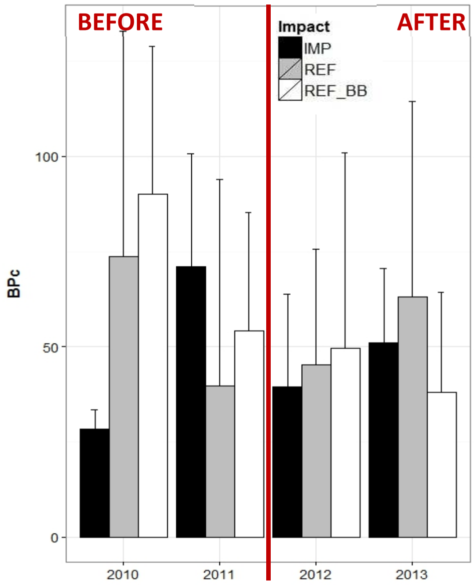

Figure 23: Average bioturbation potential for the impact and reference groups during the period 2010-2013 at the Oosthinder and Bligh Bank with indication before/after dredging.

Discussion and conclusions

A real measurable biological impact of aggregate dredging on the BPNS was only detected at the central Buiten Ratel, the most intensively used dredging area in terms of extracted volumes, and frequent presence of dredging vessels. Clear changes in species composition, density and biomass were observed. Resulting in more and different species at higher densities but at a lower biomass in the intensively impacted area. The current results are similar to previous monitoring results in this area

(De Backer et al., 2011; De Backer et al., 2014). So despite the continuous intensive dredging in the area, no collapse in species numbers and densities was observed. The dredging at the central Buiten Ratel has changed the sediment composition in such that on the one hand the sediment became coarser (more shell gravel and cobbles due to reject chute), but on the other hand there was an increased input of very fine sand as well (due to the overspill). This created a heterogenic habitat preferred by both species characteristic for very fine sand and coarser sediments The community established in the highly dredged area up to March 2011, a heterogenic, dynamic, transitional community, continued to exist until October 2013. This community was characterised as a mixture of muddy sand (*Abra alba*) and coarse sand (*Ophelia borealis*) species (De Backer et al., 2014).

Although differences in structural metrics were detected at the central Buiten Ratel, macrobenthic ecosystem functioning measured by means of BTA and bioturbation potential did not differ between the high impact and reference areas at the Buiten Ratel. Based on those two functional measures, no impact of dredging on ecosystem functioning was detected. So it appears that structural metrics are more sensitive to pick up changes in macrobenthic assemblages. Similar results were observed in other impact studies where functional recovery after impact was much faster than structural recovery (Cooper et al., 2008; Bolam, 2014). In the other studied aggregate dredging areas (Oostdyck, Thornton and Oosthinder), functional differences between sample groups, were as well less pronounced (lower Anosim R-values) in BTA compared to traditional multivariate species analysis. This indicates that although different species are present, they exert similar functions in the ecosystem, resulting in a largely similar basic ecosystem functioning. This is what one could expect intuitively, since all areas have very similar coarse permeable sandy sediments, where similar ecosystem processes are expected to occur.

Besides the observed dredging impact at the central Buiten Ratel, other signs of dredging impact on the BPNS were recorded on the Oostdyck, where densities in the impact area were reduced compared to the reference samples. Although, dredging impact on the Oostdyck is low, the continuous impact of dredging since more than 10 years, has its consequences on macrobenthic densities. However, species numbers and species composition remained stable compared to reference areas. Moreover, in most areas (Buiten Ratel LOW-IMP & HIGH-IMP, Thornton top and Oosthinder), macrobenthic biomass is negatively affected by dredging. In general, biomass is largely influenced by the presence/absence of the sea-urchin *E. cordatum*. This species is known to be sensitive to aggregate dredging (Newell et al., 1998). Even at low intensities, dredging caused *Echinocardium* to disappear or decrease in numbers, and this caused a substantial decrease in overall biomass. Furthermore, dredging in certain areas (e.g. central Buiten Ratel) influenced overall biomass as well causing older, long-living species to disappear, and inducing a higher recruitment of juvenile/young individuals, as such reducing overall biomass. A decrease in biomass is negative for the secondary production in the ecosystem, and potentially limits the food potential of the ecosystem for higher trophic levels such as epibenthos and demersal fishes.

The BEQI indicator was capable to pick up changes caused by dredging. In general, results obtained by the BEQI indicator matched perfectly the results obtained by statistically testing the univariate structural metrics and the multivariate species composition. The only case were BEQI underperformed was on species composition at the highly impacted area of the central Buiten Ratel. Because within-group variation in both the impact and the reference samples was high, differences in species composition were not detected. Since, a high within-group variation is characteristic for impact samples, it is necessary to interpret results with much caution. However, the BEQI is very useful as a quick and summarising assessment tool to detect potential dredging impact, and can thus be used in future biological impact assessment. The choice of relevant control data is imperative for reliable interpretation of the BEQI results, but this should be the case for all types of analyses in impact assessment.

A potential drawback of this study is the lack of pre-impact samples for most aggregate dredging areas on the BPNS, except for the Oosthinder. As such no real BACI- design (Before/After – Control/ Impact) is used but only a CI-design (Control /Impact). However, we tried to cope as well as possible with this pitfall by allocating suitable reference samples at similar depth profiles and within similar physical conditions for every impact area. Therefore, we are quite confident that all conclusions regarding biological effects of dredging activities based on the current CI-design are reliable. The only area which might need relocation of the reference samples is the Oostdyck to take better into account the natural gradient in sediment composition in this area.

The observed results showing such a limited biological effect of aggregate dredging are intuitively unexpected. Because most studies investigating the impact of aggregate dredging record substantial negative effects on macrobenthic assemblages (e.g. van Dalfsen & Essink, 2001; Cooper et al., 2007). The reason of the limited observed effects in our study might be twofold. First, the BPNS is an area with very high natural physical disturbances. Cooper et al. (2011) showed that the faunal sensitivity to aggregate extraction depends on the natural physical disturbance in the area, with benthic assemblages being less sensitive in areas with a high natural disturbance. Secondly, we could question whether our reference samples are really pristine samples. Fisheries on the BPNS are virtually everywhere (Vandendriessche et al., 2013; Pecceu et al., 2014), and the pressure of other human impacts (e.g. dredge disposal, offshore wind farms, shipping,…) is so high that one could wonder whether it is possible to allocate a real pristine reference area. As a consequence, we have to recognize that, even though reference samples are allocated carefully to minimise natural sources of variation, they will have been influenced by human pressure(s), and might therefore reveal a depleted macrobenthic assemblage. Because of both of the above reasons, most macrobenthic species in the BPNS are expected to be able to cope with, and to be very resilient against a certain degree of human pressure. In this respect, impacted areas are expected to be recolonised very fast by resilient and opportunistic species, even when impact is ongoing. This could explain why in most areas where the impact is relatively low, no impact was measured. On top of all this, sediments in most areas are rather uniformly dominated by medium sands, and although dredging is taking place, sediment composition has hardly changed because of the high uniformity in sediments. Only when dredging pressure is really high, and depressions are being formed like on the Buiten Ratel, sediment composition could change because other sediment layers become exposed and because of the reject chutes. As long as changes in sediment composition do not occur, no changes in macrobenthic species composition and ecosystem functioning should be expected.

To conclude, our results indicate that as long as the aggregate dredging occurs at low intensities (Oostdyck, Thorntonbank, southern central Buiten Ratel) or at high, but infrequent intensities (Oosthinder), the current sandy benthic ecosystem of the BPNS seems resilient enough to buffer the biological impact of dredging both structurally and functionally. Based on this study, no estimates can be made on the length of the period needed in between two major dredging events to allow the benthic community to buffer the impact. Therefore a more targeted monitoring should be designed. On the other hand, when the dredging pressure is high and focussed on a small surface area, that is frequently visited and dredged in high volumes, changes in sediments result in biological changes as is now visible at the Buiten Ratel. Similar observations were made in the past at the high impacted areas of the Kwintebank (De Backer et al., 2011).

Acknowledgements

This study was financed through the fund for sand extraction. Many thanks goes to the crew of RV Belgica and RV Simon Stevin and all people who assisted during the sampling campaigns. Jan Ranson is thanked for preprocessing the samples and Naomi Breine and Ellen Pecceu of the microscopy lab for processing the samples. We acknowledge José Van Acker, Elke Deboevere and the other analysts from the physics lab at ILVO for processing the sediment samples. We thank Bart Vanelslander for writing the R script to calculate all dredging parameters, and many thanks to

Elisabeth Debusschere for the help with producing graphs in R. The colleagues of FPS Economy and OD Nature/MUMM are thanked for the ‘cleaned’ black box data and the good cooperation.

Quality assurance

All analyses were performed in a NBN EN ISO/IEC 17025 regulated environment. ILVO is certified for macrobenthos species identification with NBN EN ISO/IEC 17025 (BELAC T-315 certificate).

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Integrated monitoring of sediment processes in an area of intensive aggregate extraction, Hinder Banks, Belgian part of the North Sea

Van Lancker Vera[*1a], *Baeye Matthias*[1a], *Evangelinos Dimitris*[1a,2], *Francken Frederic*[1a], *Van den Eynde Dries*[1a], *De Mesel Ilse*[1b], *Kerckhof Francis*[1b], *Norro Alain*[1b], *Van den Branden Reinhilde*[1c]

[*]*Presenting author: vera.vanlancker@mumm.ac.be*

[1a] *Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Suspended and Seabed Monitoring and Modelling, Gulledelle 100, 1200 Brussels, Belgium*

[1b] *Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Marine Ecology, 3de en 23ste Linieregimentsplein, 8400 Oostende, Belgium*

[1c] *Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Measuring Services Ostend, 3de en 23ste Linieregimentsplein, 8400 Oostende, Belgium*

[2] *MSc Marine and Lacustrine Sciences and Management (Ocean and Lakes), Ghent University, Renard Centre of Marine Geology, Krijgslaan 281 S8, 9000 Gent, Belgium*

Abstract

Integrated monitoring of the effects of aggregate extraction is needed to reach Good Environmental Status of the marine environment by 2020 (European Marine Strategy Framework Directive (MSFD); 2008/56/EC). This requires increased process and system knowledge that incorporates both natural and human-induced variability. Additionally, when exploitation is within or near Habitat Directive Areas, appropriate assessments are needed of all stressors (92/43/EEC). Recently, new extraction activities started in a far offshore sandbank area in the Belgian part of the North Sea, just north of a Habitat Directive Area. Therefore, a dedicated monitoring programme was set-up, with focus on assessing changes in seafloor integrity and hydrographic conditions, two descriptors that define Good Environmental Status.

Since extraction started in 2012, monitoring results are short-term and relate to: (1) natural variability; (2) sediment plume formation and deposition, differentiating between small and large trailing suction hopper dredgers; (3) far–field impacts, with focus on the nearby Habitat Directive Area, where ecologically valuable gravel beds occur. New insights were revealed on the three levels, though most striking was enrichment of fines in the coarse permeable sands of the gravel area. No direct relationship could yet be made between the intensive extractions and the mud enrichment, though MSFD requires further monitoring of the gravel beds, since favourable colonization and growth of epifauna is critical for the maintenance and increase of biodiversity in the Belgian part of the North Sea.

Introduction

A monitoring programme has been designed to test hypotheses on the impact of marine aggregate extraction in the far offshore Hinder Banks. Monitoring is focussed on hydrodynamics and sediment transport with feedback loops between both modelling and field studies. Hypotheses were based on findings in the Flemish Banks area where 30-yrs of extraction practices, and related research on the effects, were available (Van Lancker et al., 2010 for an overview). They have been adapted to incorporate descriptors of Good Environmental Status, as stipulated within the European Marine Strategy Framework Directive (MSFD, Directive 2008/56/EC) (Belgische Staat, 2012). In the context of the present monitoring, main targets were assessing changes in seafloor integrity (descriptor 6, D6) and hydrographic conditions (descriptor 7, D7), two key descriptors of Good Environmental Status, to be reached in 2020 (Rice et al., 2012; Zampoukas et al., 2012).

Summarized, main hypotheses are: (1) Seabed recovery processes are very slow; (2) Large-scale extraction leads to seafloor depressions; these do not impact on the spatial connectedness of habitats (D6); (3) Impacts are local, no far field effects are expected; (4) Resuspension, and/or turbidity from overflow during the extraction process, will not lead to an important fining of sediments (e.g., siltation) (D6); (5) Marine aggregate extraction has no significant impact on seafloor integrity (D6), nor it will significantly lead to permanent alterations of the hydrographical conditions (D7); (6) Cumulative impacts with other sectors (e.g., fisheries) are minimal; and (7) Large-scale extraction does not lead to changes in wave energy dissipation that impact on more coastward occurring habitats.

The monitoring follows a tiered approach, consisting of in-situ measurements and modelling. Related to MSFD requirements on hydrographic conditions, the Belgian focus is on assessing changes in bottom shear stresses[1]. Therefore, considerable effort went to current and turbidity measurements along transects crossing the sandbanks, as also on point locations for longer periods. These data serve as a reference and will be compared to datasets recorded under the events of intensive aggregate extraction. The extraction will inherently give rise to sediment plumes and subsequent release of fines in the water column (e.g., Spearman et al., 2011; Duclos et al., 2013). Insight was needed in the dispersion of the fines and the probability of siltation in the nearby Habitat Directive area. Modelling was used to assess to what extent siltation, as a result from dredging, would lead to overtopping and hence deteriorate the integrity of the gravel beds. This relates directly to Belgium's MSFD commitments stating that the ratio of the hard substrata surface area versus the soft sediment surface area does not show a negative trend (Belgische Staat, 2012). Furthermore, abrasion of the sandbank and/or enrichment of finer material, could lead to habitat changes[2], important for the assessment of MSFD descriptor 6 on seafloor integrity.

Study area

The Hinder Banks form part of a sandbank complex, located 40 km offshore in the Belgian part of the North Sea (BPNS). On the sandbanks, depths range from -8 m to -30 m (Figure 1); they are superimposed with a hierarchy of dune forms, often more than 6 m in height. The channels in-between the sandbanks reach 40 m of water depth. Extraction of aggregates is allowed in 4 sectors (a to d;

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[1] For descriptor 7 on hydrographic conditions, this monitoring programme should allow evaluating the following specifications (Belgische Staat, 2012):

(1) Based upon calculated bottom shear stresses over a 14-days spring-neap tidal cycle, using validated mathematical models, an impact should be evaluated when one of the following conditions is met:
   (i) There is an increase of more than 10% of the mean bottom shear stress;
   (ii) Variation of the ratio between duration of sedimentation and duration of erosion is beyond the "-5%, +5%" range.

(2) The impact under consideration should remain within a distance equal to the square root of the area occupied by this activity and calculated from the inherent outermost border.

(3) All developments need compliance with existing regulations (e.g., EIA, SEA, and Habitat Directive Guidelines) and legislative evaluations are necessary in such a way that an eventual potential impact of permanent changes in hydrographic conditions is accounted for, including cumulative effects. This should be evaluated with relevance to the most suitable spatial scale (ref. OSPAR common language).

[2] For descriptor 6, this monitoring programme contributes to the evaluation of the following environmental targets and associated indicators (Belgische Staat, 2012):

(1) The areal extent and distribution of EUNIS level 3 Habitats (sandy mud to mud; muddy sand to sand and coarse sediments), as well as of the gravel beds, remain within the margin of uncertainty of the sediment distribution, with reference to the Initial Assessment.

(2) Within the gravel beds (test zones to be defined), the ratio of the surface of hard substrate (i.e., surface colonized by hard substrata epifauna) against the ratio of soft sediment (i.e., surface on top of the hard substrate that prevents the development of hard substrata fauna), does not show a negative trend.

Figure 1), though most of the activity takes place on the Oosthinder sandbank (Sector 4b and 4c). Sediments are medium- to coarse sands, including shell hash, with less than 1 % of silt-clay enrichment (Van Lancker et al., 2009). Tidal currents reach more than 1 ms^{-1}; the significant wave height of the waves is easily more than 1 m. These offshore sandbanks are the first wave energy dissipaters in the BPNS.

Over a 10-yrs period intensive extraction of marine aggregates (up to 2.9 million m³ over 3 months) is allowed in this area, with a maximum of 35 million m³ over a period of 10 years. Large trailing suction hopper dredgers (TSHD) can be used, extracting up to 12,500 m³ per run. Present-day yearly extraction levels recently surpassed 3 million m³, the majority of which was extracted with TSHD of 1,500 m³. Such intensive extraction is new practice in the BPNS and the environmental impact is yet to be determined. South of the Hinder Banks concession, a Habitat Directive Area (H-D Area) is present, hosting ecologically valuable gravel beds (Houziaux et al., 2008) (Figure 1). For these, it is critical to assess the effect of multiple and frequent depositions from dredging-induced sediment plumes.

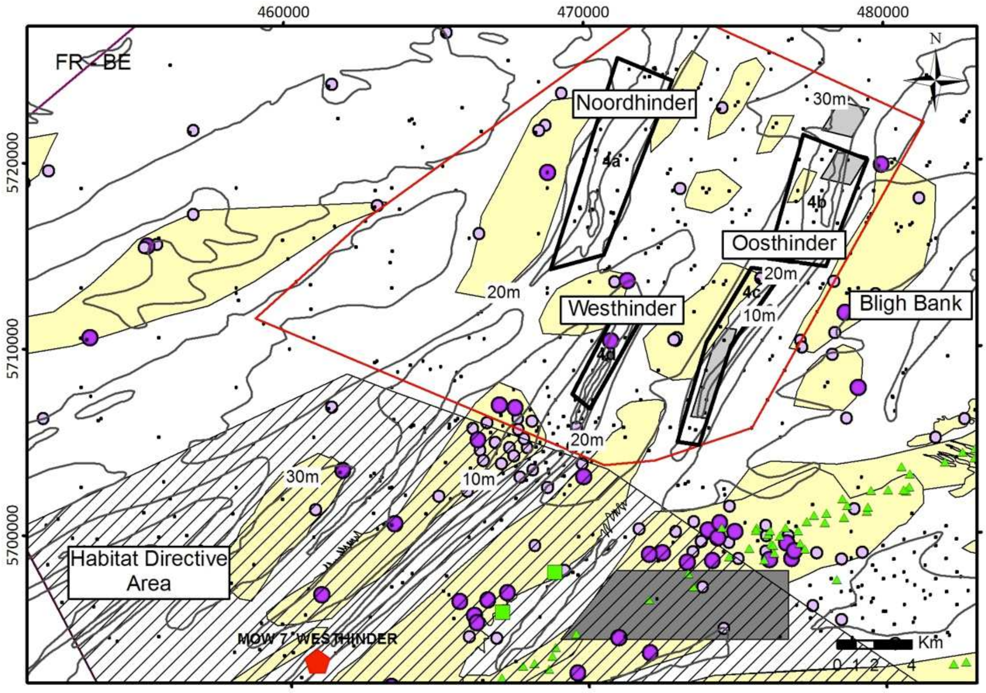

Figure 1: Area of the Hinder Banks, where intensive marine aggregate extraction is allowed in zone 4 (red line) along 4 sectors (black polygons). Within these sectors geomorphological monitoring is carried out by FPS Economy (light grey polygons). A Habitat Directive Area (hatched) is present at a minimum of 2.5 km from the southernmost sectors. Presence of gravel (purple circles) and stones (green triangles) is indicated (size/colour of the dots represents relative amounts of gravel with a minimum of 20 %). In the light yellow areas the probability of finding gravel is high (based on samples, in combination with acoustic imagery). In the gravel refugia (green rectangles), west of the southern part of the Oosthinder, ecologically valuable gravel beds are present. Black dots are positions where no gravel was sampled. Indicated also is the position of the Westhinder measuring pole (Flanders Hydrography) (red pentagon) where most of the hydro-meteorological data were derived from. Grey polygon in the Habitat Directive Area is an anchorage zone.

Material and methods

Measurements and spatial observations

Measurements and observations started in November 2011, before major extraction activities took place. Since then three 1-week campaigns a year were executed resulting in a total of 10 campaigns in the period 2011-2014, all with RV Belgica. Additional data were acquired with an underwater surface vehicle (USV) 'Wave Glider' from Liquid Robotics (www.liquidrobotics.com), and 5 longer-term deployments were made using a bottom-mounted acoustic Doppler current profiler (BM-ADCP). See Figure 2, for an overview of the locations of the data acquisition.

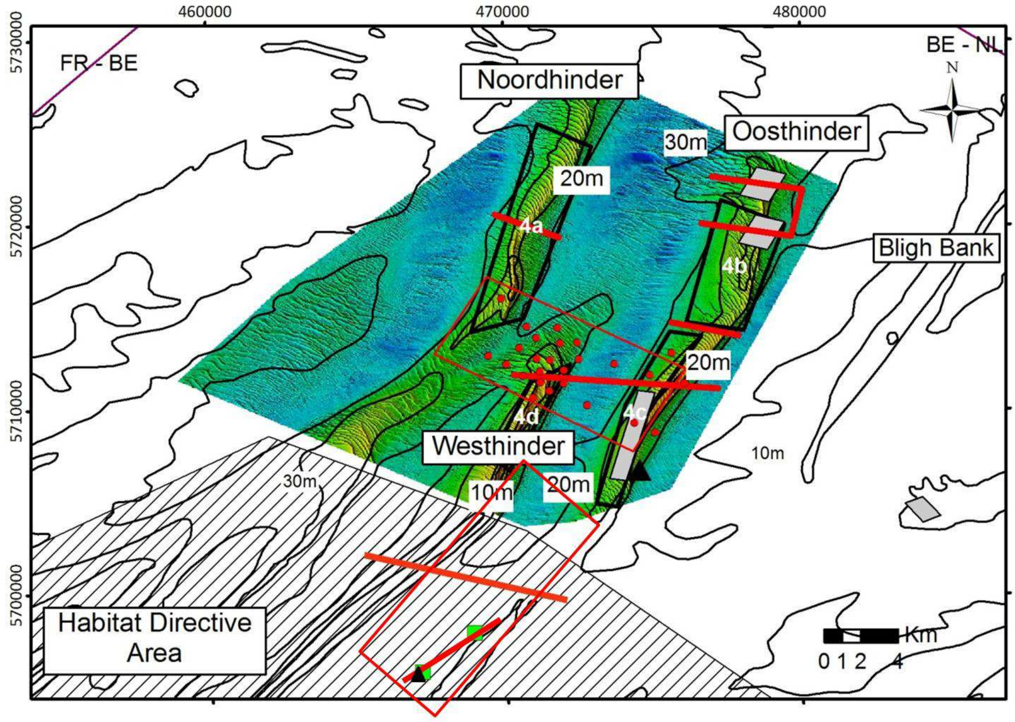

Figure 2: Areas of investigation in the Hinder Bank region. Cross-sectional lines show the locations of ADCP profiling, along which also water sampling and vertical profiling were performed. Bathymetric surveys were performed in the red delineated zones in the central and southern part of the Hinder Banks, and were validated with sediment samples (red dots). The triangles indicate the position of longer-term measurements of currents and turbidity. In the period 15/4 – 6/5 2013, the Wave Glider sailed 39 rounds around Sector 4c. Small green rectangles in the Habitat Directive area are the locations of ecologically valuable gravel beds. Grey zones: geomorphological monitoring zones (FPS Economy).

The following measurements were executed:

(1) Transect-based measurements (Figure 2) of the full three-dimensional current velocity and direction, together with turbidity assessments based on the acoustic backscatter over 13-hrs cycles (hull-mounted acoustic Doppler current profiler; HM-ADCP).
(2) Very-high resolution acoustic measurements (Kongsberg-Simrad EM3002 multibeam, MBES) to obtain depth, backscatter, and water column data.
(3) Water column measurements at fixed stations, over 13-hrs windows, to study temporal variations in salinity, temperature and depth (CTD), turbidity (optical backscatter sensor, OBS), and particle-size distributions (Sequoia type C 100X Laser In-Situ Scattering and Transmissometry, LISST). Water samples (1126 samples) were taken for direct measurement of suspended particulate matter (SPM) concentrations, and were used for calibration of acoustical/optical sensors.
(4) Bottom-mounted ADCPs were used for longer-time measurements of current and backscatter variation; they were both deployed on the Oosthinder sandbank, and in the Habitat Directive Area.
(5) Seabed sediment samples were taken to improve on sediment mapping, and to evaluate siltation. Reineck boxcores were taken on the sandbanks, and Hamon grabs in the gravel beds in the Habitat Directive Area. Reineck cores were 1-cm sliced and analysed for grain-size, organic matter and carbonate content; the same applies to the soft sediments within the Hamon grabs. Epifauna was analysed also.

(6) In the Habitat Directive Area, video recordings were made to assess potential smothering of the epifauna and to compare seabed texture and epifauna against pre-dredging data from 2006-2007 (Houziaux et al., 2008).

The Wave Glider was deployed and recovered with the oceanographic vessel RV Belgica, respectively on April 15th and May 6th 2013; the USV sailed 39 rounds around Sector 4c, Oosthinder sandbank (Van Lancker & Baeye, subm.).

For a detailed overview of all data from the period 2011-2013, as well as data-analyses procedures, see Van Lancker et al. (2014). More recent data will be reported end of 2014.

Modelling

Measurements fed into numerical models for conducting impact assessments under various scenarios of extraction activities. The following modelling suite was used:

(1) A hydrodynamic model (OPTOS-BCZ, Luyten, 2010), driving sediment transport and advection-diffusion models, was validated for its use in the Hinder Banks region. The model was two-dimensional with a ± 250 x 250 m resolution, and coupled to a ± 5 x 5 km resolution wave model (HYPAS; Van den Eynde, 1992). Meteorological information was obtained from United Kingdom Meteorological Office (Bracknell, UK). Validation was done based on the newly acquired current datasets (Van den Eynde et al., 2014). This was needed for the quantification of model accuracy, critical to detect changes in time.
(2) A total load sediment transport model (MU-SEDIM, Van den Eynde et al. 2010) was refined. Bottom shear stresses, calculated with the numerical model, were compared to the bottom shear stress, derived from current measurements (Van den Eynde et al., in prep.).
(3) The MU-STM model (Fettweis & Van den Eynde, 2003; Van den Eynde, 2004) calculating advection and dispersion, and erosion and deposition of fine-grained material and (fine) sand in the water column, was adapted for its use in sediment plume modelling. To predict the sediment release rate from dredging activities of TSHDs, TASS 4.0 software was used (EcoShape, 2013; www.ecoshape.nl; Spearman et al., 2011). The main sources of input data were: (i) characteristics of the TSHDs; (ii) characteristics of the dredging operation; (iii) hydrodynamic conditions of the dredging site; and (iv) the nature of the *in-situ* sediment being dredged. For each TSHD, the predicted releases were coupled to the effective extraction events. Additional input parameters were an erosion constant, a critical bottom shear stress for erosion and deposition and settling velocity. A final map of dispersion, including the total mass and concentration of each sediment fraction, was acquired as an outcome of the model simulations. For the whole simulation period, detailed output was generated at selected locations to investigate temporal and spatial variability of the deposition patterns.

External data

Hydro-meteorological data
Wave information (e.g., significant wave height (Hs)) was available from a Wavec buoy (Westhinder location, Flanders Hydrography) at 18 km southwest of the study area (Figure 1). Sea surface elevation and 3D currents (10 min interval) were extracted from an operational 3D hydrodynamical model (OPTOS-BCZ, Luyten et al., 2010). Wind velocity and direction originated from the fixed Westhinder measuring pole (Flanders Hydrography) (for location, Figure 1).

Electronic Monitoring System (EMS)
To detect dredging-induced sediment plumes, the timing of dredging activities was accounted for and was coupled to the relevant time series (Van den Branden et al., 2012, 2013, 2014).

Results and discussion

Natural variation

(1) All of the measurements series showed an overall competitiveness of ebb and flood currents with magnitudes of up to 1.2 ms^{-1} under spring tidal conditions (Figure 3). The western sandbanks of zone 4 (e.g., in Sector 4a) tend to be slightly more ebb dominant than the eastern ones (e.g., Sector 4b, 4c). Generally, SPM was naturally more transported to the northeast. This is likely due to a natural sediment flux to the northeast, in combination with, for the Hinder Banks, a longer duration of the flood current. This was also the case in the Habitat Directive Area.

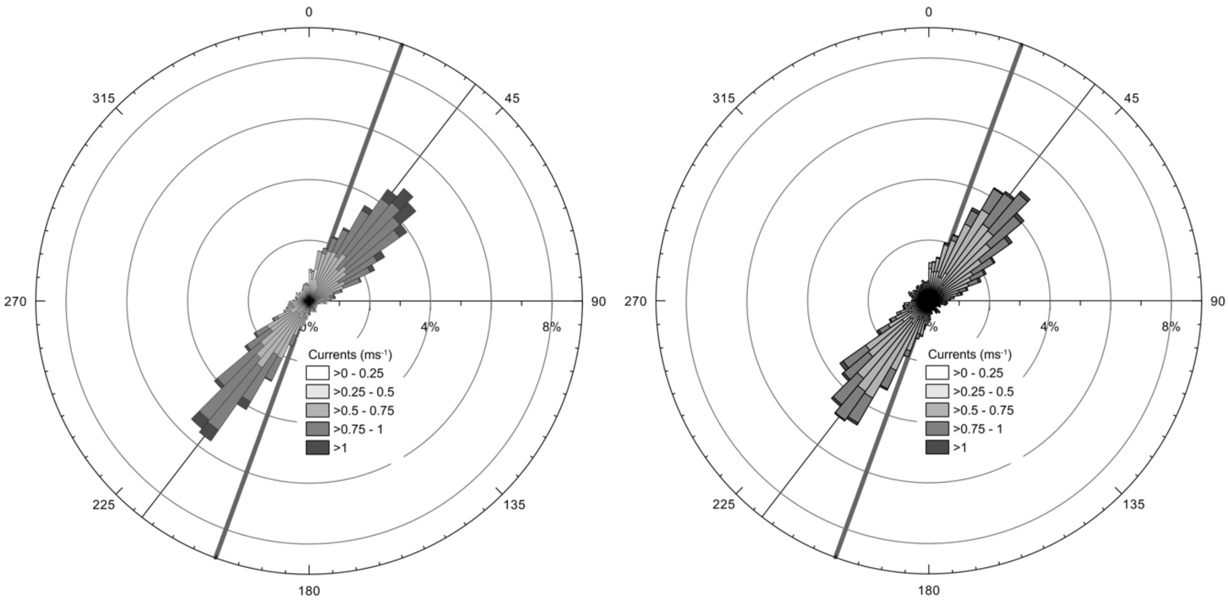

Figure 3: Frequency of occurrence of currents from all hull-mounted ADCP data series (RV Belgica) with 1 m bin size. Troughs and sandbanks are covered. Left: Measured currents for the upper water layers (angle of maximum current (-)). Right: for the lower water layers (angle of maximum current (-). Note a clockwise deviation of 17° between the sandbanks' axis (thick line) and the maximum current in the upper water layers (-). Note the very competitive nature of both current directions.

(2) In the absence of events, and in the gullies SPM concentrations in the upper water layers varied around 0.003 to 0.005 gl^{-1}, and around 0.007 to 0.010 gl^{-1} in the lower water layers. However, on the higher parts of the sandbanks SPM concentration levels easily reached 0.020 to 0.040 gl^{-1}. Over the top of the sandbanks, resuspension of sediments was frequent (Figure 4). In various datasets natural sediment plumes were observed and were correlated with the effects of spring tidal phases and maximum currents.

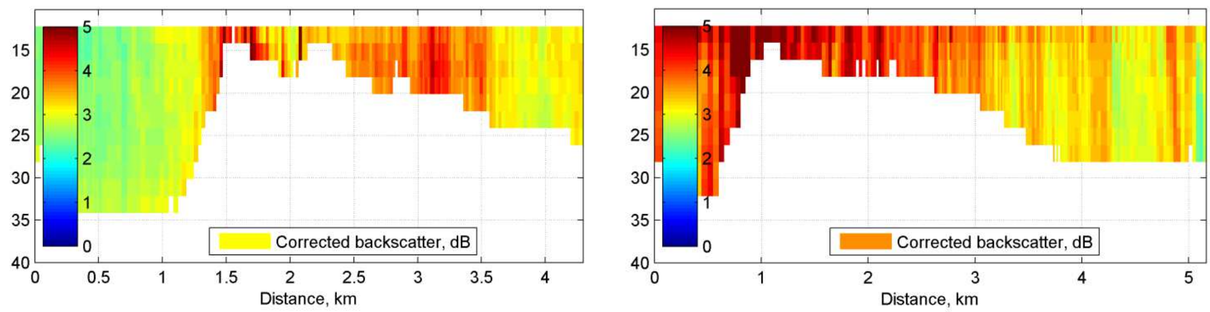

Figure 4: Resuspension events along the Oosthinder sandbank, north part Sector 4c. Left: Example of topography-induced resuspension (Hs < 1 m). Right: Example of topography-induced resuspension under higher wave conditions (Hs: 1-2 m). Wave Glider dataset (Van Lancker & Baeye, subm.).

(3) Under higher wave conditions, resuspension became very important. Wave Glider data showed that the remobilised sediments were subsequently carried away. *In-situ* measured SPM concentration levels (RV Belgica) were up to 0.070 gl^{-1} in the upper water layers, though only limited datasets were available under agitated conditions. Values are probably much higher.

(4) First calculations of current-derived bottom shear stresses resulted in 2-3 times higher values during ebb compared to flood at spring tide (Figure 5). This implies that near bottom transport is likely more directed to the southwest. This is especially the case along the eastern steep slopes of the sandbanks.

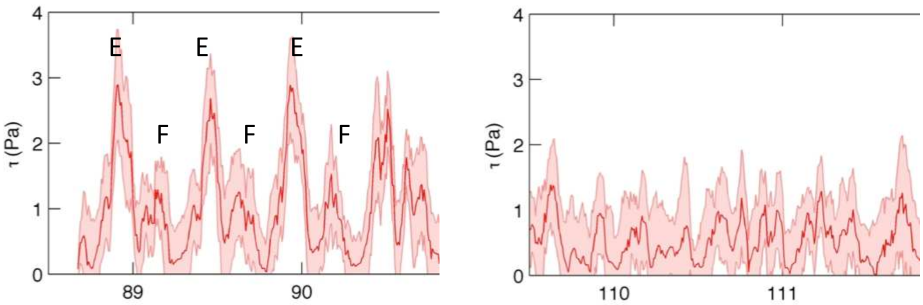

Figure 5: Extract of a 27-days time series on bottom shear stress (with error envelope, based on uncertainties in the calculations), calculated from in-situ BM-ADCP data, acquired along the east flank of the Oosthinder sandbank. Left: Spring tide; Right: Neap. Note the variation in bottom shear stress from 0 to nearly 4 Pa; and the significant difference between flood (F) and ebb (E) during spring, fading away during neap tide. Bottom shear stresses during ebb maximum currents are 2 to 3 times higher than during flood.

(5) Geomorphological monitoring carried out by FPS Economy did show clear dune migration to the northeast which contradicts the findings in (4). A possible explanation is a higher availability of sediment, mostly resuspended during ebb, and subsequently transported by the longer lasting flood current. Compared to the troughs, current ellipses on the sandbanks are more rotary, keeping sediments longer in suspension, hence prone to transport by the upcoming current.

Human-induced variation

(1) For the first time intensive marine aggregate extraction took place in the Hinder Banks region using small (2,500 m^3), medium (4,500 m^3) and large (> 10,000 m^3) TSHDs. Operations differed in the period 2012 to 2014, with simultaneous extractions in spring 2012 and 2014 (Figure 6). From the analyses of the EMS and hydro-meteo database it was evidenced that the large and small TSHDs extracted primarily during the ebbing phase of the tide.

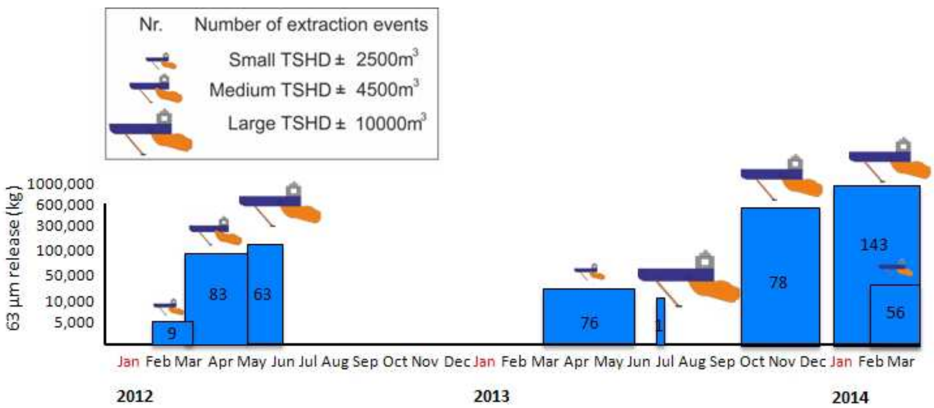

Figure 6: Extraction practices in sector 4C, Oosthinder sandbank, from January until March 2014. Periods of extraction are indicated with number of extraction events of small, medium and large TSHDs. Y-axis is an indicative estimate of the amount of release of fines (63 µm in kg) during those periods.

(2) ADCP backscatter (RV Belgica and Wave Glider) showed well-delineated sediment plumes resulting from marine aggregate extraction activities. The dynamic plume (Figure 7) deposited close to the dredge track (Evangelinos et al., subm.), whilst the Wave Glider exceptionally captured deposition of the passive plume, around 8 km off the last dredging activity, in the direction of the ebb current (Van Lancker & Baeye, subm.).

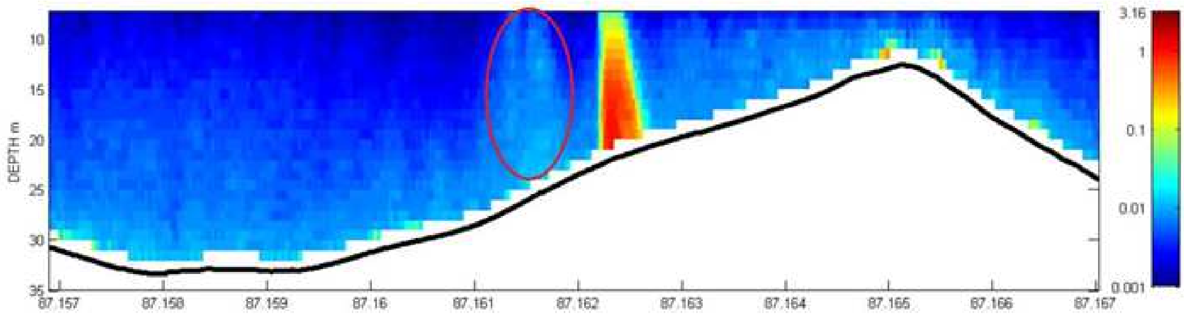

Figure 7: ADCP profile over the Oosthinder sandbank showing deposition of a 50-m wide dynamic plume of a small TSHD. ADCP-derived SPM concentrations were up to 1 gl^{-1} (right scale). Note a secondary plume with derived SPM concentrations around 0.01 gl^{-1}. RV Belgica March 2014 (Evangelinos, 2014).

(3) Near the dredge tracks, detailed core analyses showed that sediments were more heterogeneous and some fining trend was observed in the top surface of the seabed (Figure 8). Most importantly, it was evidenced that some of the *in-situ* sediments do contain mud fractions, especially near the western edge of Sector 4c. At one location, 25.3 % mud content was measured (Evangelinos et al., subm.).

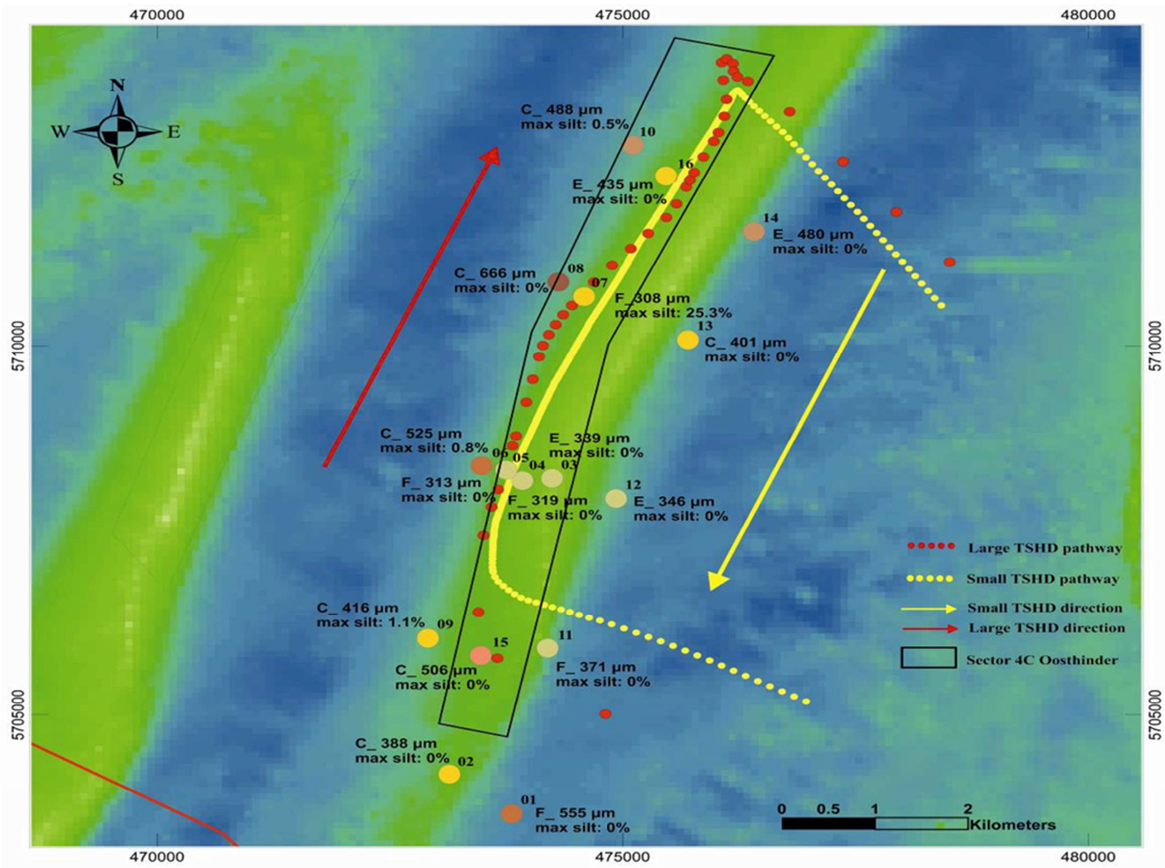

Figure 8: Sediment characteristics along Sector 4c, Oosthinder sandbank, based on shallow cores (up to ± 15 cm). Particle sizes refer to the top cm of the core; darker colours are coarser. F: indicates sediment fining in the top layers; C: indicates coarsening; and E indicates no difference. The maximum silt % in the entire core is also indicated, as also the main extraction pathways of the TSHDs (Evangelinos, 2014).

(4) Sediment particle tracking showed that fine particles (≤ 63 µm) easily reach the Habitat Directive Area under ebb conditions. Sediment plume modelling, for both small and large TSHDs, confirm deposition of fines in this area (Figure 9), though did show that, under winter conditions, these fines would be resuspended and washed away. For large TSHDs only, the fines would ultimately deposit to the northeast, given the longer duration of the flood current (Figure 10). Simulations are now needed for calm conditions and simultaneous operations.

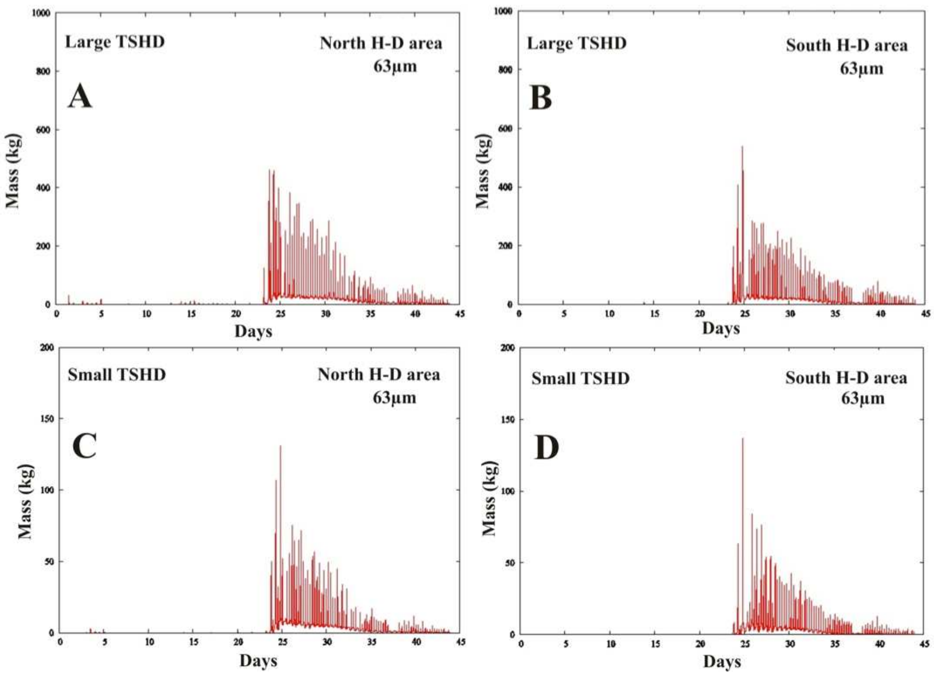

Figure 9: Simulation of the deposition of very fine sands (63 µm) in Mass (kg). Period: 15/02/2014 - 22/03/2014 (45 days). (A) Deposition of 63 µm particles along a northern location in the Habitat Directive Area (H-D Area), arising from a large TSHD. (B) Similar, but along a southern location. (C) Deposition of 63 µm particles in the North area, arising from a small TSHD. (D) Similar, in south area. Coupling with hydro-meteorological data showed the occurrence of 2 spring-neap cycles with spring tidal conditions around day 15 and day 30. Spring tide and high wave conditions (up to 3 m) in the first 24 days inhibited deposition of fines; afterwards, settling of fines started under neap tide and low wave conditions. However, fines were resuspended and washed away when tides accelerated again. At least temporarily, the gravel beds will be subdued to higher than usual SPM levels.

(5) In the Habitat Directive Area, the soft sediment samples in-between the gravel beds, showed since the first samplings in 2012 mud enrichment (July 2012, 2013, 2014; March 2014). In March 2014, up to 22 % mud was measured (Figure 11, left) (Evangelinos, 2014; Evangelinos et al., in prep.). The ecologically valuable gravel beds occur in the trough of morphologically distinct barchans dunes, composed of coarse sands. They are steep dunes and occur typically where high currents prevail over hard substrates (Belderson et al., 1982). It is hypothesized that eddy formation over these dunes efficiently traps fine sediments. Such trapping mechanisms are known in literature and have been modelled (e.g., Omidyeganeh et al., 2013). ADCP data showed rectilinear currents, hence in water depths of around 30 m, deposition of fines during slack water is likely.

However, video observations in July 2014 did not show surficial smothering of the seabed, but only some limited mud patches in the barchan dune area. Though, video from divers showed abundant release of fines when stirring the sediments (Figure 11, right). This confirms that fines are trapped, but above all buffered in the parent bed, primarily composed of coarse sands and shell hash (Figure 11, right). In literature such buffering mechanisms are described (e.g., Santos et al., 2012) and are typical in coarse permeable beds. Especially in areas with bedform migration (as is the case), obstruction and acceleration of flow over topography causes horizontal pressure gradients causing fluid transport across the sediment-water interface, transporting fluid and small particles into the bed in zones of high pressure (troughs) (Huettel et al., 1996). In permeable sediments this is a normal mechanism and ensures remineralization of the seabed, playing a major role in the functioning of the ecosystem (Precht and Huettel, 2003). If the pore waters are now being clogged by excessive fine particles, this may induce a reduction in ecosystem efficiency. Further monitoring and research is vital to validate this hypothesis.

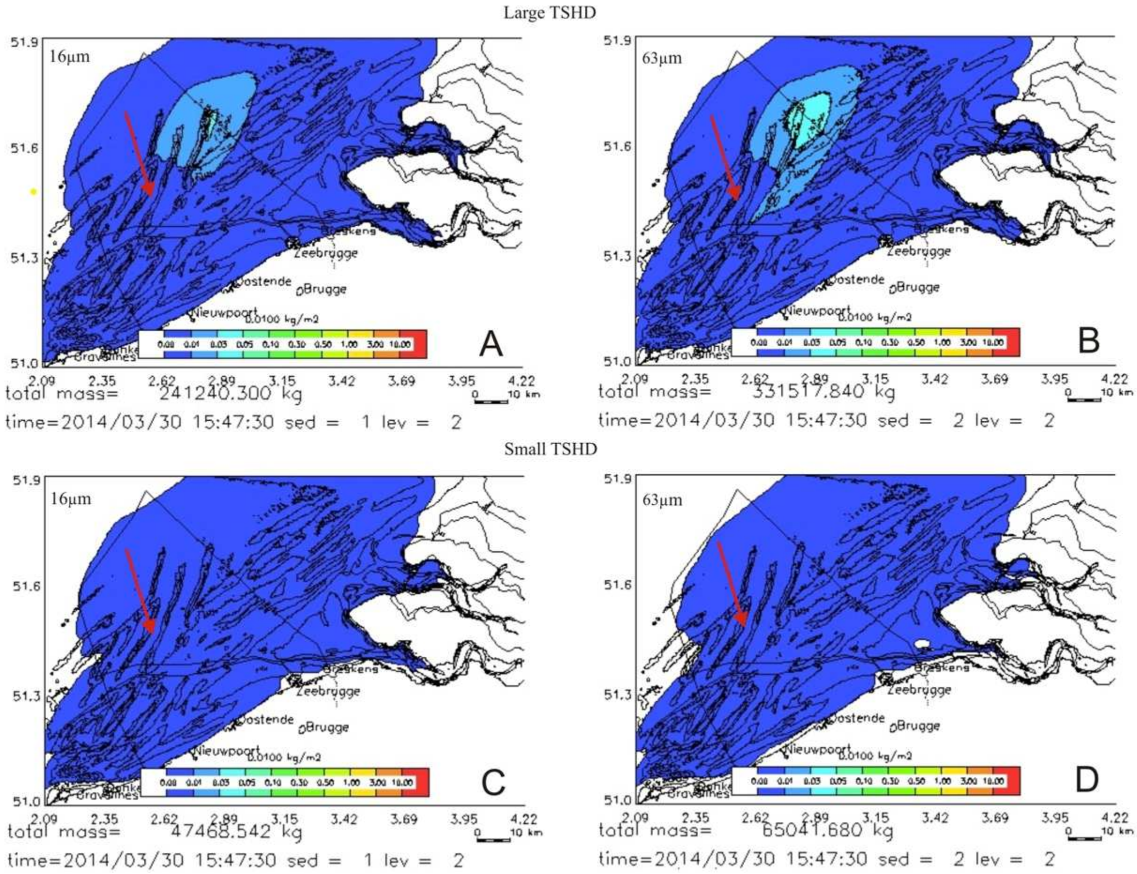

Figure 10: Results of plume modelling (MU-STM) illustrating the dispersion of fine sediment fractions from a large and small TSHD, as well as the total mass dispersed (kgm^{-2}). Period: 15/02/2014 - 30/03/2014; end result presented. (A) and (B) represent the fine silt particles released from a large TSHD. (A): 16 µm fraction and (B): 63 µm. (C) and (D) illustrate the sediment fractions released from a small TSHD: (C) 16 µm; (D) 63 µm. Red arrow indicates the location of the gravel beds. Simulations showed significant deposition for the large TSHD only, with the depocentre near the Belgian-Dutch border. Model simulations did not account for buffering of fines (Evangelinos, 2014).

For the modelling, this implies that an additional module needs implementation that allows a buffering of fines (armouring process). This would limit resuspension to higher bottom shear stresses only (e.g., storms) and likely simulations would show more permanent deposition in the Habitat Directive Area. Historic sediment (1900; 1970-2011) and video data (2006-2008) will also be re-analysed to evaluate whether or not mud was already present in the area.

The epifauna is also further investigated. From samples collected in 2013, it appears that the area is still species-rich, and has a potential for recovery. Comparison with samples collected in 2006-2007 will reveal whether shifts in functional groups are occurring. Recent fishing-intensity maps did show more disturbances in the area (ILVO Visserij, 2014). This could also explain why the number of long-living species was rather low, and species that need long periods without disturbance to establish and grow, such as members of the Porifera, were largely lacking. Hence, the ecologically valuable gravel beds may be prone to cumulative impacts, necessitating further follow-up of their evolution. This requires integrated approaches, combining sampling and visual observations, together with continuous time series of currents and turbidity.

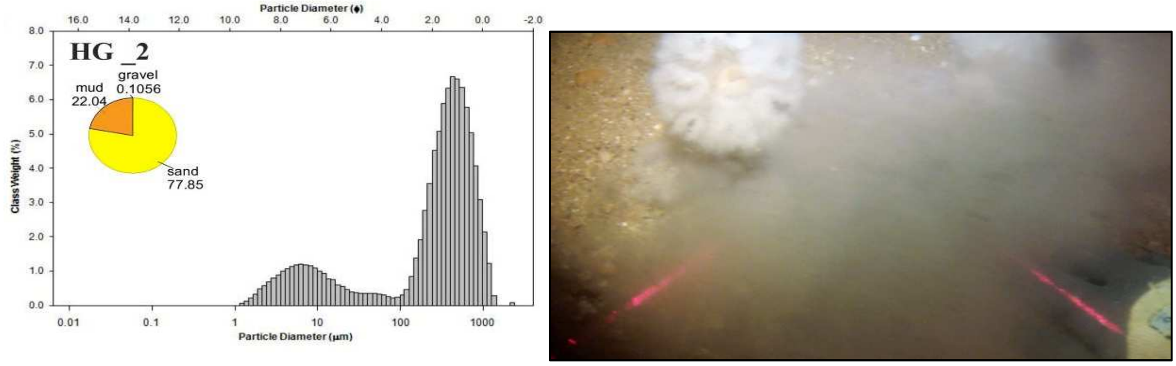

Figure 11: Seabed characteristics of the gravel-rich area. Left: Grain-size analyse of the soft sediment in-between the gravel. Sands are coarse-grained (median grain-size around 400-500 µm), however with an admixture of fines, up to 22 % (March 2014). Right: Video observation showing a coarse top surface enriched with shell hash, and a release of the fine fraction after sediment stirring (July 2014).

Conclusions

Since 2011, integrated monitoring of sediment processes is in place allowing quantification of the impacts of marine aggregate extraction in the Hinder Banks region and evaluating the compliancy of the activities with what is stipulated in European Directives. One of the issues is to assess Good Environmental Status, and therefore a number of indicators needs evaluation. These indicators relate to seafloor integrity (e.g., sediment changes), and hydrographic conditions (e.g., changes in current regime).

First of all it needs emphasis that the monitoring series is only 3 years long, implying that most of the impact hypotheses can yet not be tested. A first integrated assessment is foreseen in 2015, when all of the monitoring in the Hinder Banks region will be combined (e.g., with results of FPS Economy, SMEs, Self-Employed and Energy, and ILVO, respectively on the geomorphological and biological follow-up). Nonetheless, the monitoring provided at least three major results:

(1) Comprehensive database and knowledge on the natural variability of the Hinder Banks region, hitherto only poorly known;
(2) First data-modelling approaches that quantify the impact of differences in extraction practices, particularly related to the use of small (2,500 m^3), medium (4,500 m^3) and large (> 10,000 m^3) TSHDs;
(3) Fundamental new insights in the far field impact, referring to sediment fining mechanisms of the seabed, potentially related to the overflow of the TSHD

Given the short time span of the extractions, no changes in hydrographic conditions could be assessed (i.e., changes to current regime), though first results have become available on the natural variability of bottom shear stresses that later on will shed new light on acceptable variations in this indicator. Concerns are raised on changes in seafloor integrity, potentially due to trapping and deposition of fines in permeable coarse sands. This could lead to changes in ecosystem efficiency of which the mechanism, impact and significance requires further research.

Acknowledgements

Financial support for this study was provided through the projects MOZ4 (Flemish Authorities, Agency Maritime Services and Coast, Coast, contract 211.177), and ZAGRI, a continuous monitoring programme, paid from the revenues of marine aggregate extraction activities. Elias Van Quickelborne is thanked for his continued interest. RV Belgica shiptime was provided by RBINS OD-Nature and Belgian Science Policy (BELSPO). The commander and crew of RV Belgica, and the Measuring Service Ostend (MSO), are acknowledged for logistical support. Coupling with hydro-meteorological data was done using data from Flanders Hydrography 'Meetnet Vlaamse Banken', in combination with modelled data on currents and water levels derived from OPTOS-BCZ (RBINS OD Nature, Sébastien Legrand). OD Nature MARCHEM analysed the filtrations of the water samples. Ghent University, Renard Centre of Marine Geology, is acknowledged for providing laboratory facilities. Particularly, Sébastien Bertrand is thanked for his assistance during the sediment analyses. The Biology and Soil Sciences lab of UGent are thanked for, respectively, logistic and laboratory support. Flemish Marine Institute (VLIZ) provided LISST instrumentation, video frame and Hamon grab. Turbidity Assessment Software (TASS) was provided through EcoShape/Boskalis. Liquid Robotics are thanked for providing OD Nature the opportunity to deploy the Wave Glider© Hermes in the Belgian offshore waters. Their pilots took care of the control and guidance of the Wave Glider during the operations. Ann Verfaillie (KULAK) is acknowledged for analysing epifauna of the gravel beds. FPS Economy and ILVO are thanked for sharing data and ideas. This work contributes also to the Brain-be project TILES (Transnational and Integrated Long-term marine Exploitation Strategies), funded by BELSPO under contract BR/121/A2/TILES.

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On-demand assessment of spatial and temporal variability of sediment transport parameters, Belgian and southern Dutch part of the North Sea

*Francken Frederic[*1], Van den Eynde Dries[1], Van Lancker Vera[1]*

[*]*Presenting author: frederic.francken@mumm.ac.be*

[1] *Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Suspended Matter and Seabed Monitoring and Modelling Group, Gulledelle 100, 1200 Brussels, Belgium*

Introduction

Assessing the natural spatial and temporal variability of the seabed is not straightforward. Mostly, variations are described locally, using *in-situ* depth data (e.g., Van Lancker and Jacobs, 2000; Lanckneus et al., 2002; Degrendele et al., 2010), or are derived from newly acquired current and turbidity data (e.g., Van Lancker et al., this volume). Still, in many cases the regional context is missing, and sound interpretations on the driving forces are not possible. Moreover, the envelope of natural variation is not known, and it becomes very hard to distinguish naturally- from anthropogenically-induced variability.

We anticipate by providing long-term, and statistically sound data-analyses of most relevant sediment transport parameters, relevant for the Belgian and southern Dutch part of the North Sea. As a case study we have selected the variability in bottom shear stress, as this parameter is critical in the processes that govern the natural variability in bottom morphology and sediment transport. Bottom shear stress links the sea floor to the water column as it suspends sediment; influences and is influenced by surface sediment texture, micro-bathymetry and spatial connectedness. Moreover, it directly and indirectly impacts on benthic organisms; contributes to turbulence generation, causing dissipation of wave and current energy, and to entrainment and sediment mixing. As such, it is also a relevant parameter in the placement or design of offshore structures or other human activities (Dalyander et al., 2013).

Belgium proposed bottom shear stress as an indicator of changes in hydrographic conditions to assess Good Environmental Status within Europe's Marine Strategy Framework Directive (Belgische Staat, 2012). Under perturbed conditions, this parameter will be calculated, using validated mathematical models, over a 14-days spring-neap tidal cycle. It is amongst others stated that an impact should be evaluated when: (i) There is an increase of more than 10 % of the mean bottom shear stress; and/or (ii) The variation of the ratio between the duration of sedimentation and the duration of erosion is beyond the "-5 %, +5 %" range. In this context, it is critical to know the range of natural variability, hence strengthening the need for long-term data analyses.

In this paper an overview is provided on the methodological workflow, and a case has been selected on how the data provides insight into hydro-meteorological forcing.

Material and methods

Model data

Results from a 12-year long hindcast (1999-2010) were used to assess the spatial and temporal variability of sediment transport in the Belgian and southern Dutch part of the North Sea.

Wave hindcasts for the period were obtained using the Simulating Waves Nearshore (SWAN) wave model (Holthuijsen et al., 1993; Booij et al., 1999), a third generation phase-averaged wave model, suited for modelling waves in shallow water. The model calculates in time and space, the generation of waves, their propagation and shoaling, non-linear wave-wave interactions (quadruplets and triads), white-capping, bottom friction and depth-induced wave breaking. The wave model was coupled with the results from a hydrodynamic model, to account for current refraction and for the influence of the changing water depth on the waves. The model runs on a grid resolution of about 750 m x 750 m. The boundaries for the wave model were obtained from two larger scale WAM models (WAMDIG, 1988) covering the entire North Sea. Detailed information on the wave modelling can be found in Fernández (2011) and Van Lancker et al. (2012). The currents and water elevations were obtained from two-dimensional hydrodynamic models (Ozer et al., 1996; Yu et al., 1990). A fine model, using the same grid as the wave model, was set up for the Belgian Part of the North Sea, which was coupled with a lower resolution model for the entire West-European Continental Shelf. Atmospheric data (wind speed at 10 m height above sea level), were obtained from the United Kingdom Meteorological Office.

Currents and waves were used by the sediment transport model MU-SEDIM (Deleu et al., 2004; Van den Eynde et al., 2010), calculating the total load, under the influence of the local hydrodynamic conditions. The MU-SEDIM model was improved in the framework of this project to include a more time effective method for calculating the combined wave-current bottom stresses, using the method of Soulsby and Clarke (2005). A new implementation for the calculation of the bottom geometry (ripple height and ripple length), which is important for the calculation of the total bottom roughness (including skin bottom roughness, bottom roughness from bedload and form bottom roughness), was executed based on work of Soulsby and Whitehouse (2005). The model calculates the current and wave generated ripples and takes into account their time evolution. The total load is then calculated using the Ackers-White formulae (Ackers and White, 1973), adapted for waves by Swart (1976, 1977). Model output resulted in 30 minutes time step sediment transport parameters (bottom stress, bottom geometry, total load and bottom evolution) on a 750 m grid resolution.

Statistical analysis

The spatial variability of sediment transport parameters was characterized following the method described in Dalyander et al. (2013). In this paper, the maximum bottom stress will be used as an example to illustrate the statistical analyses for all sediment transport parameters. The yearly median and half of the interpercentile range (hIPR, half the difference between the 84th and 16th percentile) were calculated. The hIPR normalized by the median value (NIPR, equivalent to the coefficient of variation for normal distributions) was used as a measure of normalized variance. The 95th percentile (i.e., the value exceeded by 5% of the observations) was used as a measure of extreme values. The same routine was also used for every season, i.e.., spring (March-May), summer (June-August), fall (September-November) and winter (December-February), and can be applied for any desired period. Extraction of results is area- or location-based.

Results and discussion

As an example of results, a case is presented on the correlation of high bottom shear stresses with dominant north-eastern (NE) wave conditions. High bottom shear stresses may evoke seabed erosion on sandy substrates, especially when occurring over longer periods. The effect of NE conditions on seabed changes was already put forward by Van Lancker and Jacobs (2000) and Lanckneus et al. (2001), and was shown recently by Gypens (2014), investigating a 14-years dataset on multibeam bathymetry in the monitoring areas of sand extraction.

Considering the entire period 1999-2010, the highest spatial average of the yearly median bottom stress was found in 2010 (Figure 1). In that year, Gypens (2014) found a maximum number of NE wave events with significant wave heights of more than 2 m. 17 events took place, which could explain, at least in part, why the yearly median of the maximum bottom stress in 2010 was 10 % higher than in the second highest year. Highest multi-year median values in bottom stress were found on the Flemish Banks, the Belgian coastal area, the Vlakte van de Raan and off the Dutch Schouwen-Duiveland, the shallowest areas in the Belgian and southern Dutch part of the North Sea.

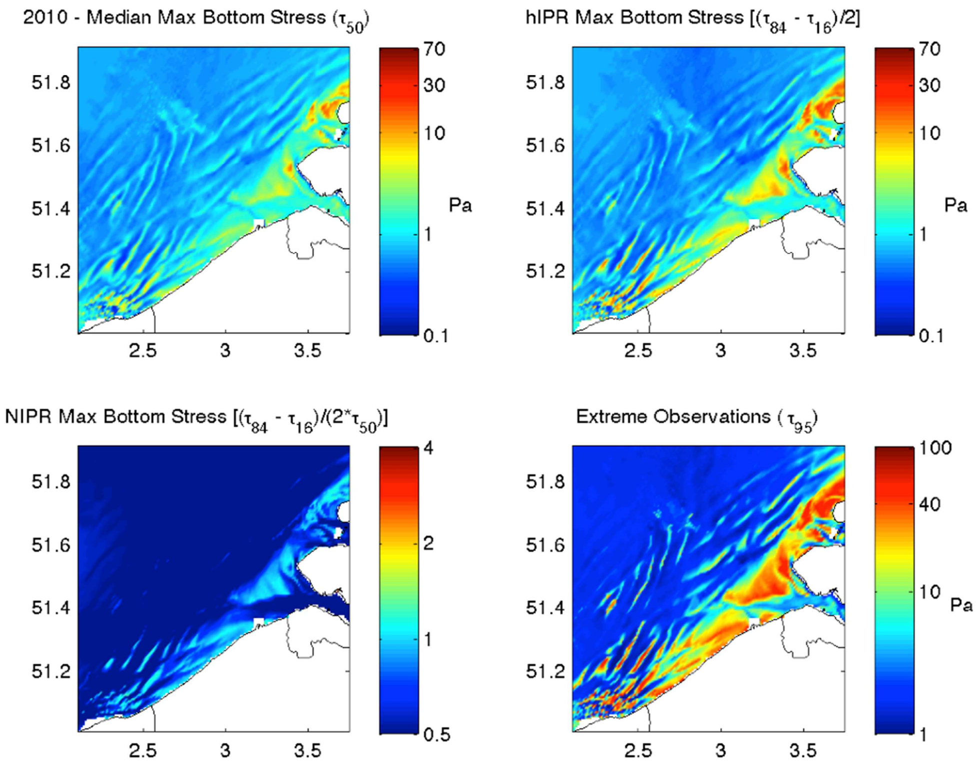

Figure 1: Median, half interpercentile range (hIPR, half of the difference between the 84th and 16th percentile), normalized interpercentile range (NIPR, half the interpercentile range divided by the median) and extreme obsevations (values exceeding the 95th percentile) of maximum bottom stress for the year 2010.

Statistical analyses revealed that higher hIPR and NIPR values (larger variability), over the same period, coincide with the areas of high bottom stress. The NIPR showed that the offshore regions were less variable. The 95th percentile of bottom stress (extreme observations) mirrored the overall spatial pattern of the median, with highest values in the coastal zone and on the Flemish, the Zeeland and Hinder banks. Seasonally, all bottom stress values were higher and had increased variability during the fall and winter months (see Figures 2, 3, 4 and 5).

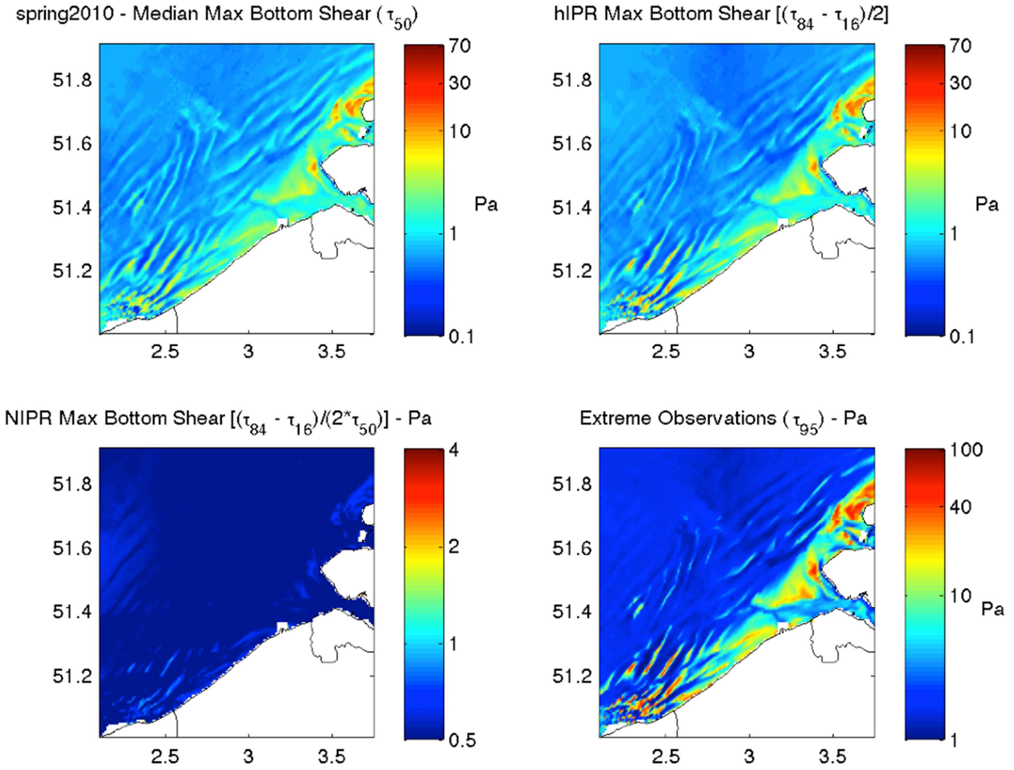

Figure 2: Spring 2010 (March – May 2010) Median, hIPR, NIPR and extreme obsevations (see Materials and Methods – Statistical Analysis for definition of the statistical parameters) of maximum bottom stress.

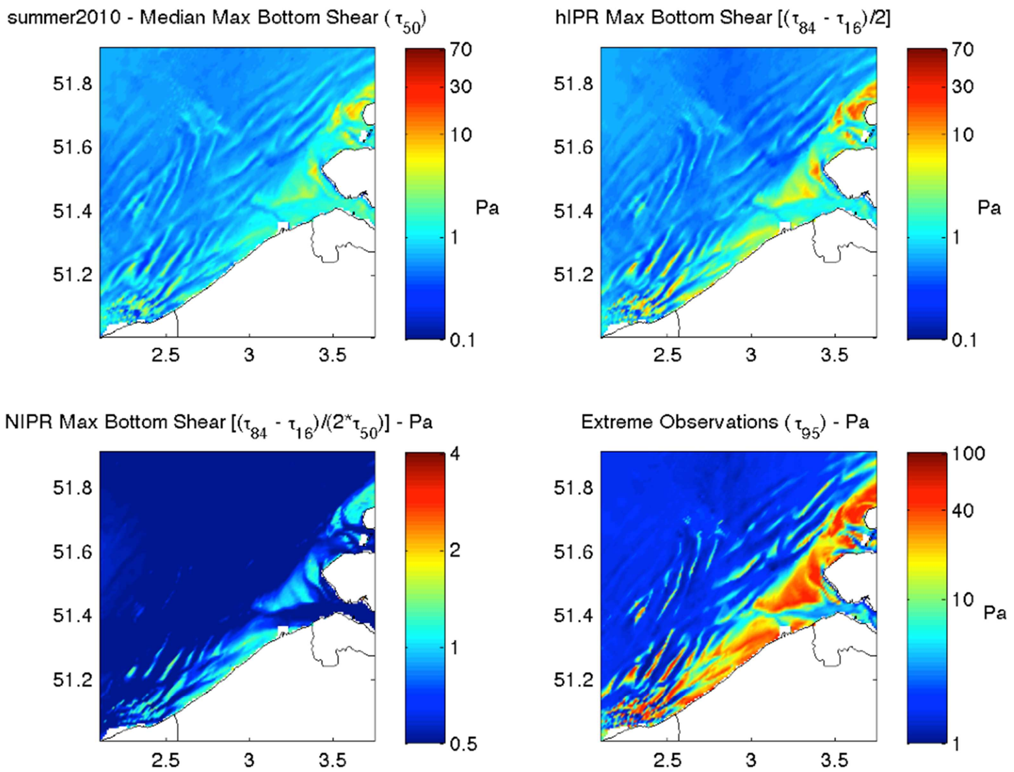

Figure 3: Summer 2010 (June - August 2010) Median, hIPR, NIPR and extreme obsevations (see Materials and Methods – Statistical Analysis for definition of the statistical parameters) of maximum bottom stress.

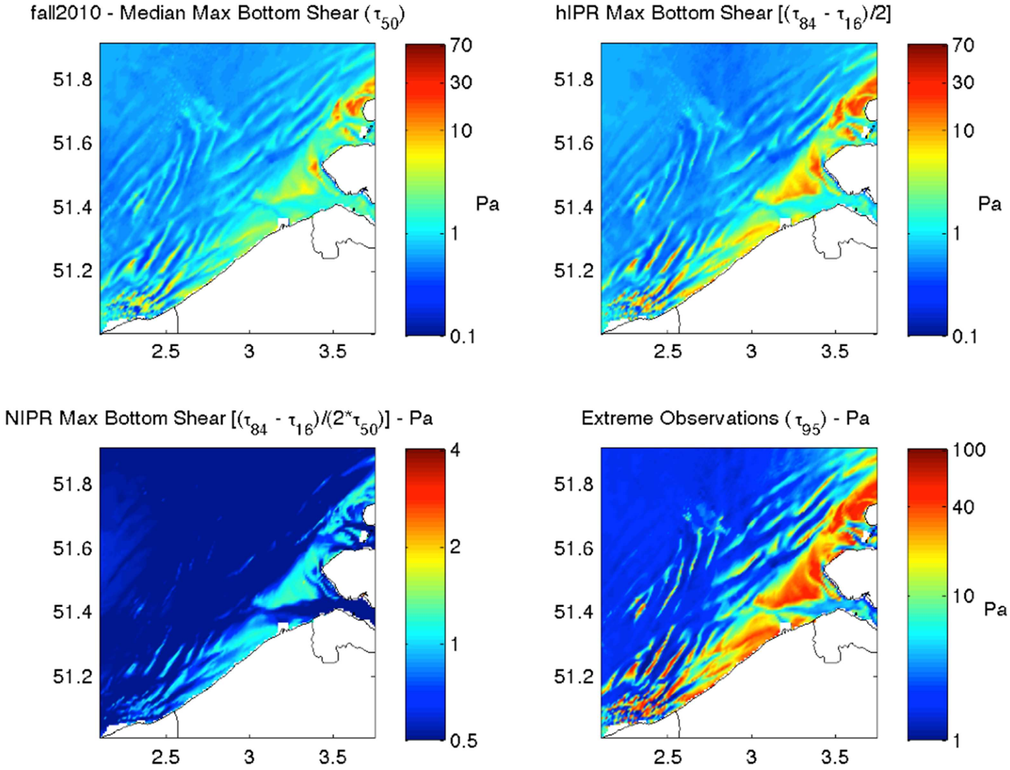

Figure 4: Fall 2010 (September – November 2010) Median, hIPR, NIPR and extreme obsevations (see Materials and Methods – Statistical Analysis for definition of the statistical parameters) of maximum bottom stress.

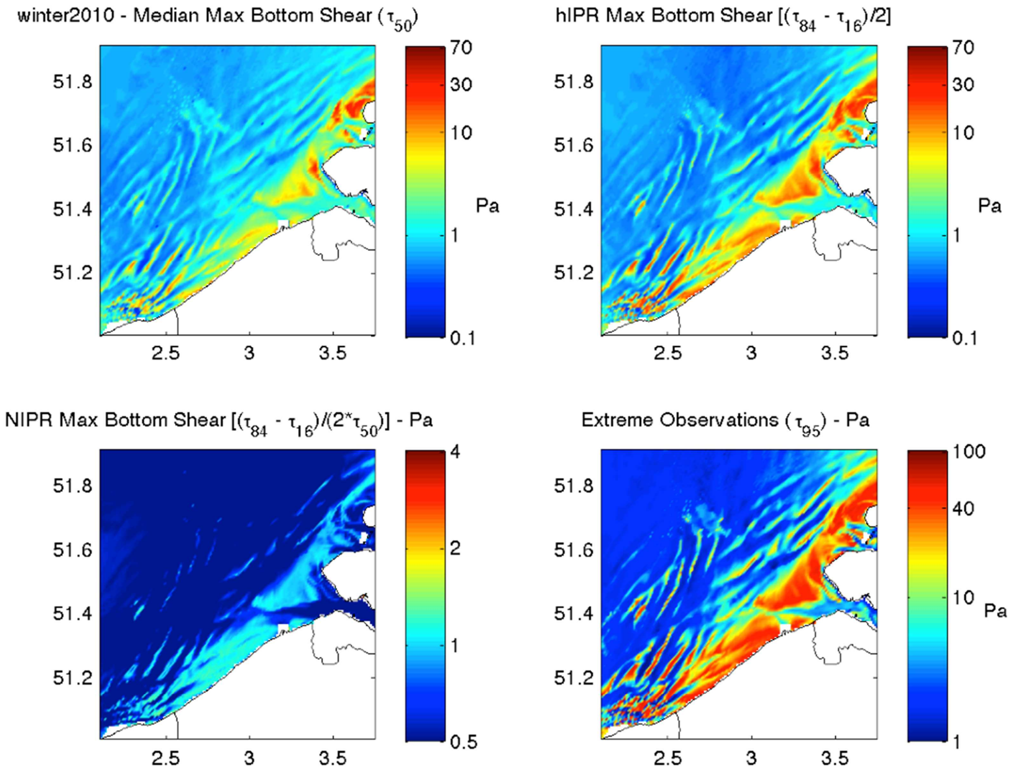

Figure 5: Winter 2010 (December 2010) Median, hIPR, NIPR and extreme obsevations (see Materials and Methods – Statistical Analysis for definition of the statistical parameters) of maximum bottom stress.

To illustrate in detail the temporal variability of the maximum bottom stress, a time series was depicted in Winter 2010 (December) as this season showed the highest variability throughout the year (Figure 6). An offshore location, on the Oosthinder sandbank (51.52°N, 2.62°E), with high temporal variability was selected. For this period a median maximum bottom stress of 6.29 Pa was calculated with values up to 60 Pa (± 10 times higher). *In-situ* data, available in the area, showed values of up to 4 Pa under normal spring tidal conditions (Van Lancker et al., this volume), hence illustrating the overall agitated conditions of Winter 2010. Most striking in Figure 5 is the correspondence of high bottom stresses with longer periods of NE wind directions.

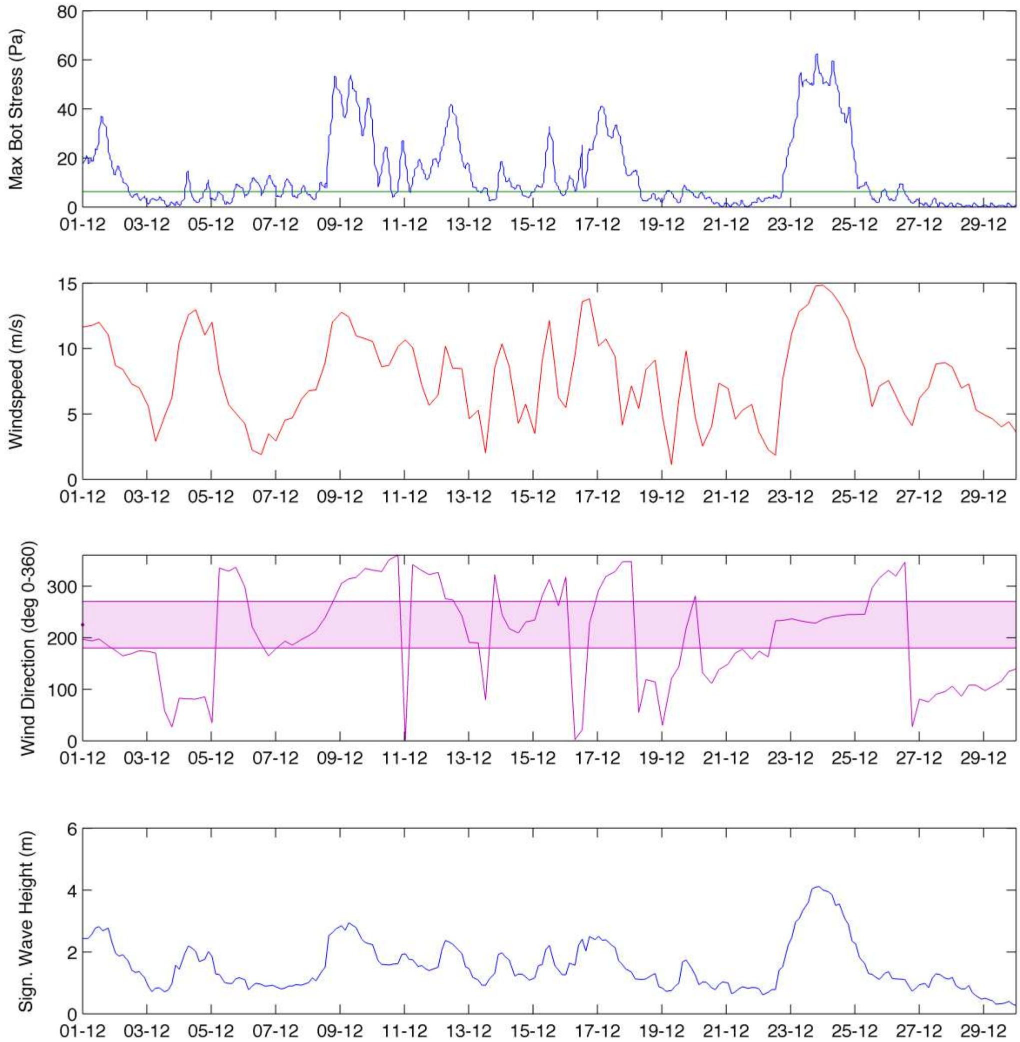

Figure 6: Winter 2010 (December 2010). From top to bottom: time series of maximum bottom stress (median value in green), wind speed, wind direction (0° wind blowing to the East, 90° wind blowing to the North - shaded area indicates NE winds), and significant wave height for a location on the Oosthinder sandbank.

Conclusions

An on-demand queryable sediment transport database has been created, covering the Belgian and southern Dutch part of the North Sea. It spans the period 1999-2010, but is expandable in time. Future applications are wide-spread and can include the estimation of the regeneration or recovery potential of the seabed, based on the natural deposition character of the area. It will also provide insight into the areas that are naturally more erosive, hence more vulnerable to the impact of human activities. With direct relevance to Europe's Marine Strategy Framework Directive, future work will concentrate also on the development of envelopes of natural variability, critical to distinguish naturally- versus anthropogenically-induced sediment dynamics.

There is scope to develop an on-line extraction tool to easily request time series on sediment transport parameters, and its associated statistical parameters.

Acknowledgements

Financial support for this study was provided through the project ZAGRI, a continuous monitoring programme, paid from the revenues of marine aggregate extraction activities. Wave analyses, KULeuven, were performed in the framework of BELSPO QUEST4D (SD/NS/06B) project. This work contributes also to the Brain.be project TILES (Transnational and Integrated Long-term marine Exploitation Strategies), funded by BELSPO under contract BR/121/A2/TILES.

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Adaptation of the reference level for sand extraction: feasible or not?

De Mol Lies[*1], *Degrendele Koen*[1], *Roche Marc*[1]

[*]*Presenting author: lies.demol@economie.fgov.be*

[1] *FPS Economy, S.M.E.s, Self-employed and Energy, Directorate-General Quality and Safety, Continental Shelf Service, Koning Albert II-laan 16, 1000 Brussel, Belgium*

Introduction

The sand and gravel extraction in the Belgian part of the North Sea (BPNS) is limited to 5 m below the reference level determined by the Fund for sand extraction (Royal Decree of September 1, 2004 Art. 31). However, the sand extraction industry and the scientific institutes involved in the monitoring of the impact are demanding to adapt this arbitrarily defined reference surface based on clear scientific criteria. To optimally use the available sand reserves in the near future, taking into account a number of key projects (such as the master plan coastal safety), this project is indispensable.

Based on a detailed seismic study, a three-dimensional map of the sand extraction areas in the BPNS will be made. This allows an accurate evaluation of the available sand reserves and the economic potential. On this basis, a new reference surface regarding the maximum extraction depth will be proposed. First, the existing and available seismic data in control zones 1, 2 and 4 will be investigated and evaluated based on quality, density and detail. If necessary, additional seismic measurements will be scheduled. Next, several possible reference surfaces will be calculated using all the seismic data combined with the bathymetric models and the available sedimentological data. Finally, these surfaces will be further analysed taking into account both economic and environmental arguments.

Material and methods

For this study the existing seismic dataset from the Renard Centre of Marine Geology (Department of Geology and Soil Science, Ghent University) will be used. This dataset has been fully analysed and interpreted within the framework of the doctoral thesis of Mieke Mathys. More than 16.000 km of high-resolution seismic profiles have been acquired on the BPNS since the end of the '70's within the framework of several national and international projects. About 4.000 km of these old high-resolution single-channel reflection seismic profiles were digitised and integrated with 1.300 km of recent seismic data. These data were obtained between September 1980 and April 2007 on board of the research vessels Belgica, Mechelen, Sepia II, Spa and Bellini with different types of seismic tools (Mathys, 2009).

In addition, the results of the seismic investigation of the Hinder Banks will be incorporated. This study has been performed in 2008 by the Coastal Division (Agency for Maritime and Coastal Services, Flemish Government) in order to investigate the distribution and characteristics of the sediment for the future exploitation in exploration zone 4 (Mathys et al., 2009).

Besides the already available data, new seismic profiles were needed in control zone 2 on the Buiten Ratel and Oostdyck due to the low density and the low quality of the existing data in the area. In June-July 2014 more than 160 km of 2D high-resolution reflection seismic data were acquired in a study by the Continental Shelf Service, using the SIG sparker 1200 seismic source of the RCMG. This source has a frequency range of 800-900 Hz allowing a penetration depth up to 100 m in sandy sediments with a vertical resolution of 50 cm.

All seismic data were integrated and analysed with the IHS Kingdom 2d/3dPAK software package.

Results and discussion

Two major geological boundaries are of great importance on the BPNS, namely the top of the Paleogene or the basis of the Quaternary and the top of the Eemian. As a case study the Hinder Banks area has been used (Figure 1).

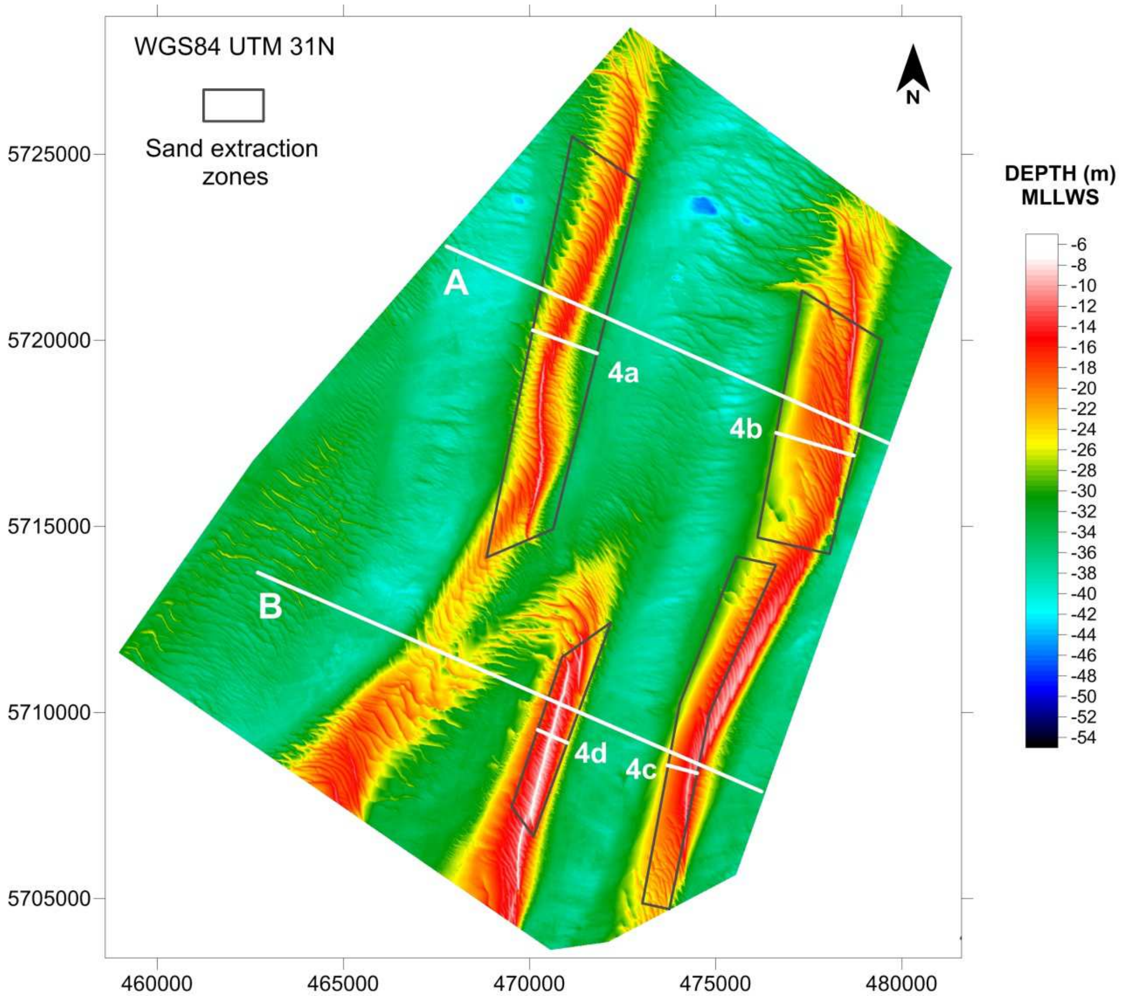


Figure 1: Bathymetric map of the case study area on the Hinder Banks including the location of the profiles.

The Paleogene deposits, mainly deposited during the Thanetian (59,2-56,0 million years ago) and Rupelian (33,9-28,1 million years ago), occur at a depth of -10 to -60 m (MLLWS), dipping in offshore direction (De Batist, 1989) and locally outcropping between the discontinuous cover of Quaternary sediments (Mathys, 2009). The top of the Paleogene is marked by a distinct angular unconformity, probably formed in marine as well as fluvial circumstances over a long period of time and under the influence of climatic changes (Mostaert et al., 1989). It is characterised by a number of planation surfaces, bounded by slope breaks and scarps, and several incised valley structures (e.g. Ostend Valley) (Mathys, 2009). Directly above the unconformity, at the base of the Quaternary deposits, a gravel lag deposit is commonly present. It consists of a heterogeneous mixture of silex and sandstone boulders and pebbles, and abundant shell fragments, mostly in a sandy matrix (Mathys, 2009). On the Hinder Banks the top of the Paleogene (Figure 2) varies between 32 m below seafloor (bsf) underneath the sandbanks and 0 m in the gullies in between the sandbanks where the Paleogene is outcropping.

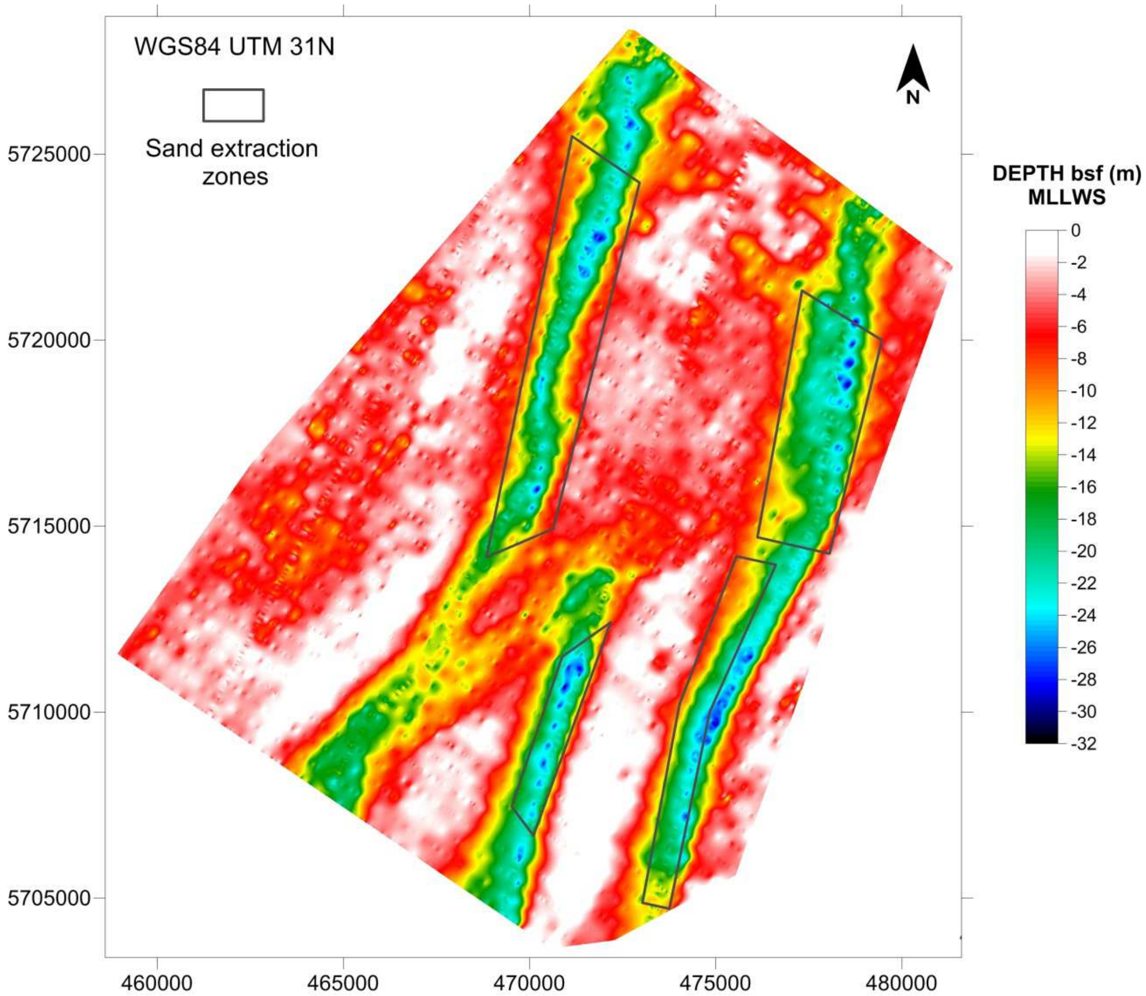


Figure 2: Depth chart of the top Paleogene on the Hinder Banks (in meters below seafloor).

The Eemian interglacial (128.000-116.000 years ago) caused a sea level rise where the coastline moved about 7 km inland compared to the present situation with even a marine influence up to 40 km inland the Flemish Valley (De Moor et al., 1996; Mathys, 2010). This sea level rise led to the deposition of a gravel layer in the BPNS from earlier infills of the Meuse and Ostend valleys (Mathys, 2010). However, this Eemian gravel layer is only fragmentary present in the BPNS where even questions rise about the correct age of these gravels (C. Baeteman, pers. comm.). On the Hinder Banks the top of the Eemian (Figure 3) varies between 26 m bsf underneath the sandbanks and 0 m in between the banks where it has been eroded.

During the Holocene (about 7000 years ago) the formation of the tidal sandbanks, such as the Hinder Banks, started on top of the Eemian marine transgressive surface (Mathys et al., 2009). These tidal sandbanks have a maximum thickness of 26 m on the Hinder Banks. An example of the internal structure of the Hinder Banks is shown in figure 4. On figure 5 two profiles through the Hinder Banks area are presented showing the most important geological boundaries as well as the current reference level of -5 m.

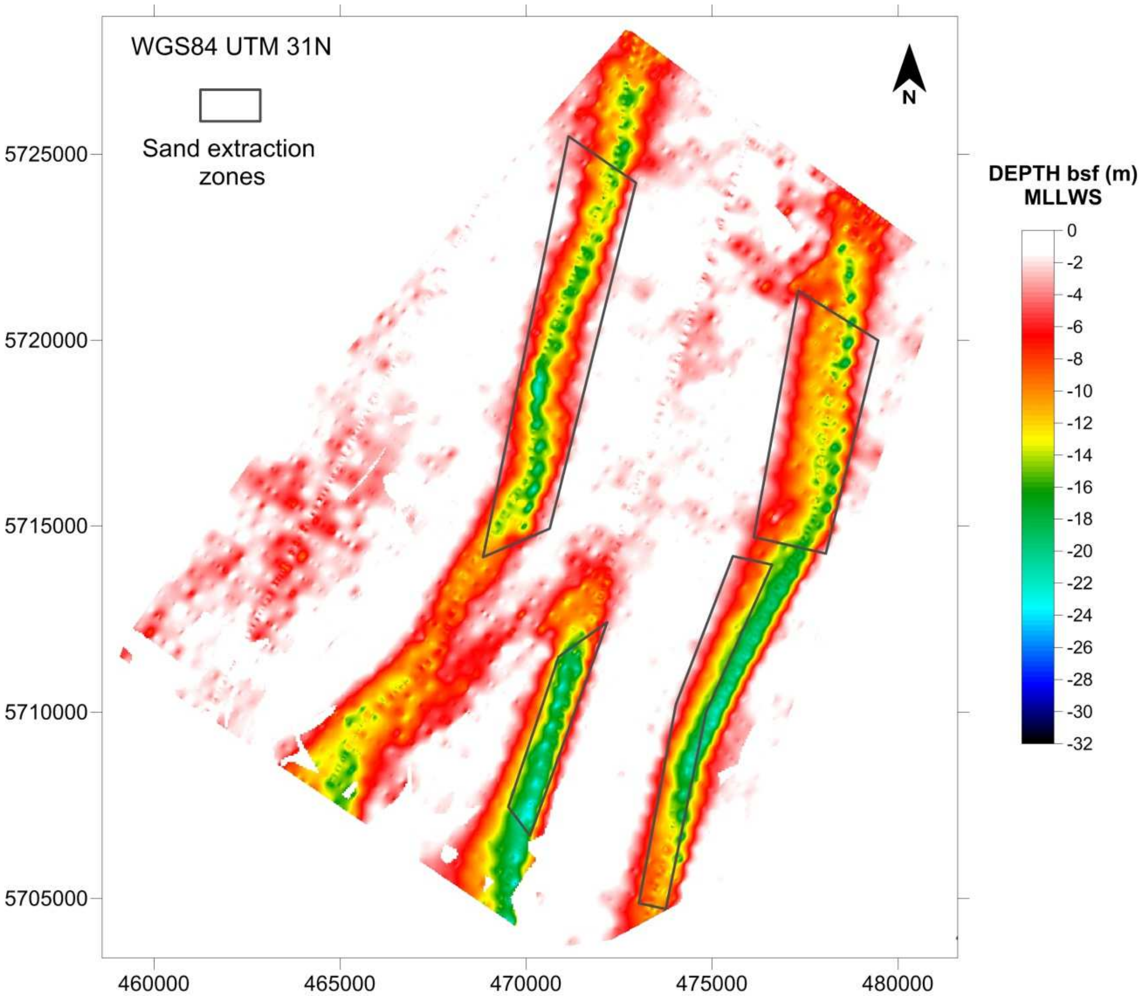


Figure 3: Depth chart of the top Eemian on the Hinder Banks (in meters below seafloor).

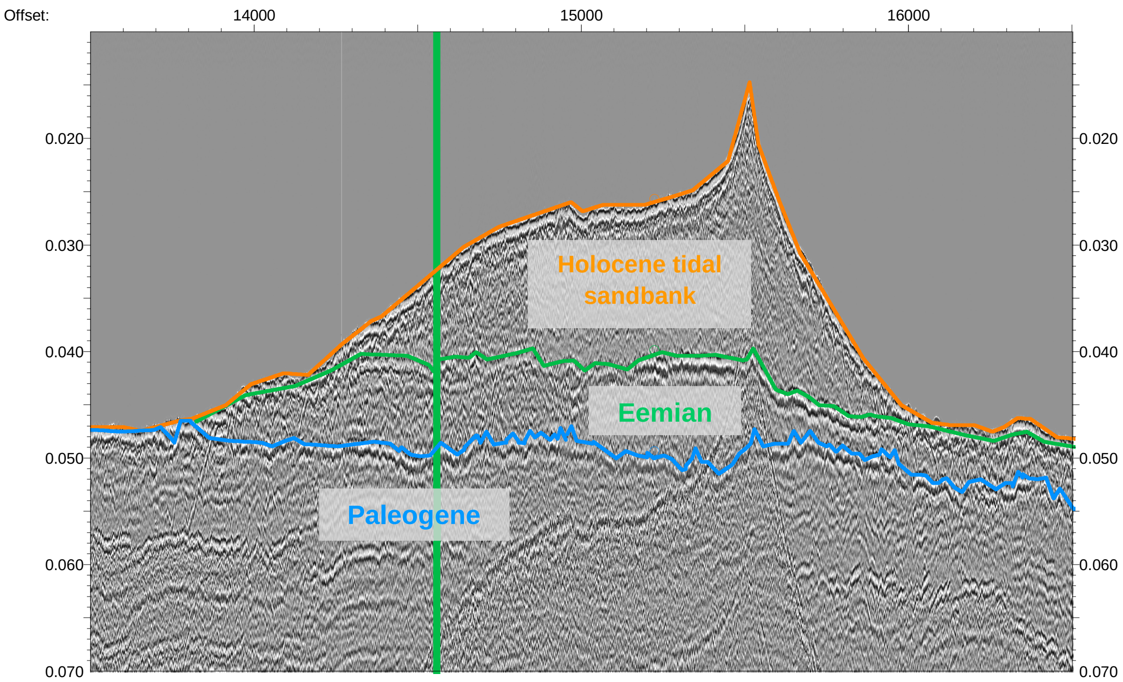
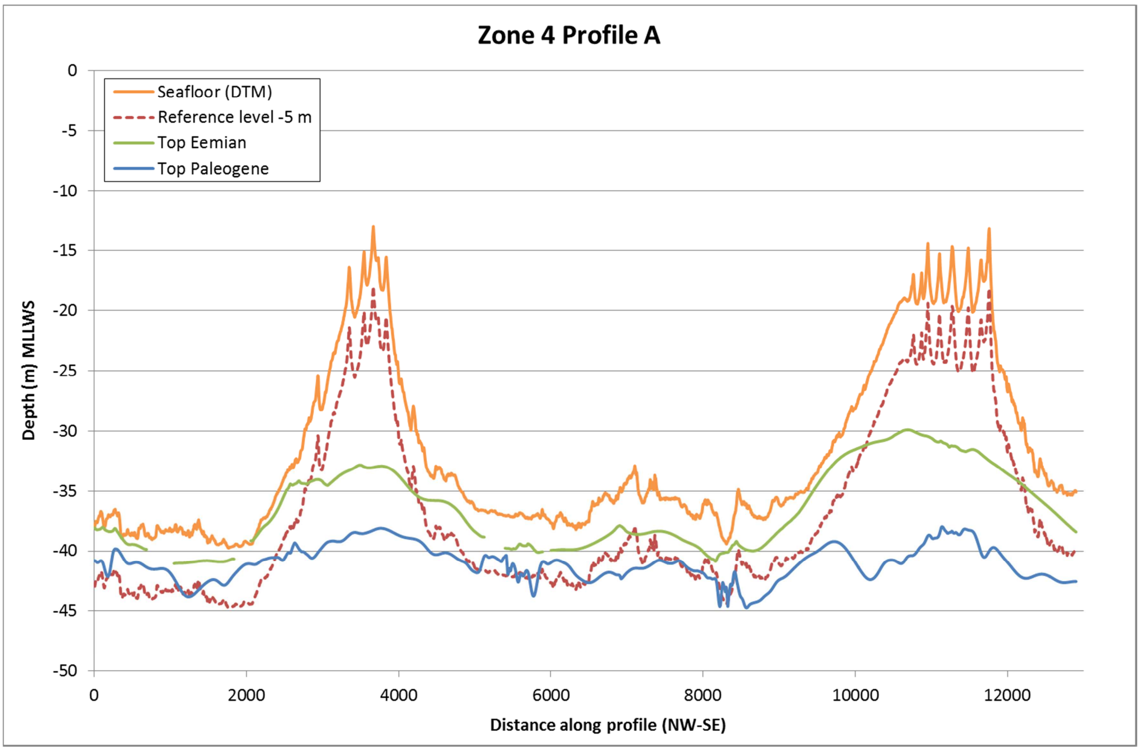


Figure 4: Example of a seismic profile showing the internal structure of the Hinder Banks (vertical scale in two-way travel time).



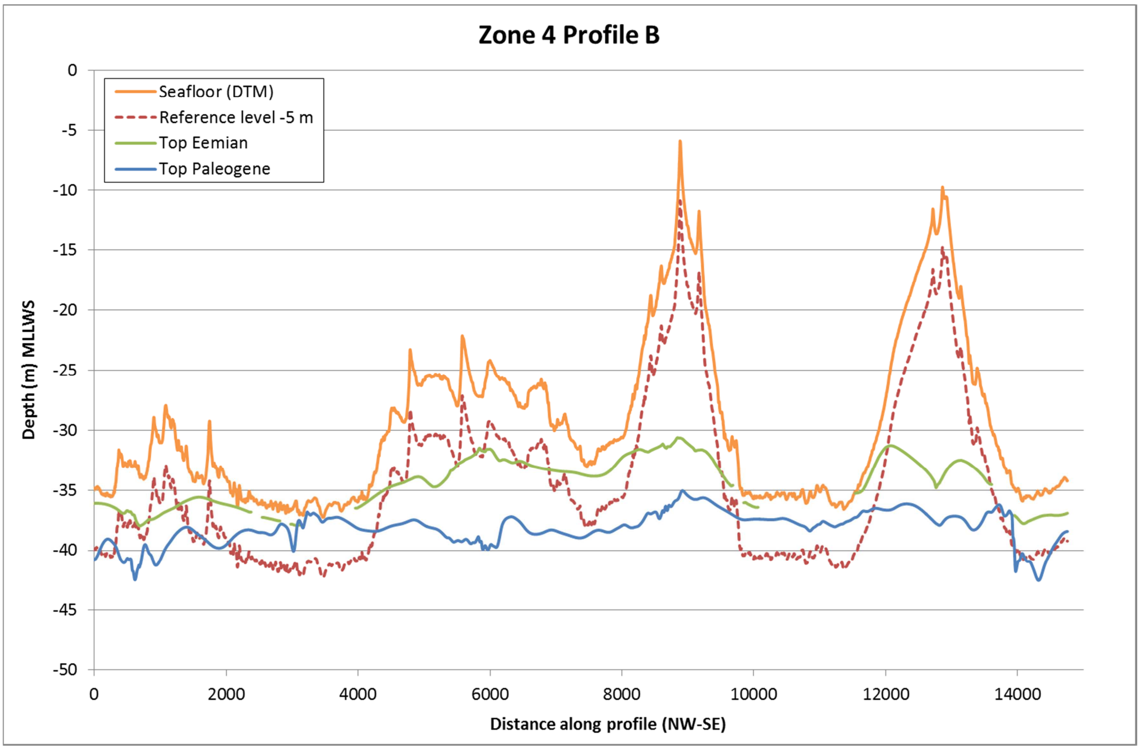


Figure 5: Profiles across the Hinder Banks (the location of these profiles is indicated on figure 1).

The following geological and geomorphological criteria will be used to define a new reference level for sand extraction in the BPNS:

- extraction is not allowed below the top of the Paleogene;
- extraction is not allowed below the top of the Eemian
- extraction on the flanks and extremities of the sandbanks as well as over 'kink' areas (if present) is limited;
- the volume of sand available for extraction should be at least the same as present.

These criteria are consistent with the recommendations for a sustainable exploitation of tidal sandbanks (Van Lancker et al., 2010). Indeed, increasing the potential volume for extraction in the upper part of the sandbanks while limiting the extraction in the less stable areas corresponds with the industrial and environmental needs.

A first proposal for a new reference surface in the four extraction sectors on the Hinder Banks is shown in figure 6. This reference level corresponds with a surface 12 m above the top of the Paleogene. In sector 4a this results in a reduction of the area, however, the total amount of available sand for extraction increases taking into account all sectors.

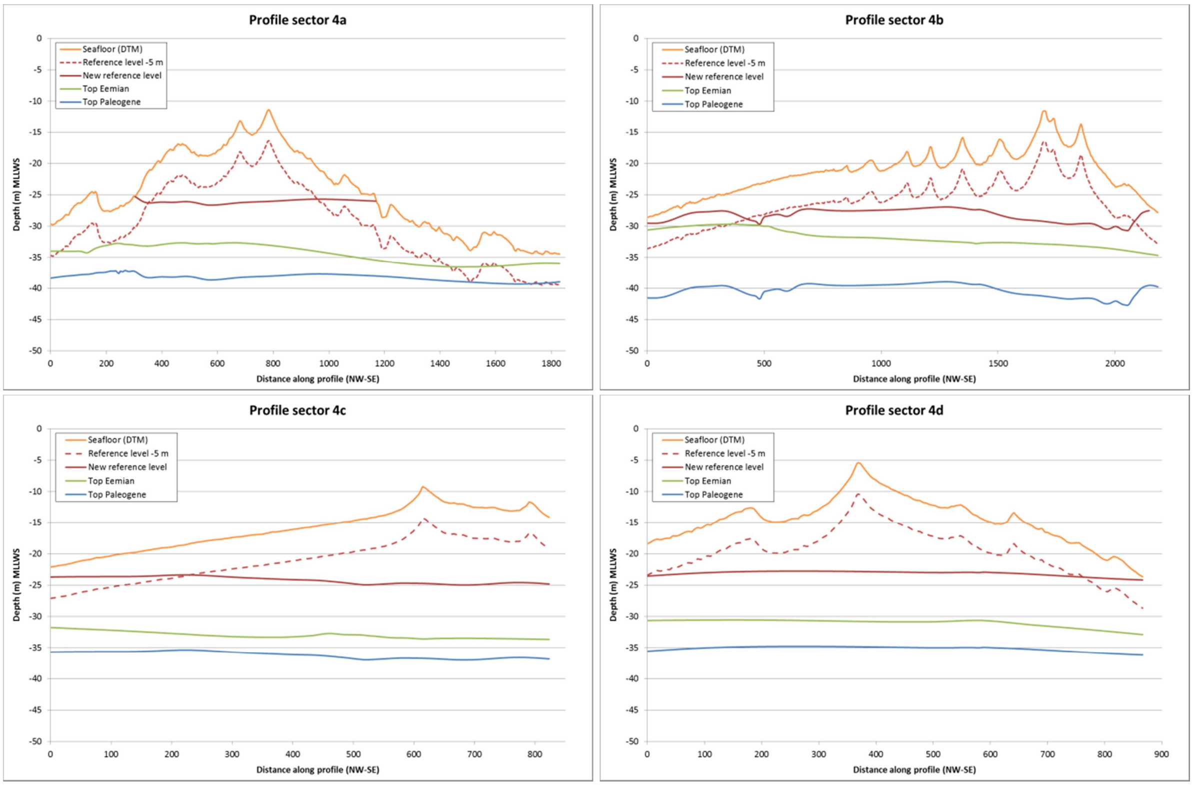


Figure 6: Proposal for a new reference level for sand extraction in sectors 4a, 4b, 4c and 4d on the Hinder Banks (the location of these profiles is indicated on figure 1).

In a next step, available sediment cores will be incorporated in order to refine the proposed reference level and the criteria. These cores will allow to include grain size distribution data which is valuable information for the sand extraction industry. Additionally, new vibrocores will be obtained, mainly on the Thornton Bank and the Flemish Banks.

Finally, an impact study will be performed in order to investigate the impact of this new reference level on the environmental and hydrodynamic conditions in the control zones as well as the impact on the coast. Taking into account the goal to reach a Good Environmental Status by 2020 (European Marine Strategy Framework Directive), no significant changes in seafloor integrity (Descriptor 6) and hydrographical conditions (Descriptor 7) are allowed.

This project, focusing on the sand extraction areas in the BPNS, shares many methodological aspects with the larger scale project TILES (Transnational and Integrated Long-term Marine Exploitation Strategies) funded by the Belgian Science Policy Office (2013-2017) (Van Lancker et al., this volume). In cooperation with the project partners this new reference surface, whose resolution will be adapted to the resolution necessary for a proper management of the sand resources and the new data on which it is based, will be integrated in the 3D geological voxel model developed in the near future.

Conclusions

Defining a new reference level for sand extraction in the BPNS is feasible, however, an extended scientific study is necessary. Based on seismic and bathymetric data a draft reference level is proposed using scientifically meaningful criteria. This reference level will be further refined using sediment cores followed by an impact assessment (e.g. changes in hydrographical conditions, impact on seafloor integrity, influence on the coast…).

Acknowledgements

The authors would like to thank the captain and crew of RV Belgica for their patience and the nice cooperation. We are grateful to Koen Derycker for the technical support during the seismic acquisition, Oscar Zurita Hurtado for the help with the seismic processing and Maikel De Clercq and Vasileios Hademenos for their advice regarding interpretation. Mieke Mathys is acknowledged for giving an introduction into her IHS Kingdom project.

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Interactive management of marine resources in the southern North Sea, a long-term perspective

Van Lancker Vera[*1], *Francken Frederic*[1], *Terseleer Nathan*[1], *Van den Eynde Dries*[1], *De Mol Lies*[2], *De Tré Guy*[3], *De Mol Robin*[3], *Missiaen Tine*[4], *Hademenos Vasileios*[4], *Maljers Denise*[5], *Stafleu Jan*[5], *van Heteren Sytze*[5]

[*]*Presenting author: vera.vanlancker@mumm.ac.be*

[1] *Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment (RBINS OD Nature), Gulledelle 100, 1200 Brussels, Belgium*

[2] *FPS Economy, S.M.E.s, Self-employed and Energy, Directorate-General Quality and Safety, Continental Shelf Service, Koning Albert II-laan 16, 1000 Brussels, Belgium*

[3] *Ghent University, Dpt. Telecommunications, Database, Document and Content Management, Sint-Pietersnieuwstraat 41, 9000 Gent, Belgium*

[4] *Ghent University, Dpt. Geology, Renard Centre of Marine Geology, Krijgslaan 281 S8, 9000 Gent, Belgium*

[5] *TNO, Geological Survey of the Netherlands, Princetonlaan 6, 3584 CB Utrecht, The Netherlands*

Abstract

Management of geological resources is based, ideally, on information on the quality and quantity of surface and subsurface litho-stratigraphical properties. Increasingly, these data become available for the offshore domain, though the integration into manageable and user-friendly applications is still at its infancy. Building on expertise from on-land data mining, we are now in the phase of creating 3D voxel models allowing for multi-criteria resource volume calculations. The underlying data are subdued to uncertainty modelling, a necessary step to produce data products with confidence limits. Anticipating on the dynamic nature of the marine environment, voxel models are coupled to environmental impact models that calculate resource depletion and regeneration under various scenarios, and using geological boundary conditions. In combination with foreseen impacts on fauna and flora, mining thresholds can be defined. Integration into a decision-support system allows for easy querying and on-line visualizations. Main aim is to provide long-term predictions on resource quantities to ensure future supplies for the benefit of society and next generations.

Key words: Sustainable Exploitation, Mining thresholds, 3D Geological Models, 4D Decision-Support System, Uncertainty modelling

Introduction

Mineral and geological resources can be considered to be non-renewable on time scales relevant for decision makers. Once exhausted by humans, they are not replenished rapidly enough by nature, meaning that truly sustainable resource management is not possible. Comprehensive knowledge on the distribution, composition and dynamics of geological resources therefore is critical for developing long-term strategies for resource use (e.g., Van Lancker et al., 2010). For the marine realm, resource management is often hampered by sparse data availability, though increasing exploitation demands call for innovative approaches that include uncertainty as a primary asset. This is the scope of the TILES project (2013-2017), set-up for managing marine aggregate exploitation in the southern North Sea, but generically designed for a broader range of resources and environments.

The ambition of TILES is to:

- Develop a 4D resource decision-support system containing tools that link 3D geological models, knowledge and concepts to numerical environmental impact models. Together they quantify natural and man-made changes to define sustainable exploitation thresholds. These are needed to ensure that recovery from perturbations is rapid and secure, and that the range of natural variation is maintained, a prerequisite stated in Europe's Marine Strategy Framework Directive (MSFD), the environmental pillar of Europe's Maritime Policy.
- Provide long-term adaptive management strategies that have generic value and can be used for all non-hydrocarbon geological resources in the marine environment.
- Propose legally binding measures to optimize and maximize long-term exploitation of aggregate resources within sustainable environmental limits. These proposed measures feed into policy plans that are periodically evaluated and adapted (e.g., Marine Spatial Planning and the Marine Strategy Framework Directive, being Federal Authority's strategic priorities).

The TILES study area comprises the Belgian and southern Netherlands part of the North Sea (BPNS and NPNS, south of Rotterdam), in total ± 9700 km². Most of the resources are extracted from the offshore sandbanks (Figure 1).

Figure 1: The Belgian-Dutch offshore area considered in the TILES project: significant volumes of sand are stored in the ebb delta of the estuaries and in sandbanks located farther seaward. North is to the West of the figure; bright to darker yellow represents shallow to deeper depths. Bathymetry data: Flanders Hydrography and Dutch Hydrographic Service & Deltares.

Material and methods

The project objectives are achieved through interdisciplinary and transnational research on the nature and dynamics of geological resources and on the environmental impact of extraction. State-of-the-art 3D geological models are being developed by transforming layer models, defining stratigraphic unit boundaries, into so-called voxel models (consisting of '*tiles'* or volume blocks) and assigning to each voxel lithological or other characteristics (e.g., Stafleu et al., 2011). The primary voxel information is based on a combination of point and line data, respectively from coring and seismic investigations. These data, and additional environmental datasets, that are added to the voxels, are subjected to uncertainty analyses, a necessary step to produce data products with confidence limits. Uncertainties relate to data and interpolation issues (van Heteren & Van Lancker, in press); their propagation is assessed throughout the data products. The geological models feed into 4D numerical impact models quantifying the environmental impact of extraction (e.g., Van den Eynde et al., 2010). Geological boundary conditions (e.g., base of extractable layers) will be used. Regeneration potential and depletion rates will be calculated per main sediment type, based on monitoring, extraction data and a 10-yrs time series of sediment transport modelling (Francken et al., this volume). Per vertical series of voxels, a sustainable extraction threshold will be proposed, taking into account the geological resource available, regeneration potential and depletion rate that will limit the resource potential to what is environmentally acceptable (Figure 2). Further constraints relate to the compatibility with other human activities, protected and exclusion zones, as well as socio-economic and other environmental factors (Figure 2).

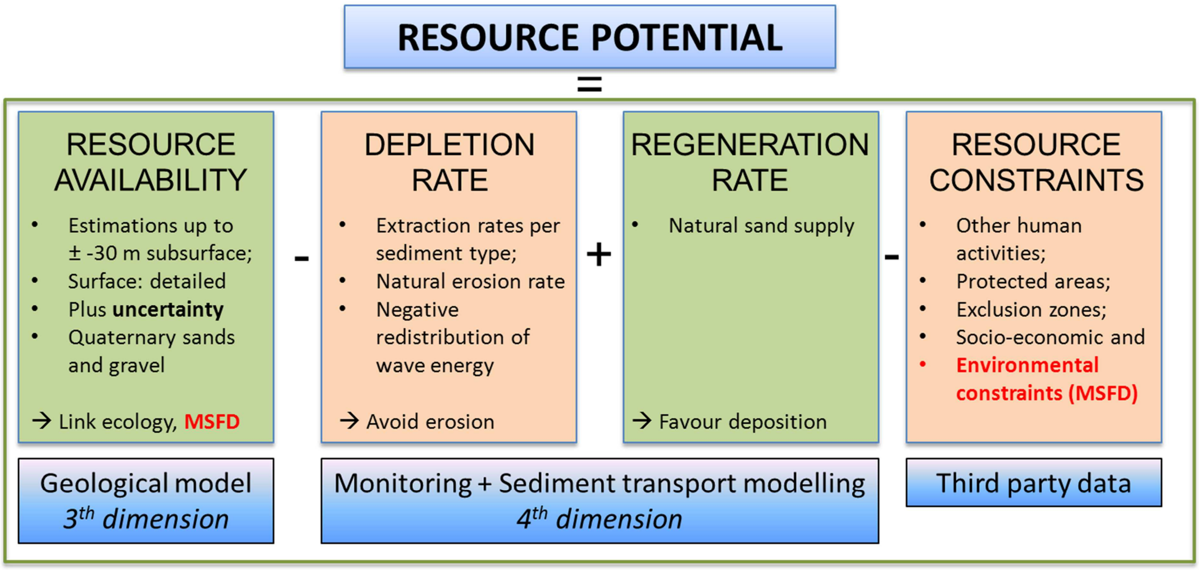

Figure 2: Definition of the resource potential within TILES. Combination of the datasets into impact modelling will yield a sustainable extraction threshold per vertical series of voxels. This will allow assessing the resource potential within sustainability limits, a MSFD prerequisite.

Finally, scenario analyses and prediction forecasts will be performed to estimate the resource potential on the long term. A newly developed multi-criteria decision-support system (DSS) will be used to run the scenarios. Advanced criteria-evaluation techniques, incorporating expert knowledge, will support the construction of suitability maps (e.g., De Tré et al., 2010). Geological boundaries, distributions of particular resource qualities, and the resource estimation at various cut-off grades will be calculated in a time-efficient manner. Sediment transport model results will be used as input and will reflect, amongst others, how the extraction scenarios lead to changes in wave energy and direction. Additionally, the DSS will allow weighing other functions on the BPNS, and take into account environmental and socio-economical parameters. Using a dedicated subsurface viewer, a suite of data products will be viewable online. They can be extracted on demand from the underlying voxel model. The flexible 3D interaction and querying is invaluable for professionals, but also for the public at large and for students in particular.

The TILES workflow is presented in Figure 3; in its entirety leading to a geological knowledge base that will function as a critical platform for the exchange of data, information and knowledge.

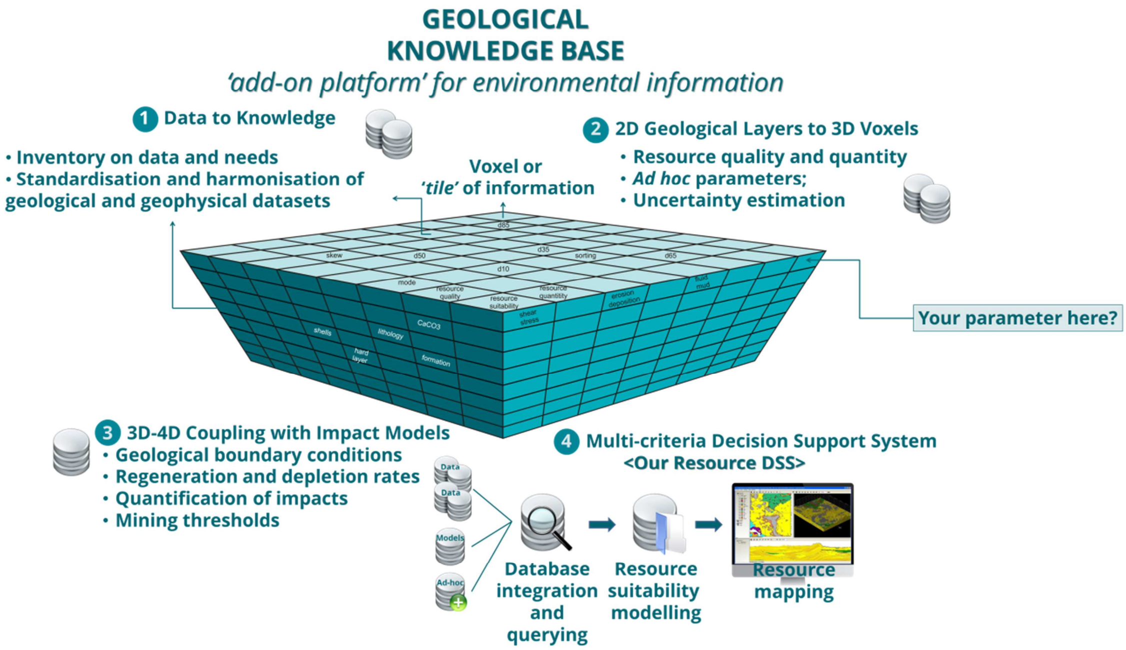

Figure 3: The set-up of a Geological Knowledge Base is promoted to advance and innovate on collaborative research and management of resources, in casu non-living, but with ample opportunities to link with the living environment.

Results and discussion

Data to Knowledge

A majority of available coring and sediment data have been standardized following European guidelines (e.g., EU-FP7 Geo-Seas for geological and geophysical data). As such for the Belgian and Netherlands part of the North Sea, cross-border harmonized mapping of the main lithological attributes (Figure 4) is feasible. Adjusted Folk classes have a direct relation to the sediment characterization of the main habitat types in the southern Bight of the North Sea (Van Lancker & van Heteren, 2013) and can be grouped into EUNIS Level 3 habitats (e.g., sandy mud to mud; muddy sand to sand and coarse sediments, as well as gravel beds) of which a constant distribution and extent is used as an indicator of 'Good Environmental Status' within Europe's Marine Strategy Framework Directive (Belgische Staat, 2012) (Figure 5).

2D Geological layers to 3D voxels

For the BPNS, the basis of the voxel model is the geological layer model developed for the study of the Quaternary evolution of the Belgian shelf (Mathys, 2009). Fine-tuning and ground-truthing of the seismically-defined units is now done in a transnational context. Preliminary results confirm the relative anomalous occurrences of medium to coarse sands in the Flemish Banks' region.

Coupling of the geological models with environmental impact models

First results have been obtained on the natural variability of sediment dynamic-related parameters (bottom shear stress, bed evolution, total sediment transport) over a time span of 12-yrs (1999-2010) using a coupled current-wave modelling approach. Results are presented in Francken et al. (this volume). The model outcome will be validated against available monitoring data (depth observation series over the same time span; FPS Economy). Next, results will be transposed to the voxel model where probabilities of erosion and deposition will be further calculated, ultimately leading to an estimation of regeneration rates per voxel.

Simple Lithology	Udden-Wentworth classes	Adjusted Folk classes	Shell content (%)
Clay	Boulder (>256 mm)	mud	little (1-10%)
Diamicton	Cobble (64-256 mm)	slightly sandy mud	much (10-30%)
Gravel	Very coarse gravel (pebble) (32-64 mm)	sandy mud	numerical range *(every range within 0-100%)*
Gyttja	Coarse gravel (pebble) (16-32 mm)	muddy sand	
Mud	Medium gravel (pebble) (8-16 mm)	slightly muddy sand	**Mud content (%)**
Ooze	Fine gravel (pebble) (4-8 mm)	sand	little (1-2%)
Peat	Very fine gravel (granule) (2-4 mm)	slightly gravelly mud	moderate (2-10%)
Sand	Very coarse sand (1-2 mm)	slightly gravelly sandy mud	much (>10%)
Shell hash	Coarse sand (0.5-1 mm)	slightly gravelly muddy sand	numerical range *(every range within 0-100%)*
Silt	Medium sand (0.25-0.5 mm)	slightly gravelly sand	
	Fine sand (0.125-0.25 mm)	gravelly mud	**Median grain-size (d50)**
	Very fine sand (0.0625-0.125 mm)	gravelly muddy sand	numerical range *(any user-defined range)*
	Silt (mud) (0.0039-0.0625 mm)	gravelly sand	
	Clay (mud) (0.001-0.0039 mm)	muddy gravel	
		muddy sandy gravel	
		sandy gravel	
		gravel	

Figure 4: Selected attributes for resource characterization, available for both the Belgian and Netherlands part of the North Sea. European standards for the description of geological data are adhered to. The first attributes are derived primarily from lithological databases. Shell and mud content, as well as median grain-size can originate both from lithological and grain-size databases.

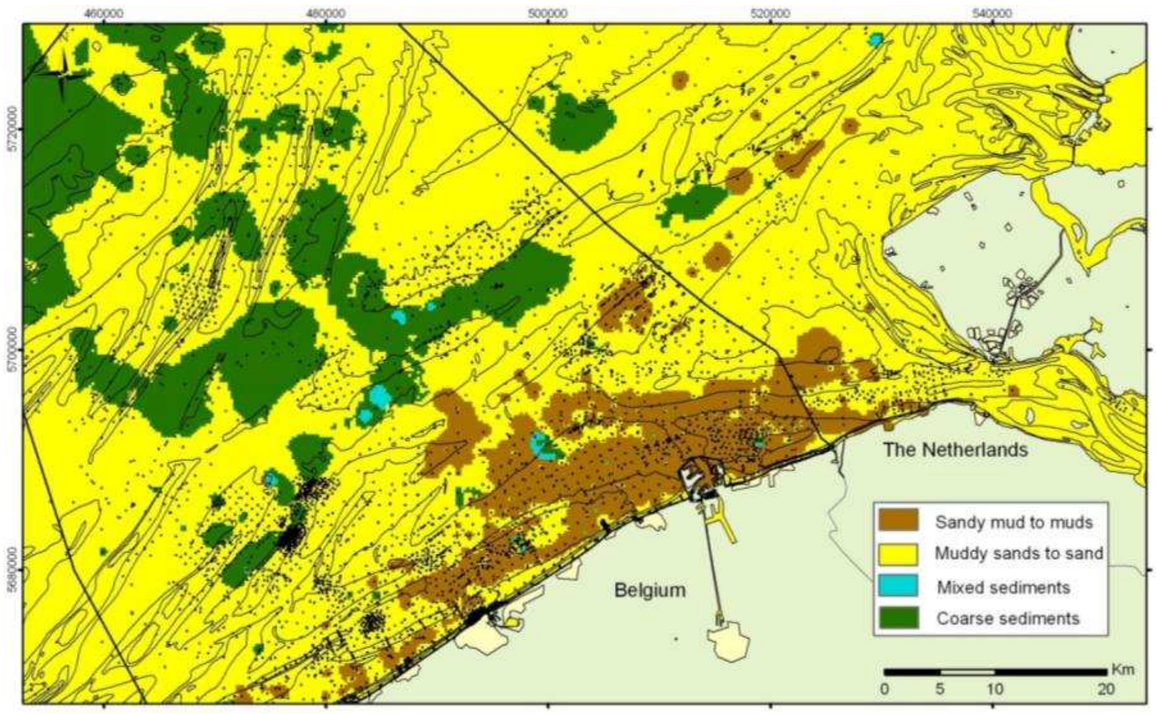

Figure 5: Grouping of adjusted Folk classes, representative of EUNIS Level 3 habitats: sandy mud to mud, muddy sands to sands, coarse sediments and mixed sediments. The distribution reflects the percentages of gravel, sand, silt and clay from sample data (black dots). Here, only sampling density is a measure of uncertainty (Van Lancker & van Heteren, 2013).

Multi-criteria Decision Support System

A DSS is being developed to answer a multitude of questions related to the voxel data. Using soft computing techniques and decision logic, a maximum of flexibility in the decision process is aimed at. A two-tiered approach is followed: (1) questions from a user need translation into requirements; (2) the system evaluates each voxel and provides a score from 0 (bad) to 1 (good) on the basis of (i) how well the voxel fulfils the requirements, (ii) how sure we are on the quality of the data; and (iii) missing data. In this process, the resource is defined following the attributes shown in Figure 4. A user can select any of the parameters listed which will then be prioritized by the system. Quality is related to data uncertainty and, based on expert judgement, incorporates methodology (e.g., coring techniques), analytical procedures (e.g., grain-size analyses), vintage, and data density. Per voxel, an interpolation-uncertainty is also provided. In this process transparency is regarded important enabling a user to trace how a certain score is obtained.

Conclusions

To anticipate on actual and future resource supplies and needs, long-term adaptive management strategies for the exploitation of geological resources are urgent requests (e.g., marine spatial planning, EU's Marine Strategy Framework Directive). They comply ideally with EU recommendations on 'Efficient use of resources' (EC COM2011_571) and ICES Guidelines for the management of Marine Sediment Extraction (ICES, 2003).

Within TILES a transnational, harmonized geological knowledge base will be provided as a critical platform for the exchange of data, information and knowledge. The set-up, functionalities, and coupling to environmental impact models are highly innovative and will herald a new age in resource management, locally and transnationally.

Acknowledgements

Research is funded by Belgian Science Policy, contract BR/121/A2/TILES. RBINS OD Nature's research is supported also by ZAGRI, a continuous monitoring programme paid from the revenues of marine aggregate extraction. This paper contributes to EMODnet-Geology (DG MARE), a European data portal for interpreted geological data.

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TILES website: http://www.odnature.be/tiles/

Marine spatial plan: sand (extraction) in Belgium

Vandenborre Steven[*1]

[*]*Presenting author: steven.vandenborre@milieu.belgie.be*

[1] *FPS Health, Food chain safety and Environment, Directorate-General Environment, Marine Environment, Eurostation, Victor Hortaplein 40/10, 1060 Sint-Gillis, Belgium*

The marine spatial plan (MSP) for the Belgian part of the North Sea is a plan organizing the desired spatial three-dimensional structure and temporal distribution of human activities, based on a long term vision and on formulating clear economic, social and ecological objectives. This plan aims at coordinating decisions having a spatial impact on the Belgian sea areas, and ensures every stakeholder to be involved in the process.

The MSP has been adopted in March 2014 and will be evaluated and revised after six years. There is a procedure for an intermediary revision.

The MSP has the following composition:

- Royal Decree establishing the marine spatial plan, including all the annexes;
- Annex 1 contains a spatial analysis of the Belgian sea areas. This includes:
  - a spatial location and a legal demarcation of Belgian sea areas;
  - the physical characteristics and existing environmental and natural conditions in the Belgian part of the North Sea (BNS);
  - inventory of the activities and use of the Belgian sea areas;
  - an overview of the spatial alliances and conflicts;
  - the planning and policy context.
- Annex 2 contains the long-term vision, objectives, indicators and spatial policy choices for the BNS:
  - core objectives and overall long-term vision;
  - spatial principles and a spatial structural vision for the BNS;
  - economic, social, environmental and safety objectives and indicators;
  - spatial policy choices for users and activities in the BNS.
- Annex 3 contains the actions for implementing the maritime spatial planning;
- Annex 4 contains all the maps.

Sand and gravel extraction is one of the historic activities taking place in the Belgian part of the North Sea and of vital importance for the construction sector and coastal defense. This important role has been validated by the MSP as follows.

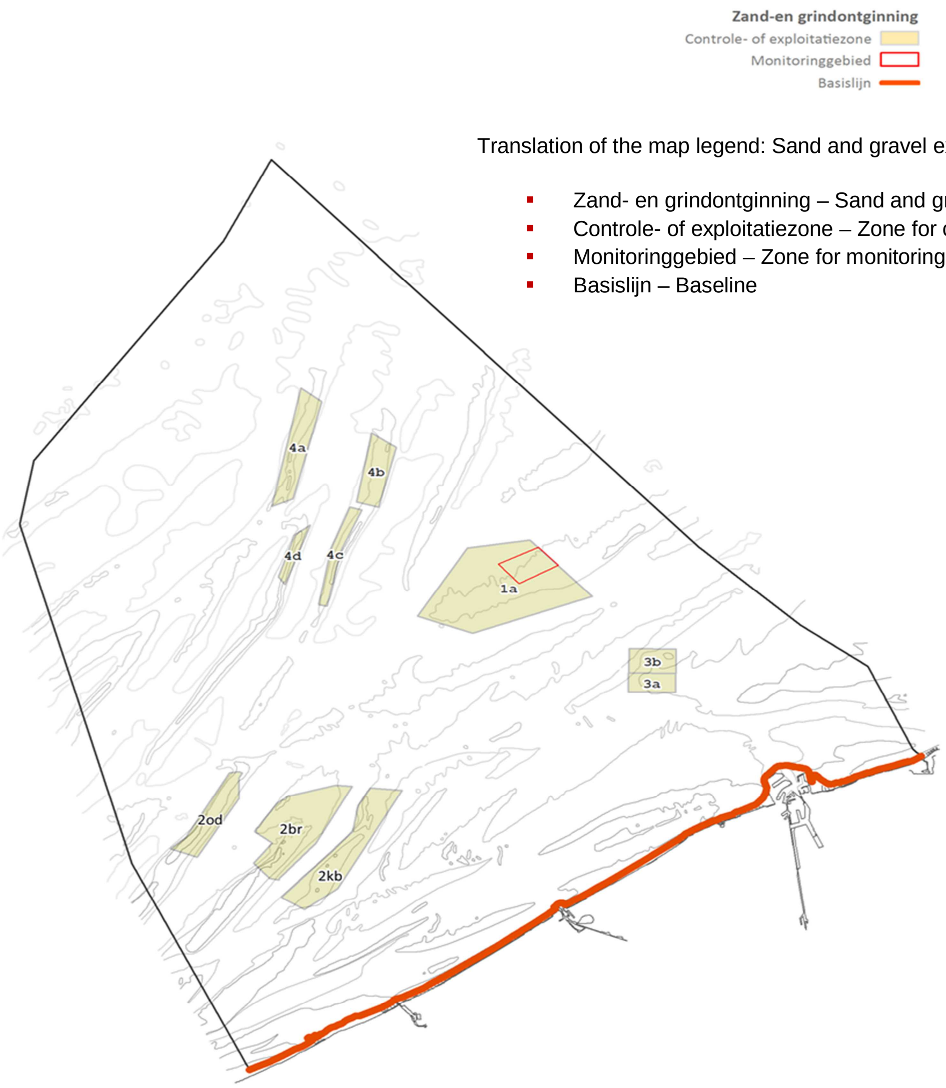
The vision is that there is a need for an optimal and sustainable extraction of sand and gravel, both for the construction sector and for the use as a function of the coastal defense against flood risks and for other applications.

The aforementioned vision has led to the following spatial options:

- Preservation of the 4 existing extraction zones;
- New definition of the sectors of zone 2 as a function of the shipping safety and nature conservation;

- Introduction of an appropriate assessment as an additional part of the environmental impact reports for concession demands within the special area for conservation ‘Vlaamse Banken’ (‘The Flemish Banks’);
- Preservation of the maximum allowed extraction volumes, with a gradual reduction of the extraction within the special area for conservation ‘Vlaamse Banken’ (‘The Flemish Banks’);
- Potential for multiple use of space;
- Combination with other activities in the extraction zones is possible since sand- and gravel extraction are temporary activities.

The aforementioned spatial options have resulted in this map:



Translation of the map legend: Sand and gravel extraction

- Zand- en grindontginning – Sand and gravel extraction
- Controle- of exploitatiezone – Zone for control or exploitation
- Monitoringgebied – Zone for monitoring
- Basislijn – Baseline

The Marine Strategy Framework Directive: Cementing monitoring efforts in Belgium and beyond

*Degraer Steven[*1], Vanden Berghe Marie[1]*

[*]Presenting author: steven.degraer@mumm.ac.be

[1] Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Marine Ecology and Management, Gulledelle 100, 1200 Brussels, Belgium

The Marine Strategy Framework Directive: Europe's marine environmental pillar under the Integrated Maritime Policy

The Marine Strategy Framework Directive 2008/56/EC (MSFD) that was adopted on 17 June 2008 and entered into force on 15 July 2008 is one of the key legal instruments of the European Union (EU) for the protection of the marine environment and its associated ecosystems and biodiversity. Before that, there were only measures within a sectorial approach, leading to a fragmented array of policies and legislations at the national, regional, European and international levels. The objective of this strategy is to protect and restore Europe's oceans and seas and ensure that human activities are carried out in a sustainable manner so that current and future generations enjoy and benefit from biologically diverse and dynamic oceans and seas that are safe, clean, healthy and productive. The MSFD serves as the legal framework to achieve this objective and as the environmental pillar of the EU's broader maritime policy.

The main objective of the MSFD is to achieve or maintain Good Environmental Status (GES) in the marine environment by 2020. GES means the environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive within their intrinsic conditions, and the use of the marine environment is at a level that is sustainable. GES and its related environmental targets (ETs) and indicators are defined on the basis of the eleven MSFD qualitative descriptors, covering environmental state (from biological over physico-chemical to commercial features of the marine ecosystem) as well as human pressures (e.g. contamination and introduced energy). The implementation of the MSFD should hence deliver an improved understanding and management of pressures and impacts arising from human activity and ultimately result in a reduction in undesirable impacts on the marine environment.

The Directive imposes a number of key steps that need to be undertaken by Member States (MSs) in order to reach the 2020 objective. MSs were first asked to perform an initial assessment of the environmental status, to analyse the socio-economic condition, to determine the characteristics of GES (i.e. what GES looks like) and to develop ETs and associated indicators for GES for their marine waters by 2012. These ETs and associated indicators help guiding progress towards achieving and maintaining GES. MSFD monitoring programmes targeting the indicators were developed in 2014 and will be executed from 2015 onwards. Finally, a programme of measures enforcing the achievement of GES by 2020, is currently being developed and will come into force in 2016.

Each step of the implementation process has to be evaluated every six years and revised if needed (first evaluation by 2018).This six-yearly management cycle means there will be regular opportunities for MSs to review the suitability and effectiveness of their determination of GES, their ETs and indicators, and their programs of measures taking into account the experience gained, the possible adoption of new norms and standards at the national and international level, as well as progress in scientific knowledge and instrumentation. The 2018 evaluation will provide the basis for such a review for the second cycle of 2018-2024.

Implementing the Marine Strategy Framework Directive in Belgian waters

The MSFD was transposed by Belgium into the Royal Decree of June 23, 2010. Belgium completed the first step of implementation in July 2012 with the publication of three reports that can be can be downloaded from http://www.health.belgium.be/eportal/Environment/MarineEnvironment/TheMarineEnvironPolicy/WorkingInAnInternational/MarineStrategy/index.htm?fodnlang=en#.UujXkbRKHs0. The Belgian 2012 report on GES for Belgian waters comprises 50 ETs which are to be complied with to have reached GES in Belgian waters. In September 2014, Belgium reported its marine monitoring programmes for the Belgian part of the North Sea (BPNS) to the Commission. For more detailed information on the implementation of the MSFD in Belgian waters, see http://www.msfd-monitoring.be.

Zooming into indicators, environmental targets and monitoring programmes relevant for marine aggregate extraction in Belgian waters.

From the list of 50 ETs, 11 prove highly to marginally relevant for the marine aggregate extraction sector. In decreasing order of relevance, those are:

1. The spatial extent and distribution of the EUNIS level 3 habitats (sandy mud to mud, muddy sands to sands and coarse grained sediments), as well as that of gravel beds fluctuate - relative to the reference state as described in initial assessment - within a margin limited to the accuracy of the current distribution maps.
2. The Ecological Quality Ratio as determined by Benthic Ecosystem Quality Index (BEQI), indicative for benthic ecosystem structure and quality, has a minimum value of 0,60 in each of the habitat types.
3. No positive trend in the yearly mean ambient noise level within the 1/3 octave bands 63 and 125 Hz.
4. An impact demands consideration if one of the following conditions – related to the bottom stress on a 14 days spring tide/neap tide cycle as computed by validated mathematical models – is met:
    a. there is an increase of more than 10% of the mean bottom shear stress
    b. the variation of the ratio between the duration of the bottom shear stress and the duration of the erosion is outside the "- 5%, + 5%" range
5. This consideration demanding impact remains within a distance equal to the root square of the surface occupied by this activity and taken from its external limit. All developments must comply with the existing regulatory regime (e.g. EIA, SEA, and Habitats Directives) and regulatory assessments must be undertaken in such a way that takes into consideration any potential impacts arising from permanent changes in hydrographical conditions, including cumulative effects, at the most appropriate spatial scales following the guidance prepared to this end.
6. Within the test zones in the gravel beds, the ratio of the hard substrate surface area (i.e. surfaces that are colonized by hard substrate epifauna) over soft sediment surface area (i.e. surfaces overtopping hard substrates and preventing hard substrate fauna development) does not show a negative trend.
7. Positive trend in median adult density (or frequency of occurrence) of at least one species within the long-lived and/or slowly reproducing and key engineering benthic species groups in … pure fine to coarse sands (i.e. larger bivalves such as *Laevicardium crassum*, *Glycymeris glycymeris* and *Dosinia exoleta*; larger gallery-dwelling organisms such as *Upogebia deltaura* and *Corystes cassivelaunus*).
8. Introduction of new human induced non-indigenous species of macrofauna and macroflora (>1 mm) in relation to the 2012 baseline is prevented. Species for which there are taxonomic disputes and for which the changes of permanent introduction, including reproduction are negligible are not taken into consideration.

9. Acute pollution: occurrence and extent of significant acute pollution events (e.g. slicks resulting from spills of oil and oil products or spills of chemicals) and their impact on biota affected by this pollution should be minimised through appropriate risk based approaches.
10. Biota and oil: the average proportion of oiled common guillemots (zeekoet - Uria aalge) is below 20 % of the total number found dead or dying on the beaches.
11. Positive trend in the number of individuals of thornback ray *Raja clavata*.

Whether or not an ET is met, is assessed through the Belgian package MSFD monitoring programmes, reported to the EU Commission in October 2014 and to be executed from 2015 onwards.

Five monitoring sub-programmes developed for the most relevant ETs described above and hence most relevant to the marine aggregate extraction sector, can be discerned:

- ANSBE-D1, 4, 6 Seabed-SP5 (delivering data to assess ET7), targeting a full-coverage seabed and transect seabed mapping of selected areas at EUNIS level 3;
- ANSBE-D1, 4, 6 Seabed-SP6 (delivering data to assess ET10), targeting the quantification of a composite index based on density, biomass, species richness and species composition of the macrobenthos at selected stations in the BPNS;
- ANSBE-D11 Energy-SP30 (delivering data to assess ET50), targeting the quantification of ambient noise level at 1 moored station inside the Belgian Continental Part of the North Sea;
- ANSBE-D7 Hydrography- SP16 (delivering data to assess ET29 and 30), targeting change in elevation, 3D currents, bottom shear stress using a validated numerical model. This programme will be performed during each licensing procedure regarding human construction at sea;
- ANSBE-D1, 4, 6 Seabed-SP10 (delivering data to assess ET17), targeting multibeam bathymetry and backscatter measurements in combination with visual observations and seabed sampling in a gravel bed in the Hinder Banks region and a gravel bed in the Flemish Banks region.

What’s next?

A FRAMEWORK FOR ENVIRONMENTAL LICENSING AND IMPACT MONITORING

The MSFD sets a series of environmental targets to achieve GES by 2020. The MSFD hence provides an ideal framework for environmental licensing and impact monitoring of human activities at sea. Human activities compromising achieving GES should be maximally avoided or mitigated to the benefit of an environment-friendly exploitation activities and techniques. Distinguishing between significant and non-significant impacts is of utmost importance here. While until now such distinction was left to expert judgement inherent to the environmental impact assessment procedure, we now have a well-deliberated reference framework against which (predicted) impacts can be assessed and valued. In a context of marine aggregate extraction in Belgian waters, especially the above mentioned eleven environmental targets will need specific consideration. Also the post-decision monitoring can now be targeted more transparently and objectively, because such monitoring may now set priorities based not only on impact magnitude (i.e. size of the impact), but also impact significance (i.e. importance for decision-making). In case of knowledge gaps to properly assess the interaction between the human activity and achieving GES, the monitoring may now also target addressing these knowledge gaps as to lower impact assessment uncertainty (for future licensing procedures) within the MSFD assessment framework. It should however also be clear that next to the MSFD also other (environment-driven) legislation is applicable to Belgian waters, e.g. the Habitats and Birds Directives, each of which with specific (conservation) objectives and hence all completing the scene for environmental impact assessment and monitoring.

A FRAMEWORK FOR CONTEXT SETTING AND INTEGRATION

The MSFD provides a framework to move away from an assessment of how much an impact site deviates from a reference location to how an impact compares to the desired environmental status of the Belgian part of the North Sea and by extension, the North Sea as a whole. As such an impact assessment is being put into a wider perspective, which opens the door to better address the most important “so what” question: does it really matter... In other words, while until now the impact size is quantified for a given human activity without reference to other activities, we now have the possibility to also qualify the impact against the impacts of other human activities and hence to relativize human-induced impacts. Such setting the scene, will better allow for an objective evaluation of impact and its consequent need for mitigating measures for a given activity, compared to other human activities. While targeting such wider perspective, moving away from formerly sector-oriented monitoring programmes to an integrated MSFD monitoring programme, will now also facilitate a higher level of efficiency and effectiveness of the monitoring programmes. The ecological status of sites impacted by various human activities, can now be compared with a series of reference sites, which will drastically increase detection power and hence the likelihood of a correct impact quantification. The integrated MSFD monitoring programme will as such offer a good platform to simultaneously assess impacts of multiple human activities and to advise on where the programme of measures should focus. A challenging, yet exciting and promising way forward.

STAKEHOLDERS ALLOWED!

The MSFD is not only directed to national environmental authorities but also towards all stakeholders, specifically those who have an interest in marine affairs, such as industries with economic activities at sea, environmental NGOs, research centres,… An active participation of those stakeholders is therefore highly recommended and is more than beneficial to achieve a coherent and harmonious implementation of the MSFD. The Directive indeed foresees a transparent decision-making process allowing stakeholders to express their vision on the proposed indicators and environmental targets, monitoring programmes and the future programme of measures. Public consultation hence is required at the end of each step of the implementation and is one of way in which stakeholders can influence decision-making (see figure 1). In addition, stakeholders were invited to and actively contributed to workshops aiming at the definition of GES for Belgian waters. Moreover, the six-yearly management cycle will provide regular opportunities for stakeholders’ participation in order to assess the effectiveness, quality and comprehensiveness of indicators and environmental targets, monitoring programmes and measures. The identification of gaps and issues and suggestions on how to do better in the future would be most welcome. In other words, your opinion counts.

Offshore wind farms: sand as indispensable as wind

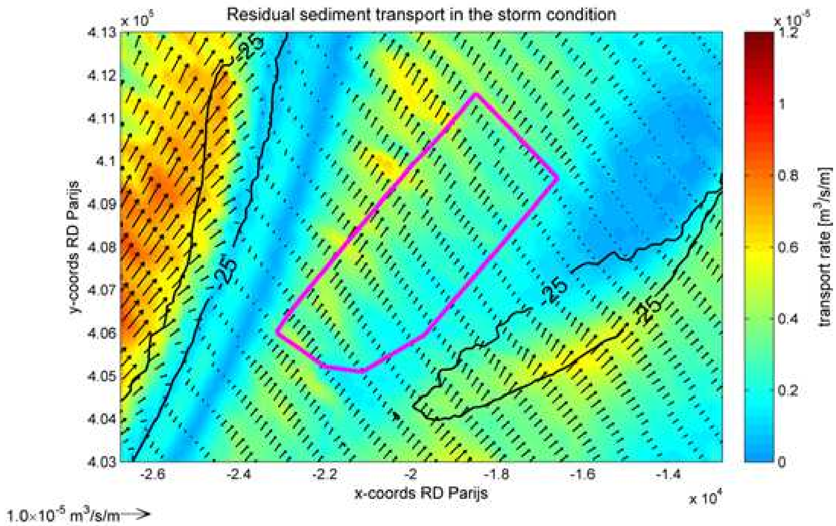
*Vanden Eede Sarah[*1], Mathys Mieke[1], Haerens Piet[1], Smits Michiel[1], Sas Marc[1]*

[*]*Presenting author: sarah.vanden.eede@imdc.be*

[1] *International Marine and Dredging Consultants (IMDC), Coveliersstraat 15, 2600 Berchem, Belgium*

For the energy production of offshore wind farms, wind is the main factor of interest, but during the construction and maintenance of offshore wind farms not only wind plays an important role. The impact of wind turbine foundations on the seabed, the change in local morphology and sediment transport during construction works and the operational phase plays a significant role in the design and maintenance strategy of offshore wind turbine foundations, and is also crucial to assess the environmental impact of wind farms. The construction of a wind farm often includes dredging works for levelling the seafloor at the foundation locations, for pre-trenching part of the cable route to assure sufficient burial depth during the lifetime of the project, for the creation of foundation pits (e.g. in case of gravity based foundation) and to cross navigation channels with the electrical cables. Also during the operational phase, the presence of the wind turbine foundation and the cables still can have an impact on the local seabed- and hydrodynamics e.g. in form of scour around the foundations or cables if not sufficiently buried.

These phenomena are typically studied in view of the design of the foundations, the definition of the cable trajectory and the Environmental Impact Assessment (EIA). In the framework of several Environmental Impact Assessments (EIAs), IMDC has setup numerical models that assist in estimating the expected sediment transport in the vicinity of the wind farms. These models simulate the natural tidal currents, wave action and sediment transport in the concession areas to evaluate the natural evolution of the seabed (Rentel (IMDC, 2012), SeaStar (cf. adjacent Figure, IMDC, 2013a), Mermaid (IMDC, 2014a in prep.) and Northwester 2 (IMDC, 2014b in prep.)). Not only sediment transport in the concession areas is studied, but also the effect of dredging activities as such is assessed. Hereto IMDC performed dredging plume model studies to assess the background turbidity and suspended sediment levels due to dredging and dumping activities. The studies focus on the excess sediment dispersion caused by the activities necessary for different dredging works during the construction phase, e.g. dredging of foundation pits.



To gain insights into the evolution of the current-, wave and turbulence conditions around wind turbine foundations and the potential development of scour pits, IMDC designed a frame equipped with several measurement tools to monitor potential scour around a jacket foundation in the C-Power wind farm (cf. Figure, lowering of frame). The frame is equipped with a Scour Monitor, an ADCP (acoustic current profiler), an AWAC (acoustic wave and current profiler) and vector velocity probes. While ad-hoc multibeam measurements only provide a snapshot of the seabed at a certain time, without having information on the hydrodynamics, the frame allows continuous measuring, also during storm events of both seabed variations and hydrodynamic parameters. Especially storm data (autumn and winter period) will provide valuable information to allow better understanding of the scour phenomenon in function of waves, currents and turbulence. The measurement campaign is set-up in a way that the collected data is sent to shore in real-time, giving the opportunity to monitor the seabed evolution and sea state conditions at any given time.

In view of the further development of the offshore wind at the Belgian Part of the North Sea, Elia Asset nv foresees in the realisation of a Belgian Offshore Grid (BOG) as a the next step in an optimisation of transporting the offshore generated energy to shore by means of a redundant system (MER BOG, IMDC 2013b). The BOG consists of the creation of at least one offshore high voltage station on the Lodewijkbank (OHVS Alpha) and the connection to land with several cables. In the near future the offshore wind farms will be able to plug into the OHVS Alpha to allow a bundled and redundant transport of their energy to shore. In EIA BOG, the OHVS Alpha is proposed as an artificial island on the Lodewijkbank.

Sediment transport and dredging activity not only relate to the foundations but also to the cable installation, since cables have to be buried over a certain depth. Hereto typically a burial risk assessment is performed that includes the assessment of the burial depth along the entire cable route. Laying offshore cables at the required depth can be achieved by several techniques, such as jetting, ploughing or trenching. When trenching is chosen, it requires dredging of trenches with a base width of about 5 m for each cable. The dredged material is than temporarily stored in a designated area and later re-used as backfill after completion of the cable laying process. If the trenching technique would be selected for laying the entire cable route stipulated in the BOG project (IMDC, 2013b), approximately 11 million m³ of sediment need to be dredged. Dump losses are estimated at around 3 million m³ of material before storing. The estimation of 30% of sediment losses during and after dredging-dumping works is based on observations on the Thornton Bank (Van den Eynde et al., 2010). During the backfill process, another 2 million m³ of material will be lost again, counted over the entire cable route. Around 0.5 million m³ of material will be permanently stored in the designated dump area. Laying these cables by applying the trenching technique would cause a temporary increase in turbidity, especially in the nearshore zone where finer material is present in the subsurface. Since this is also the area with naturally higher turbidity levels, the impact of the activities is negligible with a local but temporary disturbance of the benthos, avifauna and marine mammals.

Also for the creation of the artificial island that will support the OHVS Alpha sand extraction will be needed. The necessary sand volume for the creation of an artificial island Alpha as proposed in the EIA BOG will be about 5 million m³ (IMDC, 2013b). It comprises the creation of a flat base layer with a core of sand on top of it. Considering again dredging losses of about 30% after dumping (Van den Eynde et al., 2010)), about 7 million m³ needs to be extracted, equating a loss of about 2 million m³ of sediment. The nearby Blighbank is considered as the most suitable location, both technically and economically, for sand extraction. At the Lodewijkbank, at the location of the Alpha island (present water depth between -17 and -28 m LAT), the presence of the island will impact the local morphodynamic equilibrium and grain size distribution. The local bathymetry will here protrude above the water surface. These morphological alterations will change the local flow patterns and as a consequence scouring of the seabed around the Alpha island is expected if no additional protection is installed.

During the dredging works for the creation of the sand base and upper core, the turbidity will locally and temporarily change. Hereto different dredging scenarios are simulated. Model results show that the background value in the region of 4 mg/l (Van den Eynde et al., 2013) will not be exceeded for more than 20% of the dredging time for a scenario with one trailing suction hopper dredger (TSHD) of 10,000 m³ (IMDC, 2013b). For a scenario with 2 TSHD of 5,000 m³, involving more frequent dredging and dumping, the background value of 4 mg/l will not be exceeded for more than 30% of the time. The dredging activity causes the highest turbidity. The dredging plume is higher in concentration but smaller in size for the scenario with 2 TSHD. The dredging plume contour is more than 1,300 m long and moves over a distance of up to 2.5 km. Compared to turbidity concentrations during natural storms, this is a small negative effect, with temporary habitat disturbance of the benthic fauna, fish and marine mammals.

In conclusion, recent monitoring results, modelling effort and ongoing measurements have shown that during the entire life cycle of offshore projects, the impact of these infrastructures (i.e. foundations, cables, island,...) on the local morphology, hydrodynamics and sediment transport should be taken into account not only for design aspects, but also when assessing the environmental impact of the projects. It is further important that these assessments are done based on a combination of modelling studies and real-life monitoring of the processes prior to the works, during the works and during the operation and maintenance period. IMDC hereto has gained experience in all of these fields and combines the knowledge to provide an integrated assessment.

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Electronic Monitoring System (EMS) for sustainable management of sand and gravel resources

Van den Branden Reinhilde[*1]*, De Schepper Gregory*[1]*, Naudts Lieven*[1]

[*]*Presenting author: zagri-ost@mumm.ac.be*

[1] *Royal Belgian Institute of Natural Sciences, OD Nature, Measuring Services Ostend, 3de en 23ste Lnieregimentsplein, 8400 Ostend, Belgium*

Sand extraction on the Belgian part of the North Sea started in 1976. But it is only since 1996 (due to the Royal Decrees of 1996 and later: koninklijke besluiten betreffende de exploratie- en exploitatievoorwaarden verbonden aan de concessiebesluiten) Electronic Monitoring Systems (EMS) are used to record and control the sand and gravel extraction activities on the Belgian part of the North Sea. Over the years, slight adaptations were made in the legislation and agreements concerning EMS obligations resulting in full EMS data records (from extractions performed by the private sector) available since June 2002. In addition of OD Nature's responsibility to manage and process the EMS data (agreement with FPS Economy, Continental Shelf Service), data was also processed and reported (from various logging systems) from extractions with trailing suction hopper dredgers (TSHD) without EMS in the framework of the construction of submarine pipelines in 1997 (Interconnector and NorFra) and of coastal protection (beach nourishments) and other maritime works (Flemish Region, Coastal Division and Division Maritime Access) in 2004 and 2005. Afterwards, activities on the license of the Flemish Region are also monitored by the EMS.

The obligation to install an EMS on the TSHD that meets the technical specifications is regulated as a condition for the concession. The EMS automatically records among others the following parameters: identification of the vessel, the code of concessionary, the date, the time, the geographical position, the speed, the status of dredging pump(s) and the dredging activity. All necessary sensors are installed to enable the recordings of the parameters above-mentioned. On the one hand, this closed and sealed system (and its recorded and processed data) allows to verify whether other conditions of the concession are respected: permitted areas, minimum average speed during extraction and, if necessary, the to be respected distance between multiple extraction vessels. The processed data gives also an indication for the maximum volume that has been exploited. On the other hand, the recorded and processed EMS data is one of the tools for the continuous monitoring of sand and gravel activities. This in addition to the data derived from the registers and from the regular bathymetric, hydrodynamic and sediment transport surveys. The presence of an EMS on the dredging vessels is also controlled by the Aerial surveillance team of RBINS-OD Nature-MUMM (SURV), which reports on the observed dredging vessels and their extraction activities.

Since 2014, new EMS-systems are operational. The main reason for the renewal was the ability to follow up more frequently the proper operation of the recording device and the recorded data (via telemetry) (schematic view, see Figure 1). Another change is the entry by the crew of the parameter 'actually extracted volume' after every trip. During the pilot project a system that complies with the new specifications was placed parallel to a former EMS for detailed comparison and evaluation purposes. The final results of the pilot were presented to the Advisory Committee on June 25, 2013 followed by a circular of Continental Shelf Service to the concessionaires on August 22, 2013. Herewith, all concessionaires were informed of the revised technical specifications and guidelines for the EMS which they had to fulfill by the beginning of 2014. The new systems permit short-term data availability, which allows a better monitoring of the extraction activities as well as taking faster appropriate policy measures (for example closure or opening of certain parts of the sand and gravel extraction zones) when needed.

The EMS data records (both from the old and new systems) also allow for an estimation of sand extraction intensity (extracted volume of trailing suction hopper dredger per timeframe by using the declared load (new EMS) or the known fixed loading capacity (old EMS)). This enables the final data table to be used to evaluate the extracted volume on any surface and for any timeframe as well as making grids of extracted volumes per year.

The new EMS truly fulfills the expectations, seen the following characteristics:

- low cost, easy to install and to maintain, reliable performance;
- data falsifications is almost impossible;
- the compatibility with the demands of the ICES WGEXT working group and OSPAR makes the correct reporting of the analyzed electronic monitoring data (geospatial data on extraction locations in the form of shape files) straightforward.

The only disadvantage of the current system is that extracted volumes (per timeframe) are estimations (as the EMS is not equipped with sensors to record the load) but practice shows this approach is more than satisfactory.

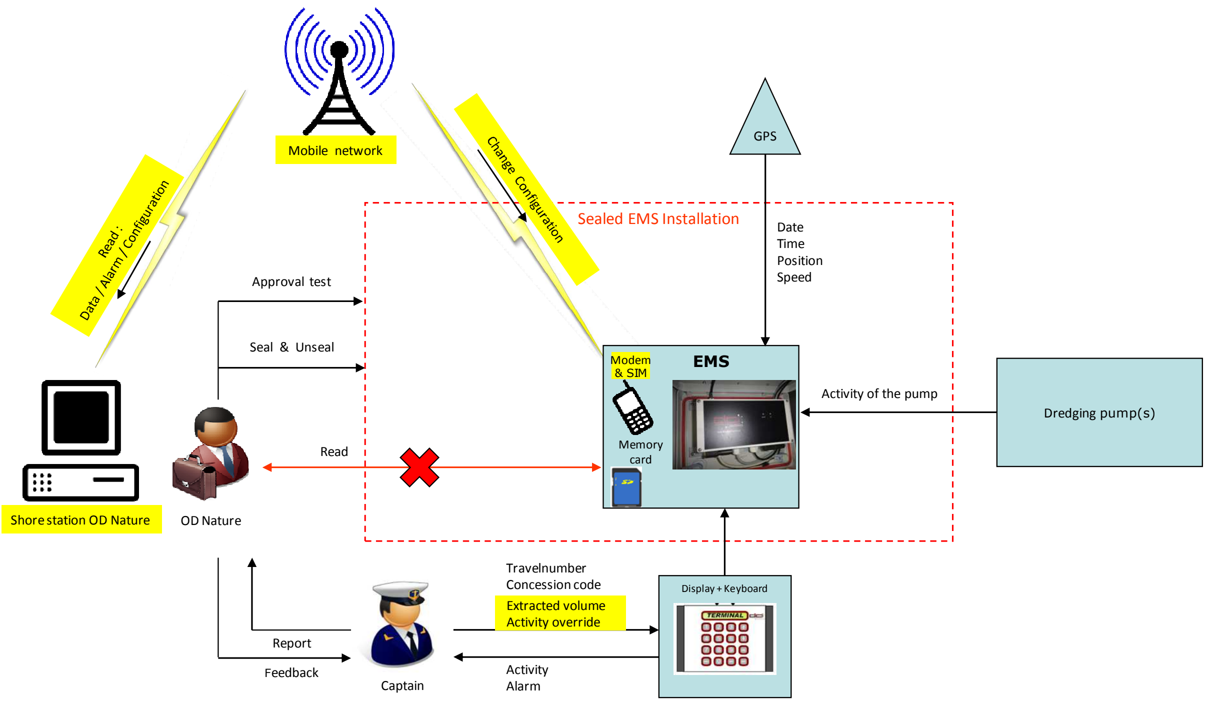


Figure 1: Schematic overview of the EMS as in use since early 2014 (EMS 2.0), the interaction with the system and the changes relative to EMS 1.0 are marked in yellow.

Master Plan Coastal Safety: work in progress

Van Quickelborne Elias[1]

Presenting author: elias.vanquickelborne@mow.vlaanderen.be

[1] *MDK, Afdeling Kust, Vrijhavenstraat 3, 8400 Oostende, Belgium*

Already over three years ago, on June 10th 2011, the Flemish government approved its Master Plan Coastal Safety. It was a milestone that led to numerous investments scattered over the entire coastal stretch. The Coastal division came up with solutions and alternatives to reduce the flood risk and to protect us against a 1.000 year storm event up to 2050, taking into account current and predicted hydraulic conditions and thus also climate change. The plan combined so called hard and soft measures to improve the safety level along our coast while the environmental impacts, social and cost benefits and – above all – consultations with other stakeholders, were anything but overlooked.

Besides hard measures in and around residential areas and harbours, nourishments in particular are still the primary action taken by the Coastal division to strengthen the sandy part of the coastline. Existing extraction zones were not appropriate and could not cope with the increasing demand of such a huge amount of sediments with the most appropriate characteristics. Following a preliminary investigation in the area of the Hinder Banks, i.e. a zone with massive tidal sandbanks known for their coarse grained surface sediments and based on the integration of seismic and vibrocore data, 4 new extraction areas were delimited allowing public and private parties to extract as from 2011. This indeed significantly broadened the options for the government regarding grain size availability and hopper sailing distance.

The true start of the Master Plan Coastal Safety took place in October 2011 in the community of Koksijde with a small beach nourishment and subsequently projects in De Panne and a medium size nourishment in Wenduine. Wenduine 2012 was also the first nourishment with sand originated from the Hinder banks. It also confirmed the previously obtained scientific outcome and the results of the field research with respect to the extracted sediment characteristics.

However it was until autumn 2013 and spring 2014 when the extraction volume for beach nourishments truly peaked. Westende, Middelkerke, Raversijde, Mariakerke, Oostende, Bredene, Wenduine, Blankenberge and Knokke-Heist all were tackled partly accelerated by a severe storm event December 5th & 6th 2013.

That storm was in the first place a test for the readiness of the public authorities. With historic water-levels and luckily changing wind and storm conditions, the damage to the primary sea defence i.e. the beach and dunes was notable and in need of fast repairs though the nourishment works from the past have proved that they were absolutely necessary to withstand the storm.

Between September 2013 and June 2014 a total of over 4 Million m³ sand (excl. extractions through beneficial use of sediments f.i. nourishment works combined with dredging works in non-controlled areas) was extracted, putting the dredging industry in Flanders in higher gear.

Sustainability of those replenishments could indeed be questioned. Maintenance is however inherent to nourishments and all kinds of soft protection measures to protect us against the quirks of nature. The Coastal Division is therefore exploring the usefulness of for instance foreshore nourishments. Early results of a pilot foreshore nourishment in Mariakerke show that those can be particularly cost-effective due to beneficial use of sediments and higher dredging efficiency.

Also, there will be strived for a sustainable management of the exploitation zones through spreading or rotation with an accompanying and extensive monitoring program on both the extraction areas and the beaches.

Meanwhile cranes and bulls are still shaping our beaches, dunes, seawalls and harbours while other realized projects along our coastline are already part of the image of the coast today and one can only see the past on dated aerial images.

Aggregate extraction versus archaeological heritage: how to reach a win-win?

Van Haelst Sven[1], Pieters Marnix[1], Demerre Ine[1]*

**Presenting author: sven.vanhaelst@rwo.vlaanderen.be*

[1] Onroerend Erfgoed, Phoenixgebouw, Koning Albert II-laan 19 bus 5, 1210 Brussel, Belgium

During the last ice age, some 20.000 years ago, the sea level was about 120m lower than today and large parts of the Southern North Sea were land. As the climate improved and the ice sheets started to retreat about 18.000 years ago, these extensive lowlands with river valleys and lakes, were inhabited by our predecessors for several thousands of years and have ever since been drowned by sea-level rise. Remains like human bone fossils, stone tools, worked animal bone and associated deposits from these ancient times can reveal details of human evolution and the social development of prehistoric communities. Sea level rise permitted seafaring, first in logboats and then in increasingly sophisticated watercraft. Maritime transport has played a tremendous role in the history of the countries bordering the North Sea. The study of shipwrecks and seafarers can provide insights into lifestyles, trade, communication, warfare, technology, industry, economics, and many other aspects of society from prehistory to modern times.

The discovery of archaeological sites in the North Sea, sometimes thousands of years old, clearly demonstrate that not only artefacts, drowned settlements, wrecks and structures, but even complete landscapes can stay preserved underwater. Furthermore the waterlogged anoxic conditions create the optimum circumstances for the preservation of organic materials that generally do not survive on archaeological sites on land. This unique archaeological and palaeontological record is largely unknown and unexplored. It does however contain an incredible wealth of information about the environment of prehistoric man and the historical development of marine regions. However this unique underwater archive is in danger due to increasing commercial activities at sea such as aggregate extraction, wind farming, dredging, cable/pipeline projects, intensive fishing, etc.

Through the extraction of sand and gravel, dredging activity inevitably disturbs the seabed and its associated underwater cultural heritage. In an optimal scenario the disturbed heritage will be partly recovered or noticed by the dredgers. As well as being potentially archaeologically important, recovered artefacts may also indicate the presence of a previously unidentified obstruction.

On the other hand, from the perspective of the aggregate industry, there is an obvious incentive to be able to locate wreck features in licensed areas so that they may be avoided proactively. Irrespective of whether a feature is a medieval trading vessel or a Second World War aircraft, they have the same potential to cause extensive and expensive damage to a dredgers underwater equipment. Additionally, ancient peat layers or the wood and coal often associated with older wrecks can contaminate otherwise clean marine sand and gravel deposits, potentially limiting their end use as a construction aggregate.

To deal with this and many more issues concerning underwater cultural heritage, the IWT SeArch project: “Archaeological Heritage in the North Sea”, will offer solutions through the realization of three objectives:

1) To develop a reliable survey methodology based on geophysical and remote sensing techniques that allows accurate and cost-effective evaluation of the archaeological potential of marine areas

(offshore, near shore & intertidal). This will avoid costly damage and loosing valuable time during the preparatory and operational phase of the works.

2) Work out comprehensive proposals for a transparent and sustainable management policy and for the further development and implementation of a legal framework based on the international commitments (UNESCO-convention).

3) Offer guidance to the stakeholders (marine industry, government agencies, fisheries, harbor authorities, and the public/social sector) and increase the general awareness with regards to underwater cultural heritage.

The 4-year project started in January 2013 and is funded by the Flanders Agency for Innovation by Science and Technology (IWT). It involves a multidisciplinary consortium between Ghent University, Flanders Heritage Agency, Deltares (The Netherlands) and Flanders Marine Institute (VLIZ).

One of the mitigation options chosen by the SeArch project are protocols to report and deal with archaeological finds made in the course of dredging or during the further processing of the aggregates in wharves on land. Furthermore it wants to provide guidance, advice and procedures for every stage of marine aggregate development and operation, from assessment of new license areas, to mitigation and monitoring of sensitive sites and reporting and evaluating finds.

In 2013 Belgium has ratified the UNESCO 2001 Convention on the Protection of the Underwater Cultural Heritage and this year the new law “Wet betreffende de bescherming van cultureel erfgoed onderwater” came into force, appointing the Governor of West Flanders as the “Receiver of Cultural Heritage Underwater”. This new law states that finds, made within the Belgian part of the North Sea, have to be reported to the “Receiver of Cultural Heritage Underwater” and it allows to protect and preserve the Underwater Cultural Heritage which is an important element in the history of peoples, nations, and their relations with each other.

Hopefully an open and constructive partnership approach will lead to a better management and understanding of the Underwater Cultural Heritage within our waters.

Interactive presentation of the geographic information on the Belgian part of the North Sea

*Degrendele Koen[*1], De Mol Lies[1], Roche Marc[1], Schotte Patrik[1], Vandenreyken Helga[1]*

[*]Presenting author: koen.degrendele@economie.fgov.be

[1] FPS Economy, S.M.E.s, Self-employed and Energy, Directorate-General Quality and Safety, Continental Shelf Service, Koning Albert II-laan 16, 1000 Brussel, Belgium

During its legal mission, the Continental Shelf Service (FPS Economy, S.M.E.s, Self-employed and Energy) has accumulated a large amount of geographic knowledge on the Belgian part of the North Sea: detailed models and maps used for the monitoring and cartography of the extraction areas, and all available spatial administrative and economic information. The content of this geographic dataset is available and free to our colleagues, stakeholders and the general public. To encourage the exchange of this information and to facilitate the communication to a broad public, the Continental Shelf Service recently started a project to develop an interactive display of all the available spatial data and knowledge.

The Continental Shelf Service already possesses a physical 3D model for exhibition, but this is limited to the detailed representation of the seabed in the extraction area on the Flemish Banks. The new project works on the scale of the entire Belgian part of the North Sea and is not limited to only a representation of the morphological aspects of the seabed. Furthermore, the interface must be constantly adjustable to the rapidly emerging and changing regulation and the constant inflow of new maps and models. Since the display has to encompass very diverse information, a high level of interaction must allow the users to easily choose which information is visible. And finally, the installation must be mobile to allow the use on a maximum number of occasions. As a result, the choice was made for a large multi-touch screen mounted on an adjustable platform, with an easy and well known interface and easy access to internet.

The interface used for the geographical data is Google Earth (see figure 1), well known to a large public and easy accessible on different platforms. This will in the future allow the online availability of the information. At present following data is incorporated:

- Specific maps and data concerning the aggregate extraction (regulation, monitoring and black box data).
- All data from the geographical database managed by the Continental Shelf Service: this includes spatial data related to marine regulation, regularly updated and obtained from the Flemish Hydrography, BAZ (fortnightly publication with information important for marine traffic), and published federal and regional legislation.
- Models and maps resulting from the cartography performed by the Continental Shelf Service: bathymetry, sedimentology and geology. In the future this can be supplemented with external data.
- Spatial data from the Marine Spatial Plan (MSP) coordinated by the FPS Health, Food Chain Safety and Environment.

Since the platform is multi-touch enabled, the interaction with the user happens primarily through multi-touch gestures, increasing the accessibility. Hopefully, this intuitive and easy interface will boost the access to the abundant but not always transparently available marine spatial information.

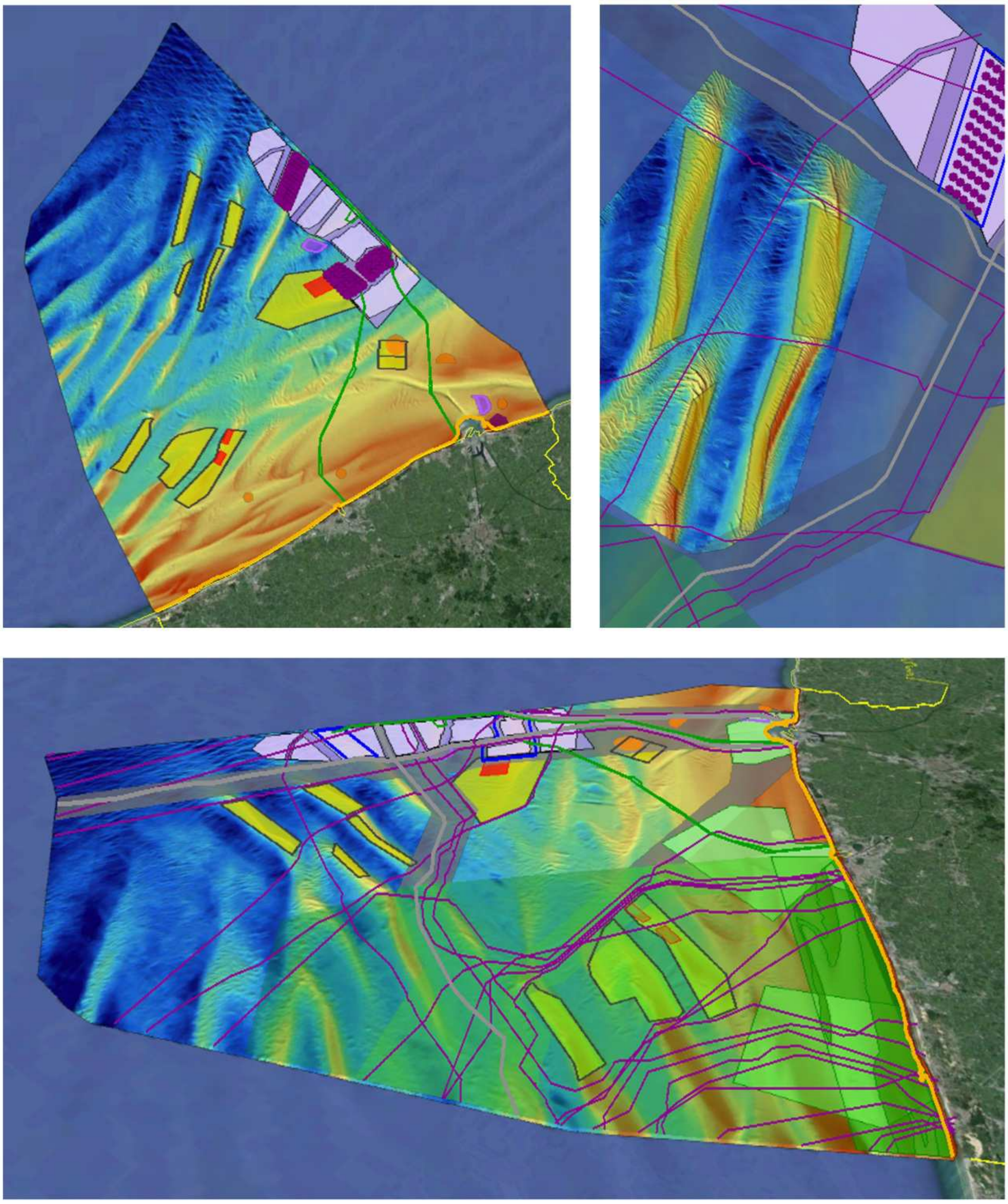


Figure 1: Example of displays of spatial data using Google Earth as interface.

Marine aggregate dredging from a fished point of view

De Backer Annelies[1], Hostens Kris[1]

[1] Institute for Agricultural and Fisheries Research (ILVO), Animal Sciences Unit, Aquatic Environment and Quality, Ankerstraat 1, 8400 Oostende

Marine aggregate dredging is expected to have an impact on the marine ecosystem. While the direct and indirect effects of marine aggregate dredging on macrobenthos are well documented, less is known of the effects upon epibenthos and demersal fish.

Several trawl samples were taken both inside and outside the aggregate dredging areas on the Buiten Ratel, the Oostdyck, the Thorntonbank and the Hinderbanken. Sampling was done with an 8 m beam trawl with a fine-meshed shrimp net (stretched mesh width 22 mm in the codend) in both spring and autumn between 2010 – 2014.

The general temporal and spatial patterns, known from the Belgian part of the North Sea, were dominant in structuring the epibenthos and fish assemblages from the marine aggregate dredging areas. Different assemblages were observed in spring and autumn. Some species occurred only in one season such as sprat in spring, and horse mackerel and striped red mullet in autumn. While others occurred in much higher abundances in one of the two seasons e.g. brown shrimp in spring and squids in autumn. Besides the dominant seasonal pattern, a clear spatial pattern in each season was observed. On the Hinderbanken and the Oostdyck, fewer species, and in spring as well in lower densities were observed. Samples in autumn were dominated by lesser weever and horse mackerel, samples in spring only by lesser weever, supplemented with brown shrimp and sprat in some locations. On the Buiten Ratel and Thorntonbank, a higher number of species occurred and especially in the gullies in higher densities. In spring, samples were dominated by brown shrimp in both areas, supplemented with mainly hermit crabs and starfishes on the Buiten Ratel, and with several other species on the Thorntonbank. In autumn, the impact area on the Buiten Ratel was dominated by starfish, hermit crab, brown shrimp and swimming crab, while in the reference area, one location was dominated by lesser weever and horse mackerel and the other location by starfish and hermit crab. In the autumn samples on the Thorntonbank, different species occurred in more or less equal densities, however with a slight dominance of lesser weever on top of the bank.

Although there is no clear overall impact of aggregate dredging measurable on the epibenthos and demersal fish assemblages, there are some indications of impact on species level. On the Buiten Ratel, densities of hermit crabs and starfishes were much higher compared to the nearby reference location suggesting attraction of scavengers to the disturbed area. Furthermore, the occurrence of the green sea urchin in the impact area from 2013 onwards, a species known to prefer coarse gravelly sediments. This suggested a change in sediment composition towards coarser sediments caused by the intensive dredging in this area. On the Hinderbanken, there is an indication of decreasing densities of lesser sand eel (in spring) in the impacted area compared to the reference area on the same sandbank. Lesser sand eel is known to be sensitive to dredging, and it was observed floating damaged on the water surface in spring 2014 immediately after dredging of the area.

Deep large-scale sand extraction and ecological landscaping, short-term impact results from the Rotterdam harbour Maasvlakte 2 borrow pit

de Jong Maarten[*1]

[*]*Presenting author: maarten.dejong@wur.nl*

[1] *IMARES Wageningen UR, Institute for Marine Resources & Ecosystem Studies, Bevesierweg 4, 1781 AR Den Helder, The Netherlands*

The demand for marine sand in the Netherlands and worldwide continuous to rise. In the Netherlands, 24 million m^3 marine sand is used yearly for coastal nourishments and construction. Due to sea-level rise, a possible increase of annual nourishments up to 85 million m^3 is anticipated. The Dutch authorities permitted deep sand extraction, down to 20 m below the seabed, to decrease the surface area of direct impact of a 220 million m^3 sand extraction project for a 2000 hectares harbour expansion of Port of Rotterdam. To guarantee sufficient supply of marine sand in the intensively used Dutch coastal zone, the authorities continue promoting sand extraction depths over 2 m. The ecological impact of deep sand extraction, however, is still largely unknown.

This project focusses on the short-term impact of deep large-scale sand extraction and ecological landscaping on macrozoobenthos, demersal fish, sediment characteristics, bathymetry, sedimentation rates and hydrodynamics. We developed ecosystem-based design rules for future borrow pits based on insights from the short-term impact studies and baseline study resulting in the highest biodiversity and high sand extraction yield. The project is part of EcoShape Building with Nature, a public-private innovation program which is committed to the integration of infrastructure, nature and society in new or alternative forms of engineering that meet the global need for intelligent and sustainable solutions.

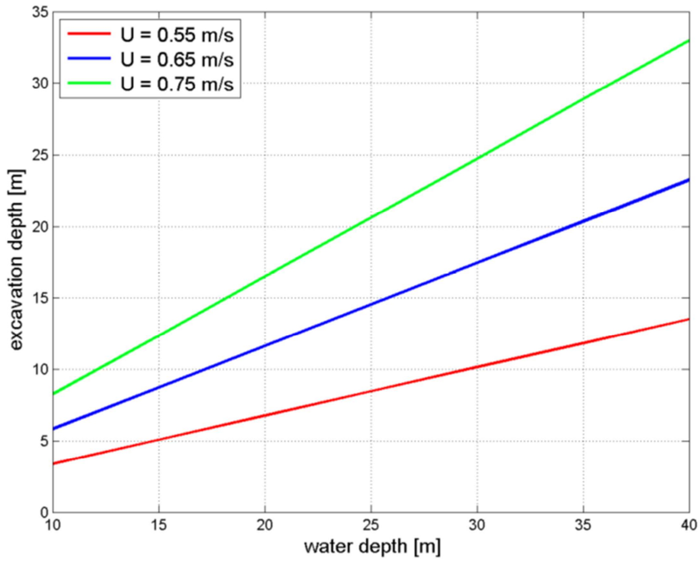
We used a boxcorer to sample macrobenthic infauna, a bottom sledge to sample macrobenthic epifauna and a 4.5 m wide commercial beam trawl to sample demersal fish. Sediment characteristics were determined from the boxcore samples, bed shear stress and near-bed salinity was calculated with a hydrodynamic model. The dredging companies collected multibeam data. Two sandbars were excavated on the seabed of the extraction site to investigate the applicability of ecosystem-based landscaped sandbars in borrow pits. The sandbar parallel to the tidal current was completed in spring 2010 with a 700 m long and 70 m wide crest at a water depth of 30 m and troughs over 45 m depth. In 2011, the second sandbar was completed with an orientation oblique to the tidal current, due to time constraints, the difference in depth between crest and trough was less pronounced.

Macrozoobenthic biomass increased fivefold in the deepest areas, species composition changed significantly and white furrow shell (*Abra alba*) became abundant. Macrozoobenthic assemblage and biomass is correlated to time after cessation of sand extraction, sediment and hydrographical characteristics. Furthermore, sediment characteristics significantly changed in 2012 in the deepest parts. We observed increased sedimentation rates in the troughs of the parallel sandbar, which presumably led to unsuccessful boxcore sampling. Demersal fish biomass increased 20-fold and fish species assemblage changed significantly, inside the borrow pit plaice (*Pleuronectes platessa*) was dominant whereas dab (*Limanda limanda*) dominated reference areas. Increased demersal fish biomass is closely linked to increased white furrow shell (*Abra alba*) biomass. Ecological landscaping sandbars influenced macrozoobenthic and demersal fish assemblage.

We observed significant differences in epifaunal and demersal fish samples in the southern trough of the parallel sandbar in 2012. Epifauna was characterised by a maximum biomass (601.36 g WW m^{-2}) with serpent star (*Ophiura ophiura*) as most abundant species whereas demersal fish biomass and species composition returned to reference levels. These changes may be related to the high sedimentation rate (0.75 m y^{-1}) or to the increase of organic matter and mud in the sediment or a combination of these factors resulting in reduced dissolved oxygen (DO) levels.

For future borrow pits, information on sediment characteristics is lacking but bed shear stress (τ) can be calculated with water depth, extraction depth and depth-averaged peak flow velocity. Based on shear stress, a distinction was made between two clusters (τ < 0.37 N m^{-2} *Abra alba*, τ > 0.40 N m^{-2} *Echinoidea* spp. – *Phoronida* sp. assemblage. This is a starting point for design options for a borrow pit, the largest biodiversity can be expected when shear stress values are around 0.4 N m^{-2}. For the Maasvlakte 2 borrow pit, extraction depth would be 12 m and a post-dredged water depth of ~32 m.

A morphological model study predicts 5 m sedimentation in 30 years, backfilling of the borrow pit may take decades or even longer. We recommend ongoing macrozoobenthic monitoring with the inclusion of sedimentation rate and oxygen measurements.



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DGGE fingerprinting for microbial community monitoring as a new tool for anthropogenic impact assessment on the Belgian part of the North Sea

*Devriese Lisa[*1], Maes Sara[1], De Tender Caroline[1,2], Baeyen Steve[2], Bekaert Karen[1], Cremelie Pieter[2], Vandecasteele Dimitri, Robbens Johan[1]*

[*]Presenting author: Lisa.Devriese@ilvo.vlaanderen.be

[1] The Institute for Agricultural and Fisheries Research (ILVO), Animal Sciences Unit, Aquatic Environment and Quality, Ankerstraat 1, 8400 Oostende, Belgium

[2] The Institute for Agricultural and Fisheries Research (ILVO), Plant Sciences Unit, Crop Protection, Burgemeester Van Gansberghelaan 96, 9820 Merelbeke, Belgium

Human activities at sea, such as sand extraction, may have an effect on the health status of the marine ecosystem. The assessment of the microbial communities on sediments will provide additional information on the potential impact of disturbances on biodiversity. A new assay for the evaluation of microbial diversity on sediments on the Belgian Part of the North Sea (BPNS) in relation to physical impact, based on the clustering of DGGE (denaturing gradient gel electrophoresis) profiles, will be presented.

Sediment samples were collected at 6 different locations on the BPNS using a Van Veen grab. DNA was extracted from the sediments and specific primers for bacterial (V3 region), protist (V8 region) and Archaea (V3 region) communities were used for the amplification with various PCR-techniques. These PCR products were loaded on a DGGE gel using an optimized protocol, which resulted in a clear DGGE fingerprint. Clustering of the genetic fingerprints was performed using Bionumerics.

The developed DGGE fingerprinting assay allows differentiating between sediment type, location on BPNS and used PCR technique based on the bacterial communities living on sediment. Since the used PCR techniques clearly influences the DGGE profile, it is important to develop a standard operating protocol for sampling and analysis. The standardized fingerprinting assay is a useful tool to integrate in monitoring programmes for the assessment of anthropogenic impact.

The genetic fingerprints revealed a higher bacterial diversity on muddy sediments compared to sandy sediments. To improve the taxonomical knowledge on the achieved bacterial profiles, bacterial species present on sediment could be identified using V3-V4 16S rDNA amplicon sequencing.

In 2015, the microbial diversity on sediment samples of the different marine sand extraction areas on the BPNS will be further evaluated using the DGGE fingerprinting clustering assay. Impact versus reference sites will be evaluated for each extraction area.

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