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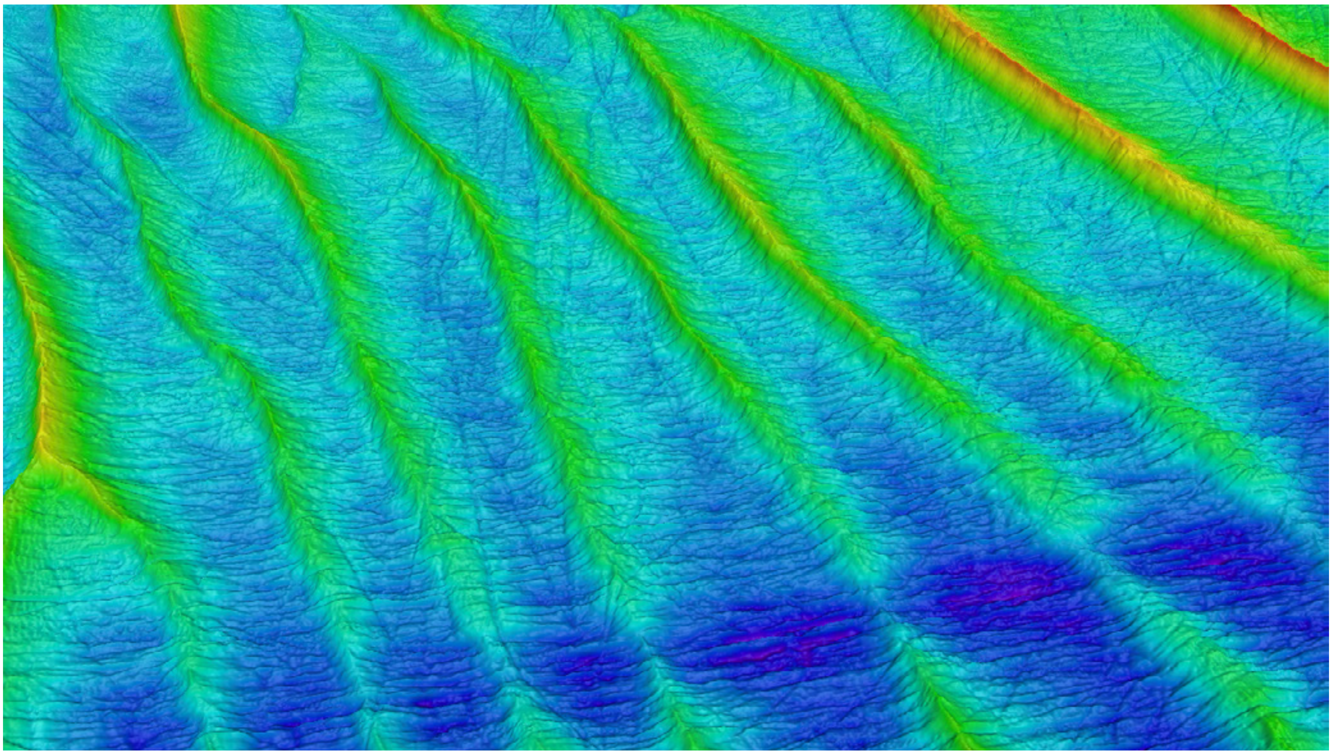
Belgian marine sand: a scarce resource?



Study day

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Hotel Andromeda - Ostend

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CONTENT

REGULAR CONTRIBUTIONS

Multi time and space scale monitoring of the sand extraction and its impact on the seabed by coupling EMS data and MBES measurements

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Introduction

The aim of this 2017 study day contribution is to provide a perspective view on the sand extraction in the Belgian part of the North Sea (BPNS) through factual information derived from the monitoring data available from 2003 to 2016.

Two main categories of information derived from monitoring data are presented: history, cartography and trends of the extracted volumes resulting from the analysis of the extraction registers and the Electronic Monitoring System (EMS) data and, at different space and time scale, variation of the bathymetry, the morphology and the nature of the sediments based on bathymetric and backscatter acoustic data from multibeam echosounder (MBES). The combined analysis of these different types of data allows the environmental impact assessment of the extraction as a function of its intensity.

This contribution starts with a historical overview of the extraction from 2003 to 2016. The central debate of this study day —is marine sand a rare resource?—poses many questions that revolve around the same subjective and temporal notion, the sand reserve. The monitoring time series of the extraction itself offers a specific perspective on the evolution of the sand reserve in its legal and useful sense and therefore, nourishes the debate on the durability of the sand extraction in the BPNS.

Under national and supranational legislation, the monitoring of the effects of sand extraction on the marine environment is a legal obligation (Law of 13 January 1969, article 3, § 2, 3 and Royal Decree of 23 June 2010 transposing the EU Marine Strategy Framework Directive). The monitoring part of this contribution concerns this environmental impact evaluation which is based essentially on the MBES data surveyed between 2009 and 2016, mainly with the RV Belgica EM3002d, on active and passive monitoring areas and on a large scale across the sandbanks following the DECCA reference lines. For each monitoring area as well as for the DECCA lines, the data of the extracted volumes are presented in parallel with the bathymetric and backscatter data with time as their common denominator. This approach correlates the impact of extraction on the bathymetry and on the nature of the seabed with the intensity of extraction.

The public participating in this 3-yearly organised seminar on sand extraction in the BPNS is varied: dredging industry members, marine scientists, engineers and technicians involved in the extraction activities and its potential impact on the marine environment, managers of the marine environment, economists, policy makers and citizens interested in the marine domain... In order to best meet the expectations of this wide audience, the style of this contribution is deliberately factual. More in-depth information can be found in previous publications from the Continental Shelf Service and the listed references. For the technical details of the acquisition and processing methods used, we refer the readers to Roche et al. (2009, 2011 and 2013), Degrendele et al. (2002 and 2014) and Van den Branden et al. (2014 and this volume).

Evolution of the extraction from 2003 to 2014

On the BPNS scale, the evolution of the extraction of marine sand is illustrated in Figure 1 which distinguishes between the volume of sand extracted per year according to its destination. These values are based on the declared volumes by the extraction companies in the registers. How should this chart be interpreted?.

The last four years have been marked by the large volumes of sand used for beach maintenance under the "Masterplan Kustveiligheid" for the protection of the coast. In 2014, 3.5 $10^6 m^3$ has been extracted for this purpose.

Regardless of the large amounts of sand extracted for coastal protection and in the context of offshore work, the volume of sand extracted for industrial purposes also shows a marked increase, from 2 $10^6 m^3$ in 2013 to practically 3 $10^6 m^3$ 2016; compared to the initial volume, this represents a growth of 50% in 3 years.

However, the most striking feature of the last 10 years is the steady, almost linear growth of the volume of sand discharged in ports of neighboring countries. As a percentage of the total, from 2013 to 2016, this export volume increases from 27% to 49% of the sand extracted for industrial purposes. If this trend continues at this rate, in 2025, 60% of the volume of sand extracted for industrial purposes will be unloaded in ports of neighboring countries.

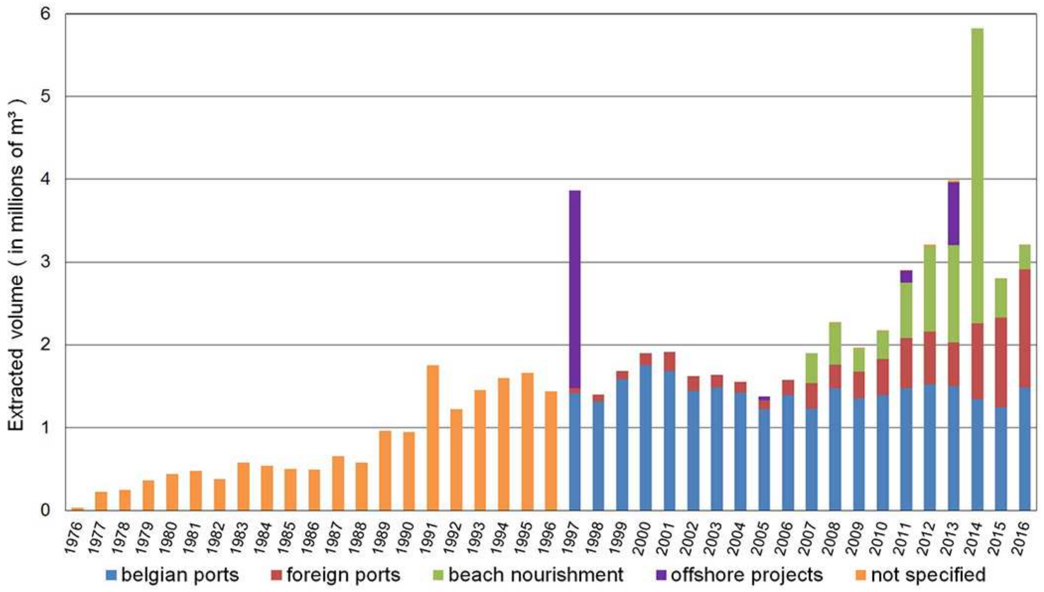

Figure 1: Evolution of the sand extraction in the BDNS from 1976 to 2016.
Statistics based on extraction registers.

In addition to the declared volumes in the extraction registers, dredged volumes can be estimated and mapped from EMS data. This assumes that dredging vessels are always using their maximum capacity (Roche et al., 2011, Van den Branden et al., 2014 and Van den Branden et al., this volume). The reliability of the dredged volumes estimation from EMS data can be evaluated by comparing the annual volumes derived from EMS data with the annual volumes from the extraction registers (Table 1). The discrepancies between the EMS volumes and the volumes reported in the registers show a clear linear trend (Figure 2). In 2015 and 2016, the deviation exceeds 10%. Such a discrepancy may be related to two reasons: an overestimation of the volumes from EMS data and an underestimation of the volumes reported in the registers. A cross-analysis by vessel and trip of EMS data and registers is currently underway to determine the precise origin of this difference and to take the necessary action to correct it.

YEAR	EMS $10^6 m^3$	REGISTER $10^6 m^3$	Δ EMS-REGISTER / REGISTER %
2003	1.7	1.6	3.6
2004	1.7	1.6	10.6
2005	1.4	1.4	0.3
2006	1.6	1.6	-0.7
2007	1.8	1.9	-3.2
2008	2.3	2.3	-0.8
2009	1.9	2.0	-4.3
2010	2.2	2.2	1.7
2011	3.0	2.9	3.6
2012	3.4	3.2	7.0
2013	4.2	4.0	5.4
2014	6.2	5.8	5.7
2015	3.1	2.8	12.1
2016	3.5	3.0	14.0

Table 1: Yearly volumes reported in the registers, yearly volumes estimated from EMS data, and the difference between both.

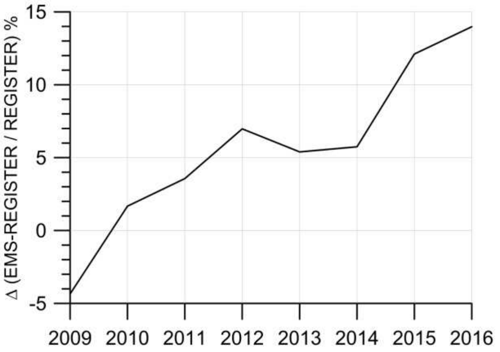

Figure 2: Evolution of discrepancies between the cumulative volumes reported in the registers and the cumulative volumes estimated from the EMS data from 2009 to 2016.

On the basis of all available EMS data, a cartography of the cumulated dredged volumes per unit area (m^3/ha) from 2003 to 2016 in the extraction sectors, as defined by the Marine Spatial Plan (MSP) in 2014, is presented in Figure 3. A year by year cartography of the dredging intensity for the last 3 years is presented in Van den Branden et al. (this volume). Complementing this, the evolution of the annually extracted volume for each sector is presented in Figure 4. Taking into account all the information it is possible to retrace the evolution of the extraction in the BPNS since 2003. Three partially overlapping phases can be distinguished:

1. The Kwintebank (S2kb) phase: until 2007, the extraction is concentrated on the S2kb sector; From 2003 to 2016, the total volume dredged on the Kwintebank reached 5.8 $10^6 m^3$; Since 2003, probably as a result of the closure of the KBMA zone in February 2003, the sand extraction decreases on sector 2kb and moves to the neighboring sector 2br, on the Buiten Ratel sandbank.
2. The Buiten Ratel (S2br) phase: started earnestly in 2005, the volume extracted on this sector reaches $10^6 m^3$ in 2008 and increased gradually to exceed 2 $10^6 m^3$ in 2011; from 2012 to 2016, the volume of sand dredged on S2br decreased progressively, reaching $10^6 m^3$ in 2014, and arriving at the current level of 0.2 $10^6 m^3$. In total, 11.6 $10^6 m^3$ were extracted from S2br, mainly between 2007 and 2014. In January 2015, the central zone of the Buiten Ratel was closed to extraction.
3. The Thorntonbank S1a, Sierra Ventana S3a and Oosthinder S4c phase: after 2014, extraction moves to these 3 sectors to meet the needs of the industry and the coastal protection plan. In sector 1a, the extraction begins in 2003, increasing gradually from $10^6 m^3$ in 2012 to more than $210^6 m^3$ in 2016. For S1a, the cumulative volume reaches 10 $10^6 m^3$ in 2016. This sector has become the epicenter of the industrial sand extraction. Intended for coastal protection, the evolution of the volumes extracted on the S3a and S4c show a certain parallelism. In these two sectors, extraction will remain below $10^6 m^3$ in 2013 to increase strongly in 2014, with a substantial extraction peak of 2.6 $10^6 m^3$— more than half of this volume extracted in 2 months time— for sector 4c and above $10^6 m^3$ for S3a.

The volumes extracted on the sectors S2od and S4b remain largely below the volumes evoked above. For S2od, after a drop in extraction from 2003 to 2011, volumes extracted have increased significantly since 2012.

This analysis demonstrates the ability of the sector to migrate within a few years from one extraction site to another in response to the closure of areas where the extraction level has exceeded the current legal limit of 5m below the reference surface. The new reference surface project (see Degrendele et al., this volume) implies a regular updating of available volumes maps based on the extracted volumes estimation from the EMS data. For the sector, such a dynamic monitoring done in open mode should allow a better planning of dredging activities on a long term.

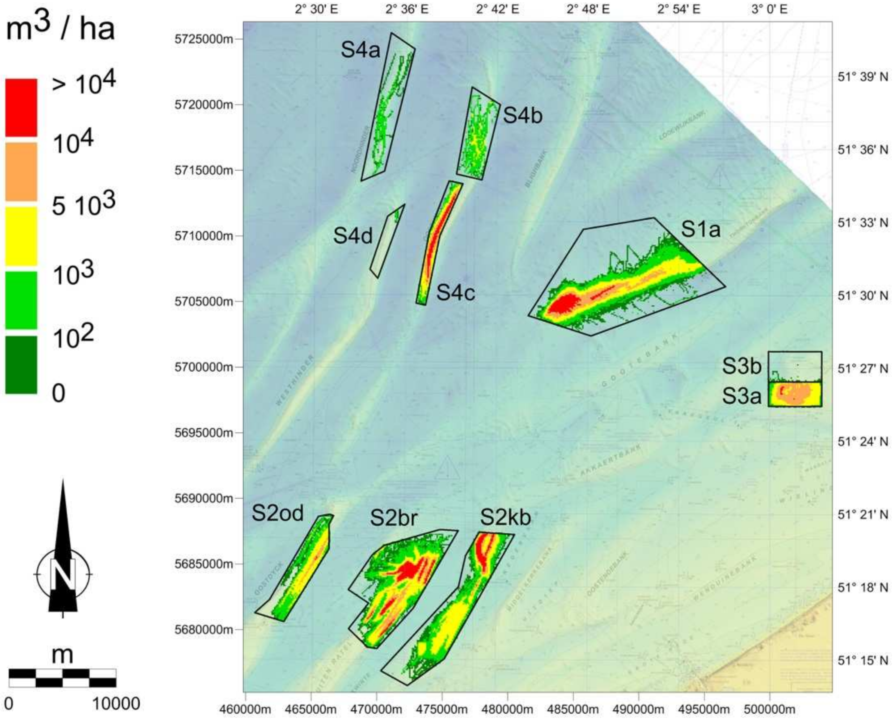

Figure 3: Cumulative volumes extracted per unit area of the extraction sectors sensu MSP 2014). Volumes from EMS data from 2003 to 2016.

<u>Note:</u> Background for all maps presented in this contribution: COPCO DTM of the Belgian part of the North and BE-BNZ-2014 from the Agency for Maritime and Coastal Services – Flemish Hydrography

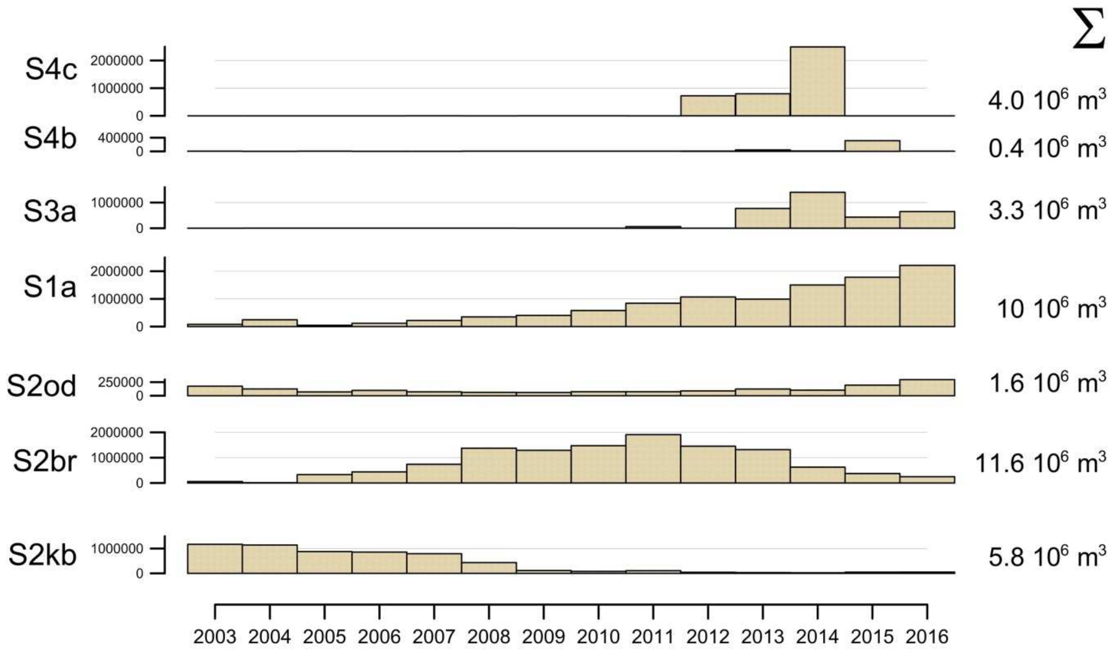

Figure 4: Evolution of sand extraction with total volumes extracted in sectors as defined in the Marine Spatial Plan (2014) from 2003 to 2016. The right column provides the cumulative volume per sector.

Evolution of the useful legal sand reserve

Different criteria can be used to define the sand reserve in the BPNS. From a pragmatic point of view, which could be that of the sector itself, the sand reserve can be considered in a sense that combines legality and utility. All sand qualities combined, this useful legal reserve is approximated by considering the sum of the areas occupied by the sandbanks within all the extraction sectors. The isobath of 20m is used to approximate the areas occupied by the sandbanks inside each sectors. Since no extraction takes place in the channels, the area limited both by the sector bounds and the isobath of 20 m may reasonably be considered as the useful surface for extraction. The useful legal reserve volume is simply calculated by multiplying this total useful surface by 5m, which is the current legal vertical limitation of the extraction. Figures 5a and 5b illustrate the cartographic evolution of the areas granted to sand extraction on the BPNS from 1977 to 2016 and show the evolution of the useful legal reserve as a function of changes in the delimitation of the sectors and the extraction itself.

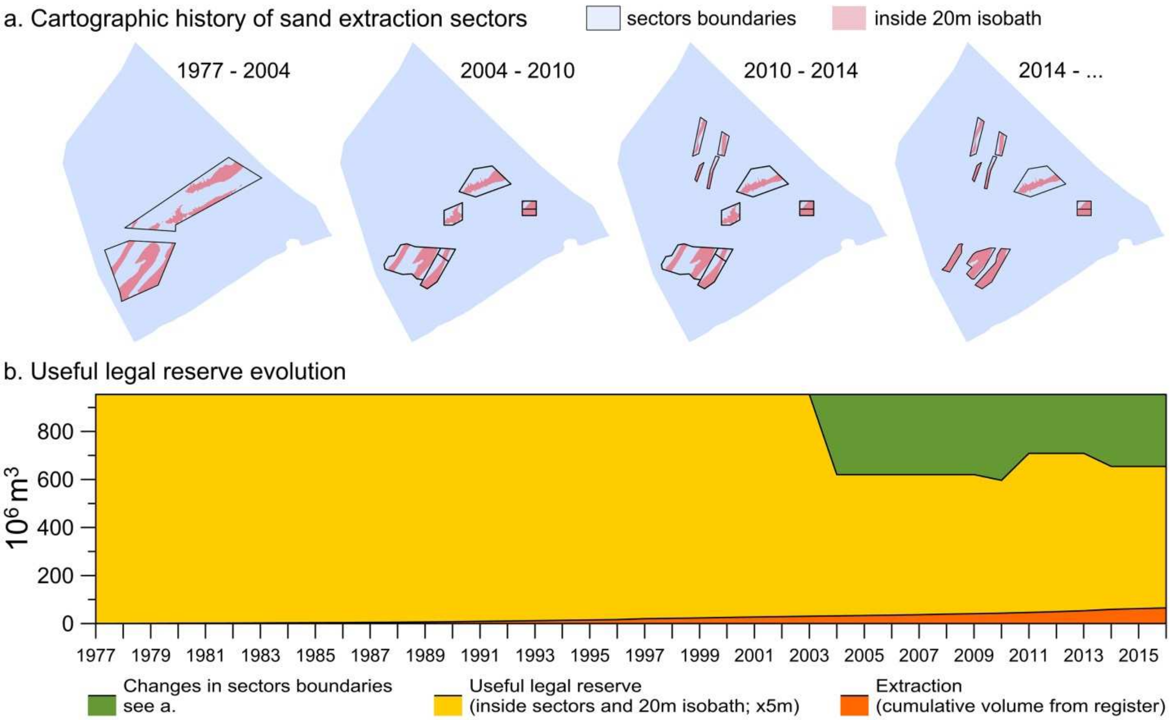

Figure 5: a. Cartographic history of the sand extraction sectors in the BPNS from 1977 to 2014.
b. Useful legal reserve evolution from 1977 to 2016. Cumulative extracted volume is based on register data.

In 1977, the legal useful reserve level for all sand qualities combined was estimated at 954 $10^6 m^3$; in 2016 this reserve is only 590 $10^6 m^3$, i.e. 62% of the initial reserve. This decrease is related to the surface loss linked to the successive modifications of the extraction sectors boundaries (see Figure 5 a.) consequently to changes in legislation and to the cumulative volume of sand actually extracted. During the period considered, the total variation in extraction areas accounts for 82% of the decrease in the legal reserve, while the remaining 18% is linked to the extraction itself. The BPNS is a small space that combines many activities. For the sand sector, such a context implies a strong spatial pressure linked to the need to share the available space with the others actors working in the BPNS. For the sand extraction sector, it is essentially this spatial pressure combined with the environmental constraints that controls the level of legal useful reserve of sand, rather than the extraction itself.

Another central theme of this study day is the geological approach of the BPNS sand resources. The project to define a new reference surface contains an evaluation of the volume of sand based on a 3D mapping of the bathymetry and the internal geological boundaries of the sandbanks in each extraction sector (see Degrendele et al., this volume). The "Transnational and Integrated Long-term Marine Exploitation Strategies" project (TILES) allows a large scale estimation of the natural sand resource according to the different sand qualities based on a geostatistical voxelization of all the available geological data (see Van Lancker et al ., this volume). These approaches are of primary importance for a sustainable and balanced sand management in the BPNS.

Monitoring

Dataset and methods

MBES technology providing simultaneously bathymetric and backscatter data is used by the Continental Shelf Service since 1999 to carry out the monitoring of the impact of the sand extraction on the seabed.

Pragmatically, the monitoring of the sand extraction uses successive MBES surveys on monitoring areas, located in the extraction sectors, and along the DECCA reference lines across the sandbanks, at medium to long term time scales (months to years). Such an approach makes it possible to assess the direct impact of extraction on the areas where it is most intense on a local spatial level, as well as the impact on a wider spatial scale by integrating measurements on areas with varying extraction.

A large part of the MBES bathymetric dataset has been recorded in DGPS mode following a conventional hydrographic acquisition and processing chain. The resulting DTMs of the successive surveys compose the bathymetric time series data. For each sector a reference model is established based on the first complete survey of the area. Since the time period of the surveys varies, so will the reference models. The comparison with the reference models provides an estimation of the depth differences that can be correlated with the extraction intensity.

For the backscatter, things are much more complex. MBES backscatter is the intensity of the received echo. It may be used as a measure of the acoustic scattering properties of the seafloor which are correlated with the sediment interface nature and morphology. Coarse sediments - rough interface, such as coarse shelly sand - scatter much more acoustic energy back than fine sediments - smooth interface, such as a muddy silt. Using the backscatter as a proxy of the seabed interface in a framework of a monitoring program implies a full control and stabilization of the acquisition parameters (specifically the pulse length) of the MBES on board the vessel and the absolute correction for radiometric (source level and beam pattern) and geometric (range, and grazing angle) factors that are specific for each MBES (Lurton and Lamarche, 2015). As the intrinsic response of the seabed to an acoustic pulse is related to the wavelength of the acoustic signal, for a same seafloor area, backscatter levels recorded with MBES using different frequencies are not simply comparable. Unlike the bathymetry, up to now the backscatter time series cannot be compared with a backscatter reference model.

Backscatter data post processing must also be considered with great care. The Continental Shelf Service uses the following approach: for each survey, the backscatter mean level is estimated from the raw uncompensated backscatter signal corrected for the real time attenuation and the instantaneous insonified area based on the real grazing angle measurement. Only the backscatter values within the restricted angular sector of ±[30°-50°] are used to compare over time. Such a specific approach is implemented in the MBES processing software SonarScope from IFREMER (Augustin, 2016). Without an absolute calibration, this standardized processing method which does not introduce any “a priori and local compensation” makes it possible to compare rigorously the evolution of the average backscatter levels over time.

It should be noted that several studies are underway to quantify the external factors that may affect MBES backscatter measurements in order to assess its potential within a MSFD compliant monitoring of the seabed (see Roche et al., 2015, Montereale-Gavazzi et al., 2017 and Montereale-Gavazzi, in progress).

The location of the monitoring areas, the DECCA lines and the bathymetric and backscatter reference area used in this contribution are presented in Figure 6. The time line of all the surveys is presented in Figure 7.

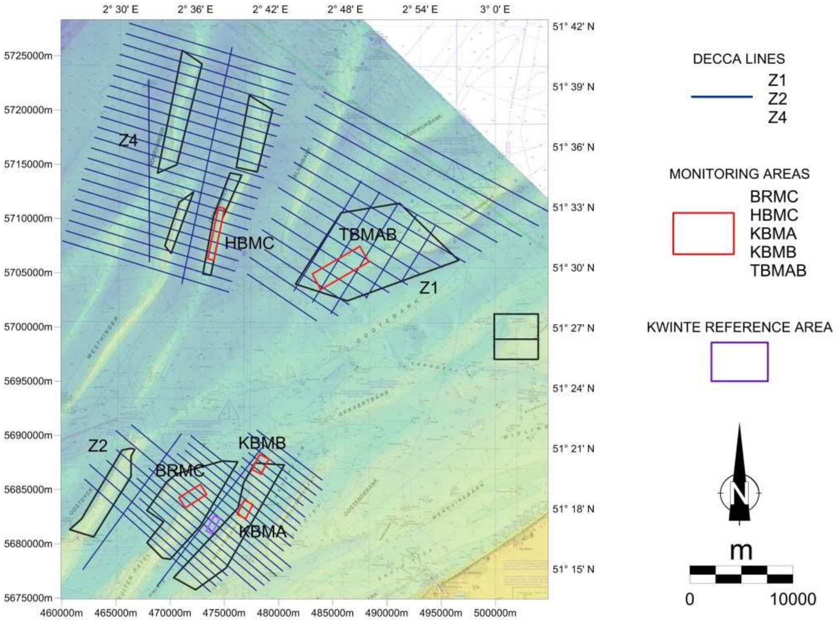

Figure 6: Location of the reference area, monitoring areas and DECCA lines used in this contribution.

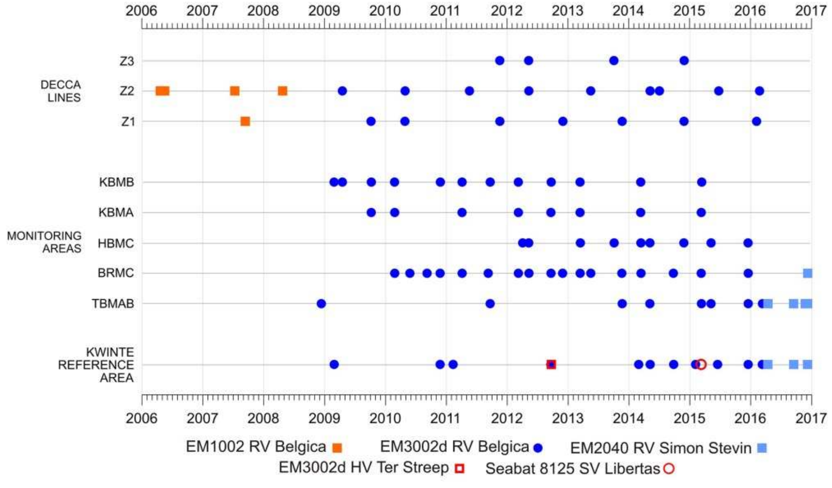

Figure 7: Time line of the data set and MBES considered in this contribution (location Figure 6). All MBES datasets are used for bathymetry analysis. Only data from the RV Belgica EM3002d are considered for backscatter analysis. Data from HV Ter Streep and SV Libertas are courtesy of the Agency for Maritime and Coastal Services – Flemish Hydrography.

Successive generations of Kongsberg MBES have been used from 2008 to present: the RV Belgica 100kHz EM1002 from 1999 up to 2008 and the RV Belgica 300kHz EM3002d from 2009 to present. Most of the data presented in this contribution come from the RV Belgica EM3002d.

In 2016, after establishing a stable GNSS Real Time Kinematic (RTK) correction, the EM2040 (200/300/400kHz) installed on the RV Simon Stevin became fully operational for bathymetric measurements of excellent hydrographic quality. This high resolution MBES has been used for 4 surveys on the TBMAB and one on the BRMC monitoring area in order to compensate for the non-availability of the RV Belgica during 2016. Unfortunately, due to lack of ship time, the other monitoring areas as well as the DECCAS reference lines have not been surveyed since the beginning of 2016. On the Kwinte reference area (see further on), two dataset surveyed by the Flemish Hydrography and a sub-contractor have been used as well to complete the bathymetric time series.

All the data are used for bathymetric analysis. For the backscatter, only the RV Belgica EM3002d data are used to ensure comparability of data.

Obviously, the “bathymetric and backscatter time series” approach for monitoring of the seabed implies the assurance of a stable data quality. The guarantee of a stable measurement system over the time interval of the monitoring program is provided by the comparison with a stable reference, assuring the repeatability of the bathymetry and the backscatter measurements with MBES.

Bathymetric data quality control and uncertainty

The hydrographic quality assessment of the EM1002s and EM3002d was carried out in June 2010 in cooperation with the French “Service Hydrographique et Océanographique de la Marine” (SHOM) on the SHOM reference area in the bay of Brest (Carré Renard for Z quality assessment). For its entire 75° swath, the EM3002d was compliant for the depth measurement (Z-value) with the International Hydrographic Organization S44 special order (IHO S44 SO) specifications. The EM1002, which was used to establish the reference models of the sand extraction sectors in the previous decade, has been certified for the IHO S44 Order 1 (a lower order). In June 2015, based on a new survey of the Carré Renard, the RV BelgicaEM3002d once again has been certified IHO S44 SO by the SHOM. The IHO S44 SO certification of the EM3002d is not a measure of its overall uncertainty. The metrological evaluation of the uncertainty of the depth measurement carried out with a MBES requires a complete propagation model of uncertainties that integrates all the elements related to the MBES itself and its auxiliary sensors (positioning system, motion sensor, draft and draught measurement, sound velocity value at the transducer…). This was not the case for the RV Belgica EM3002d, and this certification only provides the guarantee that the bathymetric data are within the precision limits in Z defined by the IHO for its highest quality level. For instance, for a depth of 20m, the SO imposes a Z accuracy of 0.28m, meaning that 95% of the soundings are inside the depth interval of 19.72 to 20.28 m.

A comparison, based on a common survey, shows that the mean difference between the depth resulting from the conventional tide and draught correction and the depth based on the GNSS Real Time Kinematic (RTK) correction can attain a value of 0.29m. Taking into account such level of difference, we consider that the global uncertainty for the EM3002d data surveyed using the normal DGPS mode is practically 0.3m. This global empirical confidence level of ± 0.3m integrates all the source of uncertainties from the EM3002d itself as well as from its auxiliaries sensors. This value is certainly necessary to incorporate the systematic errors on the EM3002d measurement in the “classical” DGPS positioning system, due to the draft measurement and the *M2*tidal reduction method (Van Cauwenberghe et al., 1993). The Ellipsoid –GNSS RTK correction method improves a lot the accuracy of the soundings measured by high resolution shallow water MBES and should be used systematically (Brisette, 2012 and Wells, 2017).

Such a wide confidence interval of 0.3m imposes the relativity of the bathymetric variations within this amplitude.

Backscatter data quality control and uncertainty

While usual hydrographic standards (IHO, 2008) provide a framework for assessing the quality level and the repeatability of bathymetric measurements, little to say no attention has been given to assess the quality level of MBES backscatter data. Only recently the backscatter started to be the subject of specific recommendations in the context of a reference document defining contract specifications for hydrographic surveys (LINZ, 2016). The upstream delivery of MBES fully calibrated for the backscatter by the manufacturers themselves would certainly constitute a solid foundation and impulse for defining absolute backscatter quality levels. The extra service to the user to establish a relative backscatter calibration specific for each MBES (Kongsberg Maritime, 2017) is a notable advance in the direction of a better control of the backscatter. But unfortunately, at this time, a quality standard for the MBES backscatter is not available. Consequently, no level of reliability can be associated with the time series of dB values, that geoscientists would like to use as a proxy for changes in the seabed. Measuring the level of accuracy, defining quality standards for the MBES backscatter and evaluating the backscatter quantitative capabilities and limitations to monitor the seabed integrity remain critical challenges (Lurton & Lamarche, 2015). If repeated backscatter measurements with a same MBES are organized as a part of a scientific monitoring program, the time series of backscatter processed data that will be used to estimate the changes of the seabed is by nature relative: the backscatter data of the same MBES is compared with previous measurements without any absolute reference (This can be compared with successive temperature measurements with a non-calibrated thermometer). In this case, an evaluation of the accuracy of the backscatter measurements is not mandatory, but at least, a regular assessment of the repeatability of the MBES for the backscatter is required. Such relative assessment involves the use of a stable target. In coastal zones, the use of an assumed stable reference area for backscatter allows this test of repeatability (Roche et al., in progress).The reference area on the BPNS (KWGS) is located in the Flemish sandbank area, in the Kwinte channel between the Kwintebank and the Buiten Ratel sandbanks (Figure 8 a.). The area is oriented SW-NE and covers 0.96 km² (1.6x0.6 km). This area is proposed as a reference area for the bathymetric measurements. A subarea of 0.12 km² (0.4x0.3 km) is proposed as the backscatter reference area for the BPNS.

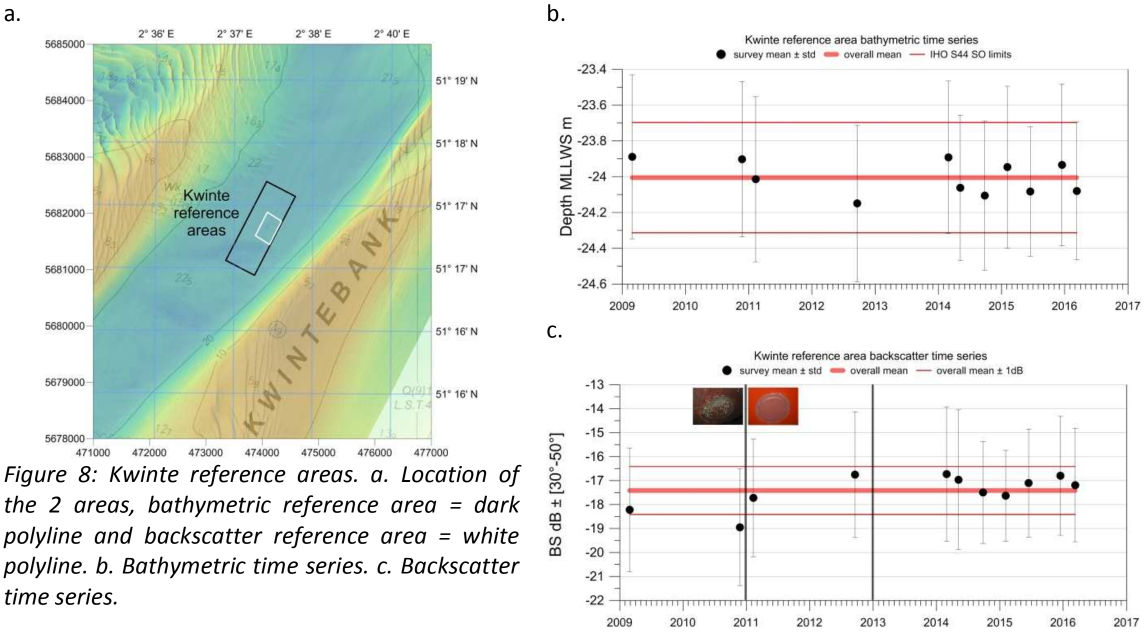

Figure 8: Kwinte reference areas. a. Location of the 2 areas, bathymetric reference area = dark polyline and backscatter reference area = white polyline. b. Bathymetric time series. c. Backscatter time series.

Since 2009, numerous MBES bathymetric and backscatter surveys using different acoustic systems with *in situ* control (video and samples) have been conducted on this area. The multi-year time series confirms the stability of the bathymetry and the morphology of the area. All bathymetric surveys made since 2009 are compliant with the IHO S44 SO quality level. Survey averages are all included within the SO limits of the overall mean and no significant trend is observed. Formally, regarding the bathymetry, the Kwinte reference area can be considered as stable without significant accretion or erosion (Figure 8 b.).

The RV Belgica EM3002d backscatter time series of the Kwinte BS reference subarea is presented in Figure 8 c. With the exception of value measured end of 2010, all the backscatter levels are included within a 1dB range around the overall mean. The backscatter level is extremely stable without any trend. The short term drift in 2010 correlates with a strong biofouling event (barnacles with few oysters) covering the transducers. The transducers were cleaned during the following winter (2010-2011) dry dock period (Rice et al., 2015). A same biofouling event has been notified during the 2013-2014 winter dry dock. As a result, the backscatter levels measured during the autumn campaigns in 2011 and 2013 are subject to caution.

Both the bathymetric and backscatter time series recorded on the Kwinte reference area with the RV Belgica EM3002d demonstrate a correct stability of the entire measuring system including the MBES and its auxiliary sensors. This approach demonstrates the scientific value of using a reference area and regularly performing control measurements.

In order to ensure the stability of the Kwinte seabed, the Continental Shelf Service has applied to the MRP 2020 Commission for closing this area to all non-scientific human activities. This request is supported by the Flemish Hydrography, the Flanders Marine Institute and the Operational Directorate Nature of the Royal Institute of Natural Sciences.

Results at short spatial scale: the monitoring areas approach

The short spatial scale monitoring of the sand extraction is carried out in restricted monitoring areas. The delimitation of these monitoring areas is based on the monitoring of the extraction activity itself: they coincide with the most extracted areas at a given time. The monitoring areas are mapped at regular intervals with a full MBES coverage. As the MBES surveying with full coverage of the seabed requires significant navigation time, which is a function of the surface that has to be covered, this approach is only possible with a limited number of monitoring areas. The density of a full MBES coverage allows the calculation of bathymetric and backscatter high resolution models and accurate derived statistics which make it possible to follow the local impact of the extraction where it is most intense and to control if the extraction does not exceed the limit of 5m authorized by the law.

First, this contribution focuses on two active monitoring areas where the extraction has been particularly intense over the last three years:

- The Thorntonbank TBMAB monitoring area was defined and surveyed in 2008 but extended in 2013 to account for the increasingly importance of the S1a sector for the sand industry. This area has become the epicenter of the industrial sand extraction since 2014.
- The Oosthinder bank HBMC monitoring area has been created in 2012 in order to monitor the intensive and focused in time extraction of sand for coastal protection.

Secondly, after an intense period of extraction, two zones of the Kwintebank and one on the central part of the Buiten Ratel, where the extraction exceeded the legal limit of 5m below the reference level, were closed. On the central and north part of the Kwintebank, KBMA area was closed on 15/02/2003 and KBMB area on 01/10/2010. The BRMC area in the central part of the Buiten Ratel is closed since 01/01/2015. After closure, these areas continued to be surveyed with the MBES on a low frequency basis. The data acquired on these passive areas make it possible to evaluate the local recovery potential of the seabed after the closure of extraction.

Active monitoring areas

TBMAB

Located in sector 1a, in the western part of the Thorntonbank, the TBMAB monitoring area covers 8.4 km² (Figure 9). This area totals a cumulative volume of 6.6 $10^6 m^3$, mostly extracted from 2012 on. Increasing systematically since 2010, the extraction level exceeds 1.2 $10^5 m^3$/month in 2015. In 2016 the total volume extracted over this area is 1.45 $10^6 m^3$, or virtually 50% of the annual extraction of all sectors. However, unlike the situation of hyper concentration of the dredging activity previously observed in the years 2000 to 2010 on the Kwintebank and between 2009 and 2015 on the Buiten Ratel, the extraction in sector 1a tends to spread out more evenly across the sandbank (see figures 3 and 33 and the annual extraction maps in Van de Branden et al, this volume).

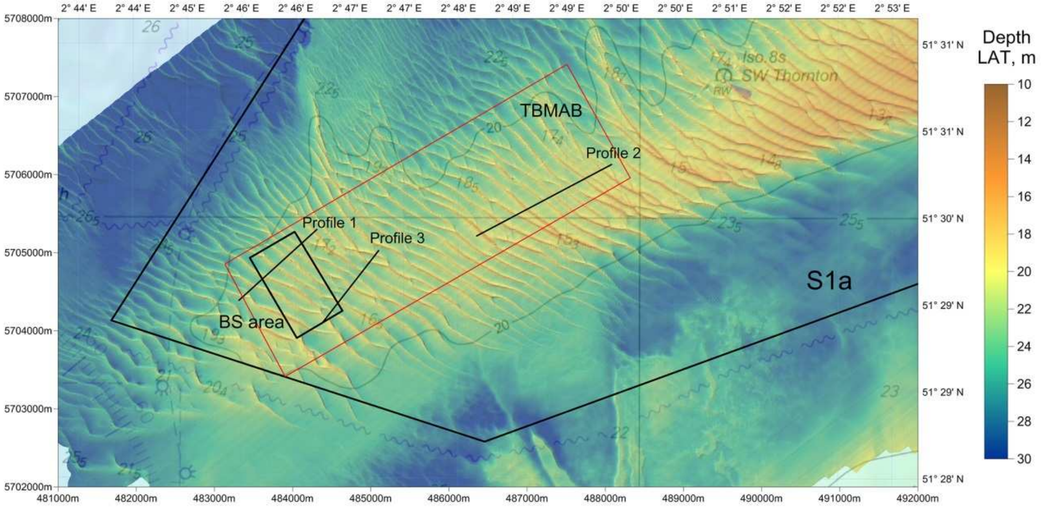

Figure9: Reference model of S1a (2001-2004), location of the profiles and the BS area for specific backscatter analysis inside TBMAB area.

The impact of the extraction on the scale of the TBMAB area is illustrated by the depth difference between the models of the last 3 MBES surveys with the reference model of S1a, resulting from the EM1002 MBES data acquired between 2001 and 2004 (Figure 10). This map clearly shows two SW-NE oriented areas where the extraction concentrates and generates depth differences exceeding 4m. Outside these two areas, the difference in depth remains limited and does not exceed 1m. The depth difference map also reveals the dynamics of the large dune on the Thorntonbank.

Within the most intensively dredged areas, profiles in a vertical plane allow to evaluate the evolution of the successive bathymetric levels compared to the 2001-2004 reference level of S1a. These profiles are shown in Figure 11. Profile 1, located along the axis of the main dredging zone in an area of very large symmetrical and stable dunes, shows that in March 2016 the 5m limit was reached at the dunes crests. Between March and December 2016, the bathymetric level remained stable, demonstrating that around the profile 1, extraction decreased sharply. In the inter-dune zones, a margin of 2m to 3m still exists. In line with current legislation, that implies a volume of sand sufficient to let the extraction continue in this part of the sandbank. Profiles 2 and 3 show a significant decrease of the bathymetry between 2001-2004 (MBES data acquisition period of the S1a reference model) and 2011. This decrease matches the increase of the extraction on sector 1a from that period. In 2012 the extraction on the S1a crosses the threshold of $10^6 m^3$/year. According to profiles 2 and 3, the useful reserve of sand on the S1a remains significant, with in 2016, an average bathymetric level remaining at least 3m above the reference level.

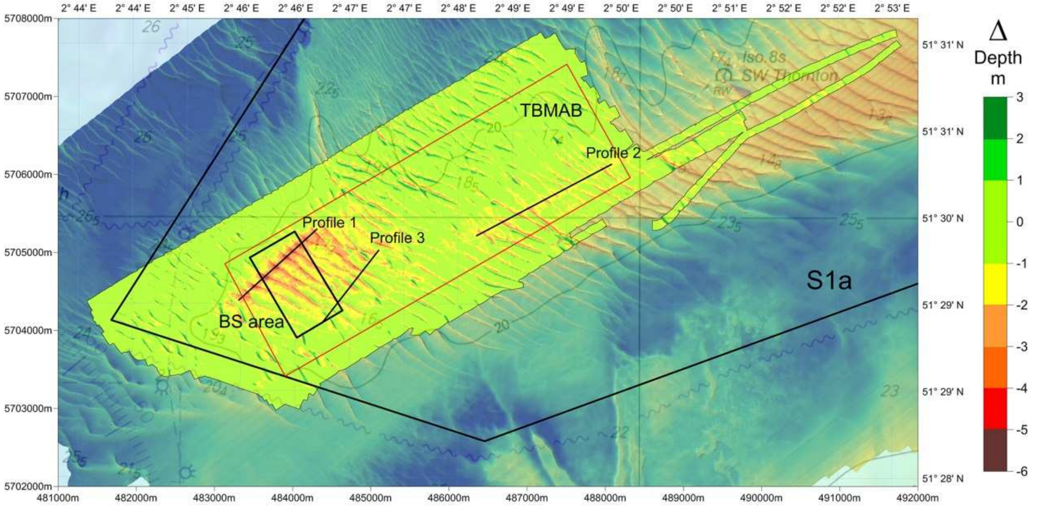

Figure10: Depth difference between the most recent surveys (Belgica EM3002d c1533 - 16/12/2015; Simon Stevin EM2040 c16900 - 23/11/2016 c16930 – 07/12/2016) and the reference model of S1a (2001-2004).

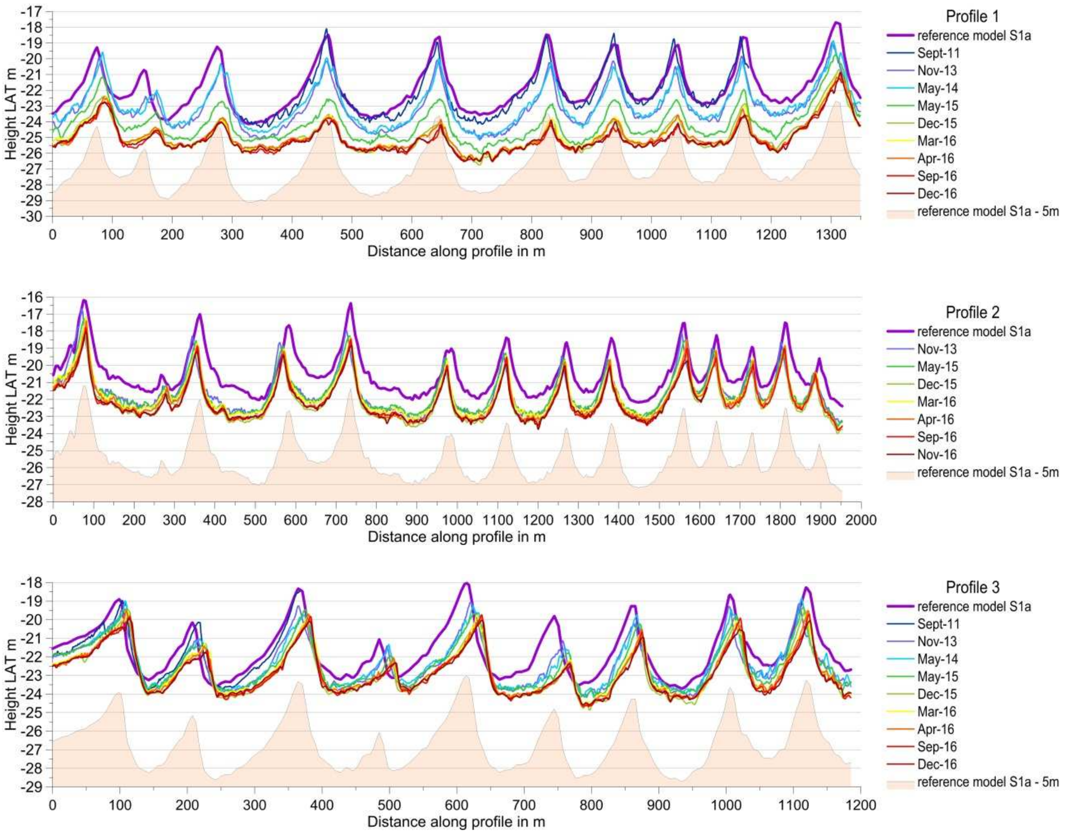

Figure11: Bathymetric TBMAB profiles 1, 2 and 3 (location on figures 9 and 10)

Using the mean extracted volume inside a buffer of 10m (area = 2.8ha) around profile 1, Figure 12 shows the temporal evolution of the extracted volumes estimated from the EMS data (monthly volume and cumulative volume) with the temporal evolution of the mean bathymetric difference compared to the S1a reference model. In this zone, the main phase of extraction between mid-2014 and the end of 2016 induces a drop in the average bathymetry of nearly 2m. Hereafter, the bathymetry slowly decreases until the end of 2016.

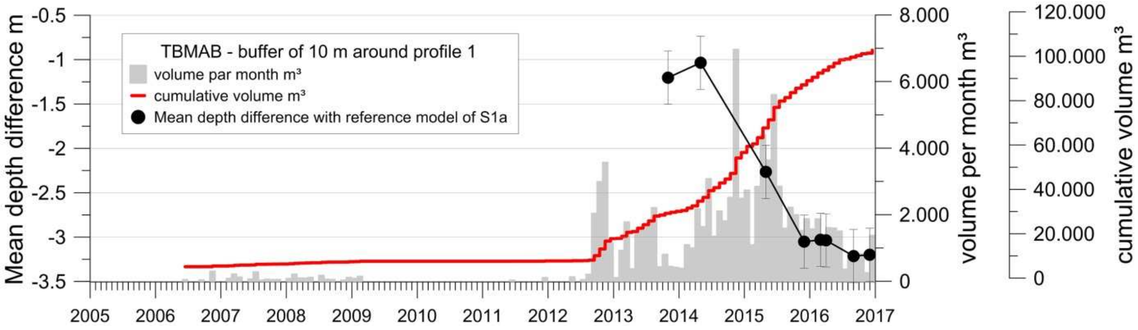

Figure12: Extracted volume per month, cumulative volume and mean depth difference with reference model of S1a (2001-2004) inside a buffer of 10 m around the TBMAB profile 1 (location on Figures 9 and 10).

At the time of each MBES survey, the extracted cumulative volume based on EMS data may be translated into a bathymetric difference by simple division with the surface under consideration. Figure 13 illustrates this approach, showing in parallel the evolution of the bathymetric difference measured by MBES with that of the bathymetric difference estimated from the cumulative volumes deduced from the EMS data.

The evolution of the two curves is very similar, confirming on a local scale the close relationship between the extracted volume and the intensity of the bathymetric variation. The decimeter differences between the two curves could be related to the uncertainties that affect all the bathymetric measurements performed through the conventional method (positioning in DGPS mode, draft measurement and tide correction according to model *M2*). A simple decimeter bias of the reference model can explain the difference between the 2 curves. The uncertainty that affects the volume estimation from the EMS data could also contribute to this shift (see above). Various arrangements for improving the accuracy of EMS data are discussed in Van den Branden et al. (this volume).

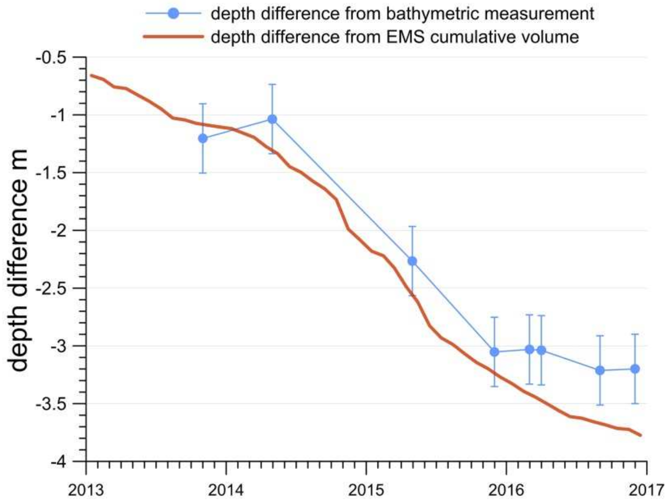

Figure13: Evolution of the mean depth difference with reference model of S1a (2001-2004) and the derived depth difference from EMS cumulative volume inside a buffer of 10 m around the profile 1 (location on Figures 9 and 10).

The common coverage area of all the RV Belgica EM3002d surveys (location in Figures 9 and 10) is considered to evaluate the evolution of the backscatter in parallel with the extraction as a function of time. The time series is shown on Figure 14.

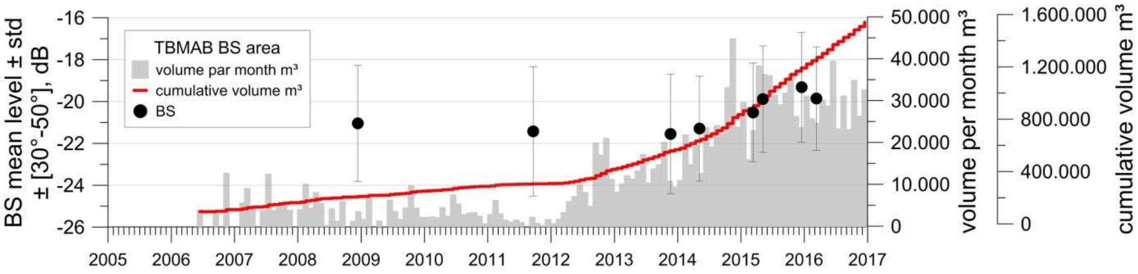

Figure14: Extracted volume per month, cumulative volume and backscatter evolution inside the BS area of TBMAB area (location on Figures 9 and 10).

After a period of stability from 2008 to 2013, the average backscatter level shows a positive trend increasing from [-22, -21]dB in 2014 to [-20, -19]dB in 2016. After 2013, the mean dB levels are well correlated with the cumulative volume curve.

These results demonstrate that the extraction modifies the nature of the seabed at a local level. Several effects of the extraction can combine to progressively change the average backscatter level:

- The mechanical impact of the dredging head on the seabed, at the dredging grooves, causes an increase of the seabed roughness and subsequently of the backscatter. If intensive dredging operations occur for a while, the increased density of the dredging grooves induces an increase of the backscatter level because at oblique incident angles, the steep slopes of the grooves act as strong backscattering surfaces (Roche et al., 2011).
- By concentrating the coarse fraction and especially the shells, that are strong acoustic scatterers, the screening induces a change of the acoustic properties of the sediment interface. This is marked by a notable increase of the mean backscatter level. The Sediment profile imaging (SPI) images taken in April 2016 in the most intensively dredged part of S1a along profile 1, show a high concentration of shells at the top of the seabed. These observations are confirmed by the granulometric measurements from grab samples collected at the biological sampling stations in the mostly dredged part of the S1a (De Backer et al., this volume).

For the TBMA area, both effects can be evoked to explain the increase of the average backscatter level. The witnessed backscatter evolution can be interpreted as the acoustic response to a deletion scenario: a drastic change of the sediment type due to the removal (by dredging operation) of a finer upper layer, causing the progressive excavation of a deeper and coarser layer.

An initial evaluation of the mean backscatter level before the extraction starts is of prime importance to correctly explain the evolution of the backscatter in parallel with the evolution of the extraction. Furthermore, the knowledge of the surface and subsurface geology of the sandbank is decisive in this respect.

HBMC

The HBMC zone was created in 2012 to evaluate the impact of sand extraction in sector 4c. It occupies the summit of the Oosthinder in the central area of sector S4c and covers 2.8km^2 (Figures 15 and 16). Between 2012 and 2014, over a total period of 18 months, the cumulative volume extracted on S4c is 4 10^{6}m^3, a volume intended 100% for beach maintenance. With a cumulative volume of 2.3 10^{6}m^3 for the same period, the HBMC area includes more than 50% of the extraction on the sector S4c, while covering only 34% of its surface.

The difference between the depths resulting from the last survey, at the end of 2015, with the reference model of S4c, established between 2004 and 2006, is illustrated in Figure 16. The map shows an elongated zone on the western side of the bank where the extraction has been concentrated, resulting in a significant drop in bathymetry of 2 to 3m over a short period of time.

The abrupt changes in accretion and erosion that follow the ridge patterns of the very large dunes, that model the top of the bank, reflect the importance of the dynamics of the sediment transport in this area, an importance confirmed by the results from Francken et al. (this volume).

For HBMC, an approximation of the volume of sand between the bathymetric surface modeled by the dunes and the oscillatory surface envelope of the bank (Debese et al., 2016 and Degrendele et al., this volume) concludes that 1.8 10^{6}m^3 could be involved in the dune dynamics in this area.

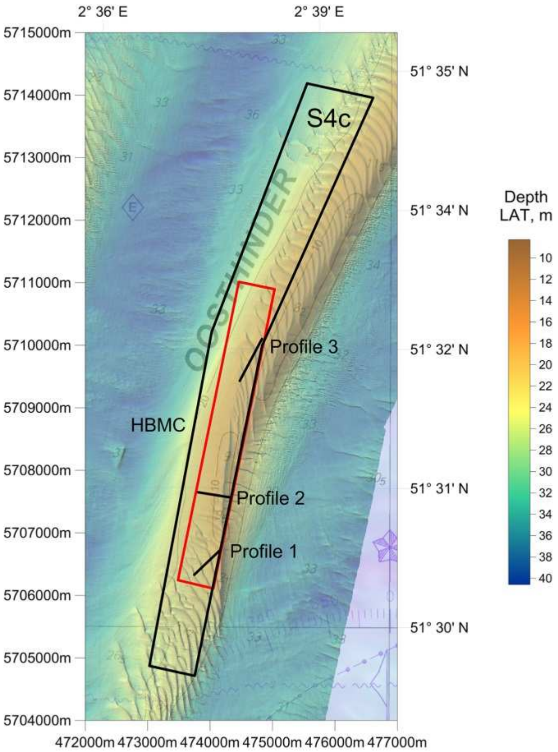

Figure 15: Reference model of S4c (2004-2006), location of HBMC monitoring area and the reference profiles.

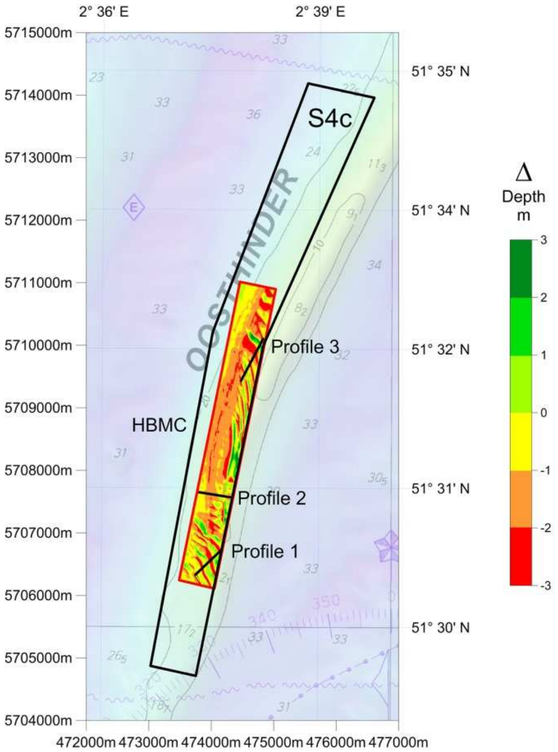

Figure 16: Depth difference between the most recent survey (Belgica EM3002d c1533 - 16/12/2015) and the reference model of S4c (2004-2006).

The three vertical profiles in the southern, central and northern parts of HBMC area (Figures 15 and 16) allow an estimation of the local incidence of the extraction and a quantification of the dune dynamic.

In profile 1, the extraction impact is marked by an erosion of the dune crests of more than 1m locally from April 2012 to December 2015. Profile 1 is clearly dominated by a strong dune dynamic. The very large dunes prograde from SW to the NE summit of the bank over 100m for the period considered. This corresponds to a mean displacement of about 30m/y.

In the middle part of the monitoring area, the profile 2 captures most of the impact of extraction on the western flank of the sandbank. In this zone, following the intense extraction concentrated in May and June 2014, the bathymetry locally dropped by more than 2m between the measurements made in early May and those at the end of November 2014. The main ridge of the bank appears to be oscillating from west to east around an equilibrium position with an amplitude of 50m between the most western and eastern positions respectively observed in April 2012 and March 2014.

Profile 3 provides information similar to profile 1: between April 2012 and December 2015, the incidence of extraction is marked by a lowering of the dunes crests by ±1m; As in profile 1, the dunes show an average displacement of 30m/y.

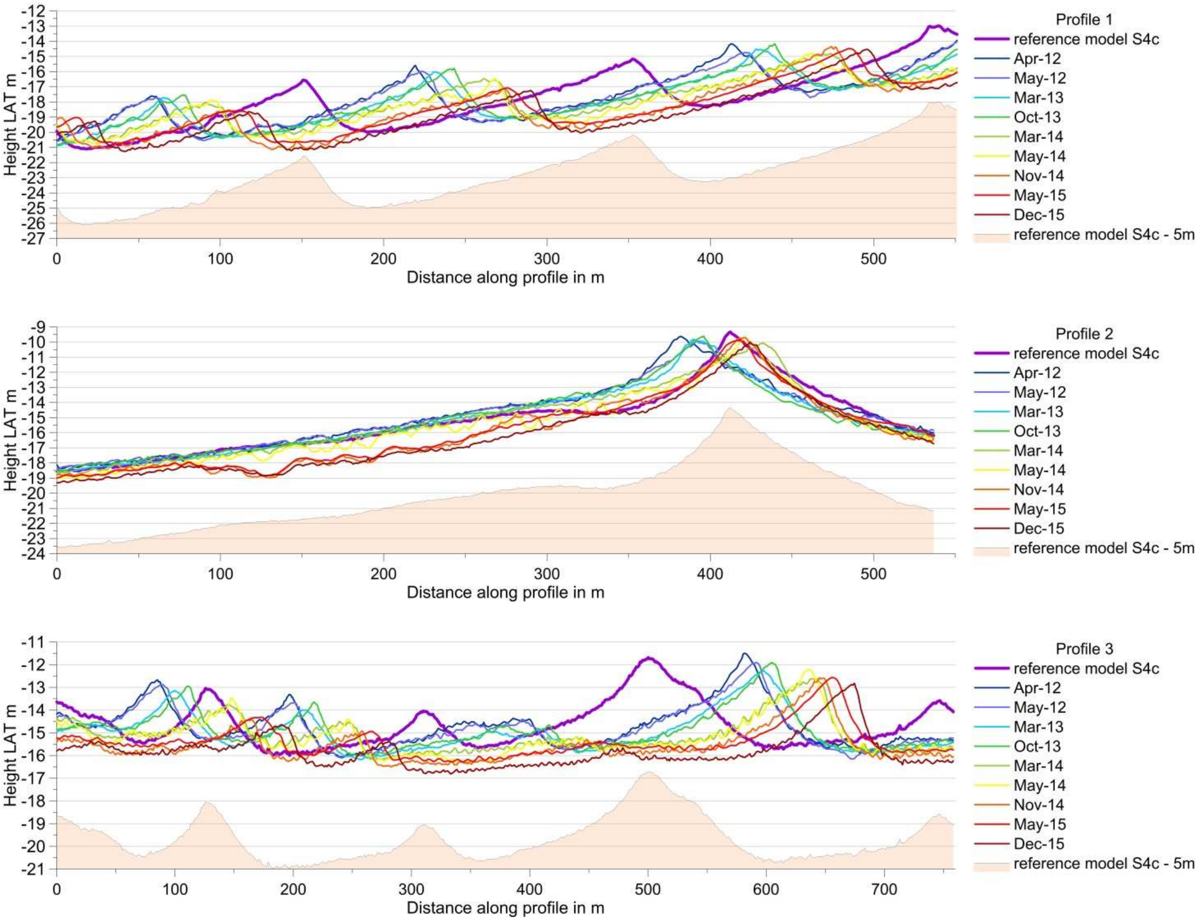

Figure 17: Bathymetric HBMC profiles 1, 2 and 3 (location figures 15 and 16).

Figure 18 presents the temporal evolution of the extracted volumes estimated from the EMS data (monthly volume and cumulative volume) with the temporal evolution of the mean bathymetric difference compared to the S4c reference model based on 2004-2006 EM1002 MBES data.

After the main extraction phase which ended in June 2014, the S4c sector was not submitted to extraction in 2015 and 2016. The bathymetry shows a linear decrease of the order of 2m from 2012 to the end of 2016. An acceleration of the bathymetric lowering is observed between May and November 2014 in response to the intense extraction phase of May and June 2014. Despite the absence of extraction in 2015 and 2016, the last measurement of the time series suggests a continuation of the erosive trend that needs to be confirmed by additional measurements.

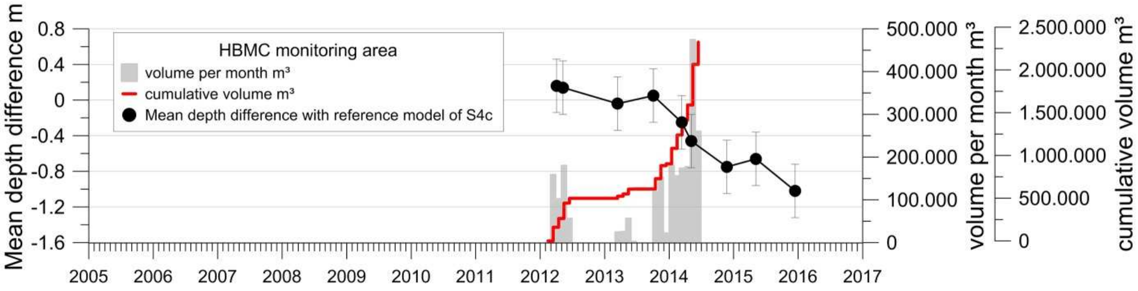

Figure 18: Extracted volume per month, cumulative volume and mean depth difference with S4c reference model (2004-2006) of HBMC monitoring area (location Figures 15 and 16).

The extracted volumes estimated from the EMS data are converted into bathymetric difference by simply dividing the total volumes with the area of the HBMC zone. Evolution of the two depth difference curves are presented together in Figure 19. The trends of the two curves remain relatively similar, showing a good local correlation between the intensity of the extraction and the decrease of the bathymetry. Again, decimeter deviations can be related to systematic errors that affect the bathymetric data in a similar order of magnitude (see above). The relatively constant difference could be linked to a bias on the bathymetric reference model of S4c. The established differences remain inside the level of uncertainty of the bathymetric measurements. An increase of the bathymetric measurement precision and an uncertainty assessment on the volume estimation from EMS data is mandatory to better understand the correlation between the extraction and the bathymetry. Better still, the reference model of this sector should be updated with rigorous bathymetric surveys with GNSS RTK correction.

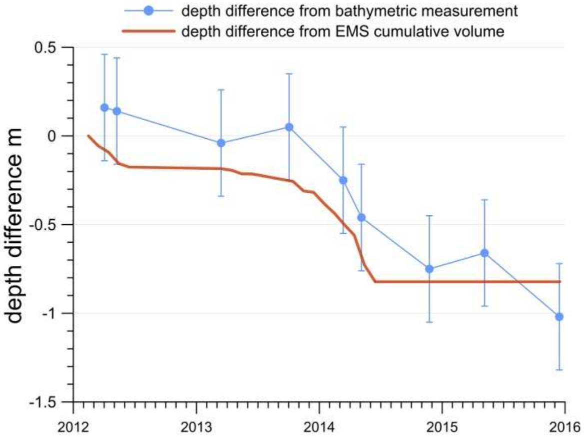

Figure 19: Evolution of the mean depth difference with reference model of S4c (2004-2006) and the derived depth difference from EMS cumulative volume of HBMC reference area (location figures 15 and 16).

Figure 20 a. presents the backscatter time series in parallel with the evolution of the volume and the cumulative volume per month. The backscatter curve shows a negative trend correlated with the extracted volume. The first measurements made in early 2012 show average backscatter levels of [-25, -26]dB. In 2015 the mean level has descended to app. -28dB. A deletion scenario can be used to explain such a negative trend. This scenario is illustrated in figure 20 b., which shows the averaged (10x10m) mosaics of 4 HBMC surveys from 2012 to 2015. The initial situation of the HBMC area before extraction shows a clear boundary between the west and east sides of the sandbank. The western flank is characterized by backscatter values of the order of -20dB, which are considerably higher than in the eastern part of the sandbank where the average level is around [-28,-30]dB. On the western side of the Oosthinder, a surficial coarse sand layer with abundance of shells could explain this high backscatter level. On the eastern side, relatively fine sand dominates. The boundary between these acoustic zones coincides spatially with the crest of the Oosthinder which separates its two flanks.

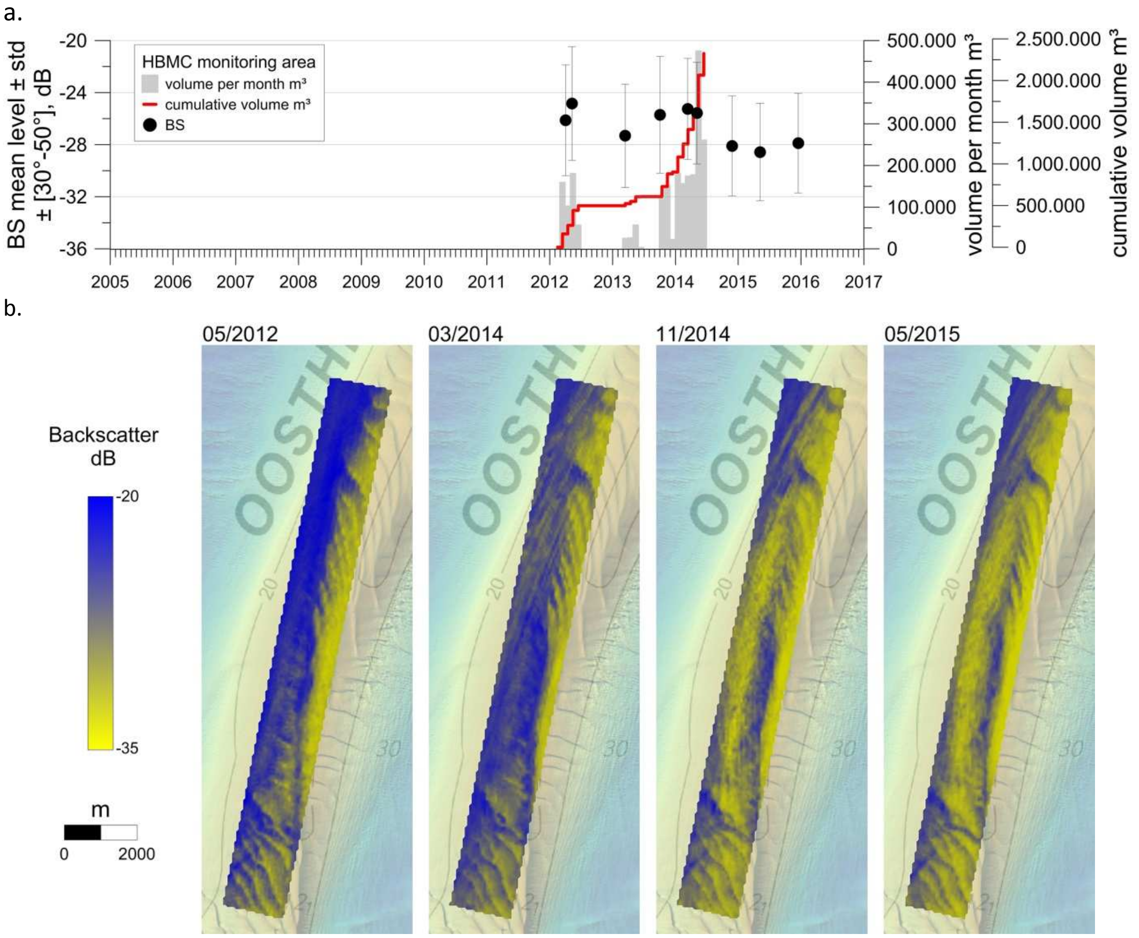

Figure 20: a. Extracted volume per month, cumulative volume and backscatter evolution ofHBMC area. b. Backscatter mosaics (mean level in 10x10m grid) of HBMC area (location figures 15 and 16).

On the MBES backscatter image of March 2014, the dredging traces that begin to "clear up" the western part are obvious. After the most intense extraction phase in May and June 2014, the coarser sand layer, which has been dredged intensively to a depth of more than 2m, has virtually disappeared. Its removal reveals an underlying layer of finer sand with acoustic properties similar to the surficial sediment covering the eastern flank of the bank. The comparison of these results with the particle size analysis of the sediment samples and the images available on HBMC is underway.

Compared to the TBMA area, the backscatter trend measured on HBMC imposes an inverse scenario of modification of the seabed due to extraction. Here, the change in the nature of the seabed is the result of the deletion of an upper coarser layer of sediment, excavating the underlying finer layer.

Closed areas

Since 2003, three areas where the extraction has exceeded the limit of 5m below the reference level have been closed (Figure 21). Since their closure, these three areas continue to be subject to regular MBES measurements to assess the potential for restoration of the seabed after cessation of extraction.

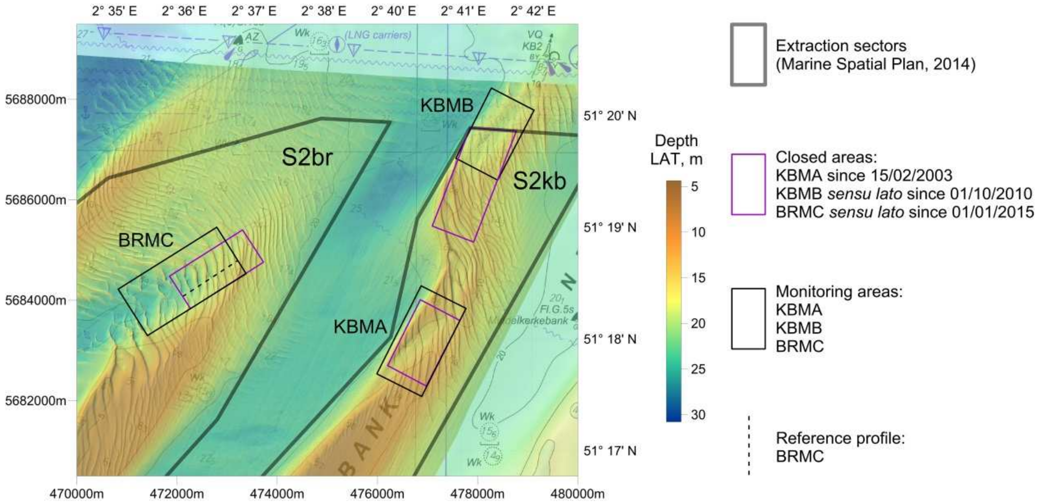

Figure 21: Reference model of sectors S2kb and S2br (2000-2003), location of BRMC, KBMA, KBMB monitoring areas, closed areas and BRMC reference profile.

BRMC

Located in the central part of the Buiten Ratel, the BRMC zone was created in 2010 to follow the development of the extraction that concentrates there after the closing of the northern part of the Kwintebank (Degrendele et al, 2014). Between 2009 and 2013, 4 10^6m^3 have been extracted from this area of 2.5km^2, representing virtually 30% of the total volume extracted in all the sectors. The most recent bathymetric model, acquired in December 2016, 23 months after the closure of the BRMC area, still reveals the major morphological changes due to the intense extraction; the two depressions associated with the accumulation of the dredged furrows are still clearly visible on the bathymetric model (Figure 22). The depth difference between this recent model and the reference model of S2br (2000-2003) shows that in the most intensively dredged part, the bathymetric level remains below 5m compared to the reference model (Figure 23).

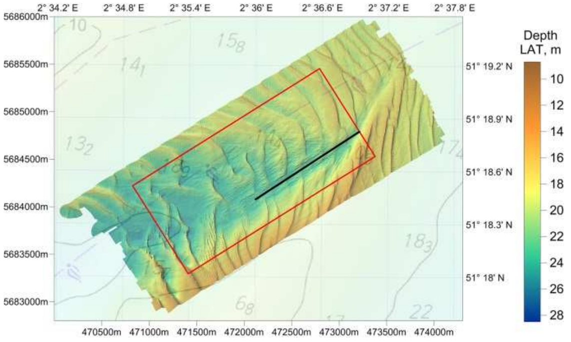

Figure 22: High resolution bathymetric model of BRMC monitoring area (RV Simon Stevin EM2040 survey - 07/12/2016). Surveyed 23 months after the closure for extraction.

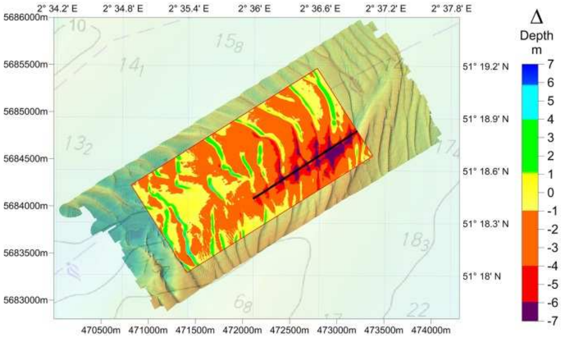

Figure 23: Depth difference between the most recent survey (RV Simon Stevin EM2040 - 07/12/2016) and the reference model of S2br (2000-2003).

The profile through the BRMC monitoring area illustrates the bathymetric evolution from 2010 to the end of 2016, during the extractive phase and after the closure of the zone in January 2015 (Figures 22 and 23 for location and figure 24). The 2016 profile is very close to that of 2015, demonstrating the bathymetric stability after the closure.

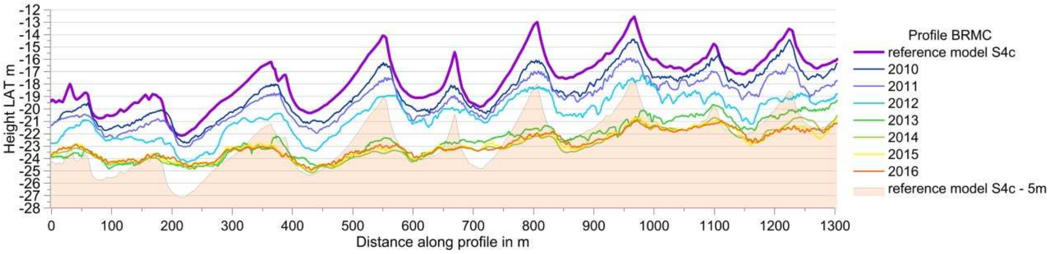

Figure 24: Bathymetric BRMC profile (location figure 20)

As before, the differences in depth with the S2br reference model (2000-2003) are presented as a function of time in parallel with the estimated monthly volumes and cumulative volumes from the EMS data. Clearly, the drop in bathymetry is correlated with the volume extracted and stabilizes at -1.75m by 2014, one year before the zone closes (Figure 25).

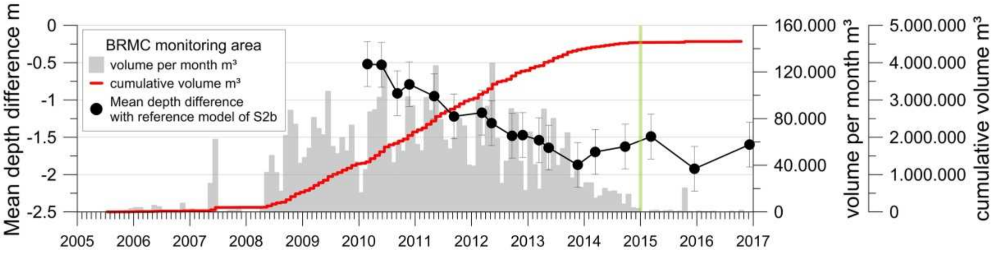

Figure 25: Extracted volume per month, cumulative volume and mean depth difference with S2br reference model (2000-2003) of BRMC monitoring area (location figure 21).
Light green line indicates the closing date of this area.

The depth difference based on EMS volumes is extremely well correlated with the MBES measurements (Figure 26). The vertical difference between the two independent curves is less than 10 cm for the majority of the measurements, suggesting a correct bathymetry of the reference model of Sector S2br. However, the surveys carried out in 2015 and 2016 with the RV Belgica EM3002d show larger discrepancies, the cause of which remains unclear. The average bathymetry of the last survey in December 2016, carried out with the Simon Stevin EM2040, is at the same level as that recorded before the zone closed.

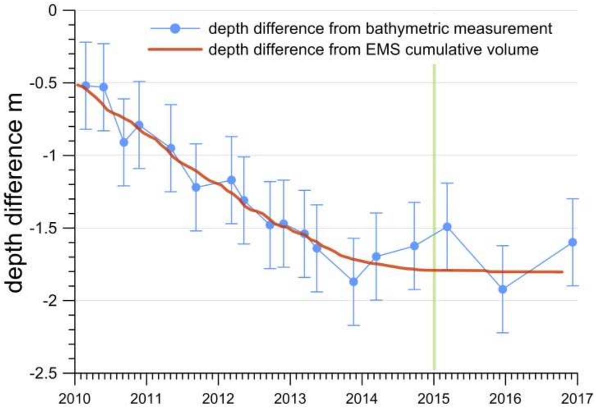

Figure 26: Evolution of the mean depth difference with reference model of S2br and the derived depth difference from EMS cumulative volume of BRMC reference area (location figure 21). Light green line indicates the closing date of this area.

The BRMC area bathymetric time series follows very well the curve of the cumulative volume during the extraction phase. As soon as the extraction is stopped in 2015, the bathymetric level shows no significant variation, oscillates around a stable level, demonstrating the absence of erosion and accretion.

The evolution of the mean backscatter level is presented in parallel with the monthly volumes and cumulative volumes. Measurements with the EM3002d begin only in 2010. The mean backscatter level of the BRMC area before the extraction started is not available and for this reason the extraction impact on the initial nature of the seabed in this area cannot be evaluated. During the extraction phase the backscatter level is relatively stable, oscillating around -20db. At the end of the extraction phase and after the closure, from 2014 to 2016, the average level of backscatter drops slightly to [-21, -22]dB. This slight negative trend may be related to a decrease of the median grain size of the sand fraction, as observed by De Backer (this volume). Local dredging plumes sedimentation could be evoked to explain this slight fining upward trend after the main extraction phase (see Van Lancker, V. *et al.*, this volume).

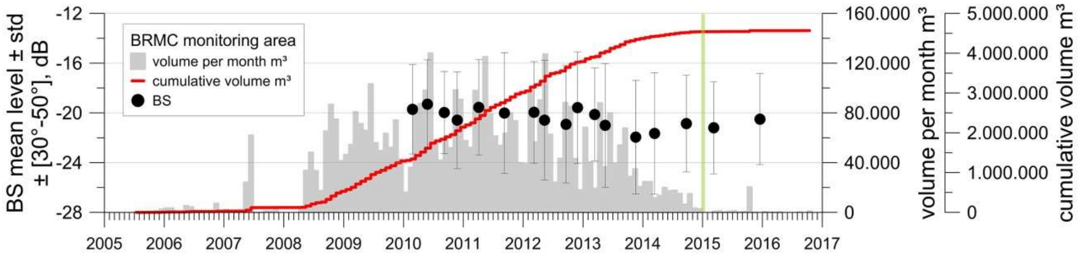

Figure 27: Extracted volume per month, cumulative volume and backscatter evolution of BRMC monitoring area (location figure 21). Light green line indicates the closing date of this area.

KBMA

Intensely dredged until 2002, the KBMA monitoring area of the central part of the Kwintebank (S2kb) has been closed to extraction in February 2003. This area has centralized some fundamental issues related to sand extraction (Degrendele et al., 2002, Bellec *et al.*, 2010, Degrendele *et al.,* 2010, Van Lancker *et al.*, 2010). MBES surveys combined with sedimentological and morphological analysis based on data acquired from 1999 to 2005 (during and after the extraction period) have demonstrated the relative bathymetric stability of the Kwintebank central depression after its closure. With no apparent recovery, the sand must be considered as a non-renewable resource.

What is the situation today? Figure 28 presents all the bathymetric data acquired from 1999 up to 2015 on the KBMA monitoring zone.

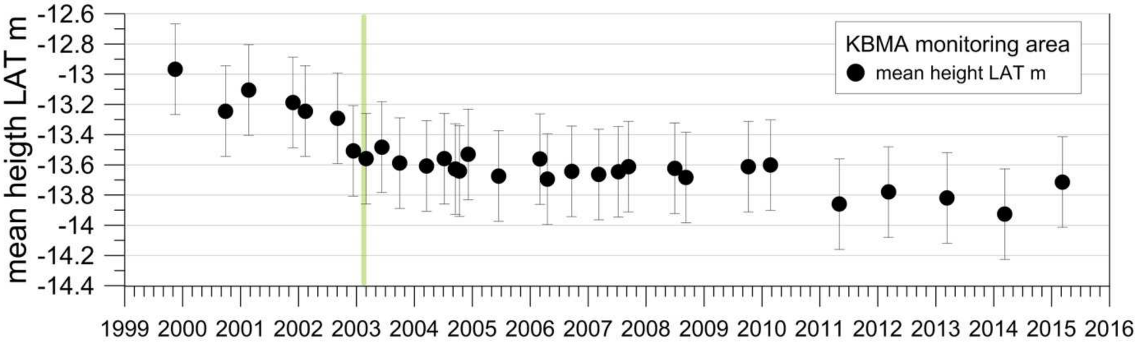

Figure 28: Bathymetric evolution of KBMA monitoring area (location figure 21). Light green line indicates the closing date of this area.

After the cessation of extraction in February 2003, the average bathymetric level remains practically stable from 2005 to 2010. A slight shift of -0.2m is observed from 2010 to 2011. The mean level appears stable up to 2014. The last measurement carried out in 2015 goes back to an intermediate bathymetric level in between the 2010 and 2011 levels. Overall, the recent data confirm the findings made in 2010 regarding the lack of restoration of the central depression of the Kwintebank.

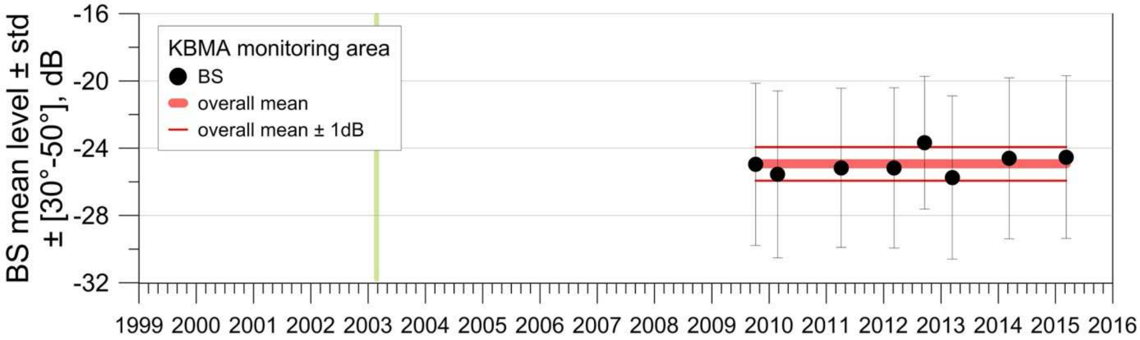

Figure 29: Backscatter evolution of KBMA monitoring area (location figure 21). Light green line indicates the closing date of this area.

MBES EM3002d measurements done between 2009 and 2015 make it possible to evaluate the variations of the seabed on the basis of the backscatter used as a proxy. The time series of the mean backscatter levels of KBMA area is presented in Figure 29. No trend is observed. The levels are extremely stable over the last six years. Virtually all the individual mean backscatter levels are included within a 1dB range on either side of the overall mean, suggesting that no significant change of the seabed interface has affected the KBMA monitoring area during this period.

KBMB

In March 2003, the KBMB monitoring area was created to assess the impact of extraction on the northern part of Kwintebank in former control zone 2 (*sensu* 1977). Following the modification of the extraction zone boundaries in 2004, the zone KBMB was only partially included in zone 2 and subsequently in sector 2kb. In 2009, following a complete survey of the northern part of Kwintebank, the northern depression related to the extraction largely exceeds the 5m limit (Roche et al., 2009). Subsequently, the KBMB area *sensu lato* was closed in October 2010. The whole bathymetric time series before and after the extraction closure is shown in Figure 30.

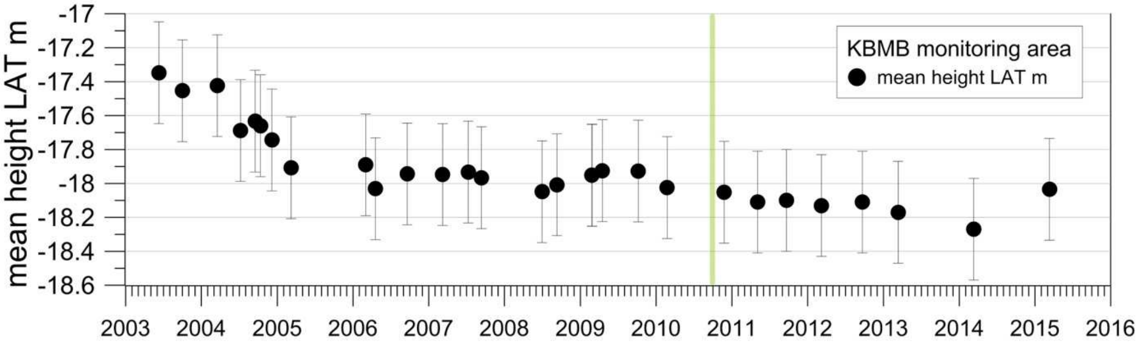

Figure 30: Bathymetric evolution of KBMB monitoring area (location figure 21). Light green line indicates the closing date of this area.

After 2011, the average bathymetric level oscillates around 18.1m without showing any trend, demonstrating the absence of significant sedimentary accretion and erosion.

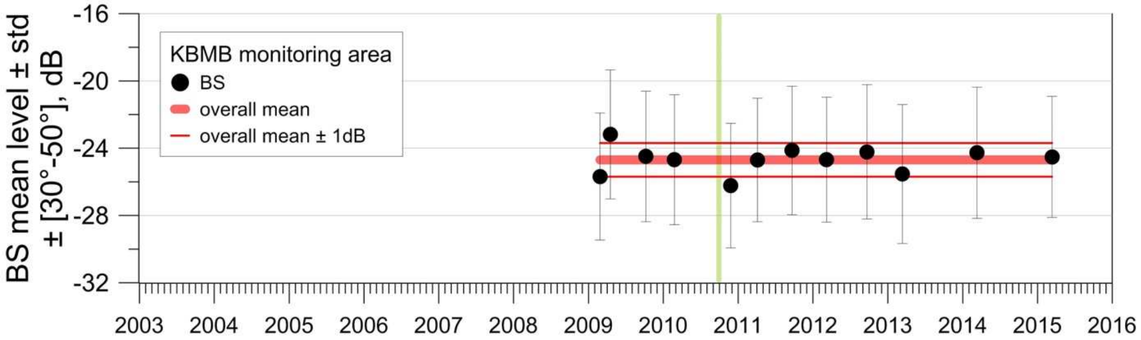

Figure 31: Backscatter evolution of KBMB monitoring area (location figure 21). Light green line indicates the closing date of this area.

The backscatter measurements presented in Figure 31 suggest a remarkable stability of the seabed after 2011. All measurements are within a 1dB range around the overall mean. The lower backscatter level observed at the end of 2011 may be related to the biofouling event that colonized the antennas of the EM3002d (see Figure 8c and related text). Both the bathymetric and backscatter time series confirm the stability of the KBMB zone after its closure for extraction.

Results at long spatial scale – the DECCA lines approach

In 2006 the Continental Shelf Service started studying the impact on a larger spatial scale by surveying along DECCA-lines across the control zones (Figure 6). Although the study of the most extracted areas, discussed above, provided some clear insights in the impact on sediments and topography, the effects on a larger area remain less obvious. The first analysis of the bathymetric evolution along DECCA lines on zone 2 in 2011 (Roche et al., 2011) and on zones 1, 2 and 4 in 2014 (Degrendele et al., 2014) resulted in a clear spatial relation between the extracted volumes and the changes in bathymetry measured with MBES. But quantitatively the correlation is less straight forward. In all control zones a uniform shift (positive in 2011, negative in 2014) between the reference surfaces and the measurements was observed. On the small monitoring areas under heavy extraction this trend is drowned by the sheer volume of the extracted volume and deepening of the bathymetry, but on the less or non-extracted areas it sticks out.

With the growing number of surveys along the DECCA lines, the chances for more robust conclusions should increase significantly. However, the DECCA time series has been recently disrupted by the unavailability of the RV Belgica (Figure 7). The overview below is limited to the presentation of the most recent surveys and the difference with the reference survey for each zone. An overall comparison between the extracted volumes (based on EMS) and the measured volume difference (based on MBES) is presented as a synthesis.

Zone 1

The most recent survey on zone 1 dates from the beginning of 2016. On the difference map (Figure 32) the dense extraction in the east of the area is apparent, with a deepening of locally more than 3m. This area coincides with the TBMAB monitoring area, as described above. For the remainder of the zone, the depth difference is almost uniformly negative (average value of -0.4m for the entire covered area). A comparison with the thickness of the sand layer that was extracted (Figure 33) shows that this overall deepening is not the direct *in situ* consequence of the extraction. The volume associated with the measured depth difference (6.9 $10^6 m^3$) largely exceeds the total extracted volume along the DECCA lines (1.8 $10^6 m^3$). The only positive depth differences measured in zone 1 are caused by the shift of large sand dunes on the Thorntonbank.

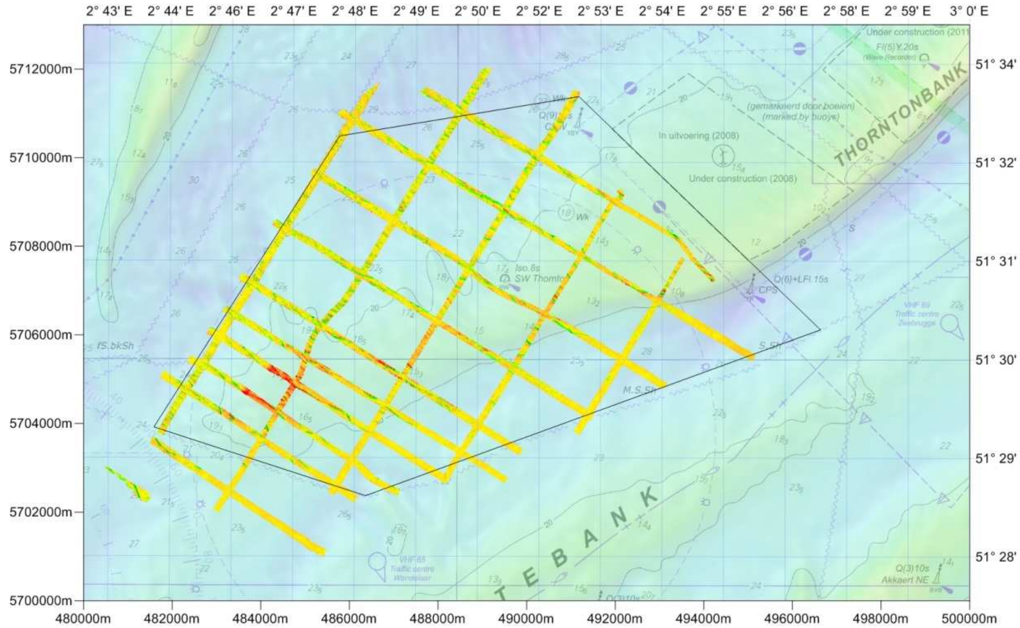

Figure 32: Measured depth difference between the most recent DECCA survey (Belgica EM3002d c1605 - 04/02/2016) and the reference model for zone 1.

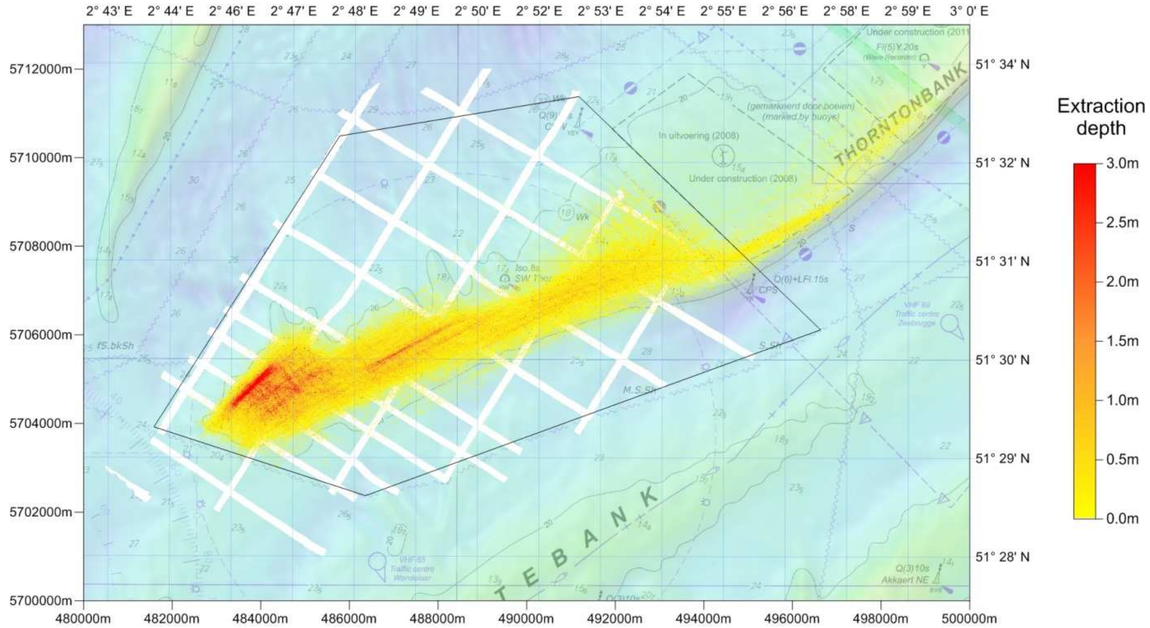

Figure 33: Extraction depth between 04/02/2016 (Belgica EM3002d c1605) and 2003 (reference model for zone 1). The part of the MBES covered area along the DECCA lines with no extraction is shown in white.

The Figure showing the average measured depth difference of the consecutive surveys (Figure 34) confirms that the trend is negative despite of the positive values of the first surveys in 2008, 2010 and 2011.

The depth evolution in the MBES covered area is calculated separately for the area where the extraction is effective (EMS>0) and for the area without extraction (EMS=0). Although the depth differences in the extracted area are more negative, both areas provide similar trends (Figure 34). The trend of the depth differences in the area without extraction (EMS=0) is subtracted from the overall trend on the entire covered area. Based on this resulting "corrected" trend, the volume associated with the depth difference becomes comparable with the total extracted volume along the DECCA lines: 1.4 $10^6 m^3$ for the MBES based volume for the most recent survey, and 1.8 $10^6 m^3$ total extracted volume from EMS data in the same area. The thus calculated "corrected" values result in a smooth and gradually dipping curve (Figure 34), quite well correlated (R-squared = 0.99) with the extracted volumes. This could be described as the basic impact of extraction without the underlying general trend.

From one survey to another, the established average depth differences on the non-extracted areas (EMS=0) are not constant and could be the result of different factors that justifies this trend correction:

- An offset between the surveys models and the reference model due to systematic uncertainties (draught is the most obvious source of uncertainty) for both models. As stated previously (see bathymetric data quality control and uncertainty), a comparison between of the GPS RTK Ellipsoid correction with the traditional draught/tide correction demonstrates a shift of 0.29m of the mean depths resulting from the two corrections.
- Dispersed impact of human activities in the area. Most plausibly sand extraction, but others like fisheries and wind mills can't be excluded.

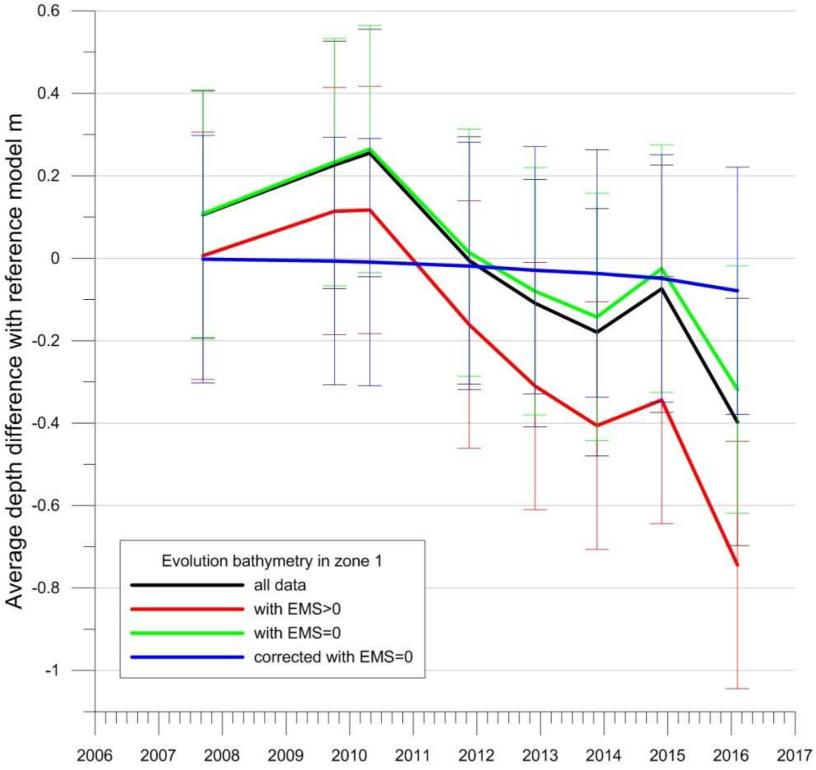

Figure 34: Bathymetric evolution along DECCA lines in zone 1.

Zone 2

The results for zone 2 are very similar. The most recent survey on zone 2 dates from the same period as zone 1: the beginning of 2016. Qualitatively the relation between the MBES measured differences (Figure 35) and the thickness of the extracted sand layer (Figure 36) is clear.

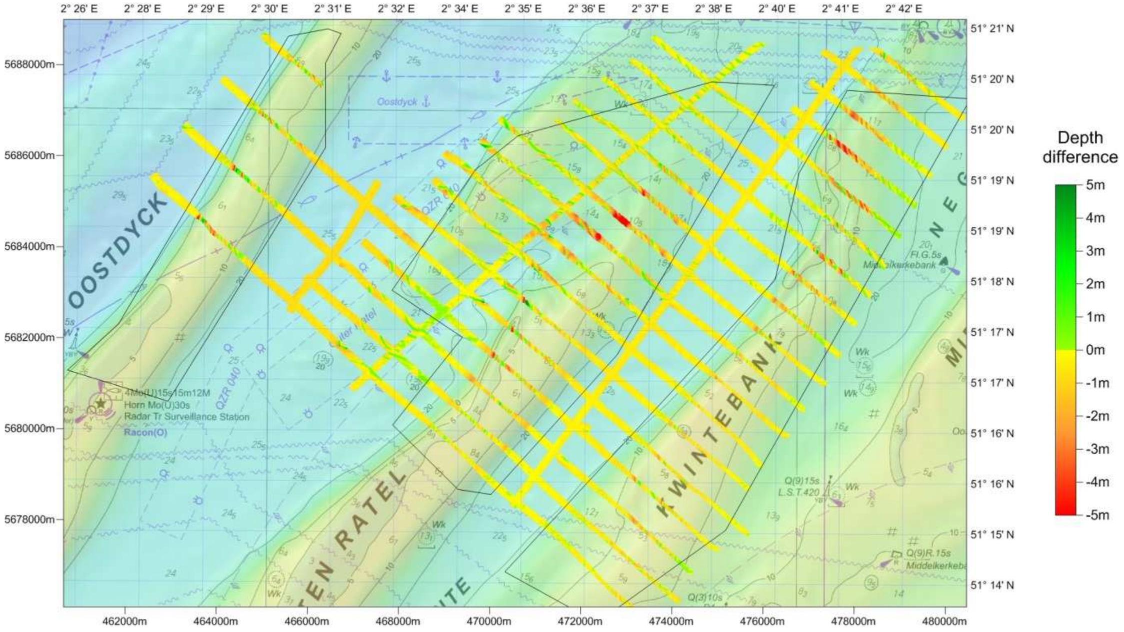

Figure 35: Measured depth difference between the most recent DECCA survey (Belgica EM3002d c1608 - 22/02/2016) and the reference model for zone 2.

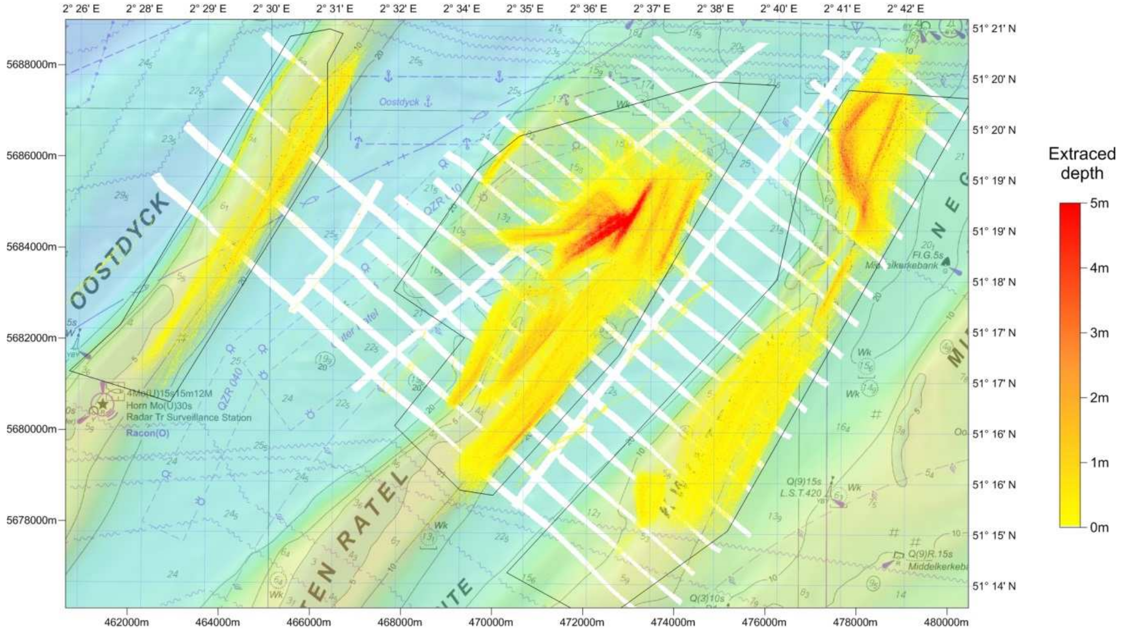

Figure 36: Extraction depth between 22/02/2016 (Belgica EM3002d c1608) and 2003 (reference model for zone 2). The part of the MBES covered area along the DECCA lines with no extraction is shown in white.

But again, an almost uniformly negative depth difference (average value of -0.42m for the entire covered area) is observed, and the volume associated with the measured depth difference (13.3 $10^6 m^3$) largely exceeds the total extracted volume along the DECCA lines (3.2 $10^6 m^3$). As above, the only positive depth differences are due to the movement of large sand dunes on the Kwintebank, Oostdyck and especially the Buiten Ratel. The negative trend is not limited to the sand banks, but is apparent in the swales between Kwintebank, Buiten Ratel and Oostdyck.

In the analysis of the evolution on the Kwinte reference area (see figure 8), this negative trend was not observed. The Kwinte area is covered by at least one of the DECCA lines, suggesting offsets between the DECCA surveys and the full coverage surveys of this area. Since the full coverage surveys only occasionally took place during the same Belgica campaign (Figure 7), systematic errors could explain the difference in the observed trend.

Although the surveys along DECCA lines in zone 1 and 2 rarely coincide during the same campaign, the average measured depth difference of the consecutive surveys (Figure 37) provides a very similar evolution. Before 2011 the trend seemed positive, but the more recent surveys lead to an overall negative trend. Again the evolution inside and outside the extracted areas (EMS>0 and EMS=0) is almost identical. The volumes calculated for the MBES models and EMS models are totally different. The MBES volumes corrected with the offsets with no extraction (EMS=0) result in comparable volumes: 3.2 10^6m^{3}total extracted volume in the covered areas and 2.6 10^6m^{3}calculated MBES measured volume difference (numbers for the most recent survey). The resulting “corrected” curve (blue line on Figure 37) shows a gradual deepening and is well correlated (R-squared = 0.90) with the extracted volumes.

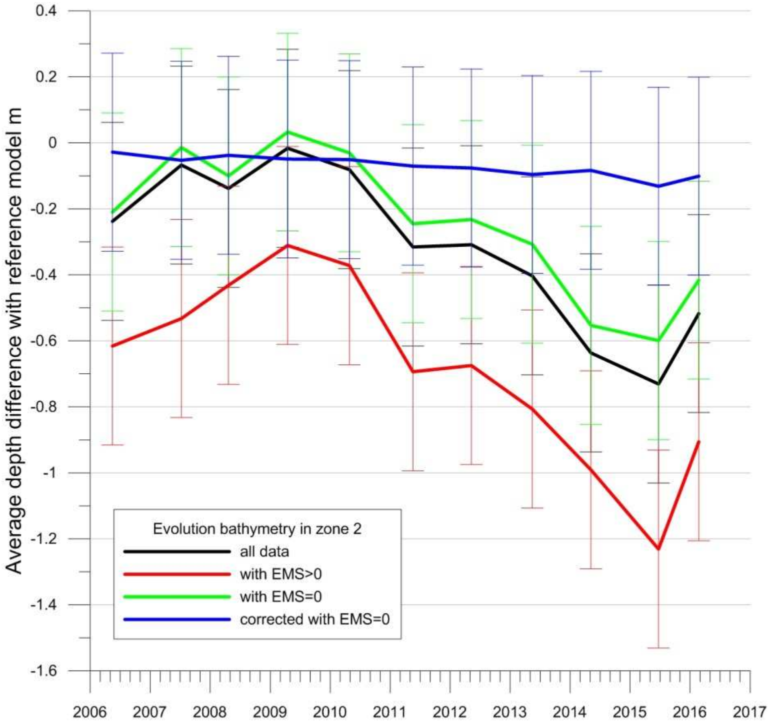

Figure 37: Bathymetric evolution along DECCA lines in zone 2.

Zone 4

The time series on the Hinderbanken is less furnished then the ones on zone 1 and 2. The results however are similar. The average difference between the surveys and the reference surface is always negative and varies around 0.2 to 0.3m (Figure 38). Since the extraction only started in 2012, the first survey at the end of 2011 should have no offset with the reference surface. A systematic error on the reference model could explain the observed offset of app. 0.2m. Without the average offsets on the areas with EMS=0 (no extraction), the measured depth differences coincide very well with the extracted volumes.

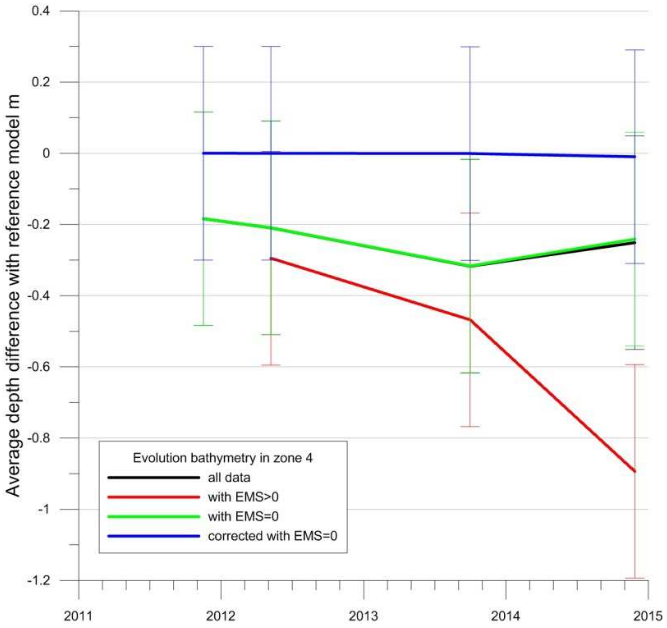

Figure 38: Bathymetric evolution along DECCA lines in zone 4.

A closer look on the values on the areas with extraction (EMS>0 on figure 38) illustrates a big difference with zone 1 and 2. The comparison between the extracted volumes and the volume differences measured with MBES shows a ratio of almost one to one (Figure 39). This good correlation can be explained by the nature of the extraction on zone 4: it is concentrated on one area (HBMC, see above), which makes up for only a very small part of the DECCA surveys. The very high values on a small surface drastically reduce the impact of relatively small offsets (on the much larger surface of the entire DECCA survey this shift is translated in very large volumes). The same offset (of 0.2 – 0.3m) could explain the vertical offsets between the curves on figure 19. This suggests that the offset would be primarily due to a systematic error on the reference model for zone 4.

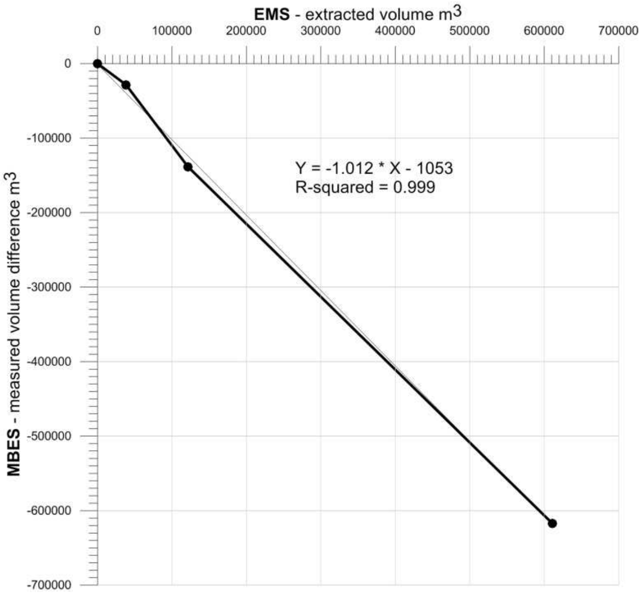

Figure 39: Correlation between MBES measured volume differences and the extracted volumes on the areas of the DECCA surveys on zone 4 with extraction (EMS>0).

Correlation with EMS

Figure 40 shows the correlation of all the volume differences on the DECCA surveys (zone 1, 2 and 4) with the extracted volumes. The volumes on extracted areas (red curve) have a good correlation, but the measured volume differences exceed the corresponding extracted volumes (Y=-1.43X). As discussed before, this is most likely principally the result from offsets on the models. If we eliminate these offsets (blue curve), we get an even higher correlation (R2=0.984). The volumes from EMS are now higher than the volumes measured with MBES (Y=0.847X). This result can be either due to an overestimation of the extracted volumes (see above), a net influx of sediment, a redistribution of sediments in the extraction sectors (Terseleer et al., 2016) or a combination of these factors. A net influx of sediment has never been observed on the evolution of the monitoring areas and seems unlikely. The discrepancy between the EMS data and the registers will be investigated in detail (see above). Based on this outcome a clear conclusion can be drawn.

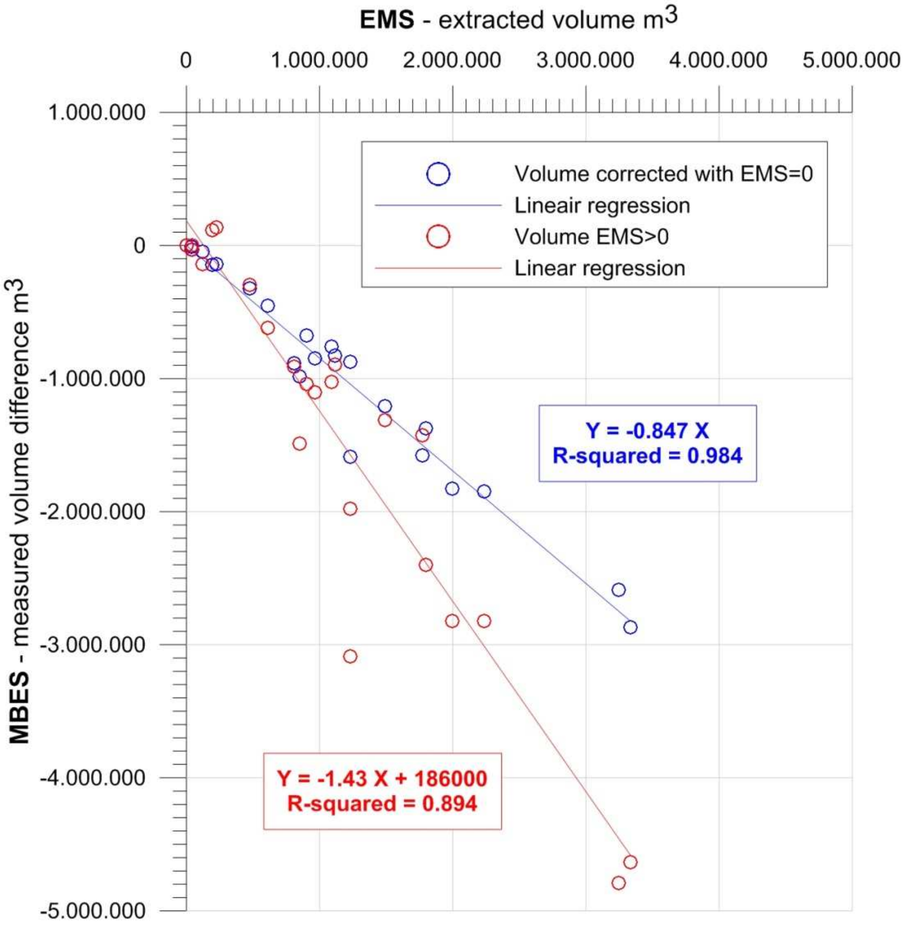

Figure 40: Correlation between MBES measured volume differences with the reference model for all DECCA surveys and the extracted volumes during the same time period and on the same area.

Conclusions

The combined use of registers and EMS data allows a spatial and temporal perspective view of the sand extraction in the Belgian part of the North Sea (BPNS). The last four years have been marked by the large volumes of sand extracted for the "Masterplan Kustveiligheid". The volume of sand extracted for industrial purposes shows a marked increase that represents a growth of 50% in 3 years. However, the most striking feature of the last 10 years is the steady, almost linear growth of the volume of sand discharged in ports of neighboring countries. The cartographic and statistical analysis of EMS data makes it possible to sketch the evolution of sand extraction in the BPNS from 2003 to 2016. Three successive overlapping phases can be distinguished, demonstrating the ability of the sector to adjust to the changing legal boundaries and to the closure of areas where the extraction level has exceeded the current legal limit.

The BPNS is a small space that combines many activities. For the sand sector, such a context implies a strong spatial pressure linked to the need to share the available space with the others actors working in the BPNS. For the sand sector, rather than the extraction itself, it is essentially the spatial pressure combined with the environmental constraints that controls the level of legal useful reserve of sand.

Since 1999, MBES technology, providing simultaneously bathymetric and backscatter data, is used by the Continental Shelf Service to carry out the monitoring of the impact of the sand extraction on the seabed. Most of the data has been acquired with the EM3002d installed on the RV Belgica in 2008. In 2016, in order to compensate as much as possible the non-availability of the RV Belgica, some surveys were carried out with the RV Simon Stevin EM2040. The data from the different MBES’ can be combined for the bathymetric analysis. For the backscatter analysis, only the RV Belgica EM3002d dataset is used to ensure a strict comparability along the time series.

For its entire 75° swath, the EM3002d has been certified in June 2010 and 2015 by the “Service Hydrographique et Océanographique de la Marine” (France) as compliant with the International Hydrographic Organization S44 Special Order specifications. Taking into account the differences between conventional depth measurements (DGPS, draught and tide correction) and GNSS RTK corrected depths, a global uncertainty of ± 0.3m is considered for all RV Belgica EM3002d surveys. Using the backscatter as a proxy of the seabed interface in a monitoring program implies a full control and stabilization of the acquisition parameters of the MBES on board the vessel and the absolute correction for MBES specific factors. The establishment and use of a standardized backscatter processing method which does not introduce any “a priori and local compensation” makes it possible to rigorously compare the evolution of the average backscatter levels over time. Bathymetric and backscatter time series acquired on the Kwinte area demonstrate its relevance as a reference area for the hydrographic quality control, the control of the repeatability of the backscatter and the comparison between different MBES’.

The monitoring of the sand extraction is organized through successive MBES surveys on monitoring areas located in the extraction sectors and along the DECCA reference lines across the sandbanks. Both are carried out at medium to long term time scales (months to years), to assess the direct impact of extraction at the local level on the most extracted areas, as well as the impact on a wider scale with surveys incorporating areas with and without extraction.

At a local scale, the bathymetric time series on S1a-Thorntonbank, S4c-Ooshinder and S2br-Buiten Ratel, confirm the strong correlation between the depth decreases measured by MBES and theirs estimations from the EMS volumes. The decimeter differences between the approaches can be related to the uncertainty introduced by the depth correction methods and by the volume estimation from the EMS data. This approach by comparing new measurements with a reference model based on MBES data mainly acquired between 2000 and 2006, reaches its limit of resolution.

On the Thorntonbank TBMAB and Oosthinder HBMc monitoring areas, the backscatter time series demonstrate a modification of the seabed nature caused by the extraction. At different scales and depending on the initial seabed stratification, the increased density of the dredging grooves, the concentration of the coarse shell fraction by screening, and the removal of a surficial sediment layer can combine to progressively modify the average backscatter level during the extraction period. The bathymetric and backscatter time series of the 2 Kwintebank central and north areas and of the central part of the Buiten Ratel demonstrate their relative stability after their closure to extraction. No significant accretion neither erosion is observed on the 3 areas. The lack of restoration confirms the non-renewable nature of the sand resource over decades.

The measured volume differences on the DECCA surveys and the extracted volumes on the same area are well correlated. However, a trend is observed on all zones that is independent of the level of extraction. This trend causes an offset between the measured volume differences and the extracted volumes. This is most likely the result from systematic errors on the models. Without this offset the extracted volumes are now higher than the volumes measured with MBES, either due to an overestimation of the extracted volumes, a redistribution of sediments in the extraction sectors, or a combination of these factors.

Despite a high level of extraction in recent years in sectors S1a and S4c, both on local and large scale, the bathymetric monitoring demonstrates that the bathymetric level is still far from having reached the legal limit of 5m. The continuation of the sand extraction in these sectors is still possible in short term if the level of extraction remains comparable to the present one.

An improvement of the bathymetric measurement precision and an uncertainty assessment on the volume estimation from EMS data is mandatory to better understand the correlation between the extraction and the bathymetry at a decimeter level. Better still, the reference model of extraction sectors should be updated from rigorous bathymetric surveys using the GNSS RTK correction.

Acknowledgements

The crew of the RV Belgica is thanked for the numerous campaigns dedicated to MBES data acquisition. 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 RV Belgica. The VLIZ and the crew of the RV Simon Stevin are acknowledged for the providing of ship time, the organization and the excellent execution of the campaigns. The colleagues from ILVO, BMM and OD Nature are thanked for the collaboration in the establishment of a balanced and all-embracing monitoring program.

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The Electronic Monitoring System (EMS) as a minimum requirement for monitoring the extraction of an increasingly scarce raw material

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Introduction

This contribution outlines the Electronic Monitoring System (also referred to as EMS, black box or automatic registration system), its renewal in 2014, the obtained data results since its introduction as well as possible future improvements of the system.

1. History and evolution of the Electronic Monitoring Systems

Sand extraction in the Belgian part of the North Sea started in 1976. As a result of the Royal Decrees of 1996 and later, the EMS was introduced in 1996 and installed on dredging vessels to record and control the sand and gravel extraction activities in the Belgian part of the North Sea. Over the years, the legislation and agreements concerning EMS obligations improved which resulted in a complete EMS-dataset from June 2002 onwards. From 2006 onwards, extraction activities for the protection of the Belgian coast are also being monitored by this EMS.

Since 2014, the new EMS (the EMS 2.0) with remote data-transfer capabilities is being installed to replace the obsolete EMS 1.0 and to allow a more frequent follow-up of the correct functioning of the recording devices. The main advantages of the new system are: remote data transfer, remote configuration changes, automatic alert messages and local keyboard input for the obliged parameter ‘declared load’ (see Fig. 1). As a result of this renewal operation, the percentage of missing data could be further reduced to around 0% during the last 3 years.

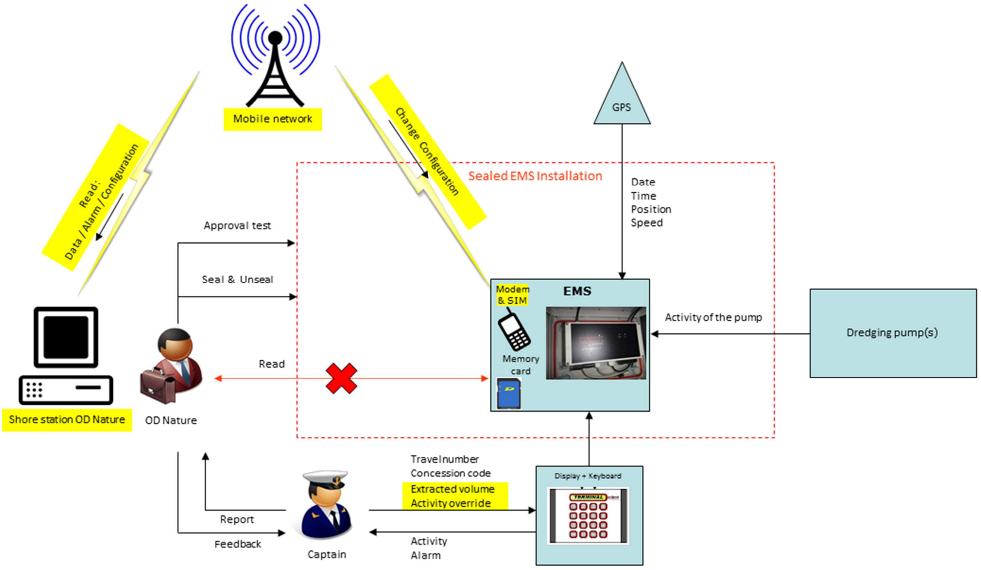

Figure 1: Schematic overview of the EMS 2.0 and the interaction with the system. The changes relative to the EMS 1.0 are marked in yellow.

2. Principle of the Electronic Monitoring Systems

The obligation to install an EMS, in accordance with specific technical requirements, on dredging vessels is bound to a concession to verify whether certain conditions of the concession are respected, i.e. permitted areas, minimum average speed during extraction and, if necessary, to verify the minimum distance between multiple extraction vessels. The presence of an EMS on the dredging vessels is additionally controlled by the Aerial surveillance team of RBINS-OD Nature-MUMM (SURV), which observes and reports the activities of dredging vessels.

Figure 2: Aerial surveillance: a. A dredging vessel extracting in sector 1a ; b. Fully loaded dredging vessel returning from sector 1a

Figure 3: An installed EMS 2.0 system and its sensors

The closed and sealed system automatically records, among others, the following parameters: identification of the vessel, the code of concessionary, the date and the time, the geographical position, the speed, the status of dredging pump(s) and finally the dredging activity.

The recorded and processed EMS data provides one of the main sources for the continuous monitoring of sand and gravel activities in the Belgian part of the North Sea. Other sources include data derived from the registers and from regular bathymetric, hydrodynamic and sediment transport surveys performed with e.g. the RV Belgica. The processed EMS data also gives an indication for the volume that has been exploited and allows to follow-up the evolution in space and time of the extracted volumes.

The EMS has the following benefits: low cost, easy to install and maintain with 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 through shape files) straightforward. In addition, the recent upgrade to the EMS 2.0 (2014) greatly reduces the chance of data loss and also allows for a better follow-up of the system's functioning as well as faster and more regular data processing intervals. Ad-hoc data processing on request is also possible and has proved its value already.

3. Data processing procedures

The EMS data records (both from the old and new systems) allow for an estimation of the sand extraction intensity, in particular the volume extracted by the dredging vessel per time frame by using either the declared load (available since 2014 based on the information entered by the crew) or the known fixed loading capacity (available since June 2002) (see Fig. 4). This enables the final data table to be used to represent the extracted volumes in space (grids of 100m x 100m) and time (overviews per year).

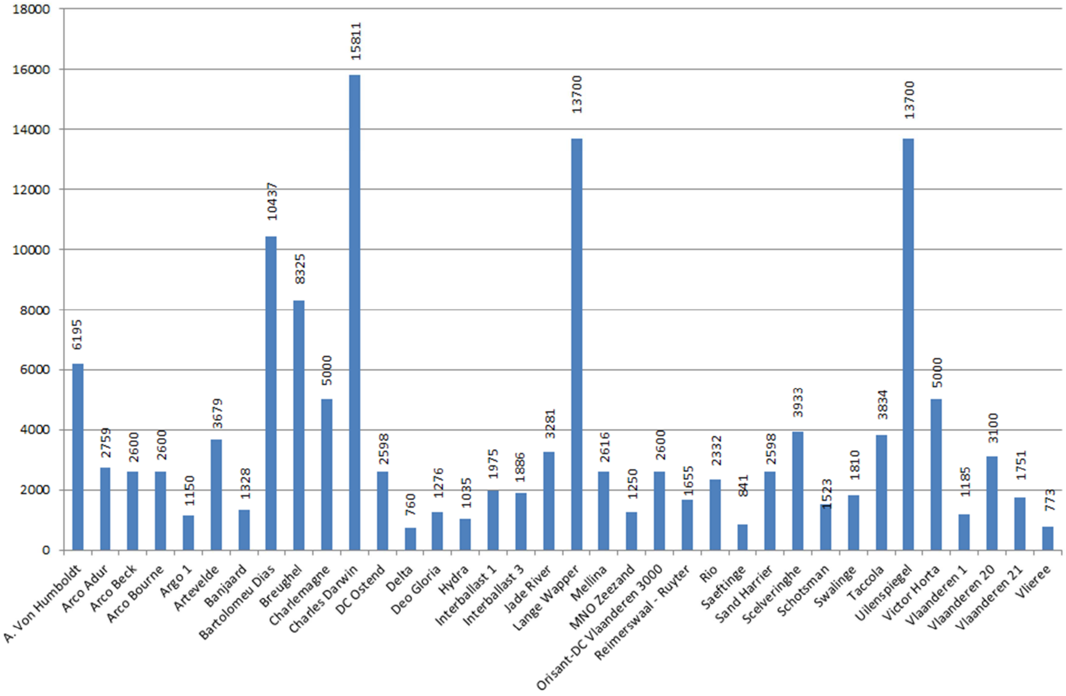

Figure 4: Overview of the used fixed loading capacity (m³) (specified by the concessionaire or calculated as average of the declared extracted volumes) of the vessels (ever) equipped with an EMS.

A comparison between the annual extracted volumes, on the one hand based on the vessels fixed loading capacity and the number of trips recorded and on the other hand on the reported volumes and the number of trips from the registers indicates an increasing difference between both (Roche et al., this volume). A detailed analysis and cross check of the EMS database with the ship registers is carried out to identify the causes. However, a determination of the extracted volumes was never a design requirement of the Electronic Monitoring System.

4. EMS statistics

Based on all available EMS data and the above described method (making use of the vessels fixed loading capacity), the cumulative extracted volumes are presented as an annual overview in figure 5 (2003-2016) and as a geographical distribution (100 m x 100 m grids) in the figures 6 to 8 (2016-2014). For the geographical distribution of the EMS data for the period before 2014, reference is made to the conference proceedings of the previous study days of October 2014 and October 2011.

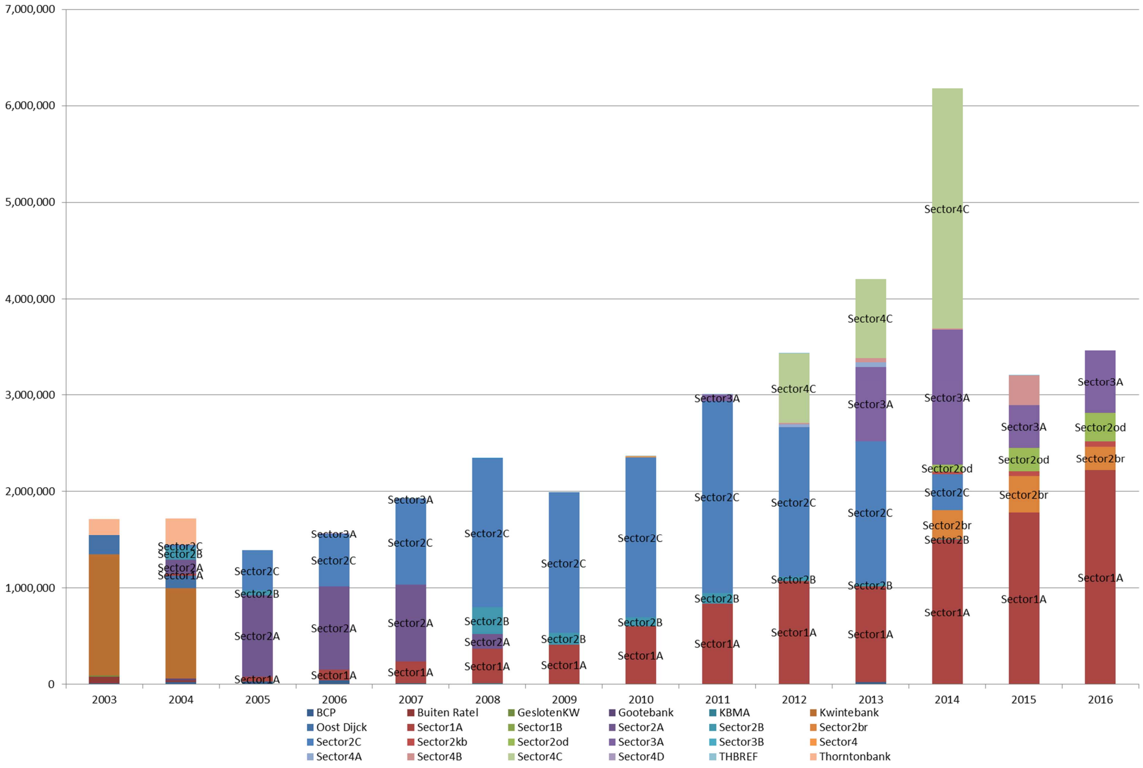

Figure 5: yearly extracted volumes (m³) versus sector

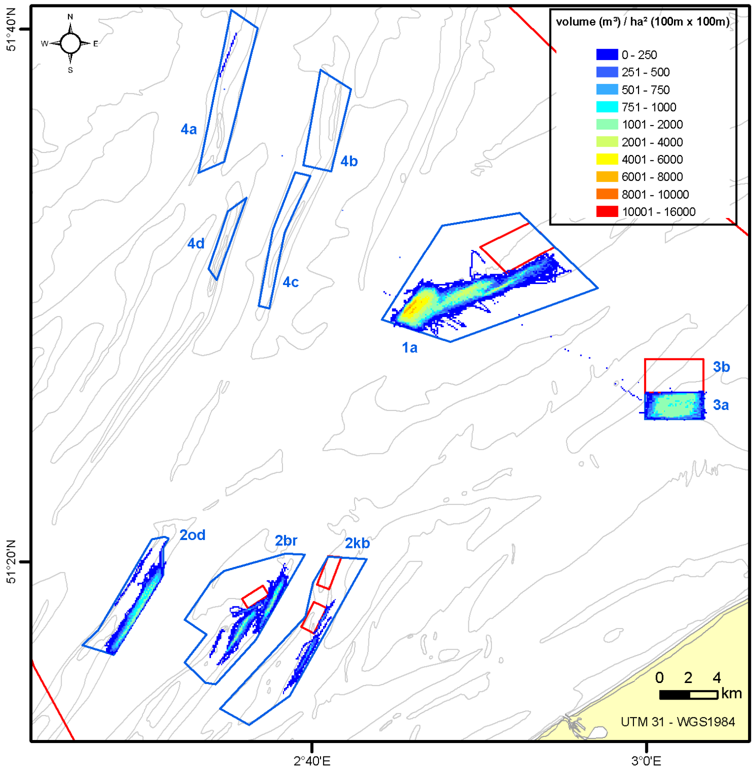

Figure 6: geographical distribution of the cumulative volumes (m³/ha²) for 2016

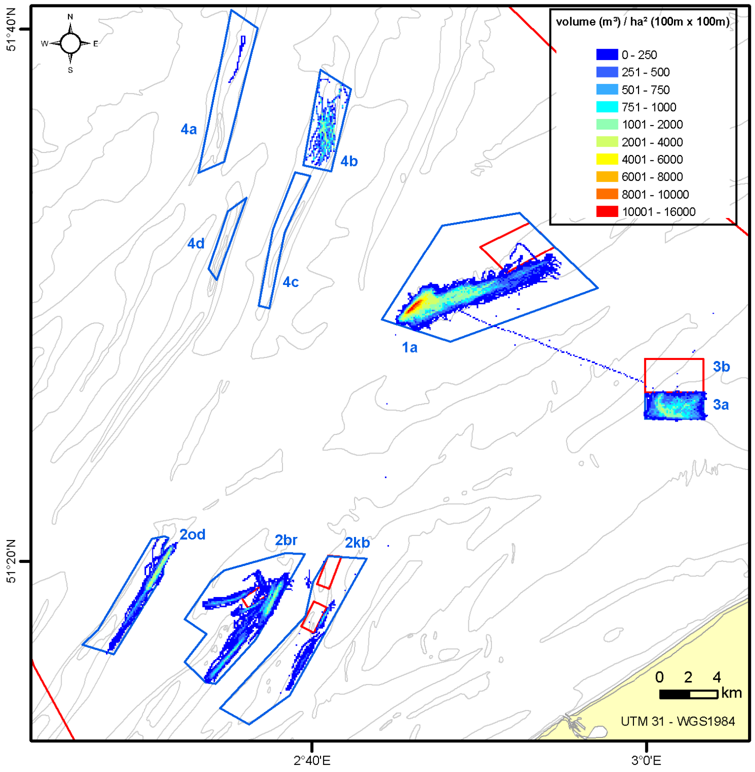

Figure 7: geographical distribution of the cumulative volumes (m³/ha²) for 2015

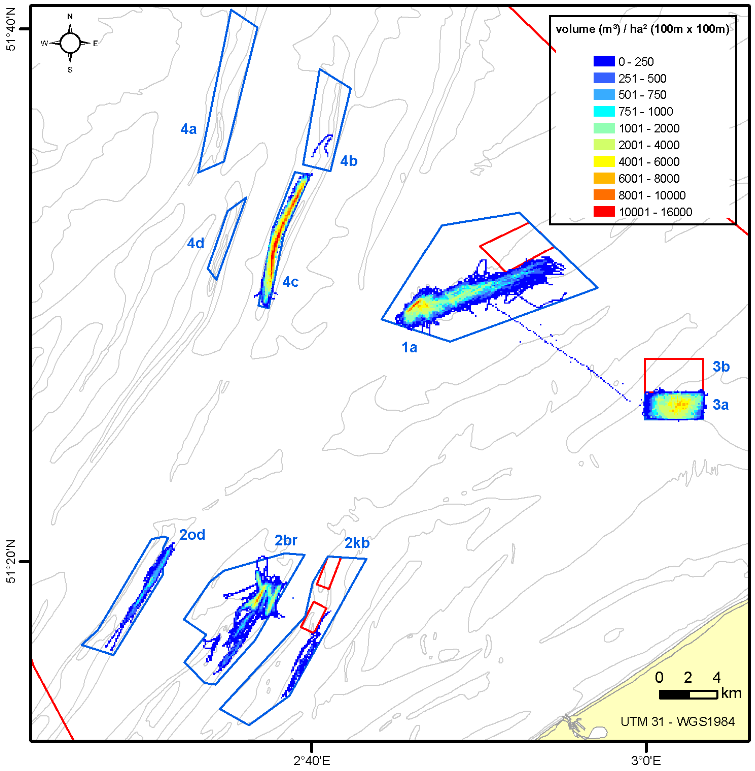

Figure 8: geographical distribution of the cumulative volumes (m³/ha²) for 2014

5. Possibilities for improvement

The monitoring of the bathymetric evolution of the sand extraction areas, with e.g. RV Belgica, is performed with increased accuracy. This is the result of the introduction of new devices, i.e. on RV Belgica a multibeam echosounder system Kongsberg EM3002D as well as a new single beam echosounder system Kongsberg EA400 was installed in 2009 and a new Septentrio RTK GNSS receiver with heading option was installed in 2014. The evolution to be able to measure with higher accuracy and resolution will continue in the near future with newly available devices on the planned new Belgian research vessel. The new research vessel will be taken into service in the second half of 2020.

Based on the monitoring results, there is a linear correlation between the extracted volumes and the bathymetric evolution (Roche et al, 2014). However, when EMS data of one extraction activity is compared with bathymetric data (traces of one sand extraction journey), a position shift is determined (Roche et al., 2015). Improving EMS-data by entering a correction for the GNSS-antenna – dredge head offset could be considered in the future to compensate for this inaccuracy.

Another missing functionality in the current EMS-system is the lack of sensors to determine the effective load (through measurements of density, ship weight and hopper capacity). These measurements could allow a check on the declared load and would provide more certainty about the actual extracted volumes.

The above proposed improvements will definitely make the system more complex, more expensive and they would require regular calibrations. Moreover, automatic measurements of the hopper capacity are complex and not as accurate for sand loads (technical dossier BIS, 2006, Flemish government). For this kind of upgrade, a cost-benefit analysis is definitely needed. Due to the recent renewal of the EMS system, a new upgrade is currently not on the agenda.

Conclusion

The regulations for the EMS obligation have made it possible over the last 15 years to make a reliable analysis of the extraction activities, both in space and time, based on the extracted volumes derived from EMS data. This dataset is used as one of the main sources for the continuous monitoring of sand and gravel activities in the Belgian part of the North Sea. The recent upgrade to the EMS 2.0 (2014) allows for a better follow-up and more regular data processing. Further improvements of the EMS system are complex and are not being planned for the moment.

Acknowledgements

The colleagues from the Continental Shelf Service are thanked for the very constructive cooperation.

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Ecological assessment of intense aggregate dredging activity on the Belgian part of the North Sea

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Abstract

Yearly around 3 million m³ of marine sand is extracted in the Belgian part of the North Sea (BPNS) both for construction purposes and coastal protection. Benthic monitoring is undertaken on a yearly basis to evaluate the potential effects of aggregate dredging on the soft sediment benthic ecosystem. During the past three years, monitoring effort has mainly been focused on the areas that are or have been most intensively dredged: Buiten Ratel (zone 2br), Thorntonbank (zone 1) and Oosthinder (zone 4c).

Closure of the most intensively dredged area of the Buiten Ratel in January 2015 (BRMC) did not alter sediment composition nor the macrobenthic community to pre-dredging conditions, two years after cessation of dredging**.** The increased percentages of shells (>1600 µm) and very fine sand (63-125 µm), as a result of the intensive dredging activity in previous years, persisted, whichsupports the survival of the heterogenic, dynamic community that was established during dredging. A peak of the early coloniser *Spiophanes bombyx* was observed, which is most probably related to the cessation of dredging.

The increased dredging on the western part of the Thorntonbank in the past years, created a local new 'biodiversity hot spot' on the Thorntonbank. The dredging induced mixed sediments with presence of mud/very fine sand, which attracts macrobenthic species that are typically correlated with fine sands in addition to the coarse sand *Ophelia* habitat species. This is a very similar pattern as was observed on the 'extraction hot spot' of the Buiten Ratel (BRMC).

Surprisingly, peak extraction on the Oosthinder in 2014 did not invoke significant sediment changes. Also, the number of macrobenthic species, nor the density or benthic community structure did change (yet), although a very high amount of sand was extracted at this site. Most probably, the extraction period was too short to lead to similar changes as noted on the Buiten Ratel and Thorntonbank.

Introduction

Yearly around 3 million m³ of marine sand is extracted in the Belgian part of the North Sea (BPNS) both for construction purposes and coastal protection. Dredging for marine aggregates inevitably results in disturbance of the seabed and it's biological habitats. Dredging impact on the seabed is both direct e.g. through removal of sediments and indirect e.g. through deposition of sediment plumes (Tillin et al. 2011). Furthermore, many studies have shown that marine aggregate dredging has the potential to change the composition of seabed sediment habitats (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). Hence, the focus for our study on the benthic habitat.

For many years, ILVO conducts benthic monitoring aimed at evaluating the potential effects of aggregate dredging on the soft sediment benthic ecosystem. Since 2010, sampling has intensified and the sampling strategy was adjusted by allocating more reference stations (De Backer et al. 2011). Aggregate dredging in the

BPNS is restricted to four dedicated zones as cited in RD 19 April 2014 and the Marine Spatial Plan RD 20 March 2014. Control on the dredging activities is done by means of an Electronic Monitoring System (EMS, the black-box) on board the extraction vessels. During the past years, biological monitoring effort has mainly been focused on the areas that are most intensively dredged according to EMS data.

EMS data showed that since 2009, extraction intensified on the central part of the Buiten Ratel sand bank (BRMC area). Between 2010 and 2014, the BRMC area was the 'hot spot' of extraction activities on the BPNS with yearly extracted volumes upto almost 1.9 million m³ (Degrendele et al. 2014). These high extraction volumes changed the sediment composition in the area to mixed sediments, as such creating a heterogenic habitat with a mixture of coarse and fine sand species (De Backer et al. 2014a, De Backer et al. 2014b). The 'hot spot of extraction' was found to be as well a 'hot spot of biodiversity' with high macrobenthic species numbers and densities. However, the high degree of extraction caused a 5 m deep depression in the area, and as a consequence the area was closed for extraction in January 2015 (Degrendele et al. 2014, Roche et al. 2017, this volume). Benthic monitoring inside the area continued after closure of the area in order to investigate whether the closure of the area had an immediate effect on the rich benthic habitat that was established during dredging.

Due to closure of the BRMC area, dredging activities gradually shifted from the central part of the Buiten Ratel towards the Thorntonbank (zone 1). EMS data showed a big increase from 2014 onwards, with 1.8 million m³ extracted in 2016. Dredging on the Thorntonbank is mainly concentrated on the western part (Vandenbranden et al. 2017, Roche et al., 2017, this volume). Upto 2013, the benthic ecosystem was not affected as there was only a low degree of dredging activity on the Thorntonbank (De Backer et al. 2014a). To find out whether the increased amount of dredging had an effect on the benthic ecosystem, we intensified the benthic monitoring on the Thorntonbank during the past years.

Furthermore, aggregate dredging for coastal protection increased steeply after the start of the Master Plan Coastal Safety, approved by the Flemish government in 2011 (Van Quickelborne 2014). For this plan, at least 20 million m³ of sand is needed to protect the Belgian coastline against extreme storm events at a 1:1000 years return period (Mertens et al. 2011). In order to be able to cope with these huge amounts of sand, a new concession zone on the Hinderbanken was agreed upon (zone 4). Since 2012, sand for some huge beach nourishment projects originates from zone 4, and more specifically zone 4c on the Oosthinder. The dredging activity in area 4c is mostly concentrated in relatively short time periods, since it is in function of beach nourishments. However, in these short time intervals, large volumes are extracted with a total of 2.5 million m³ extracted between January and June in 4c in 2014. This peak extraction was the biggest ever on the BPNS (Van Lancker et al. 2016), and thus it was important to evaluate the ecological benthic impact of such a short-term, but huge extraction event.

The benthic monitoring and subsequent data analyses for this report focussed on the following research questions:

1) What is the effect of the closure of the BRMC area (zone 2br) on the 'benthic biodiversity hotspot' that was created during intensive dredging?
2) How is the benthic ecosystem on the Thorntonbank (zone 1) affected by the increased dredging activity?
3) Did the short-term huge dredging activity in 2014 affect the benthic ecosystem of the Oosthinder (zone 4c)?

Material and methods

This study focusses on the three most used aggregate dredging areas in the period 2010-2016 on the Belgian part of the North Sea (BPNS): Buiten Ratel (zone 2 br), Thorntonbank (zone 1) and Oosthinder (zone 4c). For detailed info on extraction volumes and extraction history within these areas, we refer to Vandenbranden et al. (2017, this volume) and Roche et al. (2017, this volume).

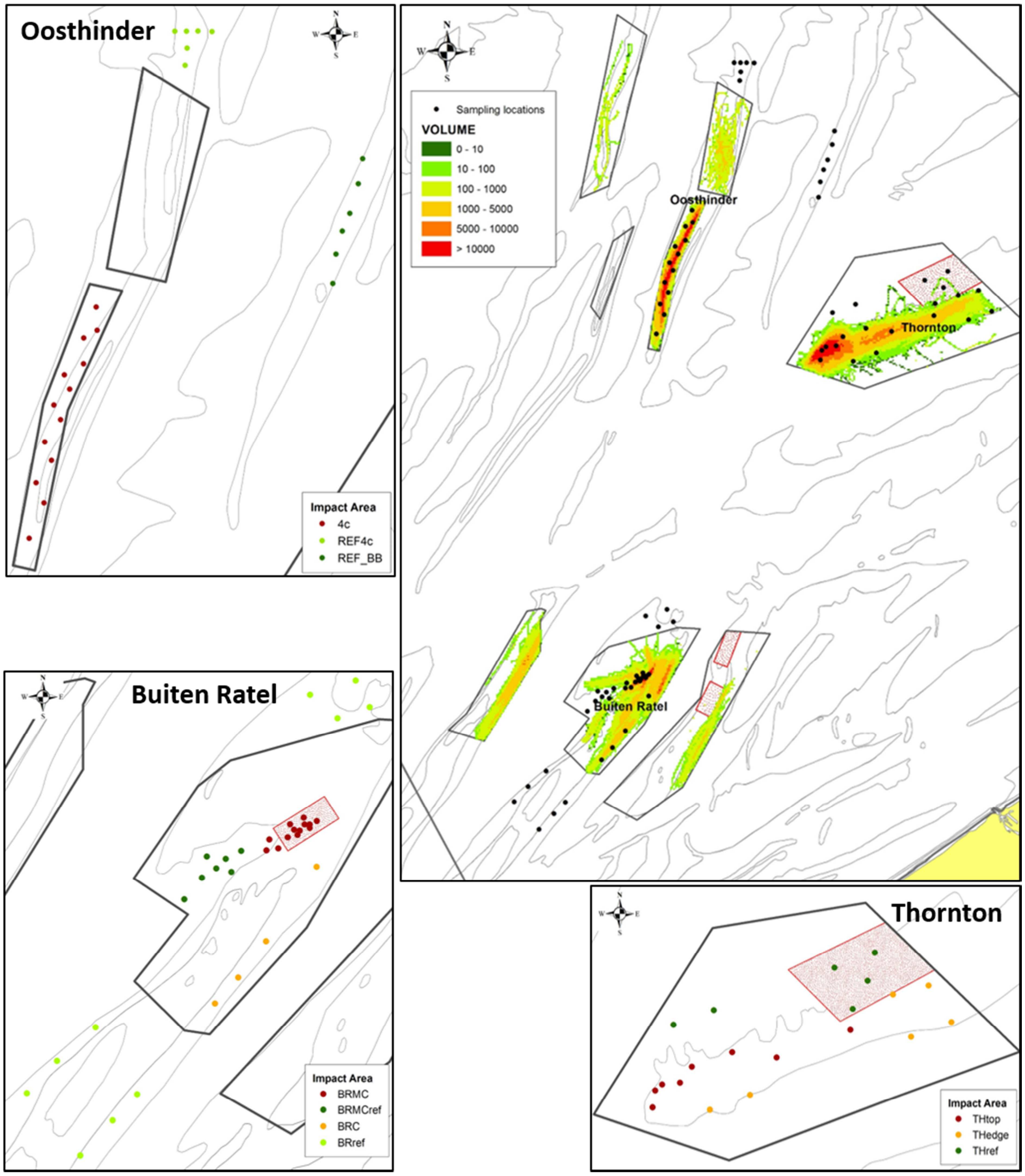

Figure 3: Map of aggregate concession areas on the BPNS with extracted volumes (m³/ha) based on black box data over the period 2013-2016 and biological sampling locations (top right). Detailed figures show impact and reference areas within each concession area.

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 an ecological impact assessment (Figure 3). Within the different concession zones, samples were allocated within different impact areas based on dredging pressure (e.g. on the Buiten Ratel, BRMC samples with high dredging pressure and BRC samples with lower pressure), and within different reference areas based on the location of the reference samples (e.g. REF4c samples on Oosthinder sand bank and REF_BB samples on Bligh Bank). In Table 1 and Figure 3, an overview is given of the different impact areas per study site.

Sampling took place on board the RV Belgica, RV Simon Stevin and catamaran Last Freedom on a yearly basis between 2010 and 2016 in autumn (September/October) and at some occasions in spring (March) as well (see Table 1 for sampling times). 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 and on the Thornthonbank, samples from autumn 2004 have been included in the analyses (Table 1).

Macrobenthos was sampled by means of a Van Veen grab (surface area 0.1 m²), one Van Veen 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).

Data analyses

In total, 618 stations have been sampled in the period 2010-2016 (incl. 2004 for Thornton area) within the different concession areas. To determine dredging intensity at the biological sampling locations, real time coordinates of every sampling location were plotted in ArcMap 10. Around each location, a circular 50 m radius buffer was drawn. The shapefile with buffer locations and the 'black box' data were imported in R 3.0.2 (R Core Team 2013) to calculate the cumulative extracted volume within the buffer area (surface area 8000 m²) in the year prior to biological sampling. Thus, dredging intensity used throughout this manuscript refers to volumes per surface area of 8000 m² per year (the year prior to biological sampling), unless mentioned otherwise.

Species richness (S), density and biomass were calculated for every macrobenthos sample using PRIMER v6 (Clarke and Gorley 2006). Spearman rank correlations were done between univariate measures, dredging intensity and sediment parameters to identify which univariate measures or sediment parameters were possibly influenced by aggregate dredging.

First, we tested a three-factorial Permanova design with factors 'year', 'season' and 'impact' to test for differences between seasons. When 'season' was significant, further analyses were done on each season separately (only autumn data are presented in this case).

To test for dredging effects, we used a two-factorial permanova design with factors 'year' and 'impact' on an Euclidean distance resemblance matrix for univariate parameters (species number, density, biomass and sediment variables) and on a Bray-Curtis resemblance matrix for community structure. This was done for each concession zone separately. The primary aim was to analyse interaction effects between 'year' and 'impact', since these would reveal whether the changes that occurred could be attributed to changes in the dredging pressure i.e. cessation of dredging in BRMC area, increased dredging on Thorntonbank or peak dredging on the Oosthinder. When a significant effect for the 'impact x year' interaction term was found, pairwise tests were conducted to test for differences between impact areas within each year or between years within an impact area. SIMPER analyses were done to find the species responsible for the observed changes.

Table 1: Overview of impact areas (with codes used throughout the manuscript) per concession zone and indication of sampling time. Au= autumn, su= summer and spr= spring.

Concession zone	**Impact area**	**Description**	**2004**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Buiten Ratel	BRMC	Most impacted area on BPNS until 2014, closed since January 2016		spr&au	spr&au	au	au	spr&au	spr&au	au
	BRMCref	Area with similar sediments as BRMC but without dredging		au	spr&au	au	au	spr&au	spr&au	au
	BRC	Area located to the SW of BRMC on the flank of the BR with lower dredging pressure		spr&au	au	au	au	spr&au	spr&au	au
	Brref	Reference area located outside the concession area both to the north and the south		spr&au	au	au	au	spr&au	spr&au	au
Thorntonbank	THtop	Impact area with high dredging pressure located on top of the bank, increasingly used since 2013	au	au	au	au	au	au	/	au
	THedge	Impact area with very low dredging pressure located at the edges of the bank	au	au	au	au	au	au	/	au
	THref	Reference area within the concession zone but without dredging pressure	au	au	au	au	au	au	/	au
Oosthinder	4c	Impact area used mainly for dredging for coastal protection with high pressure in certain periods		spr&au	au	spr, su & au	au	spr&au	/	/
	REF4c	Reference area in the north of the Oosthinder outside the concession area		spr&au	au	spr, su & au	au	spr&au	/	/
	REF_BB	Reference area on the Bligh Bank		spr&au	au	spr & au	au	spr&au	/	/

Relationships between the multivariate data cloud and environmental variables (grain size fractions, median grain size and dredging intensity) were investigated through DISTLM (Distance-based linear models) analysis using the BEST procedure 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.

All analyses were executed using Primer v6 with PERMANOVA add-on software (Clarke and Gorley 2006, Anderson et al. 2008).

Results and discussion

BUITEN RATEL

Dredging in sampling stations

Before closure of the BRMC area on the Buiten Ratel in January 2015, average dredging intensity ranged between 3260 m³ per year in 2010 and 5900 m³ per year in 2014 around the BRN stations (buffer area 8000 m²)(Figure 4). As such the area was disturbed by dredging activity on 40 to 70 days a year. After closure in January 2015, dredging activity ceased in the area of the BRNstations, hence the steep decrease in dredging intensity since end 2014 (Figure 4). Around the BRC stations on the Buiten Ratel, dredged volumes were much lower ranging between 64 m³ per year in 2015 and 785 m³ per year in 2014 (Figure 4), equivalent to a seabed disturbance on 1 to 13 days a year. In the BRC area, dredging decreased as well after the closure of BRMC, although the area is still open for extraction.

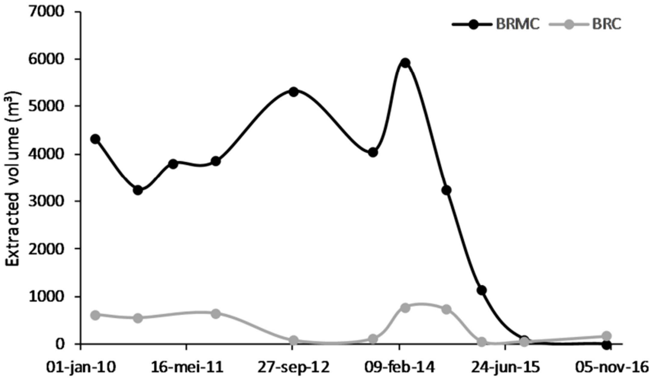

Figure 4: Average extraction volumes over time at the biological BRMC and BRC stations. Extraction volumes per year are based on EMS data, 365 days prior to the biological sampling date in a circular buffer area around the sampling location with a radius of 50 m (8000 m² surface area).

Sediment characteristics

Sediment composition was significantly different for the factor impact (p=0.0001), but it did not differ significantly over the years (p= 0.3), nor within the interaction term 'year x impact' (p=0.95). Especially, the very fine sediment fraction (63-125 µm) and the shell fraction (> 1600 µm) were significantly higher in the BRMC area compared to both reference areas (BRref and BRMCref) and the BRC area (pairwise tests, p<0.05) (Figure 5). Furthermore, both of these fractions were slightly positive correlated with dredging intensity, resp. r=0.29 and r=0.24. The higher percentage of both fine and coarse material were previously reported but sample number was too small at that time to allow for significant differences (De Backer et al. 2014a, De Backer et al. 2014b). The increased time series reconfirms, and strengthens the previous observations.

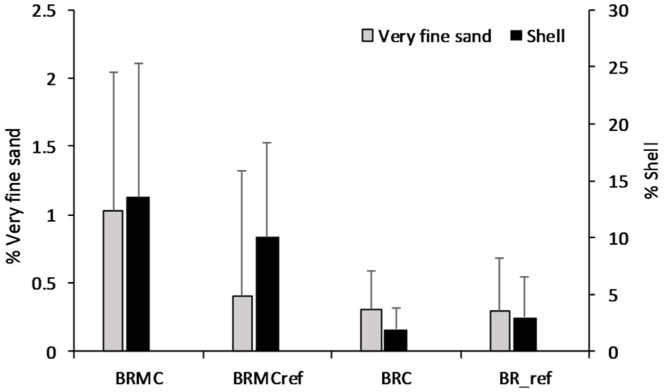

Figure 5: Average percentage very fine sand (63-125 µm, left) and shell (>1600 µm, right) for the different impact groups at the Buiten Ratel (average ± SD).

When zooming in on the BRMC area, sediment composition did not change significantly over the years (p=0.13). Also after the closure in January 2015, no changes have been observed. However, although not significant, we did observe a decreasing trend in median grain size of the sand fraction in the BRMCarea, especially during the years were aggregate dredging took place (Figure 6). This decreasing trend matches the decrease observed in back scatter values in the same area by COPCO (Roche et al. 2017, this volume).

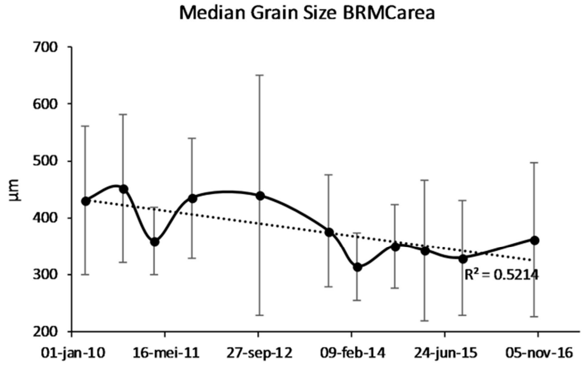

Figure 6:Time series of average median grain size of the sand fraction (± SD) within the BRMC area.

Ecological characteristics

As the ecological characteristics of both seasons differed significantly from each other in species numbers and densities, only autumn data are presented here, although overall spring patterns are very similar.

Species number S and density N differed significantly for factor 'impact' (both p=0.0001) and 'year' (resp. p=0.0019 and p=0.043), but not for the interaction 'impact x year'. Intensive dredging in the BRMC area positively affected both parameters S and N since pairwise tests showed that S and N were significantly higher in the BRMCarea compared to all other areas (Figure 7). The less intensively dredged area, BRC, did not differ significantly in S and N from the reference area BRref, indicating that dredging at intensities < 800 m^3 yr^{-1} did not affect the univariate parameters. For both parameters, interannual variation was observed with lowest S and N in 2011 for most areas (Figure 7). For biomass, only the factor 'impact' was significant with the highest densities in the reference area BRref, which is due to the higher presence of *Echinocardium cordatum* within these samples. Results for all three parameters are consistent with previous results reported in De Backer et al. (2014a).

Closure of the BRMC area in January 2015, did not cause changes in the observed univariate pattern for the years 2015 and 2016. Species number and density remained higher compared to the other areas after cessation of the dredging activity (Figure 7).

The multivariate species pattern was best explained by the environmental variables % medium sand, median grain size of the sand fraction, % shells, % very fine sand and dredging intensity, together explaining 25% of the observed variation (DISTLM, BEST-AICc). For multivariate species composition, a significant 'year x impact' effect was observed (p=0.0002). Within all years, BRMC differed significantly in species composition from the other areas BRMCref, BRC and BRref (pairwise tests within years p<0.05) (Figure 8). While BRC did not differ significantly in species composition from the reference area BRref in any year (pw test within years p>0.05) as shown by a high degree of overlap within the PCOplot (Figure 8). SIMPER analyses showed that BRC and BRref both belong to the *Nephtys cirrosa* community typical for medium sands (Van Hoey et al. 2004) characterised by *Nephtys cirrosa*, *Bathyporeia elegans* and *guilliamsoniana*, *Urothoe brevicornis, Spiophanes bombyx* and *Magelona johnstoni*. The BRMCref area is typical *Ophelia borealis* habitat characteristic for coarser sands (Van Hoey et al. 2004) with typical interstitial species. While BRMC is a mixture of species typical for *Ophelia borealis* and species characteristic for *Abra alba* such as *Kurtiella bidentata, Cirratulidae* sp.and *Lanice conchilega.* When looking between years within each zone (pairwise tests within 'year x impact' within impact), we found for BRC almost no significant differences between years, for BRMCref and BRC some years differed from each other, but many did not, while for BRMC most years differed significantly from each other. This large interannual variation within the BRMC area could be related to the higher degree of physical disturbance due to dredging within this area. The samples from the BRMC area taken after closure of the area clustered together with the samples of the area when dredging was still taking place, however they were dominated by *Spiophanes bombyx* and *Poecilochaetes serpens* (SIMPER), that is why they are on one side of the BRMC cluster in the PCOplot (Figure 8). For *P. serpens*, no ecological information is available, but *S. bombyx* is regarded as a typical 'r' selecting species with a short life span, high dispersal potential and high reproductive rate. It is often found at the early successional stages of variable, unstable habitats, and thus quickly may colonize an area following perturbation (Ager et al. 2005 and references therein).

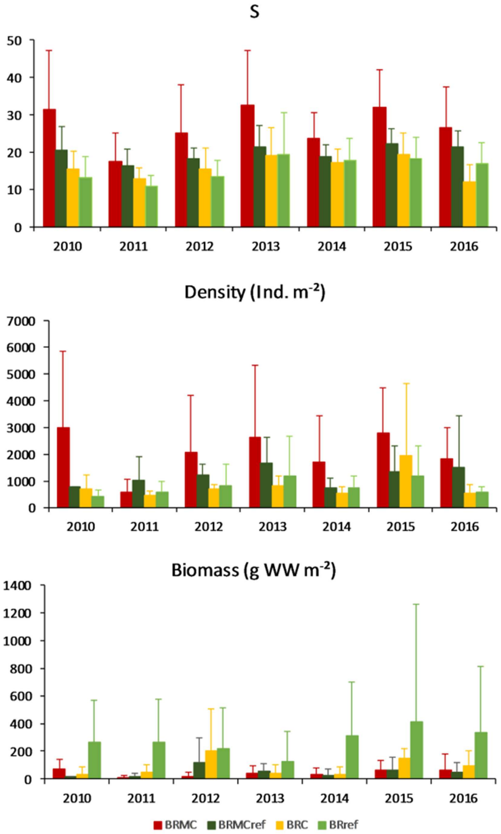

Figure 7: Univariate parameters species number, density and biomass for the different impact areas on the Buiten Ratel over time in autumn. Bars show averages ± SD.

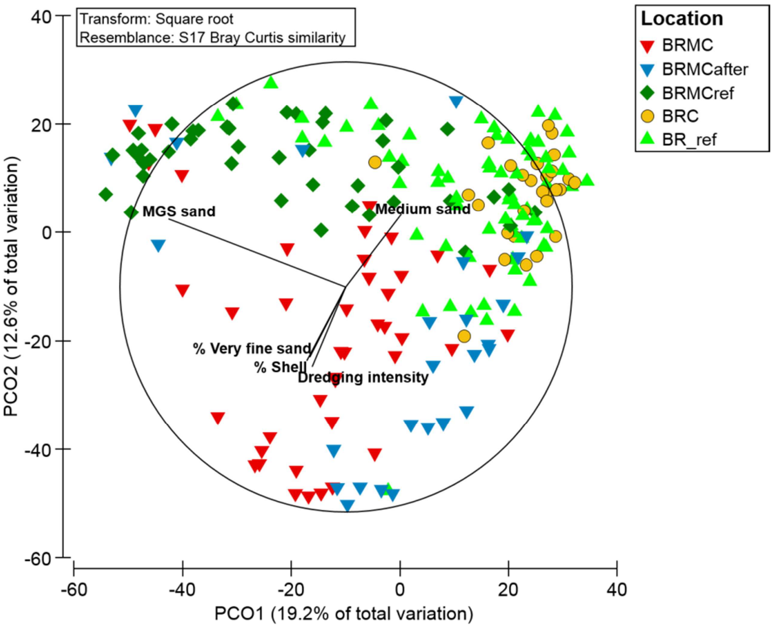

Figure 8: PCOplot based on species abundance data of the Buiten Ratel with indication of the different impact areas. Samples within the BRMC area, taken after closure of the area for dredging, have been assigned a different colour. Vector overlay shows environmental parameters correlating for at least r>0.3 with the observed multivariate pattern.

THORNTONBANK

Dredging in sampling stations

Average extraction volumes around the edge stations on the Thorntonbank (THedge) did not exceed 50 m³ per year (Figure 9), which means that there was only dredging activity on average on one day in the year previous to biological sampling. Around the top stations (THtop), however, average extraction volumes increased steeply since 2013 upto on average 2500 m³ per year (surface area 8000 m²) in 2016 (Figure 9). The stations were disturbed by dredging activity on average on 52 days per year.

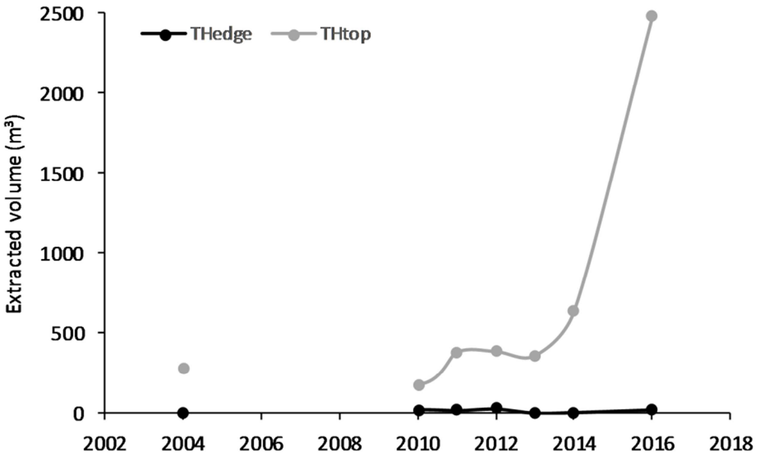

Figure 9: Average extraction volumes over time around top and edge biological sampling locations. Extraction volumes per year are based on EMS data, 365 days prior to the biological sampling date in a circular buffer area around the sampling location with a radius of 50 m (8000 m² surface area).

Sediment characteristics

Sediment composition on the Thorntonbank remained similar over the years (p=0.15), and it did also not change within one impact group over time (interaction 'year x impact', p=0.37). Significant differences were observed in sediment composition for the factor 'impact' (p=0.0091) due to slightly higher percentages of fine sand and lower percentages of coarse sand in the THedge stations (Figure 10). However, the median grain size of the sand fraction did not differ significantly over years (p=0.2), between impact groups (p=0.18) or within the interaction 'year x impact' (p=0.9). Median grain size of the sand fraction was on average around 360 - 390 µm and the dominant fraction was medium sand in all areas (Figure 10).

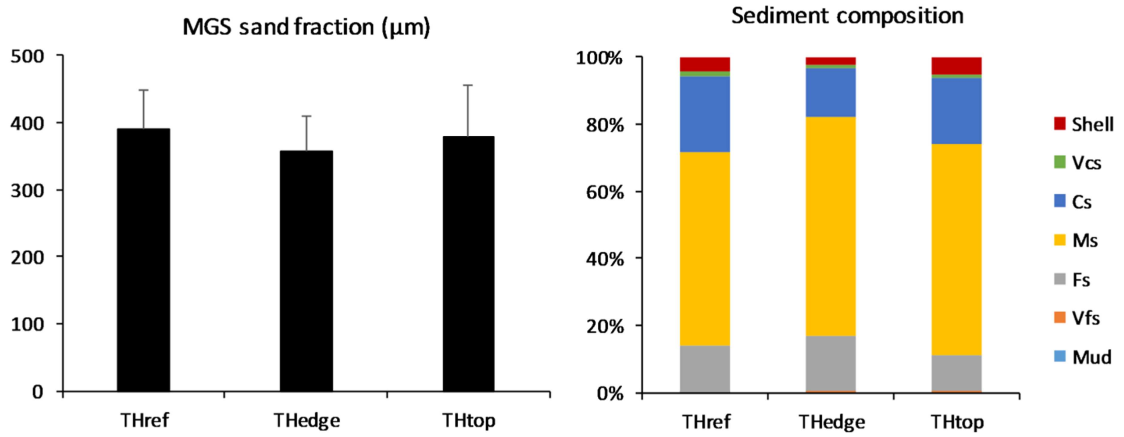

Figure 10: Average median grain size (MGS) of the sand fraction (±SD, left) and sediment composition (right) for the different impact groups on the Thorntonbank. Sediment fractions are largely according to the Wenthworth scale: mud (silt+clay < 63µm), vfs= very fine sand (63-125 µm), fs=fine sand (125-250 µm), ms=medium sand (250-500 µm), cs=coarse sand (500-1000 µm), vcs=very coarse sand (1000-1600 µm) and shell (>1600 µm).

The higher degree of aggregate dredging in THtop stations seems thus not to have changed sediments yet when taking into account all stations over the entire Thorntonbank area. However, when we zoom in on the most heavily dredged area for the year 2016, where dredging activity, based on EMS data, was high at some of the sampling locations, dredging did have a local effect on sediments. In stations TB42 and TB43 (both THtop stations), we observed mixed sediments with a higher percentage of shells (>10%) and as well presence of low percentages of mud and/or very fine sand, while these finest fractions were absent in the other stations (Figure 11). Medium and coarse sand fractions were lower in these high intensity stations (ca 5000 m³ extracted in the year previous to biological sampling) compared to the nearby stations with somewhat lower dredging intensity (<3000 m³) (Figure 11), probably because these fractions have been extracted. These findings match the backscatter results observed by COPCO, where an increase in BS is found in relation to increased dredging volumes, indicating the presence of coarser shell fragments due to screening and/or excavation of a coarser layer due to dredging (Roche et al. 2017, this volume). Furthermore, overall positive correlations were found between dredging intensity and mud (Spearman r= 0.4), very fine sand (Spearman r=0.3) and shells (Spearman r= 0.4).

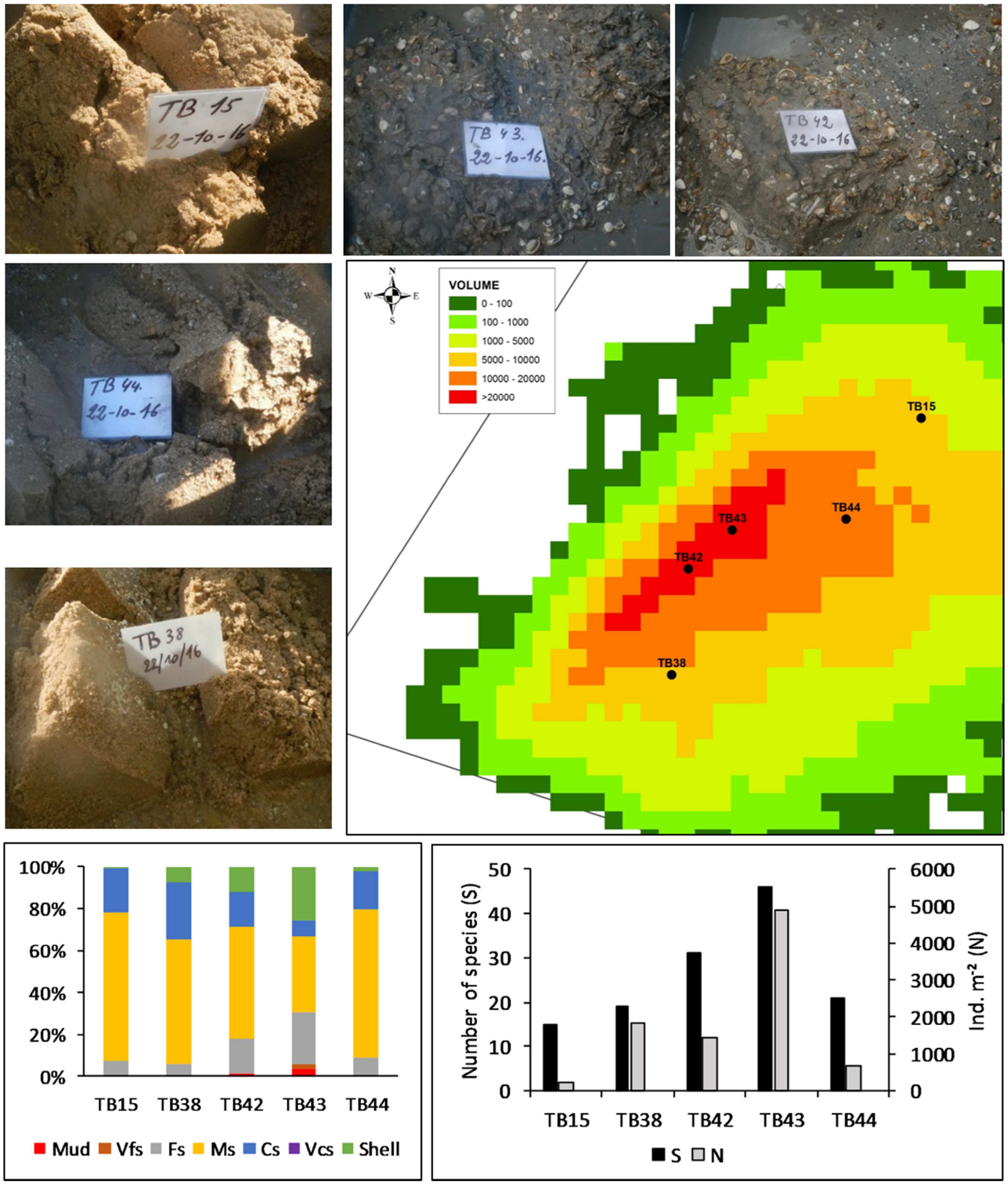

Figure 11: Detail of the high dredging intensity area on the Thorntonbank with cumulative EMS data of the period 2013-2016 in the background and location of the sampling stations. Left bar chart shows the sediment composition for each station, sediment pictures visualise the sediments sampled at each station and right bar charts shows number of species and density within the stations.

Ecological characteristics

Number of species, density and biomass were not significantly affected by the increased dredging at the top of the Thorntonbank when observing the wider area (year x impact resp. p=0.25, p=0.76 and p=0.86). Density and biomass were also not significantly different between years (resp. p= 0.07 and p= 0.29) or between impact zones (resp. p=0.16 and p=0.47). While number of species did not differ significantly between impact zones (p=0.23), but showed a significant interannual variation (p=0.0001) (Figure 12). Although not significant, biomass including *Echinocardium cordatum* was much lower in the most impacted area, while biomass without

E. cordatum was quite similar between the impact areas (Figure 12). This indicates again, just as in previous reportings (Newell et al. 1998, De Backer et al. 2014a), the sensitivity of this species for dredging activity.

When zooming in on the most disturbed area, just as for sediment composition, we see that on a small spatial scale, an increased species number and density were observed in the most heavily impacted stations (Figure 11). Especially the number of species is almost double as high as the normal observed average numbers that were around 15-20 species per sample. Furthermore, when looking at all samples correlations, between S and N and dredging intensity have been found that were positive resp. Spearman r=0.35 and r=0.4, indicating that dredging positively affected species number and density.

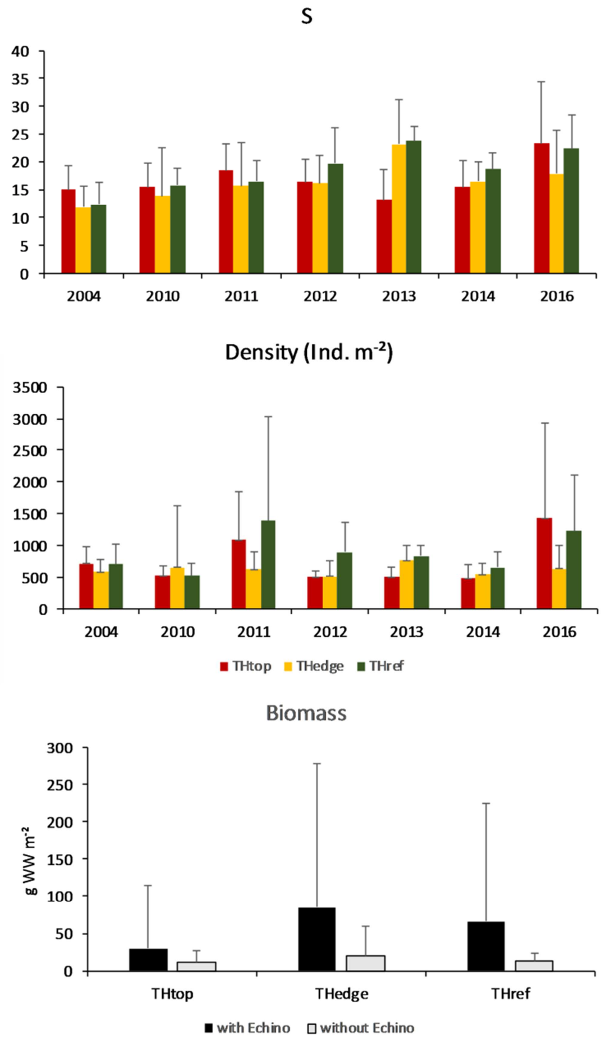

Figure 12: Univariate parameters species number and density for the different impact areas on the Thorntonbank over time. Biomass with and without Echinocardium cordatum is shown for the different impact areas. Bars show averages ± SD.

The multivariate species pattern is best explained by different sediment fractions (fine sand, medium sand, coarse sand and shell) and by dredging intensity, which together account for 22% of the observed variation (DISTLM – BEST-AICc). The increased dredging did not significantly alter the species composition in the wider THtop area (year x impact, p=0.55). Although factors ‘year’ and ‘impact’ were significant (both p=0.0001), most samples cluster together along PCO axes 1 and 2 (Figure 13), and SIMPER revealed that all impact areas are characterized by *Ophelia borealis* habitat as defined by Van Hoey et al. (2004). Differences between areas and years were mainly due to fluctuations in densities. One exception is some of the stations with higher dredging intensity, especially TB42 and 43 (ca 5000 m³ extracted in the year prior to biological sampling), which cluster a bit further apart along PCO axis 3 (Figure 13). The species composition in these 2 stations is quite different and changed towards species typical for *Abra alba* habitat like *Kurtiella bidentata, Abludomelita obtusata, Cirratulidae, Lanice conchilega, Anthozoa* and *Lagis koreni,* and additionally high densities of *Poecilochaetes serpens* were present. It is most probably the change in sediment (see previous paragraph) with the presence of mud and very fine sand that attracted these species, since all of these are characteristic for finer sediments and were normally not to be expected on the top of the Thorntonbank.

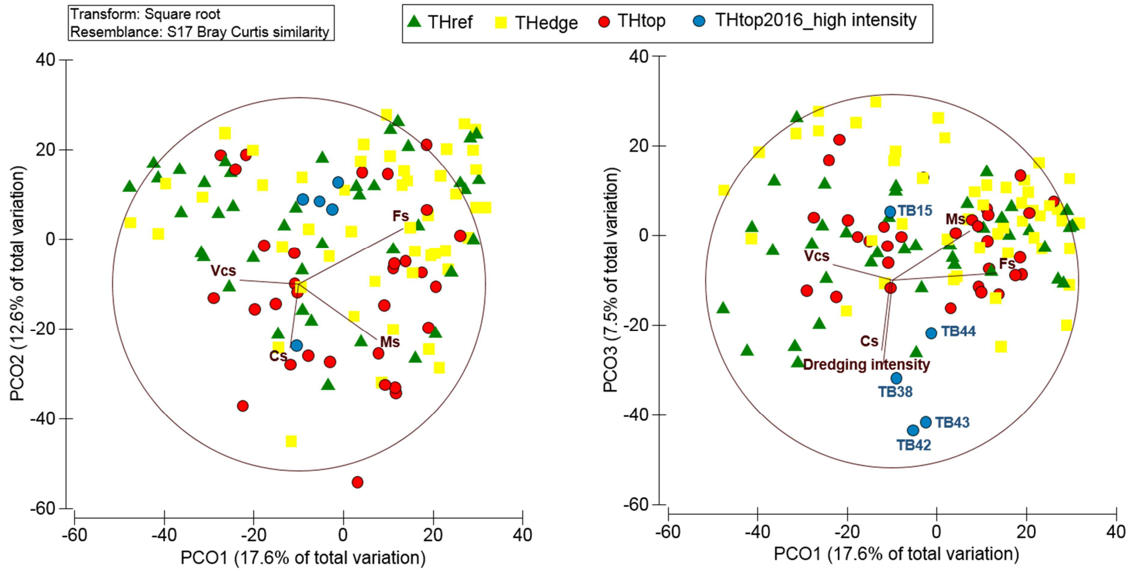

Figure 13: PCOplot showing first three axes based on species abundance data of the Thorntonbank with indication of the different impact areas. Samples within the THtop area with highest dredging intensities have been assigned a different colour. Vector overlay shows environmental parameters correlating for at least r>0.3 with the observed multivariate pattern. Fs=fine sand (125-250 µm), Ms=medium sand (250-500 µm), Cs=coarse sand (500-1000 µm), Vcs=very coarse sand (1000-1600 µm).

OOSTHINDER

Dredging in sampling stations

Aggregate dredging started in 2012 in zone 4c, and reached average extracted volumes of 700 m³ per year around the biological sampling locations (Figure 14), as such the seabed was disturbed on average on 5 days per year. In 2014, volumes increased steeply upto 4600 m³ per year around the biological sampling locations (surface area 8000 m²) (Figure 14). The seabed in the biological locations was on average disturbed on 35 days because of the dredging activity.

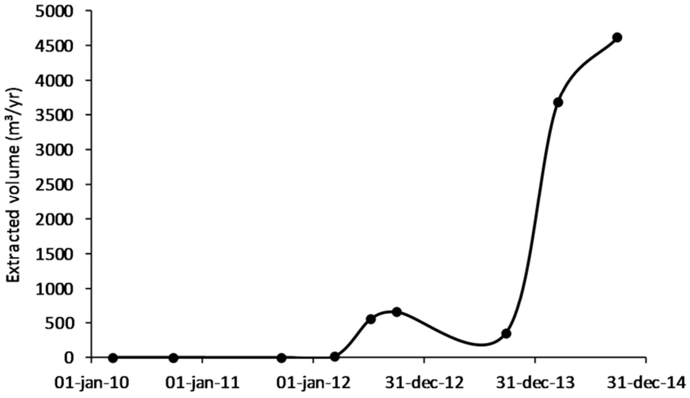

Figure 14: Average extraction volumes over time around the biological sampling locations within zone 4c. Extraction volumes per year are based on EMS data, 365 days prior to the biological sampling date in a circular buffer area around the sampling location with a radius of 50 m (8000 m² surface area).

Sediment characteristics

Sediment composition did not significantly change due to intensive dredging at the Oosthinder (year x impact, p=0.95). Medium sand was the dominant fraction in all zones over the years with on average 63% (± SD 10) in the impact area 4c, 71 %(± SD 9) in the reference area on the Oosthinder (REF4c) and 75% (± SD 7) in the reference on the Bligh Bank. However, significant differences in sediment composition were observed between impact groups (p=0.0001), and also between years (p=0.0021), but trends were similar in reference and impact areas. (REF_BB). In all areas, a slight fining of the sediment was observed over the years as can be seen from a decrease of the median grain size of the sand fraction (Figure 15), which is due to an increase of fine sand (125-250 µm), and a decrease of coarse sand in all areas (500 – 1000 µm). Although, this decrease cannot be directly related to dredging (interaction year x impact, p≥0.6 for all fractions), we found a positive correlation between extracted volume and fine sand (Spearman r= 0.5), and a slight negative correlation between extracted volume and median grain size (Spearman r= -0.3) and coarse sand (r=-0.25). Furthermore, Van Lancker et al. (2015) found a fining as well, together with more heterogeneous sediments in the dredging area, and the back scatter results on the HBMC area also show a downward shift in dB values related to extraction, again indicating fining of the sediment (Roche et al. 2017, this volume).

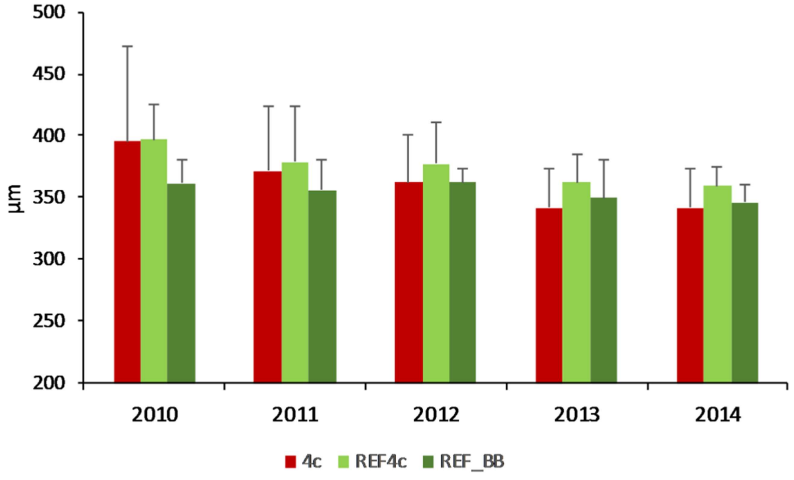

Figure 15: Average median grain size of the sand fraction over time for the different impact groups on the Oosthinder.

Ecological characteristics

Univariate parameters species number S, density N and biomass were significantly different between seasons, hence spring and autumn samples were analysed separately. Since patterns are similar between seasons, only autumn data are presented.

None of the univariate parameters was significantly affected by the dredging activity that started in 2012 in area 4c (year x impact, p>0.05). Even in 2014, just after the very intensive dredging for coastal protection, no deviations in univariate parameters were observed compared to the reference areas or to previous years (Figure 16). The only significant effect detected was a lower species number in the REF_BB area compared to 4c (p=0.02) and REF4c (p=0.016) throughout the entire sampling period (2010-2014) (Figure 16).

Also none of the univariate measures was correlated with dredging intensity indicating again that the dredging had no effect on the structural parameters of the benthic community.

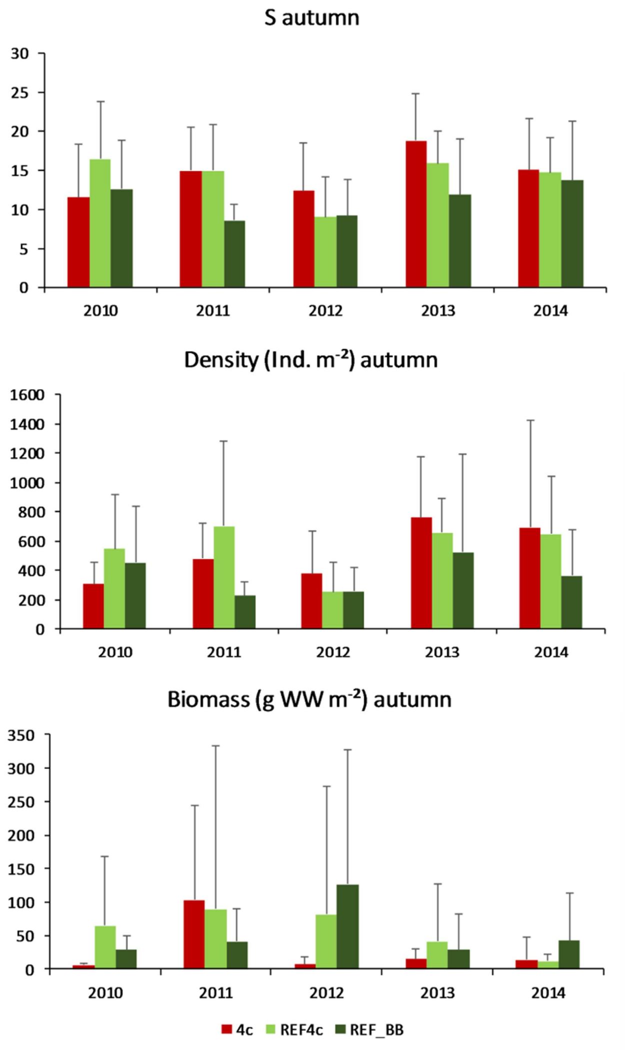

Figure 16: Univariate parameters species number, density and biomass for the different impact areas on the Oosthinder over time in autumn. Bars show averages ± SD.

DISTLM analysis selected different sediment fractions (fine sand, coarse sand and shell) together with dredging intensity as best explaining the observed variation in the multivariate species pattern, but only 17% could be explained (BEST – AICc). Although, the interaction term 'year x impact' was significant (p=0.0001), dredging activity seems not to have caused large changes within the species composition of the impacted area. The pattern shown in the PCOplot confirms this, since no specific separate cluster of 'after dredge samples' (4c_after) can be discerned (Figure 17). Samples of all areas belong to the *Ophelia borealis* habitat as defined by Van Hoey et al. (2004) characterised by interstitial species such as *Hesionura elongate* and *Microphthalmus* but also by *Ophelia borealis*, *Nephtys cirrosa* and *Gastrosaccus spinifer* (SIMPER). Area 4c differed significantly in all years from REF_BB, and except for 2010, also from REF4c (pairwise tests), so also before the start of dredging small differences were present mainly due to differences in densities of some species. Within the different areas, species composition showed as well differences between most years (pairwise tests), again owing mainly to density differences which might be related to the observed slight fining of the sediment.

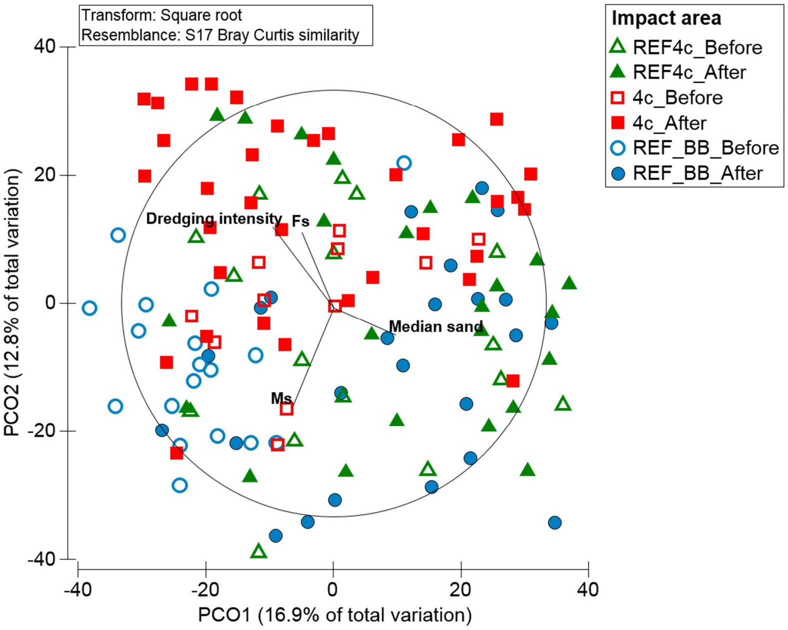

Figure 17: PCOplot based on species abundance data of the Oosthinder with indication of the different impact areas before and after start of dredging. For better visualization years have been grouped in before and after dredging period. Vector overlay shows environmental parameters correlating for at least r>0.3 with the observed multivariate pattern.

Conclusions

Benthic monitoring was focussed on three areas where intensive dredging is or has been taking place: Buiten Ratel (zone 2br), Thorntonbank (zone 1) and Oosthinder (zone 4c). The aim of this study was to evaluate the effect of the dredging activity in each of these areas on the benthic ecosystem. The main conclusions are formulated as answers to the three questions posed in the introduction:

1) What is the effect of the closure of the BRMC area (zone 2br) on the 'benthic biodiversity hotspot' that was created during intensive dredging before closure?

Results from previous reports and publications (De Backer et al. 2011, De Backer et al. 2014a, De Backer et al. 2014b) were confirmed. The intensive dredging (>10000 m^3/ha/yr) that took place in the BRMC area before the closure resulted in a sediment change with on the one hand coarsening of the sediment due to more shells and gravel because of reject chute or excavation of coarser layers, and on the other hand increased input of fines due to overspill. This created a heterogenic habitat with increased macrobenthic species numbers and densities, being inhabited by a dynamic, transitional community characterised by a mixture of muddy sand and coarse sand species (De Backer et al. 2014b). **Sediment composition and macrobenthic community did not change 2 years after closure of the area for dredging in January 2015**. In 2015 and 2016, **increased percentages of shells (>1600 µm) and very fine sand (63 -125 µm) persisted** compared to nearby reference locations, **and supported the survival of the heterogenic, dynamic community** that was established during intensive dredging activities. However, the cessation of dredging seemed to have triggered two species *Spiophanes bombyx* and *Poecilochaetus serpens*, both species peaked in the BRMC area after closure of the area for dredging. *S. bombyx* is a species with a short life span, high dispersal potential and high reproductive rate, and it is known to quickly colonize variable, unstable habitats after perturbation (Ager et al. 2005 and references therein), which explains its dominant occurrence in the closed BRMC area. This species is an early colonizer, so it would be interesting to see which steps will follow in the colonization process since perturbation due to dredging has stopped. Nevertheless, for the moment, we can conclude that after two years without dredging, the 'biodiversity hot spot' remained. Over the coming years, the follow-up monitoring will proof how sediments and the benthic community will further evolve with increasing time after dredging.

2) How is the benthic ecosystem on the Thorntonbank (zone 1) affected by the increased dredging activity?

Upto 2013, no effect on the benthic ecosystem was measured on the Thorntonbank in relation to the medium dredging intensity (<5000 m³/ha/yr) on the benthic ecosystem was measured on the Thorntonbank (De Backer et al. 2014a). After 2013, dredging activity increased, and in 2016, 1.8 million m³ was extracted in zone 1, almost double compared to 2013. Especially in 2016, intensity was high around some of the biological sampling locations (5000-10000 m³/ha/yr). Although, the wider area on the Thorntonbank did not show an effect of the increased dredging on the benthic ecosystem, we did observe an effect at a small spatial scale in the most dredged area on the western part of the Thorntonbank. Quite similar as in the BRMC area, intensive dredging on a small area changed the sediments with an increase in coarse shell fragments (>1600 µm) and a mutual increase in mud/very fine sand (<125 µm). This change of sediments caused a shift in the benthic habitat from *Ophelia borealis* habitat to a mixture of *Ophelia* and *Abra alba* habitat, similar as in the BRMC area. For the first time, typical fine sand species like *Kurtiella bidentata, Cirratulidae* and *Lanice conchilega* were observed on the Thorntonbank. Densities and species numbers increased as well, fully consistent with the effects observed on the Buiten Ratel. This indicates that the **intensive dredging in a small spatial area on the Thorntonbank created a 'hot spot of biodiversity',** comparable to the one observed in BRMC area.

3) Did the short-term huge dredging activity in 2014 affect the benthic ecosystem of the Oosthinder (zone 4c)?

Extraction in zone 4c started in 2012 with an extracted volume of 750 000 m³ over a period of 4 months (March till June), in 2013 almost 1 million m³ was extracted, and in 2014 a peak extraction of 2.5 million m³ took place over a period of 6 months (January till June). Upto 2013, no changes in sediment or benthic habitat were detected (De Backer et al. 2014a). Two more sampling events were performed in 2014 (in March and October) to evaluate whether the peak extraction of 2014 had an impact on the benthic habitat. Although, a slight fining trend was observed in median grain size of the sand fraction, which is in line with the observations of Van Lancker et al. (2015, 2016), and with the shift in back scatter values measured by COPCO (Roche et al. 2017, this volume), **no significant changes in sediment composition** could be detected. **Also species numbers, density and community structure were not (yet) impacted by the peak extraction**. The species community encountered was, comparable to previous years, a typical *Ophelia borealis* community with many interstitial species. This result seems quite surprising, since really huge volumes of sand were extracted. Possible explanations for the lack of impact could be that the sediments remained similar with a high dominance of medium sand (>60 %) or that the area has always been exposed to high natural disturbance and large sediment movements, which makes the dominant benthic organisms resistant and resilient against disturbance by aggregate dredging (Cooper et al. 2011). A third explanation may be that extraction stopped in June, which is before the summer recruitment period, so new recruits were able to directly colonise the area. In any case, benthic monitoring of this area will be continued to follow-up on coming extraction events. We will focus on the size of species and on the ratio juveniles-to-adults, in order to see whether the latter recruitment hypothesis makes sense.

Acknowledgements

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Quality assurance

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

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Effects of extraction of sand on the bottom shear stress on the Belgian Continental Shelf

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Introduction

In the Belgian implementation of the European Marine Strategy Framework Directive (Belgian State, 2012), it was stated that human impacts need consideration when the bottom shear stress, calculated with a validated numerical model, increases with more than 10 % at a specified distance of the activity. In this contribution, the impact of extraction of marine aggregates on the bottom shear stress on the Belgian Continental Shelf is evaluated with this respect.

Since in the Belgian implementation, it is explicitly stated that the evaluation has to be executed with a validated numerical model, an evaluation of the quality of bottom shear stress models is described in the first part of the paper. Firstly, the numerical models are described. The hydrodynamic model, that is used to calculate the currents and the water elevation, and the wave model, calculating the significant wave height, wave frequency and wave direction, are presented. Furthermore, different models that are found in literature to calculate the bottom shear stress under the influence of currents and waves are shortly discussed. Secondly, some measurements of the bottom shear stress at the offshore Hinder Banks are described. Acoustic Doppler Current Profiler (ADCP) data are used to calculate the bottom shear stress from the logarithmic profile of the currents in the lower part of the water column. Different measurement campaigns were executed at two stations in the Hinder Banks area. In the next sections, the validation of the hydrodynamic and wave model and of the bottom shear stress models is discussed.

In the second part of the paper, some applications are presented. First, the impact of large-scale extraction of marine aggregates is evaluated. Three different scenarios for the extraction of 35 Mm³ of marine aggregates in the extraction zone 4 in the Hinder Banks area, are modelled and the effect on the bottom shear stress in the area is assessed.

In a second application, the effects of the new extraction limit levels, that are proposed by Degrendele (2016) and Degrendele et al. (this volume), on the bottom shear stress are evaluated. The change in bottom shear stress for three different scenarios are modelled and evaluated. Two possible solutions are proposed for thoses cases, where the next extraction limit levels lead to a too high increase in bottom shear stress.

Some conclusions are formulated in the last section.

Validation of the bottom shear stress model

Numerical models

Introduction

To calculate the bottom shear stress under the influence of the currents and the waves, numerical models are used. A three-dimensional hydrodynamic model is used for the calculation of the water elevations and the currents. A third generation wave model is used to calculate the waves. Both models will be discussed shortly.

Furthermore, different methods and models are available in literature to calculate the bottom shear stress from the currents and waves. The different models that are used in this study are discussed in the next section.

Hydrodynamic model OPTOS-FIN

The three-dimensional hydrodynamic modelling software COHERENS calculates the currents and the water elevation under the influence of the tides and the atmospheric conditions. The model was developed between 1990 and 1998 in the framework of the EU-MAST projects PROFILE, NOMADS and COHERENS. The hydrodynamic model solves the momentum equations and the continuity equation with, if necessary, equations for the sea water temperature and salinity. COHERENS disposes over different turbulent closures. A good description of the turbulence is necessary for a good simulation of the vertical profile of the currents. A new version of the COHERENS software has been developed recently (Luyten et al., 2014), mainly allowing the model to use parallel computing, while adding also some new features, such as improving the numerical scheme and adding a wetting-drying mechanism. The model is further extended with a sediment transport module and a morphological module.

The model OPTOS-FIN is based on this COHERENS code and is implemented on the Belgian Continental Shelf with a grid with a resolution of 14.29" in longitude (272 to 278 m) and 8.33" in latitude (257 m). This model has 10 σ-layers distributed over the total water depth. Along the open boundaries, the OPTOS-FIN model is coupled with three regional models. The OPTOS-CSM model comprises the entire Northwest European Continental Shelf and calculates the boundary conditions of the North Sea model OPTOS-NOS. The latter model calculates the boundary conditions of the OPTOS-BCZ model, which is implemented for the Belgian waters with a three times coarser resolution than the OPTOS-FIN model. The OPTOS-CSM model calculates the depth-averaged currents and is driven by the water elevations at the open sea boundaries, using four semi-diurnal and four diurnal constituents. The bathymetry of OPTOS-FIN model is shown in *Figure 1*.

The OPTOS-FIN model was validated in the framework of the BELSPO Marebasse project (Van den Eynde et al., 2010) and the BELSPO BOREAS project (Mathys et al., 2012). More recently a first validation was executed of the model in the Hinder Banks area, using bottom-mounted ADCP results, hull-mounted ADCP measurements and Wave Glider (Liquid Robotics) measurements (Van den Eynde et al., 2014).

Wave model WAM

The WAM model is a third generation wave model, developed by the WAMDI Group (1988) and described by Günther et al. (1992). The WAM model is used both for research and for operational wave forecasting. It includes 'state-of-the-art' formulations for the description of the physical processes involved in the wave evolution. In comparison with the 2nd generation model, the wave spectrum has no restrictions and the wind sea and the swell spectrum are not treated separately.

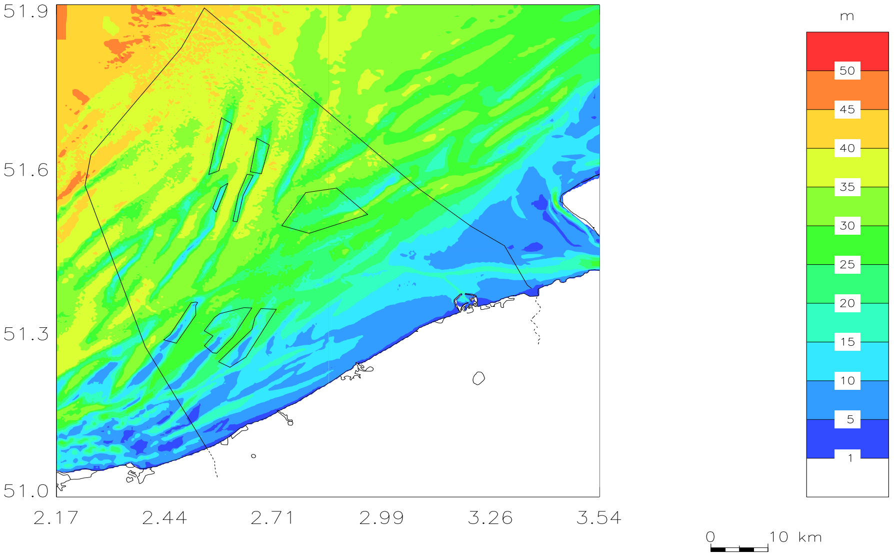

Figure 1: Bathymetry of the OPTOS-FIN model. Superimposed are the aggregate extraction sectors.

At the Operational Directorate Natural Environment, the model is running on three coupled model grids. The coarse model grid comprises the entire North Sea, the fine model models the central North Sea and the local model calculates the waves in the Southern Bight. The local model has a grid resolution of 0.033° in latitude and 0.022° in longitude.

The WAM model was recently validated by Van den Eynde (2013).

Calculation of the bottom shear stress

The calculation of the bottom shear stress is the topic of much research. The bottom shear stresses under the influence of currents alone and under the influence of waves alone over a flat bed are quite well known. However, the calculation of the bottom shear stress under the combined influence of currents and waves over a rippled sea bed is complex. The calculation of the bottom shear stress under the influence of currents and waves is not the simple vector addition of the bottom stress vectors for the currents and the waves alone, as non-linear interactions increase the mean bottom shear stress (averaged over a wave cycle).

Furthermore, the bottom roughness length, which is an important factor for the calculation of the bottom shear stress, is influenced by different factors. At the bottom itself, the roughness is a function of the grain size. This bottom shear stress, felt by the sediments, is called the skin friction. However, at a distance more than a tenth of the length of the bottom ripples, the bottom roughness is also influenced by the bed load and by the height and the length of the bottom ripples. Further away from the bottom, a new logarithmic profile is followed with an apparently increased total bottom roughness. The ratio between the skin bottom roughness and the total bottom roughness varies between 1.5 and 20.

For the calculation of the bottom shear stress under the influence of currents and waves, many different models can be found in literature, varying from simple models to very complex iterative models, resolving the stresses in the wave boundary layer and during a complete wave cycle. These very complex models are however very time consuming and not really useful to be used in sediment transport models. Recently, more realistic and simple models for the combined bottom shear stress were proposed in literature. Three new formulations were implemented and tested, for both the mean bottom stress over a wave cycle and the maximum bottom stress, within a wave cycle.

The Soulsby (1995) formula is the most simple one, consisting of the results of a two-coefficient optimisation of a simple model to 131 data points, from more complex theoretical models. More recently, Soulsby and Clarke (2005) developed a new model, assuming an eddy viscosity varying over the water column, but constant in time. The eddy viscosity in the wave boundary layer is only a function of waves and currents, so that no iterative calculations are needed. Malarkey and Davies (2012) extended the theory of Soulsby and Clarke (2005) to include additional non-linearity in the model. More information and some comparison of the results of the different models can be found in Van den Eynde (2015).

As indicated above, the bottom shear stress under the influence of currents and waves is a function of the bottom roughness length. Both for the skin bottom roughness as for the total bottom roughness, models can be found in literature, which are, amongst other, function of the median grain size, the size of the bottom ripples and the bed load transport. Different models were implemented to calculate the bottom roughness as a function of empirical models for the bottom geometry (e.g., Soulsby and Whithouse, 2005) and the bed load transport. More information and some comparison of the results of the different models can be found in Van den Eynde (2015).

ADCP measurements of currents and bottom shear stress

For the validation of the bottom shear stress in the Hinder Banks area, different measurement campaigns, using a bottom-mounted ADCP (RDI Workhorse 1200 kHz), have been executed (Van Lancker et al., 2014; 2015). This ADCP measures the profile of the water currents from the bottom upwards. The campaigns BM01, BM02, BM04 and BM05 have been executed on the same place at (51° 30.6’ N, 2° 37.94), along the eastern flank of the Oosthinder sandbank. The campaigns BM03, BM06 and BM07 have been executed around a location (51° 24.78’N, 2° 31.61’E) in the Habitat Directive area, in the south part of the Hinder Banks, in the trough of a very-large dune. Both stations are indicated in *Figure 2*. Remark that the settings (bin size, range) and the time step of the measurements were not identical during the different measurements campaigns.

The bottom shear stress can be calculated from the assumed logarithmic profile of the currents near the bottom, by fitting the measured profile to this logarithmic profile, using a least squares method. Wilkinson (1984) developed expressions for the confidence limits (for a certain degree of confidence) for the estimations of the bottom roughness length and the bottom shear stress, using the Student’s t distribution for the number of freedoms, equal to the number of velocities taken into account minus 2.

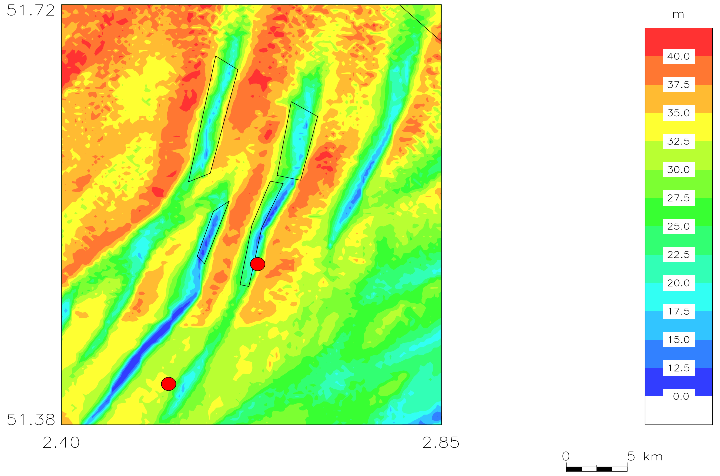

Figure 2: Position of the ADCP measurements (red circles). Polygons indicate the four aggregate sectors in the Hinder Banks region.

Validation of the models

Depth-averaged currents

The depth-averaged currents from the bottom-mounted ADCPs are compared with the model results. The measurements are first averaged over depth and further averaged over time, to obtain time series with a time step of 30 minutes.

Overall, the current magnitudes and current directions are quite well reproduced by the model for the measurements at the Hinder Banks, i.e., campaigns BM01, BM02 and BM04. In the campaign BM01, the currents were slightly overpredicted, certainly for the slack waters, while in campaign BM02, the overprediction of the currents mainly occurred during high currents. In campaign BM04, a slight overprediction of the lower currents and an underprediction of the higher currents occurred. Also the current directions are well modelled during these campaigns. Overall, the results of the model are clearly satisfactory at the station east of the Oosthinder.

For the measuring campaigns in the Habitat Directive area, south of the Hinder Banks, the results of the model are less satisfactory. Both for the campaign BM03 as for the campaign BM06, the currents by the model clearly overpredict the currents, certainly during high currents. These less satisfactory results are probably due to the specific bathymetry in the area, near the steep slope of the very large dune. Flow reversal probably exists slowing down the currents in the area. This is not well represented in the model bathymetry.

Wave height

The significant wave height, modelled with the WAM model, were compared with buoy data at the station MOW7 at the Westhinder sand bank (data from Flemish Banks Monitoring Network, Flemish Government, Agentschap Maritieme Dienstverlening en Kust).

Good results are obtained for the station at the east flank of the Oosthinder. For campaign BM01 and BM02 a scatter index of only 17 % is found; for the BM04 campaign, the scatter index is 25 %. The bias is always less than 0.07 m. These results are clearly satisfactory. For the station in the Habitat Directive area, the results are less good. The bias is higher with an underprediction of 0.12 m and 0.16 m for campaign BM06 and BM03 respectively. Also the scatter index for the BM03 campaign is higher (30 %). This probably is again an effect from specific tide-topography interactions at this station.

The waves during the periods of the measurement campaigns remain limited. During the campaign BM01 and BM02, the significant wave height remains most of the time below 2.0 m. During campaign BM04, a peak in significant wave height was reached of about 3.0 m. During the campaigns in the Habitat Directive area, south of the Hinder Banks, the waves remain lower and did not exceed 1.5 m.

Bottom shear stress

The bottom shear stress can be calculated from the current profile. In *Figure 3*, the mean profiles in the lowest 6 m of the water column for the entire campaign BM01 are presented as a function of the current direction. The highest currents are the currents in south-south-west (ebb) and in north-north-east (flood) direction. For the higher currents, the averaged currents show a relatively smooth logarithmic profile. For the slack-water profiles, the current profiles are more constant over the water depth. Remark that the current measurements in the Habitat Directive Area are lower and less logarithmic. It is clear that the individual profiles can differ more from the logarithmic profile.

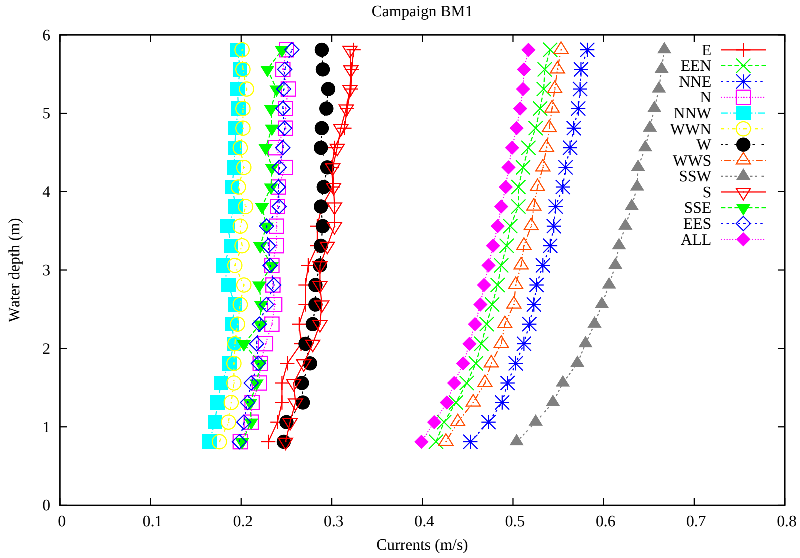

Figure 3: Mean current profiles in the lower part of the water column for campaign BM01, as a function of the current direction.

In Figure 4, the time series of the bottom shear stress, calculated using the lowest 5 m of the water column, is shown for day 1 to day 3 of campaign BM01. One can clearly see that there is still a lot of scatter in these measurements. To remove some of the scatter, a moving average filter is applied to the data with a window of two hours. Also the confidence limits (95 %) are presented in the figure.

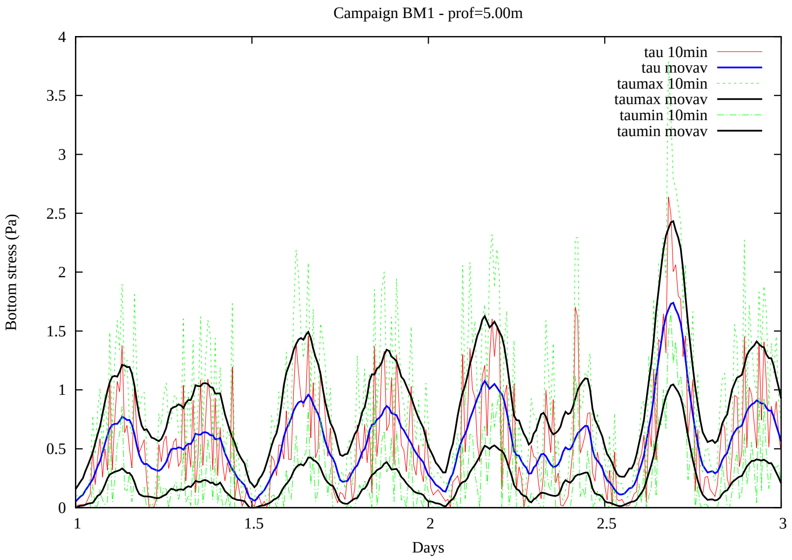

Figure 4: The calculated bottom shear stress (tau) and the maximum and minimum bottom stress with a confidence of 95 % (taumax and taumin) during day 1 to day 3 of campaign BM01 (moving average over 2 hours).

To compare these measurements with the model results of the three models, using a constant bottom roughness length, tests were executed with values for the bottom roughness length varying between 0.004 m and 0.6 m. The best overall result (lowest mean RMSE over all campaigns) was obtained with the Soulsby model, although the results with the Soulsby-Clarke and the Malarkey-Davies model were very comparable. The optimal bottom roughness for the Malarkey-Davies model for BM01, BM02 and BM04 is 0.01 m.

In *Figure 5*, the modelled bottom shear stress is given for campaign BM01, together with the measured bottom shear stress. Also the confidence limits (95 %) of the measurements are given in the plot. While the height of the peaks may differ considerable, the tidal signal is well reproduced by the model. In more than 92 % of the cases, the model results remains between the 95 % confidence limits of the measurements.

Overall, one can conclude that using a constant bottom roughness length, the numerical models give satisfactory results. A bottom roughness length of 0.01 to 0.03 m should be used. For the campaigns BM03 and BM06, where the measurements are taken in the Habitat Directive Area, the results are less good, mainly due to the very specific tide-topography interaction.

As mentioned before, the bottom roughness length can be calculated by the numerical model itself, based on empirical models for the bottom roughness length, due to bed load and due to bottom ripples. Also the dimensions of the bottom ripples are calculated by empirical models in this case. Tests however showed that the simulated bottom roughness lengths were too high and that the modelling of the bottom roughness length did not improve the results. Therefore, in the current study, a constant bottom roughness length was further used.

Remark that a further validation of the bottom shear stress models was executed, using high frequency measurements of the currents near the bottom (Van den Eynde, 2015; 2016a). For these measurements an Acoustic Doppler Velocity (ADV) profiler was used, which was mounted on a benthic bottom lander. This lander was deployed on the sea bed near the MOW1 measuring pole, in the neighbourhood of the harbour of Zeebrugge. Research showed that the turbulent kinetic energy (TKE) method showed the most promising results for the estimation of the bottom shear stress from the high frequency current measurements. The validation of the bottom shear stress models showed similar results as those reported here, showing that the bottom shear stress models give satisfactory estimates of the measurements.

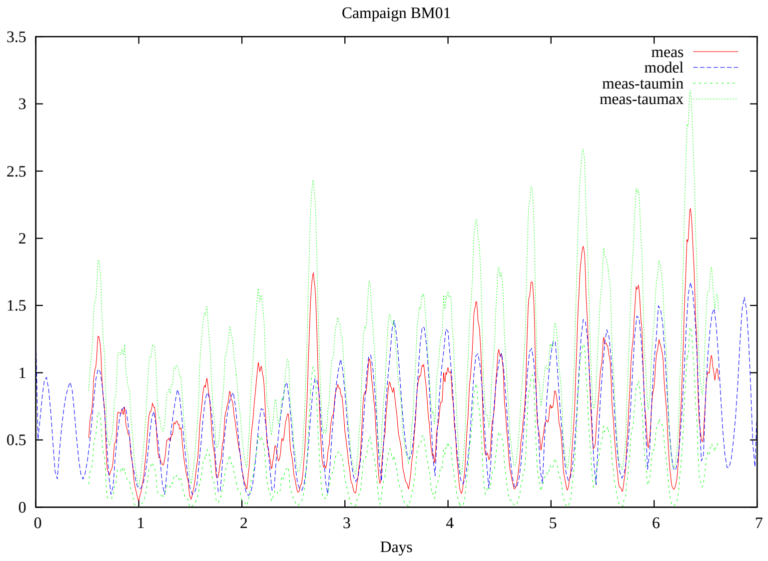

Figure 5: Time series of measured bottom shear stress (with confidence limits of 95 %) and modelled bottom shear stress, with a constant bottom roughness length, for campaign BM01.

Modelling the effect of extraction on bottom stress in the Hinder Banks area

Introduction

In the framework of Europe's Marine Strategy Framework Directive (MSFD), Belgium prepared a report, in which different indicators were defined that could be used to evaluate the impact of human activities at sea (Belgian State, 2012). These indicators are grouped to several descriptors that together need monitoring to reach a Good Environmental Status of the marine waters by 2020. Amongst these descriptors, descriptor 7, on hydrographic conditions, uses the bottom shear stress. In that report, it is stated that human impact asks consideration when the bottom shear stress, calculated by a validated mathematical model over a spring-neap tidal cycle, 1) increases by more than 10 %, or 2) that the ratio of the period for erosion and the period for deposition is larger than -5 % or +5 %. Furthermore, it is stated that the impact should stay in a distance less than the square root of the area of the zone of activity, measured from the boundary of the area. This zone is referred to further as the "buffer zone", where an increase or decrease of the bottom shear stress with more than 10 % is allowed, without further consideration.

In the Zone 4 for the extraction of marine aggregates, in the Hinder Banks area, a maximum of 35 million m³ of marine aggregates is allowed to be extracted over a period of 10 years. In this section, the effect of this maximum extraction on the bottom shear stress is evaluated, with respect to the method, defined in the MSFD.

Simulations

Three different scenarios are studied. In all scenarios, all material above a certain depth is extracted in the different sectors for extraction. In the first scenario, this depth can differ in the different sectors. In this scenario, in each sector the same maximum depth is extracted, starting from the minimum water depth in the sector. To arrive at a total of 35 million m³, a maximum extraction of 6.93 m from the top of the sandbank is applied. Almost 35 % is in this case extracted in Sector 4a (north-east), which has the largest area. In the second scenario, extraction is executed in the four sectors, to the same critical depth. In this case, extraction is executed up to a depth of 19.70 m in all sectors. In this case, most of the material is extracted in Sector 4d, since this is the sector with the shallowest water depths. In this zone, an extraction of more than 10 m is executed, to extract almost 44 % from this zone alone. In the last scenario, only material is extracted in Sector 4c, the sector, which is used most intensively at the moment and which is the closest to the coast (south-west). An extraction of almost 12 m is executed in this case, to a water depth of 26.05 m.

To evaluate whether the impact needs consideration, the changes in bottom stress, larger than 10 %, should stay in a distance less than the square root of the area of the zone of activity, measured from the boundary of the area (the buffer area). Note however, that not the entire area where extraction is permitted is effectively used.

For the different bathymetries, the bottom shear stress is calculated using the three-dimensional hydrodynamic model COHERENS OPTOS-FIN. The standard COHERENS bottom shear stress model is used, which is based on a simple quadratic bottom shear stress. The influence of waves is not taken into account at the moment. This is based on analyses showing that in deeper waters, waves do not influence the bottom shear stress significantly. Furthermore, in the report on the Belgian implementation of the MSFD (Belgian State, 2012), the influence of the waves on the bottom shear stress is not mentioned.

The simulations were executed for a full spring-neap tidal cycle, i.e., from March 29, 2013, 00h00 till April 14, 2013, 12h00.

Results

In *Figure 6*, the changes in bottom shear stress are shown, averaged over the full spring-neap tidal cycle, for the first scenario, where in each sector the same thickness in sediment is extracted from the top of the sand bank, i.e., 6.93 m. One can see that the effect remains limited to the sector of extraction. To evaluate the results more in detail, three areas are defined: the sector of extraction, the area within a distance equal to the square root of the sector of extraction from the border as defined in the MSFD report, the so-called buffer zone, and the area outside this buffer zone. Results show that in the extraction sector itself, the changes can vary between +9.7 % to -27 %, while also in the buffer zone, the changes can be larger than 10 %, i.e., an increase with 15 % (see *Table 2*). However, outside this buffer zone, the difference is limited to -2.2 % to +3.5 %. In *Figure 6*, also the position of the points outside the buffer zone is given where the changes in bottom shear stress are higher than 2 %. The area is limited to a small area south east of Sector 4d.

In *Figure 7*, the number of model grid points are plotted, where the change in bottom shear stress exceeds a certain percentage, for the different zones (extraction zone, buffer zone, outside buffer zone). For the extraction zone, the number of points decreases from 496 points, with a change higher than 1 % to 69 points, with a change higher than 10 %. Remark that a grid cell represents an area of around 70,000 m² (or 0,07 km²). In the buffer zone, where impact is allowed, in 770 grid cells, the change is higher than 1 %, but only in 6 grid cells, a change higher than 10 % is encountered. Finally, in 322 grid cells, outside the buffer zone, the change is higher than 1 %, in 17 grid cells the change is higher than 2 % and only in 3 grid cells, the change is higher than 3 %.

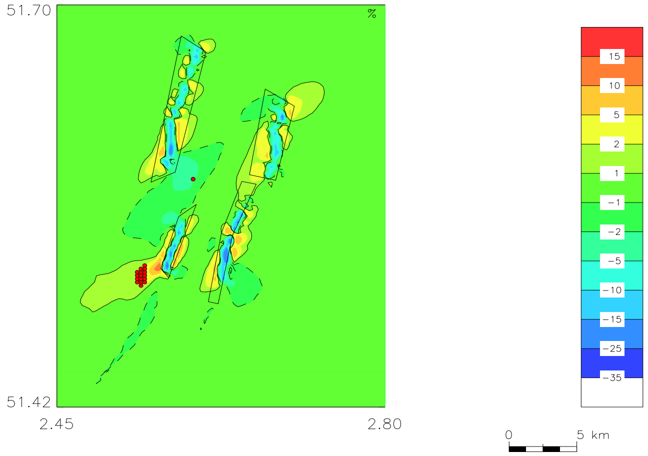

Figure 6: Aggregate sectors in the Hinder Banks along which changes of mean bottom shear stress over a spring-neap tidal cycle for scenario 1 are shown. Also indicated are the points, outside the buffer zone, where the increase/decrease is more than 2 %.

Table 2: For the three simulations ('sim'), minimum and maximum change of bottom shear stress (in percentage) in the different areas (extraction sector, buffer zone, outside buffer zone).

	Extraction zone		Buffer zone		Outside buffer zone	
	Min	Max	Min	Max	Min	Max
Sim 1	-27.33	9.71	-4.89	15.05	-2.16	3.52
Sim 2	-38.90	14.45	-6.48	26.80	-3.02	6.46
Sim 3	-35.59	12.62	-7.87	21.50	-3.46	2.58

In scenario 2, extraction is executed to a certain critical depth, resulting in less extraction in Sectors 4a, 4b and 4c and much more extraction in the shallow Sector 4d, where a maximum of more than 10 m is being extracted. In the extraction zones itself, a maximum change in bottom shear stress is found between +14 % to almost -39 % (see *Table 2*), which is considerable more than for scenario 1. Also in the buffer zone, the changes in bottom shear stress are higher, up to 27 %. However, also in this case, the change in bottom shear stress in the zone, where impact is not allowed, i.e., outside the buffer zone, remains limited and is lower than 10 %. In this case, the maximum changes found vary from -3 % to +6.5 %. The areas, where an increase or decrease of more than 2 % are located outside the buffer zone, are mainly located west and south of Sector 4d.

It is clear that the impact of scenario 2 is higher than for scenario 1, but that also in this scenario, the impact remains limited and that no changes of more than 10 % are observed in the area where impact is not allowed.

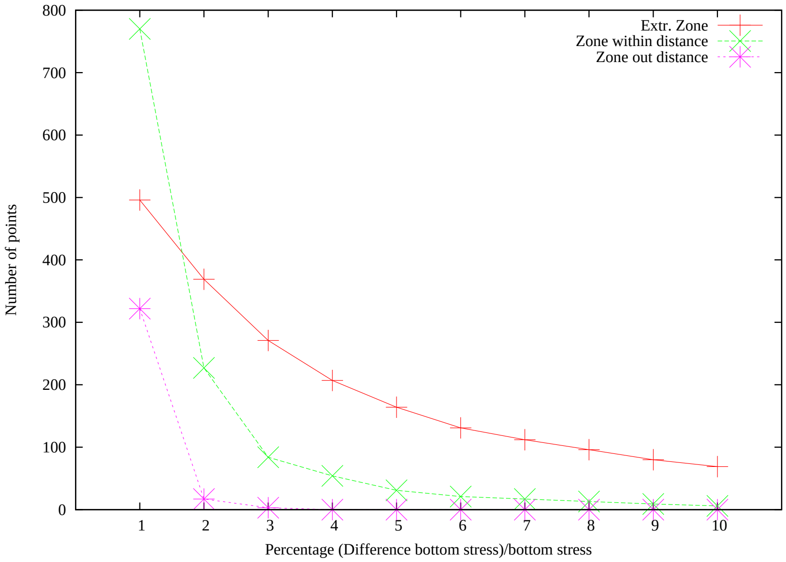

Figure 7: Number of points where the difference in bottom shear stress is exceeding a certain percentage, for the three defined areas for scenario 1.

In the last scenario, all extraction was executed in Sector 4c, the zone which is mostly used in the actual situation. A maximum of almost 12 m is being extracted. Although in this case, all extraction is executed in one sector only, the changes in the bottom shear stress remain limited. In the sector itself, the effect of an extraction of almost 12 m is of course considerable, with a maximum decrease of the bottom shear stress of -36 % and a maximum increase of 13 % (see *Table 2*, see *Figure 8*). Remark however that this is less than in scenario 2. Also in the buffer area, the changes in bottom shear stress are high, up to -8 % to +22 %. However, also for this scenario, bottom shear stress changes remain limited outside the buffer area and stay below 10 %. The maximum and minimum changes in this case are -3.5 % to +2.5 %. Apparently, the effect of the extraction in Sector 4d is larger than that of the even larger extraction in Sector 4c. This is due to the fact that the bathymetry in Sector 4d is shallower. In *Figure 8*, also the position of the area outside the buffer zone is indicated where the change in bottom shear stress is higher than 2%. This zone is mainly situated west of the extraction zone, while also in the southeast a small zone is present.

Conclusions

Three scenarios were modelled to investigate the influence of a large-scale extraction of marine aggregates (35 million m³) on the bottom shear stress in the extraction zone 4 in the Hinder Banks area. In the framework of the MSFD, Belgium stated that a human activity needs consideration when the bottom shear stress changes over more than 10 %, at a place that is farther away from the border of the zone of impact than the square root of the area of the zone of impact. This was tested for the three scenarios. The first scenario used the same maximal extraction depth in the four extraction sectors, in the second scenario the four sectors were extracted to the same final water depth, while in the third scenario, all the extraction was executed in Sector 4c. The simulations showed that for all three scenarios, the changes of the bottom stress in the area, where no impact was allowed, remains limited to less than 6 %. This is mainly due to the rather deep waters in the Hinder Banks area. More information and further results on these simulations can be found in Van den Eynde (2016b).

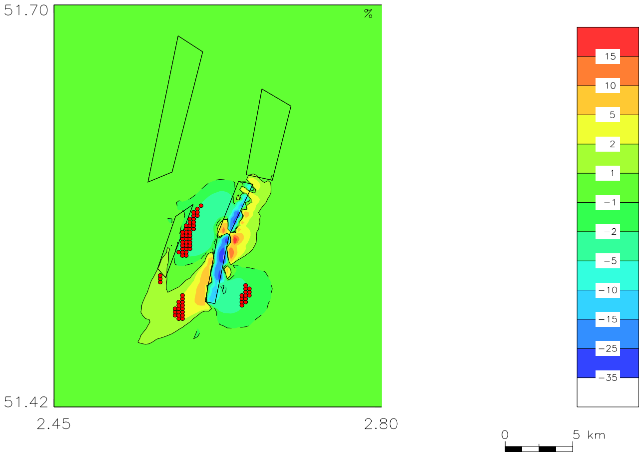

Figure 8: Aggregate sectors in the Hinder Banks along which changes of mean bottom shear stress over a spring-neap tidal cycle for scenario 3 are shown. Also indicated are the points, outside the buffer zone, where the increase/decrease is more than 2 %.

The effect of the newly proposed extraction limit level on the bottom shear stress changes

Introduction

Over the last 6 years, the extraction of marine aggregates is increasing considerably. While in the period 2003-2010, the total volume of extracted marine aggregates on the Belgian Continental Shelf remained below 2.5 Mm³, since 2011 the extraction increased, with peaks in 2013, with an extraction of more than 4.0 Mm³, and 2014, with an extraction of even more than 6.0 Mm³ (Van den Branden et al., 2016). The volumes are mostly needed in response to the needs of the Coastal Safety Plan bringing the level of protection against extreme storm events at a 1:1000 years return period, including a +30 cm sea level rise by 2050 (www.kustveiligheid.be).

The limits of the extraction is at the moment set at 5 m below the reference level, that was defined by the Continental Shelf Service of the FPS Economy (COPCO) (Law of 13 June 1969 on the exploration and the exploitation of non-living resources of the territorial sea and the continental shelf, changed by the law of January 20 1999 and April 22 1999). The reference model is based on a depth digital terrain model in the extraction zones, measured during multibeam surveys in the first half of the previous decennium. Based on this limit, three areas in the extraction zone 2 (KBMA, KBMB and BRMC), where extraction led to a deepening of more than 5 m, were closed (*Figure 9*). Also in other areas in zone 1 (TBMA) and zone 4 (HBMC), this limit is approached, which will lead to the closure of these areas following the current legislation.

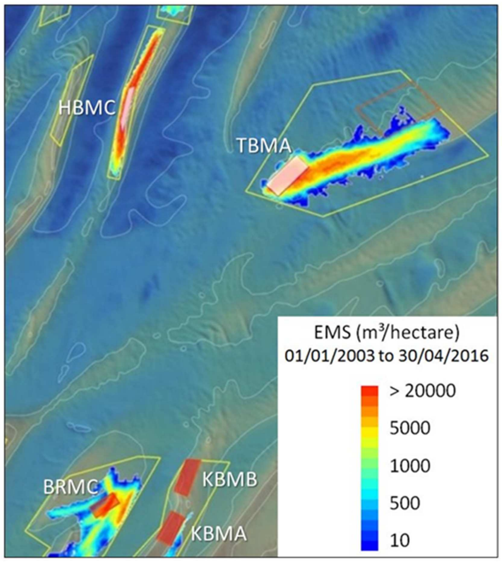

Figure 9: Areas closed for extraction (red) and areas where the limit is almost reached (rose) (From Degrendele, 2016).

However, this method does not account for the geology of the area, nor the differences in impact per sector. Furthermore, the sustainable character of the marine aggregate extraction is at stake. The areas with the best quality sands (medium to coarse sands) are being closed while zones with economically less interesting quality (fine sands) remain open. Therefore COPCO started with a new project to define a new extraction limit level based on scientific and economic criteria (Degrendele, 2016; Degrendele et al., this volume). The goal of the new extraction limit level is to limit the impact of the extraction in the most ecologically sensitive areas and to increase the economic sustainability, by accounting for the available volumes and the quality of the sands. Three scenario levels were proposed: a maximum, minimum and medium scenario based on these new criteria. Remark that in these new scenarios, the total volume of the reserves, i.e., the total volume that could be extracted, decreases from about 1,050 Mm³ to 927 Mm³, 538 Mm³ or 599 Mm³ respectively. At the moment, scenario 3 is the preferred one.

In this section, the effect of this newly proposed extraction limit level on the changes in the bottom shear stress is evaluated, with respect to the MSFD regulations, as mentioned already in the previous section.

Simulations

To assess the impact of the maximum extraction of the marine aggregates, taking into account three scenarios for the new extraction limit level, the new bathymetries were first introduced in the OPTOS-FIN bathymetry. Based on the 5 m x 5 m resolution bathymetries for the extraction zones and for the new extraction limit levels, provided by COPCO, new bathymetries with the resolution of the OPTOS-FIN model were set up and introducted in the model bathymetry. In *Figure 10*, the original bathymetry, the bathymetry of the extraction limit level, using scenario 3 and the difference between both are shown for the Sector 2b (Buiten Ratel). The difference between the original level and the level after extraction varies between 0 m and 7 m in this sector.

The volumes of extraction, calculated for the three extraction limit levels (scenario 1 to 3) are similar to the ones, calculated by COPCO, but are slightly smaller than those. This is mainly due to the difference in resolution.

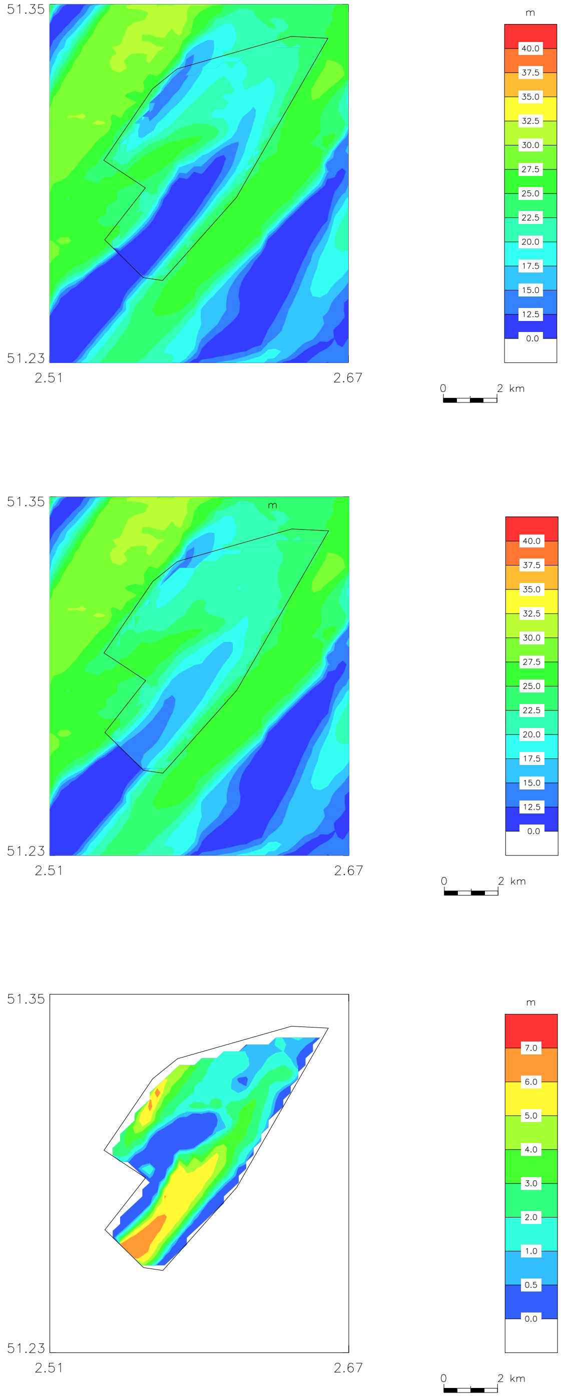

Figure 10: Upper: bathymetry of the extraction zone 2b (Buiten Ratel); Middle: bathymetry of the extraction limit level for scenario 3 in the extraction zone 2b; Lower: difference between the original bathymetry and the extraction limit level for scenario 3.

For each of the scenarios, the changes in bottom shear stress were evaluated. Also here, the COHERENS bottom shear stress is used in these first tests. The simulations were executed for a full neap-spring tidal cycle

(September 8, 2013, 01h00 till September 22, 2013, 19h30). The main goal was to determine whether outside the buffer zone for each extraction area, the bottom shear stress increased or decreased with more than 10 %.

Results

In *Figure 11*, as an example, the bottom shear stress changes are shown for the bottom shear stress using the original bathymetry and the bottom shear stress, using the bathymetry of the extraction limit level, scenario 3. One can see that in the extraction zones, due to the deepening, the bottom shear stress decreases. Outside the extraction zones, the bottom shear stress increases. Furthermore one can see that the zone of influence can be considerably, extending to the coast itself, but that the changes outside the buffe zone, remain limited.

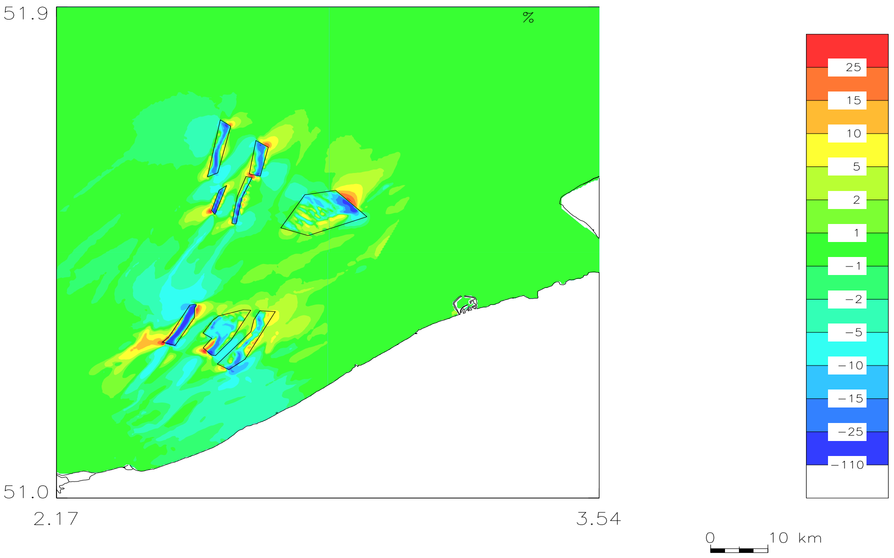

Figure 11: Bottom shear stress change on the Belgian Continental Shelf for the extraction limit level scenario 3.

In *Figure 12* the minimum and the maximum change of the bottom shear stress is shown for the different extraction zones and for the area outside the buffer zone, in the buffer zone and in the extraction zone itself, for scenario 3. The largest decrease of bottom shear stress is inside the extraction zone, while the largest increase is in the buffer zones. The largest influences are found for the extraction zone 2c, the Oostdijck sandbank, where a decrease of -56 % is found in the extraction zone itself, and an increase of +73 % is found in the buffer zone. Outside the buffer zone, the maximum increase is +13.6 % respectively, near Sector 2c. Remark that for scenario 1, also near Sector 4d an increase of the bottom shear stress outside the buffer zone of more than 10 % is found (+11.7 %). In an area of 4.90 km² outside the buffer zone around Sector 2c, an increase in bottom shear stress is found of more than 10 % for scenario 3, while for scenario1, an area of 8.38 km² and 0.21 km² outside the buffer zones around Sector 2c and 4d are found respectively. This means that also for the more moderate scenario 3, extraction up to the newly proposed extraction limit level for Sector 2c would induce an increase of more than 10 % outside the buffer zone, which is in conflict with the regulation for the MSFD.

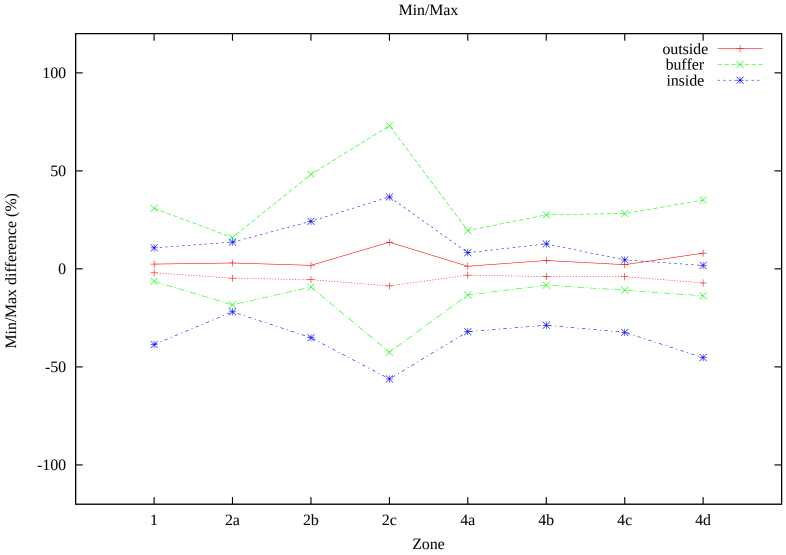

Figure 12: Minimum and maximum bottom shear stress change in the different zones outside the buffer zone (outside), in the buffer zone (buffer) and in the extraction zone (inside), for scenario 3.

Improvement of scenario 3

The current research shows that the newly proposed extraction limit level, using scenario 3, would lead to problems with the current regulations of the MSFD. The extraction of marine aggregates in the extraction Sector 2c up to the new extraction limit level would lead to an increase of the bottom stress with more than 10 % outside the buffer zone (as modelled with a validated numerical model during a neap-spring tidal cycle). Two solutions to overcome this were investigated. In the first solution, the reference level was increased in the entire zone, with a fixed level, varying from 2 m to 4 m. In the second solution, no extraction was allowed below a certain minimum depth. This minimum depth varied between 18 m to 15 m.

For the first solution (see *Figure 13*), increasing the extraction limit level with only 2.5 m still resulted in an area of about 2.0 km², where the increase in bottom shear stress was larger than 10 %, outside the buffer zone. Only with an increase of 4.0 m, no increase of more than 10 % was still present, outside the buffer area. In this case still 48.6 Mm³ was available for extraction. Remark that this is a considerable decrease compared to the original volume of 104.5 Mm³, that could be extracted when applying the original scenario 3 extraction limit level.

In the second solution (*Figure 14*), a minimum depth of about 15 m, is needed, to ensure that no changes in bottom shear stress larger than 10 % would occur outside the buffer area. Remark that in this case, only some 34.8 Mm³ is left for extraction. This is clearly the less suitable solution. More refinement could be proposed to still ameliorate the proposed solution.

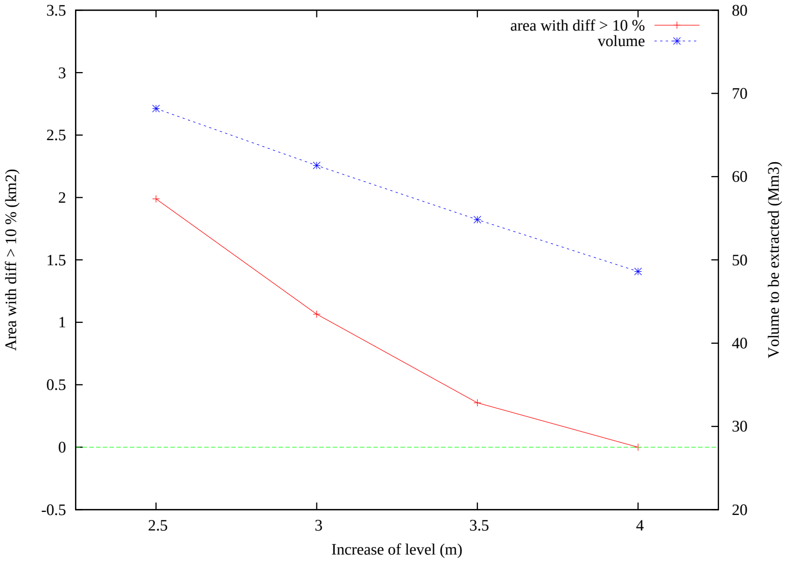

Figure 13: Area outside the buffer zone where the bottom shear stress difference is larger than 10 % (in km²) and volume to be extracted (in Mm³) for the solution 1, as a function of the increase of extraction limit level.

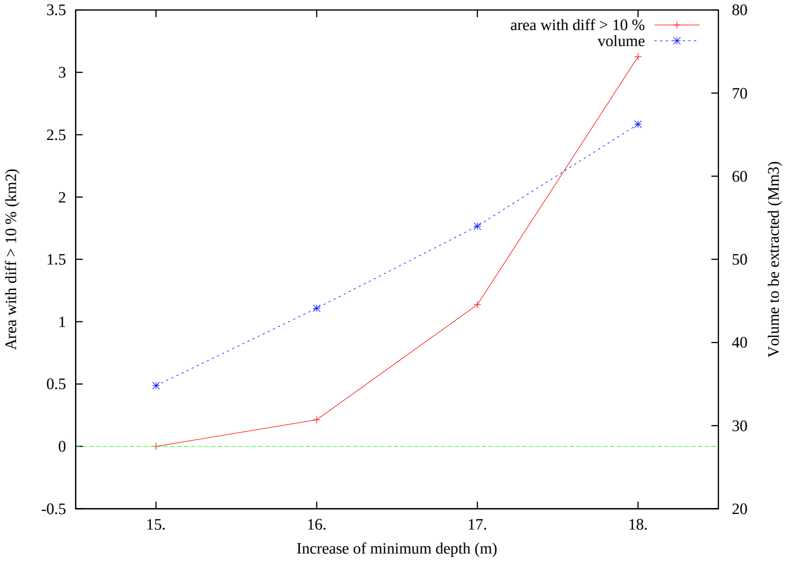

Figure 14: Area outside the buffer zone where the bottom shear stress difference is larger than 10 % (in km²) and volume to be extracted (in Mm³) for the solution 2, as a function of imposed minimum depth.

Conclusions

The bottom shear stress model was used to test whether the newly proposed extraction limit levels, proposed by Degrendele (2016) and Degrendele et al. (this volume), would still be compliant with acceptable bottom shear stress changes as defined in the Belgian implementation of the MSFD, i.e., no increase or decrease of more than 10 % outside a buffer zone around the aggregate extraction sectors. This new extraction limit level would replace the existing level, which limits the extraction at 5 m below a reference level that was previously defined by COPCO. It was shown that for the scenario 3, which is the preferred scenario, no problems are foreseen, except for the extraction Sector 2c on the Oostdijck sandbank. The compliancy with MSFD specifications would remain if the new extraction limit level would be raised with 4 m in this extraction zone. However, this results in a significantly reduced volume of extractable sediments. Remark that such exercises are done for the first time; previously, extraction levels were merely defined on an *ad hoc* basis. More information on these simulations and results can be found in Van den Eynde (2017).

Overall conclusions

In the present contribution, the effect of extraction of marine aggregates on the bottom shear stress was evaluated in the framework of the Marine Strategy Framework Directive. In the Belgian implementation of this directive, it was stated that a human impact needs consideration when the bottom shear stress, calculated with a validated numerical model, changes with more than 10% at a specified distance of the activity. In this paper, the validation of the numerical model is presented first. Thereafter, two applications of the bottom shear stress model are presented that evaluate the impact of marine aggregate extraction.

In a first part of this contribution, the validation of the numerical model was presented. After presentation of the hydrodynamic, wave and bottom shear stress models, the validation of the hydrodynamic and wave model was discussed. The validation showed that the currents at a regular sandbank location were well modelled. However, in morphologically complex locations results are less good. This is probably due to complex tide-topography interaction. Also waves were modelled satisfactorily.

Bottom shear stress measurements were obtained by applying a logarithmic profile to the current profile, measured with a bottom-mounted ADCP. The method of Wilkinson (1984) was applied to estimate the confidence limits.

The validation of the bottom shear stress model showed that the bottom shear stress could be reasonably modelled by the numerical models. Using a constant bottom roughness, best results were obtained by the Soulsby model, using a constant bottom roughness length of 0.01 m. Similar results were obtained by the other models. The bias was around 0.20 Pa, with a root-mean square error of about 0.35 Pa, for campaign BM01. Over more than 90 % of the time, the modelled bottom shear stress was between the 95 % confidence limits. Less good results were obtained for measurements in morphologically complex areas. This is probably due to the less quality of the modelled currents and to the specific tide-topography interactions at the site. No better results were obtained when calculating the bottom roughness length by empirical models.

Also high frequency current measurements were used to estimate the bottom shear stresses, mostly near the measuring station MOW1, near the harbour of Zeebrugge. Also these measurements were used for the validation of bottom shear stress models. Remark however, that the estimation of the bottom shear stresses is still a difficult task and that the less quality of the bottom shear stress measurements hampers a solid validation of the bottom shear stress models. More high quality measurements of the bottom shear stress are needed, possibly using different techniques in measurements. Certainly in more offshore regions, like the Hinder Banks, more high quality measurements of the bottom shear stress are needed.

In the second part of this contribution, two applications were presented. Firstly, three scenarios were simulated to investigate the influence of a large-scale extraction of marine aggregates (35 million m^3) on the bottom shear stress in zone 4 of the Hinder Banks. The first scenario used the same maximal extraction depth in the four extraction sectors, in the second scenario the four sectors were extracted until the same final water depth. In the third scenario, all the extraction was executed in Sector 4c. The simulations showed that for the three scenarios, the changes of the bottom shear stress in the area, where no impact was allowed, remained limited to less than 6 %. This is mainly due to the rather deep waters in the Hinder Banks area.

In the second application, the new extraction limit levels proposed by COPCO (Degrendele, 2016; Degrendele et al., this volume) were evaluated. Results showed that for the scenario 1, too high bottom shear stress changes could be expected around the extraction Sectors 2c and 4d. For the scenario 3, only too high bottom shear stress changes were expected, outside the buffer zone, for extraction Sector 2c. Two solutions were investigated. It was shown that increasing the reference level with 4 m ensured that no too high bottom shear stresses were obtained outside the buffer zone, while trying to maximize the remaining extractible volume.

The current simulations evaluated the extraction of marine aggregates in the Hinder Banks area, and evaluated the new proposed extraction limit levels, with respect to the current Belgian implementation of the MSFD regulations. Some adaptations were proposed to the new extraction limits, to assure that they are in line with the MSFD regulations. Remark however, that the MSFD regulations are subject to review and changes and that the evaluation therefore could change as well. In this respect, some remarks could be made. First of all, the concept of buffer zone might need some consideration. At the moment, the buffer zone is larger for a larger 'zone of activity'. Defining a larger zone of activity therefore could make the buffer zone larger and minimize the possible problems with respect to the descriptor 7. Furthermore, the buffer zone does not all take into account the ecological values of the area. This also could become more important in the future. On the other hand, the effect of waves on the bottom shear stress is not at all considered in the present regulations. However, it is well known that waves can have a significant influence on the bottom shear stress and could therefore be included in the evaluation of bottom shear stress changes. Finally, it is well known that sandbanks can play an important role in the breaking of the waves more offshore and therefore in the protection against coastal erosion. Also this is not at all taken into account and might be a subject of future research.

The present paper therefore must be considered as contribution to the evaluation of the impact of extraction of marine aggregates on changes in bottom shear stress and hydrological conditions in general, but it is clear that further research is still needed.

Acknowledgements

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MSFD-compliant assessment of the physical effects of marine aggregate extraction in the Hinder Banks, synthesis of the first 5 years

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Introduction

A dedicated monitoring programme in the Hinder Banks region started in 2013, though since 2011 integrated monitoring of sediment processes is in place allowing a first assessment of the impacts of marine aggregate extraction in this area and evaluating the compliancy of the activities with what is stipulated in European Directives. One of the issues is to assess Good Environmental Status (GES) to comply with Europe's Marine Strategy Framework Directive (MSFD), and therefore a number of indicators needed evaluation. These indicators relate to the MSFD GES descriptors seafloor integrity (e.g., sediment and habitat changes), and hydrographic conditions (e.g., changes in current regime). It needs emphasis that the monitoring series is only 5 years long, implying that most impact hypotheses can yet not be tested fully. The assessment here presented focuses primarily on hydrodynamics and sediment transport (RBINS OD Nature), albeit with relevance to the geomorphological (FPS Economy, Continental Shelf Service), and biological (ILVO) monitoring.

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 these sandbanks, depths range from -6 m to -40 m Lowest Astronomical tide (LAT) (Figure 15); 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; 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, 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.

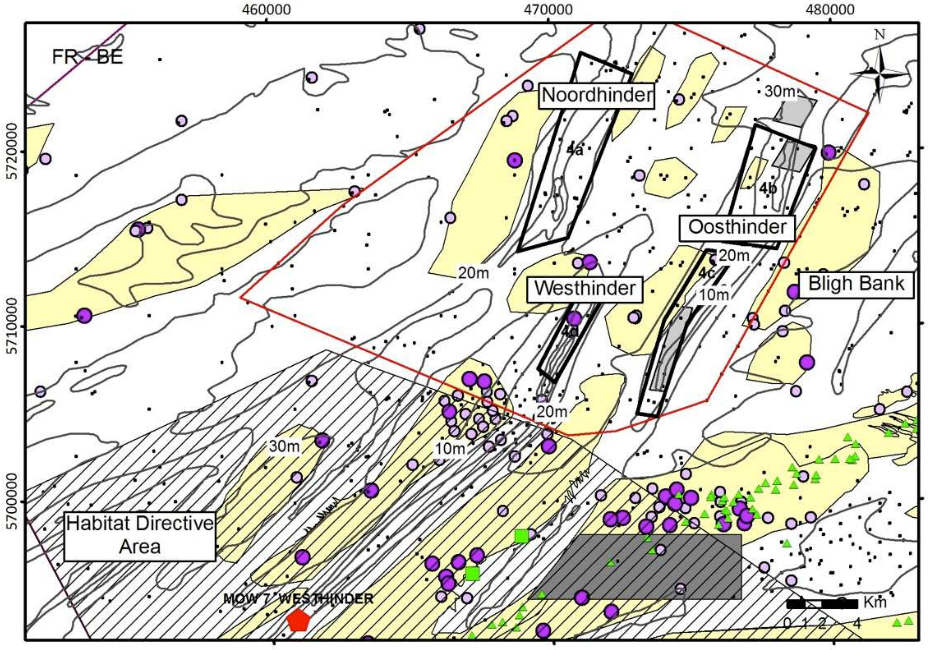


Figure 15: Area of the Hinder Banks, where intensive marine aggregate extraction is allowed in zone 4 (red line) along 4 sectors (black polygons). Within these sectors geomorphological monitoring is carried out by FPS Economy (light grey polygons). A Habitat Directive Area (hatched) is present at a minimum 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.

Over a 10 years 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. Such intensive extraction is new practice in the BPNS and the environmental impact is yet to be determined. See also Roche et al. (this volume) and De Backer et al. (this volume).

The Hinder Banks concession area is just north of the 'Flemish Banks' Habitat Directive Area (92/43/EEC; see box below) (Figure 15). The northern limit of this area was drawn to include ecologically valuable gravel beds (Houziaux et al., 2008). These beds have the status of "reefs" (Habitat type code 1170). At present, and in contrast to 100 years ago (Houziaux et al., 2008, and references therein), the extent of the reefs has become very marginal because of intensive fisheries. With the extraction activities being a new stressor in the area, it is critical to closely monitor the status of these reefs since smothering may occur from multiple and frequent depositions from dredging-induced sediment plumes. Particularly, the areas where in 2006 still hotspots of biodiversity were found were targeted, the so-called refugia, or protected gravel beds, *sensu* Houziaux et al. (2008). These occur in the troughs of morphologically steep sand dunes ('barchan' dunes; Van Lancker, 2017), and as such considered more protected from trawling activities.

Habitat Directive

http://www.health.belgium.be/en/habitats-directive-areas-belgian-part-north-sea

Implementing the Habitats Directive (92/43/EEC), the Belgian State designated a Habitat Directive Area "Flemish Banks" (Royal Decree of October 16, 2012) of 1099.39 km^2, located in the southwest of the Belgian part of the North Sea. It borders the French Birds and Habitats area "Bancs de Flandres" and extends to about 45 km offshore. The Flemish Banks were designated for the protection of the "sandbanks permanently covered with seawater" (Habitat type code 1110) and the "Reefs" (Habitat type code 1170). These sandbanks and reefs are ecologically the most valuable habitats of our North Sea. Two biotopes were characterized as "reefs": (1) reefs formed by the sand mason worms (*Lanice conchilega*), located in shallow water closer to the coast; and (2) the gravel beds occurring more offshore, especially and to a large extent at the level of the Hinder Banks. The gravel beds are a very rare and endangered habitat of gravel and boulders that may or may not be clumped together in the sandy or clayey subsoil and host a unique and rich diversity of species of fauna and flora. They once constituted the biotope of the European oyster which along with the stones were heavily colonised by a very peculiar fauna. Gravel beds fulfil an important function as spawning chamber and nursery of the fish species. Through the use of trawl nets, including the beam trawl, their extent has become very marginal (http://www.health.belgium.be/en/habitat-types-be-protected).

Material and methods

Measurements were acquired, in view of (1) characterizing the spatial and temporal variability in seabed nature; (2) building up knowledge on sediment processes in the Hinder Banks; and (3) first testing of impact hypotheses (e.g., Van Lancker et al., 2010), in which the investigation of cause-effect relationships was important.

Throughout the monitoring, a series of instrumentation and approaches have been used to study both naturally- and human-induced variability in sediment processes (Figure 2). Data prior to this period was scarce, and little was known on the sandbank dynamics, as well as of the water properties in the region (‘blue clear waters’). Therefore, in 2011-2013 emphasis was put on the spatial variability of water and sediment processes and measurements were made along transects over the sandbanks in all sectors, albeit in combination with measurements on fixed locations (e.g., with bottom-mounted acoustic Doppler current profilers (BM-ADCP)). The spatial approach was important to characterise the T_0 situation. An innovative experiment took place in 2013, using a Wave Glider (Liquid Robotics). In a period of 30-days the autonomous surface vehicle sailed around Sector 4c and monitored turbidity events under naturally- and anthropogenically-steered conditions (Van Lancker and Baeye, 2015). Also seabed mapping was invested in using a combination of acoustic measurements, seabed samples and visual observations. Complementary to the multibeam monitoring conducted by FPS Economy, RBINS acquired multibeam depth and backscatter mostly in the gullies in and out of the Habitat Directive Area. Time series were recorded along the most ecologically valuable areas (Montereale-Gavazzi et al., in press). From 2013 onwards, visual observations were conducted also, mostly in the ecologically important gravel beds in the Habitat Directive Area, but also in other parts of the gullies in the bigger study area. Video frames (VLIZ) were deployed, and diving operations (RBINS-OD Nature) were conducted. In both 2014 and 2015, opportunities were taken to obtain seabed imagery with a remote operated vehicle (Genesis ROV, operated by VLIZ). With respect to sediment transport measurements, some stationary measurements (deploying BM-ADCP), albeit short-term, were conducted in the period 2014-2015, focussing on Sector 4b-4c and on the gravel beds in the Habitat Directive Area. However, emphasis was also on the gullies to investigate the seabed substrate in more detail. Experience showed that results from measurements along transects or on drift complicated largely the interpretation as well as the quantitative correlative analyses of the data. This is due to the complex sandbank environment where sediment resuspension and advection may vary strongly with morphological position. This was shown especially with the Wave Glider capturing a multitude of turbidity increases in the water column, both naturally- and human-induced, but that also evidenced important lag effects between such increases and their drivers.

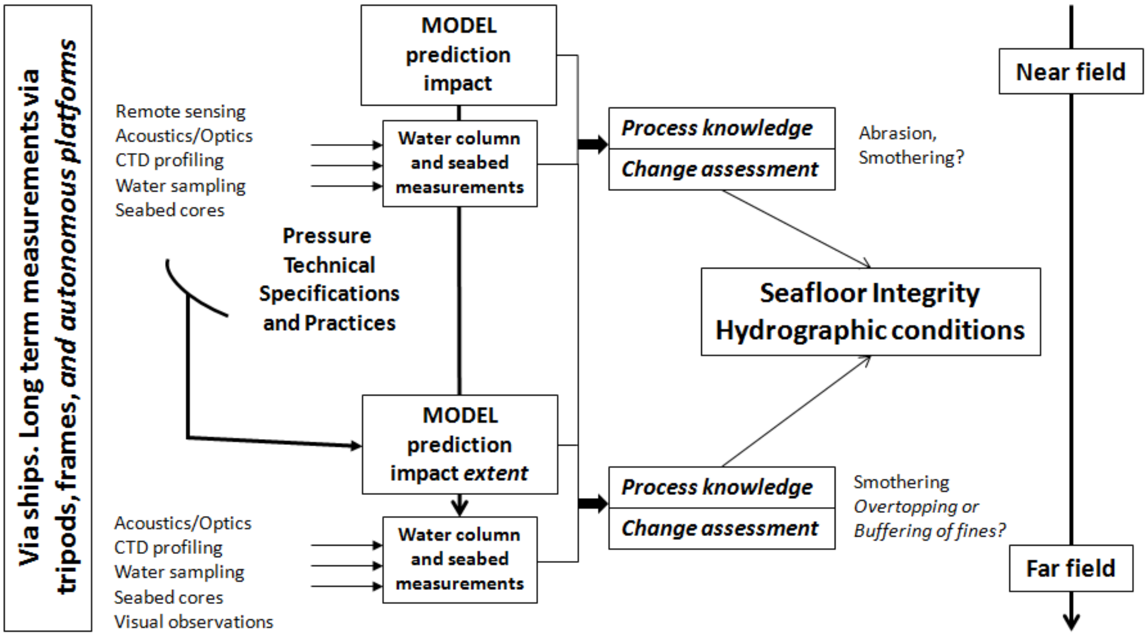


Figure 16: Overview of the RBINS OD Nature research strategy aiming at quantifying both near- and far-field impacts of marine aggregate extraction.

Regarding the mathematical models, results were obtained from a number of new modules. These were developed in view of assessing changes in seafloor integrity and hydrographic conditions, two key descriptors in the definition of GES (MSFD):

1. A new workflow for sediment plume modelling was developed coupling technical specifications of a series of trailing suction hopper dredgers (TSHD) and data on extraction activities to an advection-diffusion model that predicts the extent and total mass / concentration of sediment fractions released from the TSHDs. Effects 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 were modelled.
2. The suite of hydrodynamics and sediment transport models were validated with the newly acquired measurements to optimize modelling in the Hinder Banks.
3. Regarding bottom shear stress, a variety of calculations from measurements and modelling approaches were revisited. Recommendations were formulated when using bottom shear stress models in impact predictions under various scenarios of extraction.

See Van Lancker et al. (2015) for more detailed methodological approaches on sediment plume modelling. The methodological workflow on bottom shear stress modelling is outlined in Van den Eynde (2016) and Van den Eynde et al. (this volume).

Results

Physical impact assessment

Monitoring results

The following results were obtained on a first assessment of near- (in and around the sectors of extraction) and far-field impacts toward the south, where ecologically sensitive gravel habitats occur in the 'Flemish Banks' Habitat Directive Area. First, some characteristics of TSHDs are provided typical for the operations in extraction zone 4 of the Hinder Banks. Subsequently, some factual observations are listed. Finally, some hypothetical impact relationships are put forward that were further tested.

TSHD characteristics and their operations

1. TSHD typically operated under the ebbing phase of the tide, hence when the current was SW-directed (at least for the coastal safety-related extraction).
2. Deposition of dynamic sediment plumes, near the TSHDs, was observed using acoustic imagery (multibeam and ADCP; see also Roche et al., this volume).
3. Deposition of a passive plume, in the far field of a TSHD, was observed acoustically also, 3 hrs after an extraction event (Van Lancker and Baeye, 2015).
4. Modelling of the overflow plume showed that most of the sandy material deposits in the near field. In a tidal cycle, the finer fractions of the overflow can deposit in the ecologically valuable gravel beds in the Habitat Directive Area, though modelling results would simulate a resuspension of the material under agitated conditions (e.g., spring tide, or enhanced current-wave interaction).
5. Since the start of extraction in 2012, and especially in 2014, the activity was intense per period of extraction (high amount and extraction by multiple vessels), but was followed by long, intermittent periods, of no extraction.

See Van Lancker et al. (2015) for detailed results.

Hydrodynamics and sediment transport

6. Based on peak tidal current velocities and tidal amplitude, calculations show a tidal excursion of particles released in Sector 4c of up to 14 km. Since extractions take place during the ebbing phase of the tide, when the currents are SW-oriented, this implies that the particles can deposit in the 'Flemish Banks' Habitat Directive Area. From a risk management perspective, the ecologically sensitive gravel beds can be affected.
7. From 30-days current measurements around Sector 4c using a Wave Glider (Van Lancker and Baeye, 2015), and conform to the other measurements, flood and ebb tidal currents were overall quasi equally strong. Still, at the sandbank level, measured near-bed currents along the western slopes were flood dominated; and along the eastern slopes ebb dominated. Hydro-meteo conditions are able to reverse the residual current direction.
8. Longer term modelling of depth-averaged residual currents showed a NE-dominated sediment transport. These are reinforced when hydro-meteo conditions originated from the SW. Under longer lasting conditions from the NE, residual currents are predominantly SW-oriented, especially in the gullies. See Francken et al. (this volume).
9. Peaks in suspended particulate matter concentrations (SPMC) were linked mostly to peaks in current strength, both in the gullies, and across the sandbank crest. During spring tide, SPMC is high throughout the water column, with highest values near the seabed.

10. Tidally-induced SPMC was similar under NE- and SW-directed currents, though higher concentrations were generally measured under flood (NE) conditions. Concentrations in the surface waters were around 0.001 to 0.002 gl^{-1}, for neap and spring tide respectively. Median SPMC in the lower waters (near the seabed) were 0.011 to 0.015 gl^{-1} in the deepest areas and up to 0.019 gl^{-1} over the sandbank crests.
11. Under higher wave conditions, SPMC is high throughout the water column.
12. First results of SPMC during extraction activities showed increases with a factor of 1.25 greater than the natural background values, hence the concentrations fall within the envelope of natural variability. This applies to TSHDs of which the cargo is clean at the beginning of the operations. More turbidity arises when extraction activities alternate with maintenance dredging works in the coastal zone giving rise to remaining mud deposits in the cargo (as done in Spring 2017). SPMC measurements revealed an overflow concentration of up to 1 gl^{-1} and a particle-size distribution centred around 21 µm. (Baeye et al., this volume).
13. The gravel fields in the barchan dunes of the Habitat Directive area are subdued to a dominance of the flood current. This is derived from current measurements and based on their morphological shape. The gravel is most dense near the foot of the steep slope of the barchan dune. Here, decelerated flood currents were measured near the bed, potentially pointing to a vortex structure along the steep side of the barchans.
14. As a conclusion, natural variability of sediment processes in the Hinder Banks region was much more variable than previously expected. This relates to bedform migration (see below), bottom shear stress, as well as SPMC in the water column. This contrasts the opinions raised before the start of the monitoring: blue clear waters and low seabed dynamics because of water depth.

See Van Lancker et al. (2014, 2015, 2016), Van den Eynde (2016), Van den Eynde et al. (this volume), and Francken et al. (this volume).

Seabed substrate

15. Medium sands dominated most of the aggregate sectors on the sandbanks. Shallow seabed cores did show some finer grained layers in the upper 10-30 cm. The top zone of Sector 4c witnessed merely fine to medium sands, whilst downslope, near the foot of the gentle side of the Oosthinder sandbank, shell layers were evidenced. Combining this with geological data (UGent, RCMG), outcropping of Pleistocene deposits was shown downslope of the sandbank. Importantly, it was shown that some downslope taken cores also contained muddy layers. These constrain the extent of the extractable resource potential to the main body of the sandbank (see also Van Lancker et al., 2014).
16. In the gullies, adjacent to the aggregate sectors, medium to coarse sands predominated with shell hash deposits and geogenic gravel, locally. The Hamon grabs, that take a full sediment volume of the seabed, did show an enrichment of silt-clay in the seabed matrix. This was confirmed by video observations that showed resuspension clouds when the video frame hit the seafloor. Mostly, this fine fraction had a particle-size mode around 10 µm. Video imagery taken in March 2015 (ST1507) also showed fresh deposits of organic matter.
17. In the aggregate sector 4c, FPS Economy monitored changes in the seabed substrate for the period 2012-2015, based on multibeam backscatter time series. Changing backscatter values pointed to a sediment fining of the seabed. This became visible from May 2014 onwards (peak period of extraction). A fining of the seabed texture can imply higher seabed mobility, since seabed sediments are expected to reach equilibrium with the governing hydrodynamic conditions.
18. In the Habitat Directive Area, time series of multibeam backscatter showed changes in the areal distribution of the acoustic classes related to fine to medium homogenous sand, medium sand with bioclastic detritus and medium to coarse sand with gravel. Class changes were related to bedform

migration that mostly affected the gravel class, but the analyses also showed a more widespread distribution of the fine sand class, and local swaps between the medium sand/bioclastic and coarse sand/gravel class (Montereale-Gavazzi et al., in press).

See Van Lancker et al. (2014, 2015, 2016) for detailed results. See Roche et al. (this volume) for backscatter changes in the aggregate sectors; see Montereale Gavazzi et al. (in press) for seabed classification results and backscatter changes in the Habitat Directive Area.

Seabed morphology

17. For the period 2012-2015, FPS Economy derived important bedform migration in the monitoring area HBMC in Sector 4c (see Roche et al., this volume). Dune migration (water depths of -10 to -20 m LAT) was consistently to the NE (± 30 and 20 m yr^{-1} for a profile transecting the dunes on the western slope of HBMC, north and south part respectively), lowering and flattening of the dunes. Compared to the reference situation of 2005, the dunes migrated roughly 85 m and 65 m respectively.
18. Within the barchanoid dunes and along the top sand bank areas in the Habitat Directive Area, bedform migration was up to 40 m to the NE comparing data from 2004 against 2015. Considering the in-between surveys, it is possible to observe a progressive migration, advancing of ca. 20 m from 2004 to 2010, ca. 10 m from 2010 to 2013 and less than 5 m progressively throughout the remaining surveys up until late 2015 (Montereale-Gavazzi et al., in press). These values are less than those measured on HBMC. This may be due to a deeper water setting, to coarser sediments, but also to more counteracting forces in the ebb direction (SW-oriented) as shown in Francken et al. (this volume).

Status of the gravel beds (habitat type 'Reef', code 1170)

The gravel beds are located in the far field of the extraction activities, with the major known hotspot of biodiversity (main gravel refugium) lying 8 km southwards of the nearest extraction sector (4c). With respect to Sector 4c, the gravel bed refugia are located along the axis of the tidal stream and within the tidal excursion pathway (see above). Additionally, modelling showed that deposition of fine-grained material from Sector 4c is possible (see point 4, above).

19. The gravel bed refugia, as described by Houziaux et al. (2008,) are both positioned within the troughs of barchan dunes. Barchan dunes are very steep dunes that are typical for coarse substrates, where currents are high, and where there is sediment available to transport. The dunes are 6 to 8 m in height, with wavelengths of 150 to 200 m. Locally, their steep side is 20°. These height/slope dimensions are known to generate turbulent flow with counteracting near-bed flow. In such flow separation zones, the sand cover is minimal, but fine-grained sediments are able to settle. This was partially demonstrated from new measurements and modelling in the study area.
20. Seabed samples and video observations in the gravel bed refugia showed enrichment of silt-clay particles, and the sampled sediment-water interface clearly witnessed brown waters. Though, video data did not show a surficial smothering of fine-material at the seabed surface. Instead, the fine-grained material was buffered within the sandy substrate. This was evidenced by resuspension of sediment clouds when the seabed was agitated.
21. In the gravel bed refugia, much more sand was observed visually than expected from previous visual observations (diving observations of 2006, RBINS OD Nature, Norro et al.). The new measurements showed a very patchy distribution of the gravel blocks and they seemed partially buried in the sand. Nearest to the lee side of the dunes, in the flow separation zone, the density in gravel, at least at the surface, was somewhat higher. In 2006, sand thickness measured by divers was zero. Sand thickness at present is yet to be determined.
22. Multibeam time series (depth and backscatter) were recorded over the ecologically valuable gravel bed substrate. In the gravel refugia net losses and a gradual trend indicative of potential smothering was

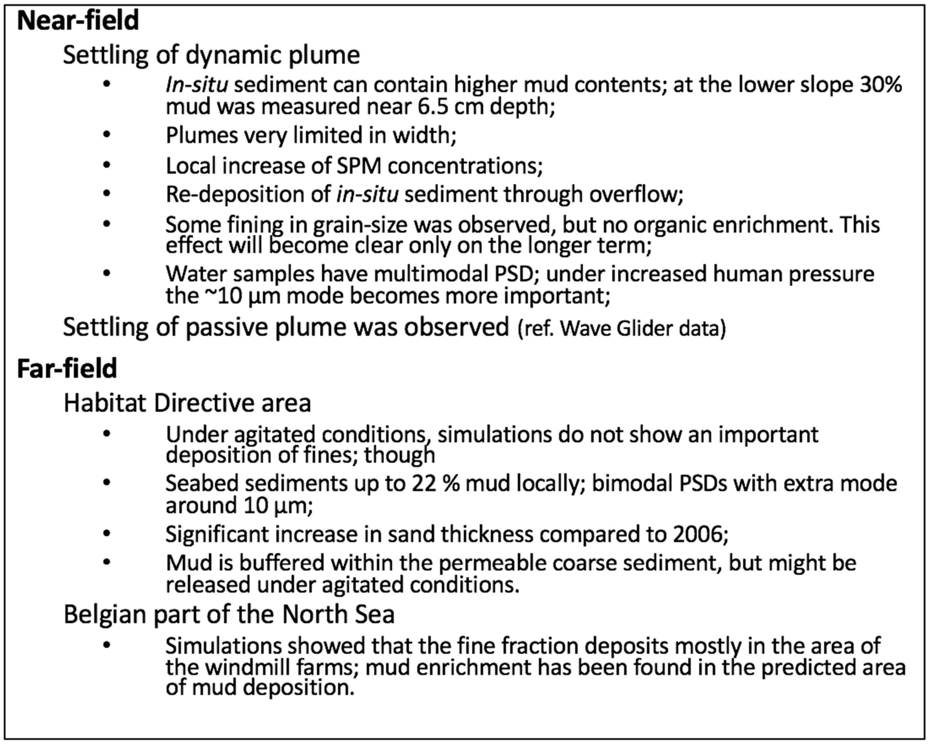
captured, including a two-dimensional morphological analysis which suggested a loss of profile complexity from 2004 to 2015 (Montereale-Gavazzi et al., in press) (see further).

23. Above findings apply mainly to the main gravel bed refugium; the barchan dunes hosting the northernmost refugium was much smaller in dimensions. Video data only showed the presence of sands and some shell hash.

See Van Lancker et al. (2014, 2015, 2016) and Montereale Gavazzi et al. (in press) for detailed results.

Summary of key findings in the near- and far-field of aggregate sector 4c, Hinder Banks, are shown in Table 1.

Table 3. Key findings on the near- and far-field monitoring (PSD: Particle-size distribution).



Near-field

Settling of dynamic plume

- *In-situ* sediment can contain higher mud contents; at the lower slope 30% mud was measured near 6.5 cm depth;
- Plumes very limited in width;
- Local increase of SPM concentrations;
- Re-deposition of *in-situ* sediment through overflow;
- Some fining in grain-size was observed, but no organic enrichment. This effect will become clear only on the longer term;
- Water samples have multimodal PSD; under increased human pressure the ~10 µm mode becomes more important;

Settling of passive plume was observed (ref. Wave Glider data)

Far-field

Habitat Directive area

- Under agitated conditions, simulations do not show an important deposition of fines; though
- Seabed sediments up to 22 % mud locally; bimodal PSDs with extra mode around 10 µm;
- Significant increase in sand thickness compared to 2006;
- Mud is buffered within the permeable coarse sediment, but might be released under agitated conditions.

Belgian part of the North Sea

- Simulations showed that the fine fraction deposits mostly in the area of the windmill farms; mud enrichment has been found in the predicted area of mud deposition.

Hypothetical cause-effect relationships

The sampling of fine-grained material in the offshore area triggered the investigation of cause-effect relationships with the aggregate extraction activities. Since multiple evidence became available on the presence of fine-grained material in the near field (Van Lancker et al., 2014, 2015, 2016; Roche et al., this volume), as well as modelling results that showed the potential of deposition of the fine-grained material in the far field, underlying processes were investigated. Most important was to investigate whether the extraction activities would induce a smothering on the ecologically valuable gravel beds in the Habitat Directive Area.

1. Hypothesis 1: **Fine-grained material can be trapped in morphologically complex areas due to enhanced tide-topography interaction** (Van Lancker, 2017). Fine-grained material was sampled in the troughs of barchan dunes along the western flank of the Oosthinder sandbank, at 8 km from the aggregate sector. From height/slope dimensional analyses of the dunes, gyres or eddies can be generated in the lee side (steep side) of the dune. As such, a flow separation zone exists characterized by low sand dynamics near the bed, but where material from the water column can settle. It is hypothesized that the more fine-grained material exists in the water column, the more material will be trapped in the trough of the dunes. Monitoring data have indeed shown the existence of a near-bed low dynamics zone, which was confirmed

by modelling results (see Van Lancker et al., 2016). The resolution of the measurements and the modelling did not allow showing increased SPMC in this particular zone. However, fine-grained material was sampled and was found to be buffered within the coarser grained permeable sand matrix. It needs emphasis that the origin of the fine-grained material cannot be unambiguously linked to the extraction activities in the Hinder Banks. Cumulative and in-combination effects may exist (see further).

2. Hypothesis 2: **Aggregate extraction, in combination with bottom trawling, extends the far field dispersal of sediment plume deposits ('in-combination effect').** It may be argued that 8 km is a too far distance to relate deposition of fine-grained material from sediment plumes to aggregate extraction activities. The monitoring showed that also in the gullies nearer to the extraction activity fine sediment clouds resuspended when agitating the seabed. During the monitoring this agitation was caused by a grounding of the video frame or ROV, or by agitation by divers. It is clear that bottom trawling, omni-present, would give rise to huge sediment clouds that are subsequently transported away by current-wave action. Important to reiterate is the fact that in the gullies there was much more sand than expected from previous seabed mapping that predicted the occurrence of gravel mainly. Geologically, the Paleogene substrate is close to outcropping, and represents a rough, hard surface. Multiple observations now show a sand cover. Quantification of the sand thickness is yet to be done. Based on expert advice from a scientist investigating bottom trawling impacts (pers. comm.) it is argued that thin sand covers over harder substrates would have been winnowed away if indeed bottom trawling, already active since 150 years, would be the sole pressure. If there is a new source of sediment, the whole winnowing process restarts.

Both hypotheses combine in a **step-wise impact hypothesis**:

1. Excess of fine-grained material and sand from overflow of trailing suction hopper dredgers;
2. Deposition in the near field and in the gullies along the tidal stream axis;
3. Resuspension by beam trawling;
4. Longer lasting deposition in morphologically complex areas that preferentially trap fine-grained sediments.

It is clear that the source of the fine-grained sediment cannot be unambiguously related to aggregate extraction. It may be a cumulative effect, hence with sediments originating from different locations where aggregate extraction takes place, and in addition to fisheries, other in-combination effects may exist, e.g., wind-mill farms that also give rise to turbidity plumes. However, according to Baeye and Fettweis (2015) the turbidity plumes generated in the wake of windmills are likely resuspended detritus and (pseudo-) faeces from epifaunal growth on the turbines that accumulated at the base of the piles.

Figure 17 provides an overview of the location of the gravel beds in the Habitat Directive Area in relation to other activities.

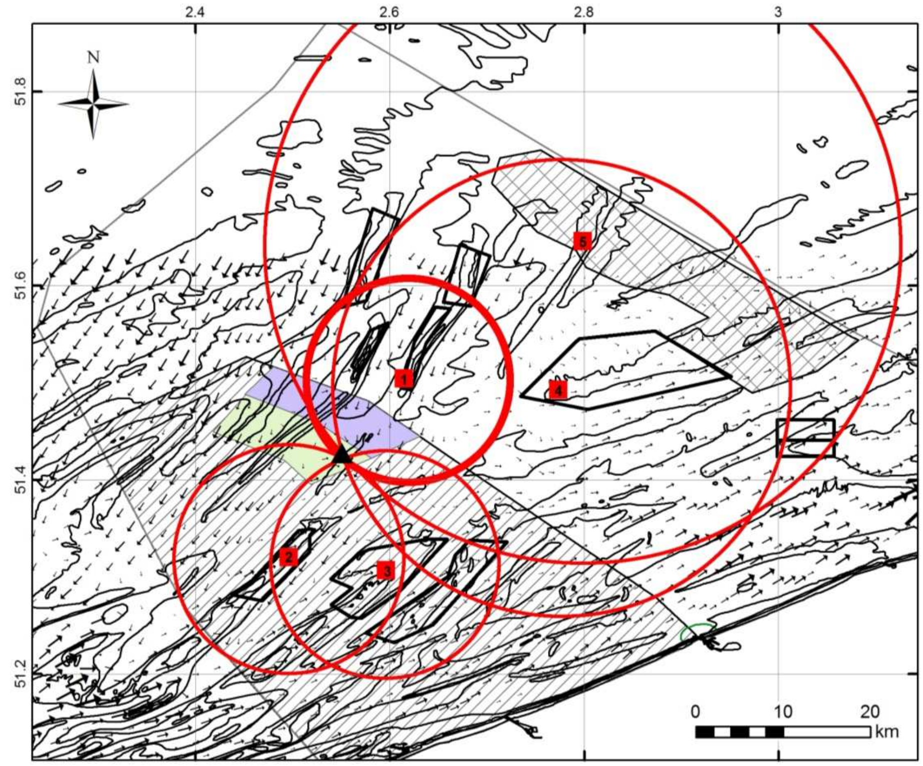


Figure 17: Ecologically valuable gravel beds in the Habitat Directive Area (centroid triangle) with the distances to the different pressures (red squares). (1) Extraction in Sector 4c, Hinder Banks; (2) and (3) Extraction in zone 2: Oostdijck and Buiten Ratel; (4) Extraction in zone 1 Thornton Bank. All of these may act cumulatively. In-combination effects may also exist, hence deposition may exist from turbidity plumes generated around the windmill structures (5). Note that these are minimally 30 km away. Importantly to note is the omni-presence of fisheries activities. On the BPNS, the influence of these activities on water column turbidity and seabed texture has not been assessed yet. To give insight in the spreading of fine-grained material, the direction and magnitude of maximum currents are indicated. Fisheries management areas are indicated also, in the north part (purple) fisheries will be prohibited in the future; in the south part (green) only alternative fishing will be allowed.

It can also be argued that the geological substratum, being composed of Paleogene clay, would be a source of fine-grained material. The thickness of the Quaternary is indeed very thin to zero in the gully in-between the Westhinder and Oosthinder sandbank (Mathys, 2009; Van Lancker et al., this volume), being the reason why gravel is occurring in this area. However, the video data in this gully showed sand predominantly and no clay pebbles were observed that could be indicative of an erosional process. The thickness of the sand layer enriched with silt is yet to be determined, but is considered to be thin since sampling with boxcores failed because of gravel presence.

Assessment of impacts w.r.t. the Belgian MSFD environmental targets

Related to the seafloor integrity criteria physical loss and damage, the Belgian State (2012) defined two environmental targets (ET), together with monitoring programmes. Since these were all newly developed, only a first evaluation is presented for the case of aggregate extraction.

1. ET 7: *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.*

To monitor this indicator, at the scale of the Belgian part of the North Sea, it was put forward to carry out (i) a full-coverage seabed mapping of a selection of areas, where the delineation of the EUNIS level 3 habitats has a high confidence; (ii) transect seabed mapping crossing the EUNIS Level 3 habitats and the gravel beds. For the methodology, a combination of multibeam bathymetry / backscatter and seabed sampling, in a stratified random sampling approach, was proposed. At least 1 mapping round per MSFD cycle (6 years) should be procured.

2. ET 17: *Within the gravel beds*[1] *(in test zones), 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.*

For this indicator an annual monitoring was proposed to enable linking observed changes to human activities. Also multibeam bathymetry / backscatter were proposed as methodology, in combination with visual observations and seabed sampling; the latter following a stratified random sampling approach.

For ET 7 the indicator implies that no transitions are allowed from the class sandy mud to mud towards muddy sand to sand and vice versa, as well as from muddy sand to sand towards mixed or coarse sediments and vice versa (Figure 18). Specifically related to coarse sediment, *incl.* gravel, enrichment of mud should not lead to muddy sandy gravel (mixed sediment). Also, it is put forward that the extent of the gravel beds should be safeguarded. The latter targets the prevention of the loss of gravel beds. Changes need evaluation against the Initial Assessment (Belgische Staat, 2012). Herewith was also stated that changes should remain within the margin of uncertainty. This quantification of uncertainty is on-going (Belspo TILES project; Van Lancker et al., this volume).

From the monitoring of the seabed substrate in zone 4, most samples fall within the classes sand, coarse sediment and gravel. The monitoring did depict a new class ‘mixed sediments’ which was not mapped in the Initial Assessment. Mixed sediments typically contain an admixture of mud. Referring to the Folk diagramme (Figure 18) sediments are classified as mixed sediments when in the gravel range of 5 % to 80 % gravel, the sand to mud ratio is lower than 9 to 1. In Table 4 the threshold of mud percentage is shown per major gravel percentage. For the higher gravel percentages, only a minor addition of mud already results in mixed sediments.

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[1] For the monitoring of this indicator, the Belgian State defined two test zones in the Habitat Directive Area: one along the southern Oosthinder sandbank (‘barchan dune’ area, here discussed); one in-between the Kwinte Bank and Buiten Ratel sandbank (‘KWGS’ area).

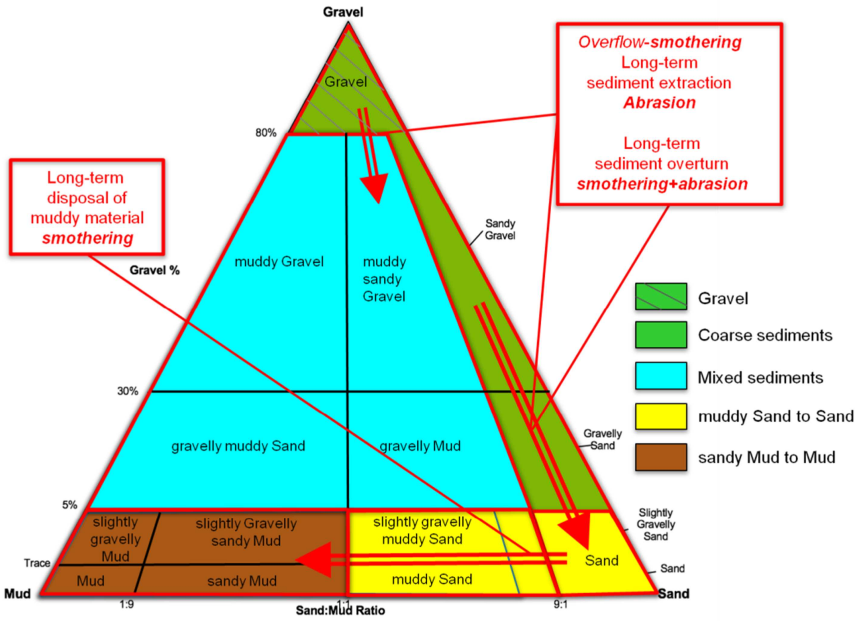

Figure 18: Relationships between EUNIS Level 3 Habitats (sandy mud to mud; muddy sand to sand; mixed sediments and coarse sediments) as derived from a grouping of the 14 Folk substrate classes (Folk, 1954). For the Belgian MSFD implementation, gravel is also considered individually. Regarding changes in this indicator of seafloor integrity, possible transitions are indicated that can occur under the influence of human activity.

Table 4: Threshold of allowable mud percentage per major gravel percentage. Higher mud percentages result in lower sand to mud ratios, classifying sediments into mixed sediments instead of coarse sediments.

% gravel	% sand	% mud	sand:mud ratio
5	85.5	9.5	9
10	81	9	9
20	72	8	9
30	63	7	9
40	54	6	9
50	45	5	9
60	36	4	9
70	27	3	9
80	18	2	9

In the databases containing particle-size distribution (PSD) data (Van Lancker, 2009) there were no samples having elevated mud percentages in the gravel areas before the start of the present monitoring activities. However, the present monitoring showed that the mud was retained in the sand matrix (within the interstitial pores). This complies with the multiple observations of ‘brown waters’ and appearance of sediment clouds when stirring the sediment (with ROV or video frame landings, or agitation by divers).

Furthermore, monitoring in the gravel rich areas showed more sand than the expected gravel clasts, which may result in a classification of sand rather than gravel. This is especially the case in areas with low gravel percentages, where an overtopping sand layer would easily prevent the detection of gravel clasts. However, the multibeam monitoring did not allow differentiating changes in the sand thickness layer beyond the total propagated bathymetric error (all sources of errors originating from the suite of instrumentation used during acquisition). Under IHO standards, the total vertical uncertainty with ± 95 % confidence levels of the depth measurements result in ± 0.40 and 0.33 m vertical error for the multibeam echosounders used (Kongsberg EM1002S and EM3002D, respectively) (Montereale-Gavazzi et al., in press). However, a sand layer thickness within this margin would already be sufficient to prevent epifaunal growth on the gravel clasts.

For a more in-depth discussion on constraints in evaluating the indicator on allowable habitat change, reference is made to Van Lancker et al. (2016). In any case, evaluation of the ET 7 indicator is difficult in areas with gravel and uncertainty in the mapping is generally high. In any case, since the sediment is a first proxy of many species and biological communities, further follow-up is needed.

For the evaluation of ET 17 on the monitoring of the ratio of the surface area of hard versus soft substrata, a standardized workflow was developed using pre- and post-seabed classification approaches (Montereale Gavazzi et al., in press). Aim was to evaluate habitat change related phenomena in multibeam backscatter within a series of repetitive measurements along the biodiversity rich gravel beds in the Habitat Directive Area. Seven time series were available in the period 2004-2015 with two surveys prior to extraction, three during extraction and two post extraction. Results indicated that after an initial gain of the soft substrata ('smothering') by spring 2014, the ratio re-established in favour of the hard substrate, and returned to the initial state. Nonetheless, in the gravel refugia net losses and a gradual trend indicative of potential smothering was captured by all methods, including a two-dimensional morphological analysis which suggested a loss of profile complexity from 2004 to 2015 (Montereale-Gavazzi et al., in press). Establishing causal relationships with natural and anthropogenic stressors is underway.

Hydrographic conditions (GES descriptor 7)

For descriptor 7 on hydrographic conditions, the Commission only put forward two secondary criteria to be assessed: (1) Spatial extent and distribution of permanent alteration of hydrographical conditions; and (2) Spatial extent of adverse effects on benthic habitats from permanent alteration of hydrographical conditions. To that end the Belgian State (2012) defined three indicators, mainly in the view of preventing permanent changes to hydrographic conditions.

1. ET 29: *A human impact demands consideration if one of the following conditions – related to the bottom shear stress on a 14 days spring tide/neap tide cycle as computed by validated mathematical models – is met: i) there is a difference of more than 10 % in the mean bottom shear stress; ii) 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*.
2. ET 30: *The impact, that needs consideration, should remain within a distance equal to the root square of the surface occupied by this activity and taken from its external limit*.
3. ET 31: *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 it 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*.

Monitoring of these changes needs execution within the permitting procedure, during the preparation of the environmental impact assessment, or during its evaluation. It will determine whether new activities will impact on the hydrodynamics and whether this requires further research (ET 29). In that case, it is expected that the impact remains limited to the environment of the activity (ET 30). It is also stipulated that depth, 3D currents and bottom shear stress need to be evaluated. Use should be made of a validated numerical model with an adapted resolution and model validation based on *in situ* measurements acquired in the area for which the permit is asked for. To evaluate the cumulative impact, a database will be developed and maintained to register the bathymetrical evolution, as well as the human activity at sea that needs consideration (ET 31).

Applied to the Hinder Banks study area, the newly acquired *in situ* measurements on bathymetry, currents and bottom shear stresses were used for the validation of the numerical models. Next a workflow was established on how to evaluate changes in bottom shear stress, compliant with the prescriptions set in the MSFD context (Van den Eynde et al., this volume). In a first research phase, some extraction scenarios were then simulated in zone 4 of the Hinder Banks and changes in bottom shear stress were evaluated. Following the permit, in total

35 million m³ of sands can be extracted in the area over a 10 years period. In a first scenario a similar maximal extraction depth was used in the four extraction sectors to reach the total volume; in the second scenario the four sectors were extracted until the same final water depth; in the third scenario, all the extraction was executed in Sector 4c. The simulations showed that for the three scenarios, changes in bottom shear stress did get higher than 10 % where extraction activities took place (ET 29), though the changes of the bottom shear stress in the area, where no impact was allowed ('outside distance' or within the buffer zone), the change remained limited to around 6 %, hence less that the maximum allowance of 10 %, as specified within the Belgian implementation of MSFD (ET 30). No research has yet been carried out on how this combines with other human activities in the area (ET 31). In Van den Eynde (2016); Van den Eynde et al. (this volume) results are given in detail and are discussed in view of future monitoring.

As a conclusion, the newly defined monitoring programmes proved successful in evaluating the mere physical MSFD indicators on seafloor integrity and hydrographic conditions as defined in 2012 (Belgische Staat, 2012). Results show that the monitoring is able to quantify changes, though the significance of the changes beyond the natural variability and error envelopes (technical and analytical) remains challenging.

Discussion

The Marine Strategy Framework Directive requires that all EU Member States take measures to ensure that human pressures do not exceed use of the marine environment for present and future generations. The whole approach is new, and especially its application in offshore waters is highly challenging since these areas suffer from data scarcity, and subsequently knowledge on the marine environment is far less than in coastal areas. This was already recognized by the Commission Decision 2010/477 EU in which it was put forward that there is a substantial need to develop additional knowledge and system understanding to implement the concept of achieving 'Good Environmental Status' in a truly science-based way. In any case, assessing the status of an environment is very difficult, the more it provides limited insight in how it should be managed. Instead it is much more practical to focus on quantifying pressures (perturbations) and their presumed impacts (i.e., changes in the state of the ecosystem), since these are in most cases manageable. A number of data and knowledge gaps were identified in the present monitoring that hamper the provision of adequate assessments:

Baseline – natural variability

Compared to the coastal area, data availability is rather poor in offshore areas, and there is only a fragmented knowledge on habitats and ecosystem functioning. Generally, time series datasets are scarce. Mostly, existing data have highly varying spatial and temporal scales implying huge uncertainties in the overall dataset. This is challenging to resolve in complex sandbank environments, where seabed nature and dynamics vary with morphological position.

Regarding knowledge on the state of the environment the main issues related to (i) Poor prior knowledge on fine-grained fractions in the seabed and poor quantification of gravel percentages, mostly due to the use of sampling gear not allowing appropriate quantitative sampling of both the fine- and coarse-grained part of the sediments. (ii) Limited to no knowledge on the sand cover overtopping the gravel lag. Video data in the gravel areas mostly showed the presence of sand with sporadically gravel occurrences. Since sand overtopping prevents biodiversity to flourish on gravel beds there is an urgent need for sand thickness estimation, which is probably only do-able by divers. A major lesson learned was the importance of knowing the geological substrate and realizing its importance in predicting habitat change (e.g., change in sediments at the lower slopes of the sandbanks).

Little is known on water column and seabed dynamics, as well as on the processes involved. Knowledge on natural processes is important for the understanding of recovery and resilience of ecosystems. How are sediments redistributed, where can fine sediments be trapped and buffered? A major effort has now been made to start building up data and information on natural variability (‘natural envelope’). Next, coupling of the observations to hydro-meteo forcing is needed. Main issues already encountered are the observed lag effects between turbidity events observed in the data and the major drivers. In this regard, the importance of the Coriolis force, and Ekman veering needs further investigation. Hence, the direction of surface and bottom sediment transport are not necessarily equal.

Last, but not least, there is yet no information on long-term variability introduced by climate change or long-term cycles in sediment dynamics (e.g., 18.6 year lunar cycle). This might also be a factor in explaining the varying sand layer observations overtopping the gravel lags in the gullies.

Cause-effect relationships

Mostly related to more adequate quantification of far-field impacts, three main caveats were identified: (i) Pressure-related information need more adequate quantification. This relates to the nature, release and spreading of fine-grained material from TSHDs. (ii) Process knowledge needs improving to understand the fate of the fine-grained material and how this may affect habitats and ecosystem functioning. E.g., what is the mechanism of uptake and release of fine-grained material in the seabed and the importance of buffering of fine-grained material in the seabed. This could affect functional biodiversity with implications for biogeochemistry and food webs. This is now investigated in the Belspo project, FACE-It[2]. In this project also the relevance on the larger scale of the North Sea will be studied. (iii) Estimation of cumulative and in-combination effects, since the origin of the fine-grained material cannot be unambiguously linked to the extraction activities in zone 4. What are indeed the effects of different combinations of stressors (aggregate-extraction at multiple sites; fishing; dredging and disposal of dredged material; windmill farms), as also climate change? It is also important to realize that an impact is not always directly related to a pressure and the typical response time of an ecosystem is largely unknown. This needs careful consideration in the monitoring phases.

Significance of the effects on larger scales

For the time being the status and dynamics of the Hinder Banks is mostly studied at the small scale, given the importance to better understand potential changes. However, at a later phase it will be critical to assess the significance of the observed changes on a regional scale. The observed buffering of fine-grained sediments will be up-scaled to the North Sea in the Belspo FACE-It project[2]. The use of multibeam monitoring of seabed changes is presently under discussion at European level and may require standardization of the approaches, as well as of data analyses. Implications and recommendations for monitoring approaches are discussed in Van Lancker et al. (2016). These may imply a drastic increase in time/effort and costs. This will need to be balanced against the relevance of the expected impacts and how this improves on the management of the marine environment, as well as on advising on better practices for the continuation of extraction.

Recommendations for the continuation of extraction

To assist in minimising the physical damage caused by the extraction activities, the original impact hypotheses, as formulated before the extraction activities, need testing. These relate to: (1) Ensuring a fast recovery of the seabed after disturbance (resilience of the system), i.e., no significant disturbance of natural processes; (2) Preventing alterations to the habitat types (e.g., sediment related); (3) Preventing unnatural fragmentation of the seabed; and (4) Preventing permanent alteration of the hydrographic conditions. In this early stage of the monitoring, these impacts cannot be assessed and continuation of the time series of impact-related phenomena is mandatory. Related to habitat changes, e.g., in Sector 4c, it is believed, that the present rates of

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[2] https://www.researchgate.net/project/FaCE-It-Functional-biodiversity-in-a-Changing-sedimentary-Environment-Implications-for-biogeochemistry-and-food-webs-in-a-managerial-setting

extraction will not lead to abrasion inducing habitat changes, except on the lower slope of the sandbanks, where the depth to the Top Pleistocene is minimal. It is advised to restrict extraction to the middle and top part of the sandbank where the geological resource is thickest. In the far field, enrichment of fine-grained material may occur under persistent extraction of the aggregate sectors nearest to the Habitat Directive Area. From this, it is advised to spread the activity over different sectors, whenever possible.

Conclusions

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). To improve the management of the activity, understanding of the causes of the impact is crucial, as well as insight into natural variability, and therefore increased process and system knowledge is required. Additionally, when exploitation is within or near Habitat Directive areas, appropriate assessments are needed of all stressors (92/43/EEC). In 2012, new extraction activities started in far offshore sandbanks of the Hinder Banks, just north of the 'Flemish Banks' Habitat Directive area. Here, ecologically valuable gravel beds occur adapted to a clear water regime. 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. Seafloor integrity relates to the functions that the seabed provides to the ecosystem (e.g., structure; oxygen and nutrient supply), whilst hydrographic conditions refer to currents, turbidity and/or other oceanographic parameters of which changes could adversely impact on benthic ecosystems.

The monitoring programme started in 2013, though first dedicated measurements were acquired in 2011. State-of-the-art instrumentation was used, to measure the 3D current structure, turbidity, depth, backscatter and particle size of the material in the water column, both *in situ* and whilst sailing transects over the sandbanks. In the most intense extraction sector, seabed sediments were sampled in detail. In the Habitat Directive area, gravel bed integrity (i.e., epifauna; sand/gravel ratio; grain sizes) was measured as well. Additionally, visual observations were made through scientific divers, video frames and a remote operated vehicle.

It needs emphasis that during this first phase of the monitoring, development of monitoring strategies and methodologies was critical, as well as setting-up baselines. Important new results were obtained; for the period 2011-2016 these relate to: (1) quantification of 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 gravel beds within the Habitat Directive area, and (4) bottom shear stress modelling in view of predicting long-term changes in hydrographical conditions.

Regarding seafloor integrity focus was on the assessment of changes in habitat occurrences and distribution. Most striking was the enrichment of fine-grained material in the coarse permeable sands of the gravel area, classifying them as mixed sediments, hitherto not mapped on the BPNS. In the gravel areas, also more sand was observed than expected from previous mapping. Although no direct relationship could yet be made with the intensive extractions a step-wise impact hypothesis is formulated that needs further investigation: (1) excess of fine-grained material and sand from overflow of the trailing suction hopper dredgers; (2) deposition in the near field and in the gullies along the tidal stream axis; (3) resuspension by beam trawling; and (4) longer lasting deposition of sediments in morphologically complex areas that preferentially trap fine-grained sediments. The mechanism of trapping was studied combining field measurements and modelling. Further monitoring is required since favourable colonization and growth of epifauna on the gravel beds is critical for the maintenance and increase of biodiversity.

Regarding extraction-induced long-term changes in hydrographic conditions, three scenarios were simulated. These showed that the changes of the bottom shear stress in the area, where no impact was allowed ('outside distance'), remained limited to around 6 %, hence less than the maximum allowance of 10 % as specified within the Belgian implementation of MSFD.

For the continuation of the extraction, it is recommended to restrict the activity to the part of the sandbank where the resource is thickest. The lower parts of the sandbank slopes are best avoided since the sediments are more heterogeneous, due to near-surface outcropping of older geological layers. Furthermore, most of the initial extraction took place in the southernmost sector, nearest to the Habitat Directive Area. Whenever possible, it is advised to spread the activity over different sectors to reduce to chance of smothering on the ecologically valuable gravel beds.

Acknowledgements

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Update environmental impact report for the extraction of marine aggregates in control zones 1, 2 and 3 in the Belgian part of the North Sea

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Introduction

ARCADIS has been chosen to draft a new environmental impact report (EIR) concerning the effects of the extraction of marine aggregates in control zones 1, 2 and 3 in the Belgian part of the North Sea. The reason is a letter from FPS Economy (dating from 12/11/2014) asking for an actualization of the EIR – dating from 2006 – for the following reasons:

- The EIR of 2006 had become too extensive because of the growing number of appendices (such as all articles of past study days);
- Several chapters were dated (such as legal and policy constraints, description of the activities);
- The lack of an appropriate assessment.

The new environmental impact report has been drafted in 2016. Following main aspects have been incorporated:

- Marine Spatial Plan: Description of all changes relevant to the sand extraction activities, due to the implementation of the Marine Spatial Plan;
- Marine Strategy Framework Directive: Additional assessment towards the relevant descriptors/targets defined for the Belgian part of the North Sea;
- Data from study days: Acquired knowledge (mainly from monitoring) that has been presented on past study days (2008, 2011 and 2014) has been incorporated in the description of the reference situation and in the impact assessment;
- Appropriate assessment: An appropriate assessment has been added to assess the impact of the extraction activities on the Special protection area 'Vlaamse Banken' (Flemish Banks).

In following chapters the non-technical summary of the EIR of 2016 is presented.

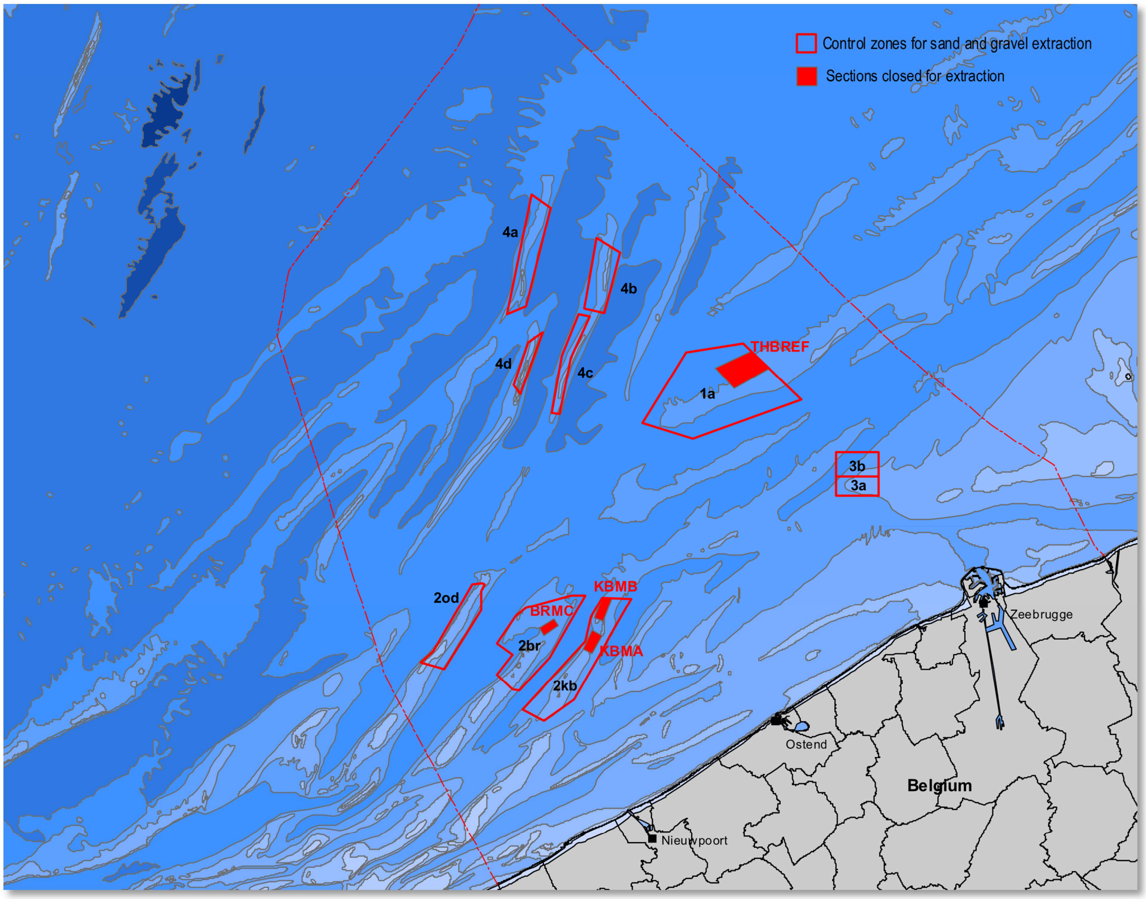
Project description

The environmental impact report has been prepared for the sand and gravel extraction carried out **in control zones 1, 2 and 3** within the Belgian part of the North Sea (BNS). This study assesses the combined effect of the extraction activities that the initiators (Zeegra, Flemish government – Coastal division and Flemish government – Maritime Access division) will develop in control zones 1, 2 and 3.

The extraction activities are carried out using trailing suction hopper dredgers. The requested extraction volume is 15 million m³ per successive period of 5 years (3 million m³/year as a rolling average over 5 years).

The extracted marine aggregates are an important source of construction materials where, depending on the quality and the grain size, the sand is used as filler or as a raw material in asphalt production or in the mortar or concrete industry. On the other hand, the extracted sediments are used for coastal protection (sand replenishments) and other marine constructions such as offshore windmills.

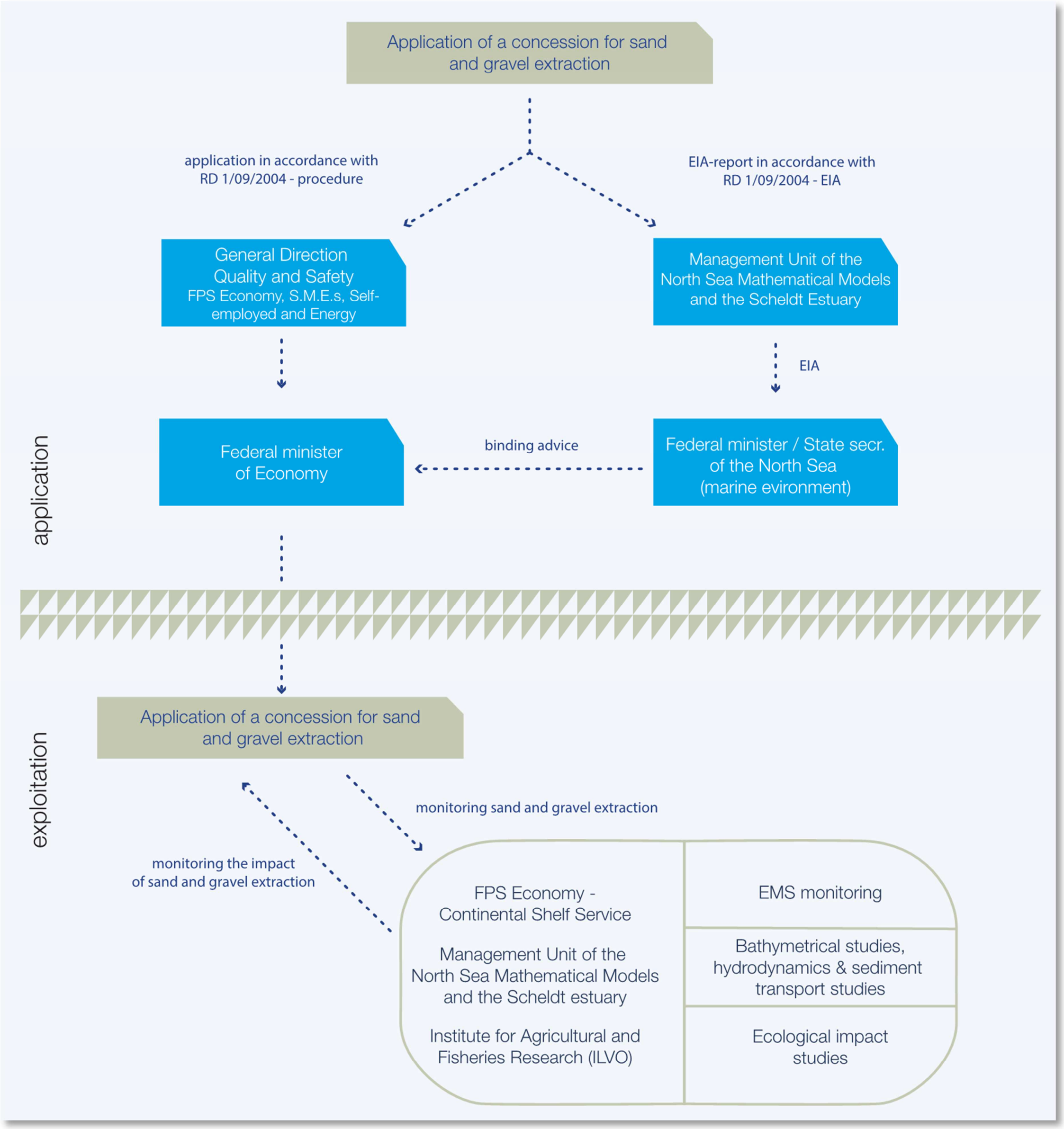
Figure 1: Control zones for sand and gravel extraction in the Belgian Part of the North Sea



Procedure

The offshore extraction of sand and gravel requires a **concession permit**. To obtain a permit, an application form has to be submitted to the director of the General Direction Quality and Safety of the FPS Economy, according to the procedure stipulated in the royal decree of 1 September 2004 concerning the granting procedure. Furthermore, the royal decree of 1 September 2004 about the environmental impact assessment (EIA) defines that an environmental impact report must be submitted to the Management Unit of the North Sea Mathematical Models (MUMM) (RBINS). The EIA by MUMM is subsequently transferred to the minister/state secretary competent for the marine environment, who in turn formulates a binding recommendation to the federal minister competent for economy.

Figure 2: Procedure for a concession permit and the exploitation of sand and gravel extraction in the Belgian part of the North Sea (Van Lancker et al.*, 2015)*



Alternatives

For this environmental impact report, two scenarios are developed that are assessed for their impact. In **scenario 1 'Business as usual'** the current situation is used, as far as possible. In **scenario 2 'Maximum dispersion',** it is assumed that there will be a maximum geographical dispersion of the extraction activities over the different concession zones (not just the maximum dispersion over the different control zones and sectors, but also over the whole area within a specific sector). For this, the total maximum quantity of aggregates to be extracted is homogenously distributed over the sand banks of the various sectors. In this scenario it is important to note that a truly homogeneous distribution of the extraction activities is an ideal situation that in reality is not feasible since it cannot be assumed that there is a homogeneous distribution of the various types of aggregate over the various zones and sectors. It can also not be assumed that it is simply practically feasible to effectively achieve a homogeneous extraction. Scenario 2 will rather be a reflection of a 'best case scenario', since a maximal geographic dispersion is assumed and the impact per m^2 is therefore minimal.

<table>
<tr><th colspan="6">SCENARIO 1: BUSINESS AS USUAL (BAU) IN CONTROL ZONES 1, 2 & 3
Extraction volumes per successive period of 5 years per sector</th></tr>
<tr><td>Sector 1a</td><td>Sector 2kb</td><td>Sector 2br</td><td>Sector 2od</td><td>Sector 3a</td><td>Sector 3b</td></tr>
<tr><td>6 940 000 m^3</td><td>2 015 000 m^3</td><td>4 030 000 m^3</td><td>2 015 000 m^3</td><td>0 m^3</td><td>0 m^3</td></tr>
<tr><td>6 940 000 m^3</td><td colspan="3">2015 1 646 000 m^3
2016 1 629 000 m^3
2017 1 612 000 m^3
2018 1 595 000 m^3
2019 1 578 000 m^3
total over 5 years: 8 060 000 m^3</td><td colspan="2">0 m^3</td></tr>
<tr><td colspan="6">15 million m^3</td></tr>
</table>

<table>
<tr><th colspan="6">SCENARIO 2: MAXIMUM DISPERSAL IN CONTROL ZONES 1, 2 & 3
Extraction volumes per successive period of 5 years per sector</th></tr>
<tr><td>Sector 1a</td><td>Sector 2kb</td><td>Sector 2br</td><td>Sector 2od</td><td>Sector 3a</td><td>Sector 3b</td></tr>
<tr><td>5 577 264 m^3</td><td>2 789 409 m^3</td><td>3 631 437 m^3</td><td>1 639 148 m^3</td><td>605 752 m^3</td><td>756 989 m^3</td></tr>
<tr><td>5.577.264 m^3</td><td colspan="3">2015 1 646 000 m^3
2016 1 629 000 m^3
2017 1 612 000 m^3
2018 1 595 000 m^3
2019 1 578 000 m^3
total over 5 years: 8 060 000 m^3</td><td colspan="2">1 362 740 m^3</td></tr>
<tr><td colspan="6">15 million m^3</td></tr>
</table>

In fact, a quantity of sand may also be extracted in control zone 4. This control zone is however not part of this project, but will be discussed in the chapter on the 'Cumulative impacts'.

Impact description and assessment

Soil / Seabed

Bathymetry – The removal of marine aggregates in the BNS has a permanent effect on the bathymetry of the seabed. The effect is however local and not cumulative. The effect of the removal of marine aggregates and altering the bathymetry of the seabed is considered to have a moderate negative impact (--) in both scenarios. The difference in the lowering of the seabed in both scenarios is limited, namely 0.40 m (scenario 1) and 0.12 m (scenario 2) over a successive period of 5 years.

Seabed morphology – The emergence of dredge tracks has a temporary and local effect on the seabed morphology. The change in the heights of sand dunes, on the other hand, is a permanent effect. Since this is a local effect, the effect of marine aggregate extraction on the morphology of the seabed is assessed as moderately negative (--). This assessment applies to both scenarios.

Sedimentological changes – For scenario 1 (business as usual) it is more likely that sedimentological changes (shift of grain sizes) will occur in one or more zones, given the extraction activities will be more concentrated than in scenario 2, where there will be maximal dispersion of the extraction. The effect in scenario 2 is considered to be negligible (virtually no effect) (0), while the effect is judged to be slightly negative in scenario 1 (-).

Water

Hydrodynamics and sediment transport – It is assumed that scenario 1 (business as usual) will potentially trigger a greater effect on the flow and sediment transport than scenario 2 (maximum dispersion) because the chances of a larger lowering of the local seabed structure in scenario 1 is larger, and so the chances of a significant effect on the water flow and geographical erosion/deposition pattern is greater. The effect of scenario 2 is therefore considered to be slightly negative (-), while the effect of scenario 1 is rated as moderately negative (--). The impact on the safety against flooding (coastal defense) is negligible (0).

Turbidity – The increase in turbidity as a result of the sand extraction is very temporary and limited in extent. In addition, the increased turbidity is at most of the same order of magnitude as the natural turbidity during a storm. Therefore, the effect of the increase in turbidity is considered to be negligible (virtually no effect) (0) in both scenarios.

Sedimentation from the turbidity plume – Sedimentation of the turbidity plume is not negligible. Monitoring results show that there is a risk that fine material from the overflow has far-field effects. Given the potential consequences for the seabed functions and thus the seabed integrity, the effect of the sedimentation of the turbidity plume is considered to be moderately negative (--) for scenario 1 (business as usual) and slightly negative (-) for scenario 2 (maximum dispersion). The extraction activities in scenario 1 are indeed more geographically concentrated and the sedimentation of fine material will be more concentrated, so that the probability of there being effects on the seabed functions and the seabed integrity is greater than in scenario 2.

Water quality – The effect of sand extraction on the water quality is considered to be negligible (virtually no effect) (0), for both scenarios.

Fauna & Flora

MACROBENTHOS

Habitat loss – In both scenarios, a major local habitat loss occurs due to the removal of the top layer of the seabed. In scenario 2, the habitat loss occurs over a larger area (more widely spread out), while the habitat loss in scenario 1 is more concentrated. Given that the extraction area in both scenarios, however, is limited in comparison with the total area of the BNS, the impact of the habitat loss for both scenarios is assessed as slightly negative (-).

Increase in turbidity – The increase in turbidity as a result of the sand extraction is very temporary and limited in extent. In addition, the maximum increased turbidity is of the same order of magnitude as the natural turbidity during a storm. Since the benthos of the subtidal sand banks is adapted to these natural dynamics, the impact of the increase in turbidity as a result of the extraction activities is considered to be negligible (virtually no effect) (0), in both scenarios.

Sedimentation of the turbidity plume – Taking into account the (possible) direct and indirect effects, the sedimentation of the turbidity plume is not negligible. Monitoring results show that there is a risk that fine material from the overflow has far-field effects. Given the potential consequences for the seabed functions and ecosystem efficiency, the impact of sedimentation of the turbidity plume is considered to be moderately negative (--) for scenario 1 (business as usual) and slightly negative (-) for scenario 2 (maximum dispersion). The extraction activities in scenario 1 are indeed more concentrated geographically and the sedimentation of fine material will be more concentrated, so that the probability of occurrence of effects on the seabed features and the seabed integrity is greater than in scenario 2.

Changes in structural and functional characteristics of the benthic ecosystem - As long as marine aggregate extraction takes place at low intensities (such as so far at Oostdyck, Thorntonbank, the southern central part of the Buiten Ratel) or at high, but infrequent intensities (Oosthinder, control zone 4), it can be assumed that the current sandy benthic ecosystem of the BNS is resilient enough to buffer the biological impact of extraction, both structurally and functionally. On the other hand, when the extraction pressure is high and focuses on a limited area, which is frequently visited and where large volumes are extracted, changes in the sediment composition are expected to lead to biological changes. Since these biological changes are, however, relatively limited and do not give rise to measurable changes in ecosystem functioning, no significant adverse effects are to be expected.

In addition, there appears to be a real chance that fine material from the overflow has far-field effects, with possible consequences for the benthic communities. Such effects are most likely to occur with intensive extraction that is localized within a limited area (whether or not frequently visited).

In scenario 1 (business as usual) the extraction activities are more geographically concentrated than in scenario 2 (maximum dispersion), thus the chance of the occurrence of changes in sediment composition in scenario 1 is larger, and the sedimentation of fine material will therefore be more concentrated. Therefore, the effect of marine aggregate extraction on the structural and functional characteristics of the benthic ecosystem is considered to be moderately negative (--) for scenario 1 and slightly negative (-) for scenario 2.

Ecotoxicological impacts – Ecotoxicological effects on benthos as a result of marine aggregate extraction are considered to be negligible (virtually no effect) (0) for both scenarios.

EPIBENTHOS & FISH COMMUNITIES

The effect of **habitat loss and habitat change**, **increased turbidity** and **mortality** on the epibenthos and the fish communities is considered to be slightly negative (-) for both scenarios.

Ecotoxicological impacts on the epibenthos and the fish communities as a result of marine aggregate extraction are considered to be negligible (virtually no effect) (0) for both scenarios.

AVIFAUNA & MARINE MAMMALS

Food availability – It is expected that a reduced availability of benthos as a food source may occur only in the intensively mined zones, with potential direct and/or indirect effects on seabirds and marine mammals. The area of the zones to be intensively mined, however, is very limited in comparison to the total area of the BNS.

At the moment there is no clear general impact of aggregate extraction on the demersal fish communities. In addition, there is no knowledge of high sensitivity (mortality) in relation to marine aggregate extraction of specific species that are of great importance in the diet of the common seabird and marine mammal species in the BNS.

On the other hand, marine aggregate extraction can also cause a temporary facilitation of food availability.

Consequently, it is assumed that both for seabirds and marine mammals almost no changes will occur in the food availability as a result of marine aggregate extraction in the BNS. The impact is considered to be negligible (virtually no effect) (0) for both scenarios.

Increased turbidity – Given that the increased turbidity occurs only temporarily and, moreover, is at most of the same order of magnitude as the natural turbidity during a storm, the impact of the increase in turbidity as a result of the extraction activities on seabirds and marine mammals is considered to be negligible (virtually no effect) (0) for both scenarios.

Disruption – Disruption as a result of marine aggregate extraction is temporary in nature and will take place in restricted zones in the BNS. The number of ship movements is limited compared to the existing shipping traffic in the Belgian part of the North Sea. Seabirds and marine mammals are mobile species that, if desired, can avoid the zones of disturbance. The loading and unloading activity in the coastal ports is part of the currently prevailing port activities to which the present avifauna is accustomed, and does not take place in the vicinity of the resting places of seals. Consequently, the effect of disruption (including noise) as a result of marine aggregate extraction is considered to be slightly negative (-).

APPROPRIATE ASSESSMENT

Control zone 2 is located inside the Special protection area 'Vlaamse Banken' (Flemish Banks). On the basis of the European Habitats Directive (art. 6) an appropriate assessment must be made for the sand and gravel extraction activities within this zone as these activities may potentially have a significant impact on the protected habitats.

Habitat type 1110 'Sandbanks which are slightly covered by sea water all the time' – The physical habitat is affected only very locally in the intensively mined areas within control zone 2. The sandbank-gullies ecosystem as a whole is not affected. Moreover, a gradual decrease in the extractable volume is enforced in control zone 2 resulting in a gradual decrease in the degree of disturbance of the habitat type 1110 within the Special protection area.

Habitat type 1170: 'Reefs – Gravel beds' – Because of redefinition of the sectors of control zone 2 and the introduction of a ban on gravel extraction in control zone 2 by introduction of the Marine Spatial Plan in 2014, the direct impact of marine aggregate extraction on gravel beds within the Special protection area 'Vlaamse Banken' is reduced to a minimum.

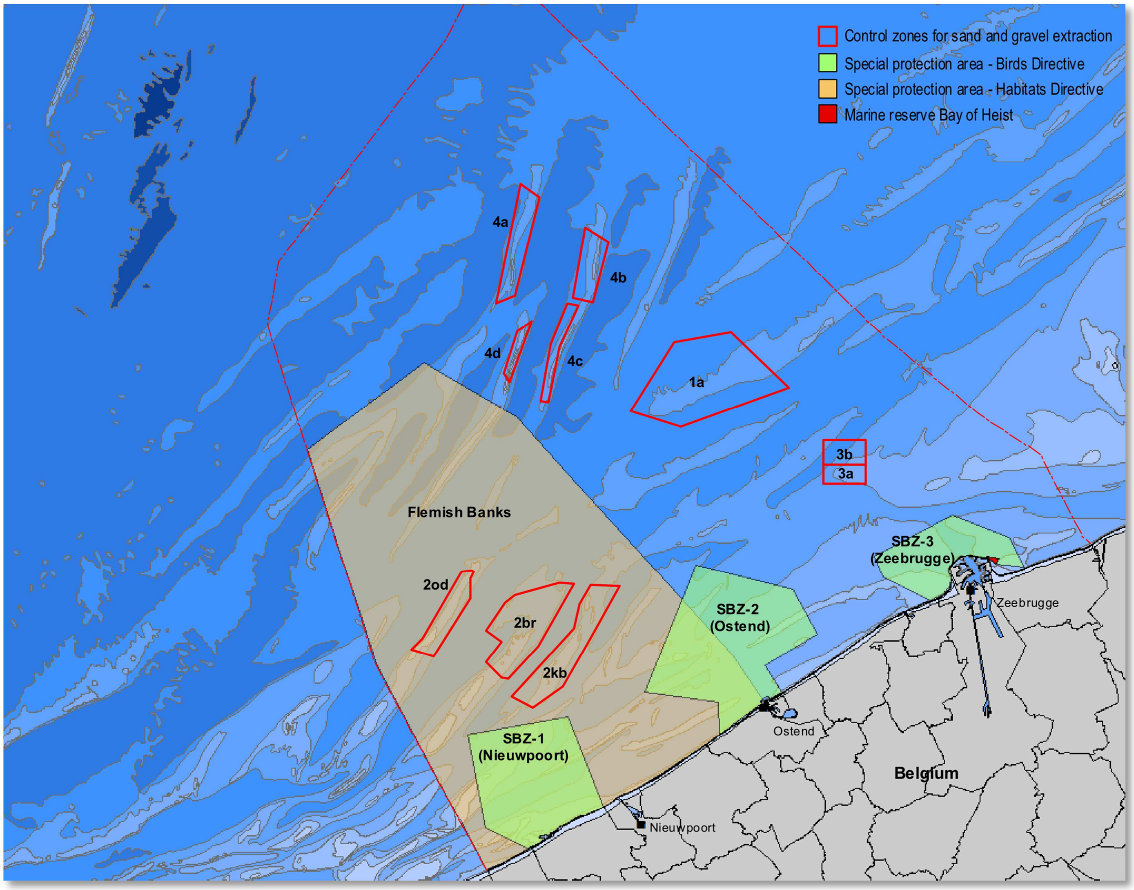
On the other hand, it appears there is a real chance that fine material from the overflow has indirect effects on gravel beds. However, no direct relationship has been established yet between the enrichment with fine material and the extraction activities.

Habitat type 1170 'Reefs – *Lanice* aggregations' – The *Lanice conchilega* aggregations within the Special protection area 'Vlaamse Banken' are mainly located near the shore, while control zone 2 is in deeper water.

Harbour porpoises – No changes are expected in the availability of food for harbour porpoises resulting from marine aggregate extraction in the BNS. The noise disturbance caused by marine aggregate extraction is temporary in nature and takes place in the restricted zones in the BNS. Moreover, harbour porpoises are mobile animals that can avoid the disruption zones if necessary.

Conclusion appropriate assessment – No significant adverse effects are expected on the Special protection area 'Vlaamse Banken' and the harbour porpoise. Any indirect effects on gravel beds as a result of enrichment of the seafloor matrix with fine sediments (possibly from overflow) however do form a gap in knowledge and should be investigated further.

Figure 3: Marine protected areas in the Belgian part of the North Sea



Air & Climate

The proportion of <u>emissions from marine aggregate extraction</u> in control zones 1, 2 and 3 relative to the total emissions from inland shipping is limited for both scenarios. Given, in addition, that the amount of material to be extracted in control zones 1, 2 and 3 (in total) remains virtually unchanged compared to the present situation and given the continuing decline in emissions of air pollutants (by systematic implementation of various standards and fleet renewal), it can be assumed that the impact of the marine aggregate extraction in control zones 1, 2 and 3 on the air quality will rather decrease with respect to the current situation or at least will remain the same. The effect of marine aggregate extraction in control zones 1, 2 and 3 on the air quality is therefore considered to be slightly negative (-).

Noise

The **underwater noise caused by marine aggregate extraction** (the dredging itself) is, in favorable weather conditions, significantly louder than the background noise up to a few kilometers from the source. The sound of the trailing hopper suction dredger(s) above the water can be observed up to at a distance of 1 to 2 km from the source. In view of the fact that the activity considered constitutes a continuation of the existing activity, there is no question of an increase of the ambient noise environment but the situation with respect to the current situation remains substantially unchanged. The effect of marine aggregate extraction (activity within the control zones) below and above water on the sound climate is considered to be slightly negative (-).

The influence of the **passing trailing suction hopper dredgers on the current overall ambient noise above and below water** is limited compared to the current shipping. The noise emissions during the loading and unloading of ships are relatively low and take place in an environment with an already highly disturbed noise environment (port area). In view of the fact that the activity considered constitutes a continuation of the existing activity, there is no question of an increase in the ambient noise environment but the situation with respect to the current situation remains substantially unchanged. The effect of ship movements for marine aggregate extraction and from the unloading of the extracted marine aggregates on the noise environment is considered to be negligible (0).

Sea view & Cultural heritage

There is no question of an increase in the **disruption of the sea view** by the marine aggregate extraction in control zones 1, 2 and 3 since it is a continuation of the already existing activity. The ship movements are not noticeable in the prevailing busy shipping traffic, which is part of the experience of the seascape. Consequently, the effect of marine aggregate extraction on the sea view is considered to be negligible (0).

Marine aggregate extraction means a possible loss of, or damage to **maritime cultural heritage**. Provided that the practical recommendations are respected and maximum use is made of the practical guide from the SeArch project, the effect is considered to be slightly negative (-).

Compatibility with other activities

Fishing – The direct effect (temporal incompatibility) of marine aggregate extraction on the fisheries is limited given the fact that benthic fisheries focus more on the flanks and gullies between the sandbanks, and the fact that shrimp fishing takes place mainly outside the zones where the most intensive extraction will take place. In addition, there is no change with respect to the current situation. The possible indirect effect is also limited since in the BNS to date no clear overall impact has been observed from aggregate extraction on the demersal fish communities. Consequently, the effect of marine aggregate extraction on the fisheries is considered to be slightly negative (-).

Marine aquaculture – Marine aggregate extraction has possible ecotoxicological effects on the (potentially future) farmed organisms in aquaculture zones by the potential release of toxic substances during the extraction activity. Due to the strong current of the sea water, however, such a rapid dilution occurs that the effect of marine aggregate extraction in the BNS on aquaculture is considered to be negligible (0).

Shipping / maritime transport – The control zones for sand and gravel extraction do not show any overlap with the main shipping routes and traffic flows that are necessary for shipping to approach the Belgian and Scheldt ports.

Shipping traffic can occur anywhere within the extraction zones. This shared space use brings a risk of collisions between ships. A discussion and assessment of the risk of collisions is given in the paragraph 'Safety aspects’.

Dredging and dumping – No geographical conflicts are observed between marine aggregate extraction and dredging activities (including the dumping of dredged materials). The effect is considered to be negligible (0).

Energy – Current knowledge indicates only local (significant) changes in current patterns and erosion/sedimentation patterns at very intensively mined zones. It can therefore be assumed that such significant changes to current patterns will not extend beyond the limits of the control zones. Therefore, no effect (0) on the stability of the wind turbines and any future energy atolls is expected.

Marine aggregate extraction has a negligible effect (0) on cables and pipelines, provided that the applicable regulations and safety perimeters are respected.

Safety against flooding – Marine aggregate extraction has a possible direct impact (increased wave impact during a storm) and indirect impact (coastal erosion) on the safety against flooding (coastal defense). Both effects are considered to be negligible (0), essentially as a result of the relatively large distance from the sand extraction to the coast and the presence of other sandbanks that weaken the wave energy.

Military use – Marine aggregate extraction has a negligible effect (0) on military activities, provided that the prohibition on access to the relevant military zones during notified military exercises and other activities is respected.

Tourism and recreation – Marine aggregate extraction has no impact on the tourist-recreational activities in the coastal area. Provided that the shipping regulations are respected, the chance of collision of an extraction ship with recreational navigation is also considered to be very small. The effect of marine aggregate extraction is considered to be negligible (0).

Safety aspects

Maritime safety – Building on the conclusions of the environmental impact reports of 2006 and 2010 for marine aggregate extraction, it can be assumed that the probability of the occurrence of an accident at the marine aggregate extraction in control zones 1, 2 and 3 is small. The increase in the risk of shipping accidents compared to the current situation due to the increasing importance of control zone 1 is negligible. The effect of marine aggregate extraction in control zones 1, 2 and 3 on maritime safety is therefore considered to be slightly negative (-).

Risk of oil pollution – The chance of oil pollution is considered to be very low. The biggest danger on the stranding of an oil spill comes from a discharge in areas 3a and 2kb (at high wind friction (5%)). The precautionary principle should be applied where, in the first place, a shipping accident must be avoided as much as possible and, if this turns out to be impossible, a discharge must be avoided or limited as quickly as possible. The avifauna in particular, and possibly also marine mammals, will mainly experience the major short term effects of oil pollution. However, it is often not easy to distinguish the effect of an oil spill from natural fluctuations in a population.

The effect of marine aggregate extraction on the probability of the occurrence of oil pollution is considered to be slightly negative (-).

Impact on the Good Environmental Status and Environmental Targets

Marine aggregate extraction has a potential impact on the Good Environmental Status and on the achievement of the Environmental Targets of Belgium as defined within the context of the Marine Strategy Framework Directive 2008/56/EC.

D1/D4/D6 (biological diversity / marine food chains / seafloor integrity) – Because of the redefinition of the sectors of control zone 2, the introduction of a ban on gravel extraction in control zone 2 and the gradual decrease in the extraction volume in control zone 2, a positive trend compared to the initial status (2012) is expected for various indicators that demonstrate the achievement of the Good Environmental Status for descriptors D1, D4 and D6 (at least with respect to marine aggregate extraction). Marine aggregate extraction does not therefore hypothecate the achievement of the Environmental Targets in the BNS for these descriptors.

The possible indirect effects as a result of enrichment of the seabed matrix with fine sediments (possibly from overflow) form a gap in knowledge and should be monitored further.

D6 (seafloor integrity) – For descriptor D6 (seafloor integrity) the assessment is nuanced:

- It is assumed that the actual removal of substrate and changes in topography due to aggregate extraction do not have a significant impact on the integrity of the seafloor and the connectivity of the habitats.
- In the near-field (in the intensively mined areas), sedimentological changes may occur; this results in a more heterogeneous habitat. There is however no question of significant unilateral refinement of the sediments. For this aspect there is likewise no significant impact expected on the Good Environmental Status of D6.

- In the far-field, no 'smothering' (suffocation) of the gravel beds was observed as a result of the turbidity plume. On the other hand, there is a risk that fine material from the overflow has far-field effects by captation and buffering of these fines in the soil matrix, with possible consequences for the seabed functions. For this aspect, a significant impact on the sea floor integrity and the achievement of the Good Environmental Status for D6 cannot be excluded.

Given the currently prevailing gaps in knowledge concerning this effect, further research and monitoring is initially appropriate. If it appears from this that the integrity of the seabed is indeed compromised, mitigating measures should be sought.

D2 (non-native species) – Marine aggregate extraction does not give rise to the introduction of new non-native species. Hence no impact is expected on the achievement of the Good Environmental Status for descriptor D2.

D7 (hydrographic properties) – On the basis of the discussions of the effects within the disciplines of 'Soil/Seabed', 'Water' and 'Fauna and Flora', it is decided that no significant impact is expected as a result of marine aggregate extraction on the achievement of the Good Environmental Status and Environmental Targets for descriptor D7 (hydrographic conditions).

D8 (contamination) – The risk of the occurrence of an accident during marine aggregate extraction in control zones 1, 2 and 3 is small. The risk of the occurrence of oil pollution is also very low. Careful compliance with the current legislation on maritime safety as a strict constraint applies at all stages of the marine aggregate extraction process. In addition, the precautionary principle must be applied where, in the first place, a shipping accident must be avoided as much as possible and, if this turns out to be impossible, a discharge must be avoided or limited as quickly as possible. These aspects taken into consideration, it can be decided that marine aggregate extraction does not therefore hypothecate the achievement of the environmental targets in the BNS for descriptor D8.

D11 (underwater noise) – In general, it is decided that marine aggregate extraction in control zones 1, 2 and 3 will not cause a positive trend in the annual average environmental noise levels since it can be considered as being a continuation of an existing activity. Marine aggregate extraction does not therefore hypothecate the achievement of the environmental targets in the BNS for descriptor D11.

Cumulative impacts

The marine aggregate extraction in control zones 1, 2 and 3 can, in combination with the marine aggregate extraction in control zone 4, lead to an accumulation of effects. In addition, cumulative effects may also occur as a result of marine aggregate extraction in combination with other human activities at sea which (partly) cause similar effects:

The construction and operation of wind farms in the BNS;
The laying of the HVDC interconnector between the UK and Belgium; the Nemo Link**;**
Dredging and dumping of dredged material in the BNS;
Fishing, in particular trawling fisheries.

In many cases, the cumulative effect is **equal to the sum of the effects** of the individual activities (1+1=2). In some cases, the cumulative effect is **less than the sum of the effects** of the individual activities (1+1>1). Finally, there are various aspects in which the cumulative effect is (potentially) **greater than the sum of the effects** of the individual activities (1+1<1).

Cumulative effect of marine aggregate extraction in control zone 1, 2 and 3 combined with	Marine aggregate extraction in control zone 4	Windfarms	Nemo Link	Dredging and dumping of dredged material	Fishing
Soil / Seabed	S	S	S	S <S	>S ?
Water	S <S S or >S ?	S	S	S	S
Fauna & Flora: macrobenthos	>S				
Fauna & Flora: epibenthos & fish fauna	>S				
Fauna & Flora: marine mammals	>S				
Air	S				
Noise	>S				
Cultural heritage	S				
Compatibility with other activities	*See maritime safety*				
Maritime safety	>S				

In the assessment of the cumulative effects, it is important to note that the activity for which this environmental impact report is produced, namely marine aggregate extraction in control zones 1, 2 and 3, is a continuation of an already existing activity. The cumulative effects discussed are already present and will, as a result of the continuation of the marine aggregate extraction in control zones 1, 2 and 3 (in much the same way, apart from some shifts in the importance of certain sectors in response to legal conditions and the economic needs) change little or not at all in the future. So there is no question of an increase in the various cumulative effects compared with the current situation (taking into account the autonomous development), regardless of the fact that the cumulative effect is the same, less than or greater than the sum of the effects of the individual activities.

Monitoring

In accordance with the law of 13 January 1969 which states that the exploration and exploitation should be subject to an ongoing review of the impact of the activities, regular monitoring of the extraction activities in the BNS has been conducted since the end of 1999.

The possible far-field effects of sedimentation should be examined in more detail within the current monitoring program.

In addition, monitoring is recommended of the cumulative impact of marine aggregate extraction in combination with trawling, and of the cumulative impact of sedimentation of the turbidity plume resulting from sand extraction in control zone 2 and 4 on the highly valuable gravel beds.

Cross-border impacts

Considering that in this environmental impact report no significant environmental effects for the Belgian part of the North Sea were identified as a result of marine aggregate extraction, it is evident that there will also be no significant adverse cross-border environmental impacts. Significant cumulative effects from marine aggregate extraction in combination with projects abroad are not expected either.

Summary and conclusions

The main effects of marine aggregate extraction relate to the disciplines soil/seabed, water and fauna & flora (macrobenthos).

- As (intensive) extraction affects the volume of sand banks (permanent impact on the bathymetry, both local and non-cumulative) this may lead to disrupted morphology and sediment dynamics. In turn, this may lead to changes in flow patterns and abnormal erosion/sedimentation patterns.
- The physical disturbance of marine aggregate extraction can lead to changes in the structural and functional characteristics of the benthic ecosystem. When the extraction pressure is high and focuses on a limited area that is frequently visited and where large volumes are extracted, changes in the sediment composition are expected to lead to biological changes. However, the biological changes observed to date remain limited.
- With regard to sedimentation from the turbidity plume, there is a risk that fine material from the overflow has far-field effects on the ecologically highly valuable gravel beds. These potential indirect effects on gravel beds are a gap in knowledge and need to be investigated further.

These main effects are considered to be **minor (-) to moderately (--) negative**. In scenario 1 (business as usual) some effects are considered to be a degree more negative with respect to scenario 2 (maximum dispersion). In scenario 1, the extraction activities are indeed more geographically concentrated so that various effects have a greater chance of occurrence in comparison with scenario 2 where the dispersion of the extraction is maximal. In both scenario 1 and scenario 2, however, all the effects remain acceptable (maximally moderately negative).

The other effects (within these and other disciplines) are all considered to be **negligible (0) to slightly negative (-)**.

Effect	Assessment	
	Scenario 1 (business as usual)	Scenario 2 (maximum dispersal)
SOIL / SEABED		
Substrate removal – Seabed bathymetry changes	--	--
Morphological changes	--	--
Sedimentological changes	-	0
WATER		
Impact on hydrodynamics and sediment transport	--	-
• Increase in turbidity • Sedimentation turbidity plume	0 --	0 -
Impact on water quality	0	0
FAUNA & FLORA – Macrobenthos		
Habitat loss	-	-
• Increased turbidity • Sedimentation turbidity plume	0 --	0 -

Effect	**Assessment**	
	Scenario 1 (business as usual)	**Scenario 2 (maximum dispersal)**
Changes in structural and functional characteristics of the benthic ecosystem	--	-
Ecotoxicological effects	0	0
FAUNA & FLORA – Epibenthos & Fish communities		
Habitat loss and habitat change	-	-
Increased turbidity	-	-
Mortality	-	-
Ecotoxicological effects	0	0
FAUNA & FLORA – Avifauna & Marine mammals		
Food availability	0	0
Increased turbidity	0	0
Disturbance	-	-
AIR & CLIMATE		
Effect on air quality	-	-
NOISE		
Effect of marine aggregate extraction (activity within the control zones) on the noise climate under water	-	-
Effect of marine aggregate extraction (activity within the control zones) on the noise climate above water	-	-
Effect of ship movements for marine aggregate extraction	0	0
Effect of the dumping of the extracted marine aggregates	0	0
SEA VIEW & CULTURAL HERITAGE		
Effects on sea view	0	0
Effects on cultural heritage	-	-

Effect	Assessment	
	Scenario 1 (business as usual)	Scenario 2 (maximum dispersal)
COMPATIBILITY WITH OTHER ACTIVITIES		
Effects on fishing	-	-
Effects on aquaculture	0	0
Effects on shipping	*See discipline 'Safety aspects'*	
Effects on dredging and dumping	0	0
Effects on energy	0	0
Effects on safety against flooding	0	0
Effects on military use	0	0
Effects on tourism and recreation	0	0
SAFETY ASPECTS		
Maritime safety	-	-
Risk of oil pollution	-	-

- slightly negative effect	+ slightly positive effect
-- moderately negative effect	++ moderately positive effect
--- significantly negative effect	+++ significantly positive effect
	0 negligible effect

References:

Van Lancker, V., Lauwaert, B., De Mol, L., Vandenreyken, H., De Backer, A., Pirlet, H., 2015. Sand and gravel extraction. In: Pirlet, H., Verleye, T., Lescrauwaet, A.K., Mees, J. (Eds.), Compendium for Coast and Sea 2015: An integrated knowledge document about the socio-economic, environmental and institutional aspects of the coast and sea in Flanders and Belgium. Ostend, Belgium, p. 105-114.

All articles of past study days for marine aggregate extraction: 2008, 2011 and 2014.

Flexible querying of geological resource quantities and qualities, a sustainability perspective

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Introduction

To anticipate on future resource supplies and needs, long-term adaptive management strategies for the exploitation of geological resources are urgently needed (cf. EU's Maritime Policy, Marine Spatial Planning, Marine Strategy Framework Directive). These are based ideally on a geological knowledge base incorporating comprehensive knowledge on the distribution, composition and dynamics of geological resources.

Such a knowledge base is being built for the Belgian and southern Netherlands part of the North Sea (Belgian Science Policy 'TILES') with the aim of providing long-term predictions of geological resource quantity and quality (Van Lancker et al., 2017, for an overview). Therefore, the lithology or sediment composition of the subsurface needs quantification which is traditionally derived from borehole point data. First these data are classified into classes, e.g., following the Wentworth scale (i.e., clay, silt, fine, medium to coarse sand and gravel), but secondly their distribution needs interpolation. Since the data are prone to a high variability, both in space and in depth, it is important to constrain the lithological interpolation within the geological unit or stratigraphy the lithoclass belongs to. This information ideally comes from seismic line data. Combining both point and line data is most efficiently done in a voxel modelling approach of which 3D volume elements are the key component. Advantages are the suite of geostatistical interpolations that can incorporate various criteria, including expert knowledge, the unlimited information that can be added to the data cube in a later phase, and the easy calculation of resource volumes per geological unit or resource quality. Importantly, the geostatistical modelling allows for probabilistic instead of static mapping providing the user with a measure of uncertainty on the lithoclass that is interpolated.

Quantifying uncertainty is indeed crucial in geological modelling and the suitability of the resource should be accompanied by a level of confidence in the data or data product. Many algorithms exist in this regard (e.g., interpolation-related uncertainty), though are mostly lacking for the geological information itself, as well as for the databases upon which the products are built. As such, uncertainty in the mapping of the lithological class and stratigraphic uncertainty are ideally incorporated. For databases comprising information over long-time spans, it is also important to quantify data-related uncertainty, e.g., to accommodate the wide range that exists in positioning techniques, vintages, as well as sampling and analytical techniques. Quantifying these uncertainties, propagating them in 3D models and combining them is not straightforward.

In a resource sustainability context, scenario analyses on resource use, but also on expected environmental impacts are important. Primarily, this includes predictions on how much the seabed can be deepened before major changes occur to the current and wave regime, but also how the seabed sediments change with implications towards biodiversity. The geological nature of the subsurface is in this respect very important, however it is hitherto never accounted for in environmental impact studies that are typically 2D and limited in time scale.

A final aspect is how bringing all of this information together in a decision support tool. From stakeholder consultation, a wide scope of needs emerged, e.g., the desire to assess local aggregate quality (incl. heterogeneity) and quantity, but also decision-making on large-scale and long-term resource use. Additionally, a flexible resource mapping and querying approach was preferred that should be most efficient and user-friendly. To accommodate these varying needs and also to provide the user with combined confidence qualifiers, a new way of dealing with the various data and modelling sources was needed.

All of the above challenges are dealt with in the TILES project, often in most innovative ways. As a result, the approach can handle small- to large-scale data and queries, making it of interest to numerous applications.

The project lasts until June 2018, hence intermediate results are presented at this stage. In the last phase, the geostatistical modelling will be refined making use of the newest data sources, as well as including sensitivity analyses on the various parametrisations that are applied to the datasets. More detailed lithological information will be added to the model, especially for the top or seabed voxel. The 4D component in the scenario analyses will be fully exploited in Autumn 2017. Challenging remains on how to demonstrate and communicate the complex information and uncertainties in a most meaningful way to the user. Continued stakeholder interaction is therefore critical.

Material and methods

On the overall methodological framework, three book chapters have been published: in van Heteren and Van Lancker (2015) on uncertainties in sediment databases; the resource context and the TILES approach in Van Lancker et al. (2017), and concepts of handling data uncertainty in decision support in De Tré et al. (in press). Papers are now prepared on the detailed methodological approaches. Status and progress are listed below.

Data to knowledge

Three main geological databases have been developed and are still further refined: (1) a database with lithological descriptions from available boreholes (Kint and Van Lancker, 2016); (2) a grain-size distribution database populated with sediment distribution curve data, incorporating recovered historical data (expanding on Van Lancker, 2009); and (3) a geophysical database containing seismic line data, as well as stratigraphical interpretation. The latter data originate primarily from Ghent University, Renard Centre of Marine Geology.

Publically available data sources were consulted, including data from neighbouring countries (mostly via national data portals). Data from industry are being incorporated as well: mostly data from non-confidential projects, or upon permission, were added through digitization from available reports. Ad-hoc arrangements can be made if the data needs to remain confidential, but usable for model improvement. All entries in the borehole database are carefully verified and metadata are maximally added for uncertainty analyses. Metadata coding followed EU guidelines (www.seadatanet.org) Main fields were positioning, timestamp (vintage), methodological and analytical techniques used. Quality flags were entered in all databases, also to the seismic lines (following www.geoseas.eu). For the latter, the discrimination potential of subsurface reflectors was accounted for, the vintage of the lines, and whether the data were digital or scanned from paper. Combining and cross-verifying all of this information significantly adds on to the geological knowledge on the marine areas under investigation.

A Belgian marine geological data portal is now under development, integrating the databases, as well as data products. As such a platform for knowledge building and knowledge management is created to serve the scientific, policy and stakeholder community, as well as the public at large.

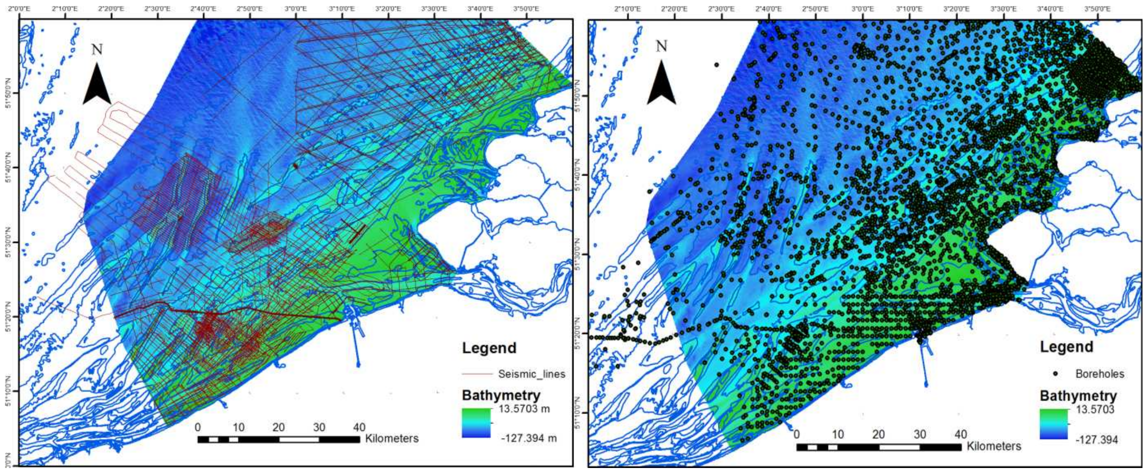

Figure 1: Available seismic data and lithological descriptions.

Geological layer models to 3D voxels

The boreholes were standardised and coded following EU guidelines on geological and geophysical data (e.g., www.geoseas.eu). These were fed into seismic interpretation software to match the boreholes with seismic data. For the Belgian part of the North Sea (BPNS) existing Top Paleogene (De Batist and Henriet, 1995) and Quaternary (Mathys 2009) layer information was extensively reviewed, and new data (newly acquired, or received from third parties) were added. Layers in the boreholes were assigned a stratigraphical and facies interpretation. This information, together with the refined 2D geological layers, was fed into geostatistical software for the voxel modelling (Figure 2).

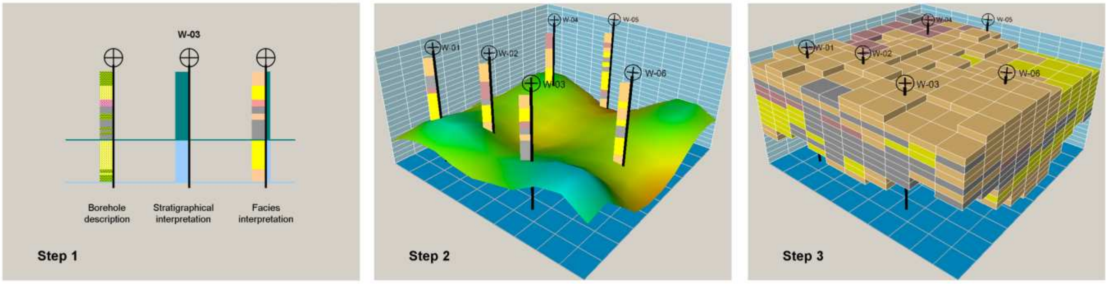

Figure 2: Basic modelling procedure. Step 1: Borehole descriptions subdivided into lithostratigraphical, lithofacies and lithological units. Step 2: 2D interpolation of the basal surface of each lithostratigraphical unit. Step 3: voxel modelling or 3D interpolation of lithofacies and lithology within each lithostratigraphical unit (Stafleu et al. 2011).

The base of the resource-relevant geological layer (Quaternary) was completely revisited, i.e., the Top-Paleogene surface and its topographical features were described in detail (e.g. valleys, flood plains, estuaries).

This research has been published in Declercq et al. (2015). Furthermore, Quaternary units were verified for lithostratigraphical relevance (i.e., in terms of aggregate quality). As a result, a four-unit geological layer model was created: upper Paleogene, Pleistocene and two units in the Holocene. Furthermore, the Holocene layer was split in two regions, on- and offshore accounting for the difference in the geology and lithological nature in both subareas (marine to estuarine environment). This was important to fine-tune the statistical parameterisation that drives the interpolation process (e.g., more clay in the Holocene layers of the nearshore). Lithoclass information was then interpolated constrained within the geological unit it belonged to. Dimensions of the main voxel model are 200 x 200 x 1 m, up to a depth of -70 m mean sea level (MSL). As a case study, the Hinder Banks concession zone was modelled at a higher resolution (100 x 100 x 0.5 m), as was suggested by stakeholders.

Once the models are developed, resource volumes are easy to compute. Sensitivity analyses are conducted on the impact of the voxel resolution, e.g., 200 x 200 x 1 m versus 100 x 100 x 0.5 m. At this stage, voxels are counted per lithological class, without accounting for the morphological complexity of an area. This will be accounted for in post-processing in the decision support module (see further). This will allow incorporating other data sources that may impact on the available resource volumes (e.g., other human activities).

Uncertainty estimation

Following the approach of Stafleu et al. (2011), estimates of the lithological class of each voxel in the model were calculated using a stochastic interpolation technique (running 100 simulations of lithoclass predictions per voxel) which allowed the construction of multiple, equally probable realisations of 3D lithological class distributions. From these realisations, probabilities of occurrence for each lithological class were calculated. In addition, the probabilities were used to compute a 'most likely' lithological class distribution using an averaging method tailored to the datasets.

For the interpretation of the probabilities in terms of likelihood of occurrence, the verbal descriptions of uncertainty, as used in the Intergovernmental Panel on Climate Change (IPCC) are suggested for use (Table 1).

Table 1: IPCC guidelines of translation of probability phrases

Phrase	Likelihood
Virtually certain	> 99 %
Very likely	> 90 %
Likely	> 66 %
About as likely as not	33 % - 66 %
Unlikely	< 33 %
Very unlikely	< 10 %
Exceptionally unlikely	< 1 %

Information entropy was calculated also. This is a single value ranging from 0 to 1 that can easily be calculated from each of the probabilities of lithological class. An entropy value of 0 means that there is no uncertainty, whereas a value of 1 occurs when all lithological classes had the same probability in a voxel. Values in between 0 and 1 account for both the number of lithological classes with a probability higher than 0 (the more classes, the higher the entropy) and the differences amongst the probabilities (the greater the differences, the lower the entropy). Entropy was calculated also on the stratigraphical unit the voxel belongs to. This was based on the geological layer model, attributed with a standard deviation of the geological bounding surfaces that defined them. The probabilities for each of the stratigraphical units were then combined into an entropy value of stratigraphy.

Variation in borehole density was accounted for as well. Many users assume a one-to-one relationship between borehole density and reliability of a model. Although this relationship not always exists (for example, a homogeneous unit may be fully characterized by a single borehole), it adheres to common sense and is therefore easily understood. Borehole density was calculated for horizontal slices through the model, each at a certain vertical position with respect to MSL. Subsequently, for each of these horizontal slices, the number of boreholes available in cells of 5 by 5 km at the depth of the slice were counted. The result was then converted to the voxel model.

A new approach is being worked out on quantifying data-related uncertainty (e.g., in the lithological and grain-size database). Uncertainty caused by differences in positioning, sampling gear, analysis procedures and vintages is now represented as a percentage flag scaling. As such, integration with other uncertainties and the voxel model itself is much more flexible. Expert knowledge is systematically revisited as to avoid totally inappropriate use of the flag scaling process.

Coupling of the geological models with 4D environmental impact models

Marine resources are subject to both natural processes (bedform migration, erosion and deposition); and human influences (e.g. dredging activities, extraction) that cause their quantity and quality to change. To understand past and predict future behaviour of the resource in this 4th dimension (time), it is necessary to couple the 3D voxel model to a suite of environmental impact models.

The model suite used in TILES contains a hydrodynamic model of the continental shelf (COHERENSv2; https://odnature.naturalsciences.be/coherens/, building upon Luyten et al., 1999), a sediment-transport model (simulating erosion, transport and deposition) and a seabed-morphology model (simulating changes in seabed composition and bathymetry). The model suite is coupled to a third-generation wave model in order to realistically account for the wave constraint on hydrodynamics and sediment transport and, in return, to evaluate the prospective effect of profound seabed changes on wave dissipation. This suite explains the static top of the 3D voxel model in terms of driving forces, and is crucial for a quantitative understanding of past as well as future resource changes resulting from natural seabed dynamics and human impact. The coupling with the voxel model offers an opportunity to initiate and parameterise the model suite with geological boundary conditions and to investigate the aggregate resource at an unprecedented level of detail and accuracy and to execute scenarios over time. The model suite is also used for detailed analyses on bedform evolution in extraction areas. Therefore, results from the multibeam monitoring are used (Roche et al., this volume) and automated procedures on quantifying bedform migration rate and direction are developed and are analysed against driving forces (natural and anthropogenic). From this, statistical models of depletion rates per substrate type are derived. As such, knowledge is gained on rates of resource depletion under present-day extraction practices, being critical for long-term predictions of resource availabilities.

A final aspect of the 4D component of the voxel modelling is the incorporation of results of a 16-yrs hindcast (1999-2015) on sediment transport parameters in the upper voxel (e.g., bottom shear stress, bed evolution, total sediment transport) (see Francken et al., this volume). In line with the methodology on geological modelling, probability maps of long-term natural erosion and deposition magnitudes and rates will be created. This information can be used to steer extraction activities towards depositional areas, and to avoid naturally erosive areas, hence minimising environmental impacts. Model results are validated with results from the multibeam monitoring (Roche et al., this volume).

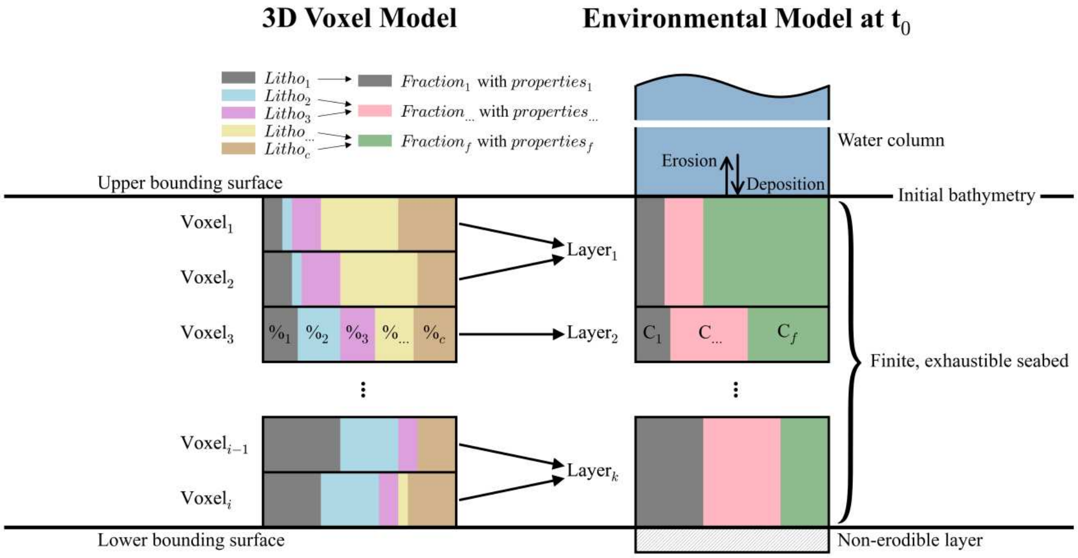

Figure 3: Coupling between the 3D voxel model (left) and the suite of environmental impact models (right). The voxel model provides percentages (%) of the different lithological classes (Litho), which are translated into concentrations (C) of the different sediment fractions to initialise the seabed of the numerical model. Properties of the sediment fractions (e.g. particle size) are provided as well to parameterise the numerical model (see Van Lancker et al., 2017 for more information).

Decision Support System (DSS)

The DSS is vital to allow easy querying of all resource-related information, as well as the accompanying model uncertainties. Furthermore, other datasets (e.g., on human activities) can be added allowing combined querying of data and information.

From fixed- to dynamically-sized voxels

To anticipate maximally on stakeholders' needs (see Introduction), a fundamental change was implemented in the way the voxel models are being used in the DSS. In the geological modelling, voxels are of equal dimension (i.e., 200 x 200 x 1 m) which proved too coarse for some detailed applications and for resource calculations in morphologically complex areas. Furthermore, most voxel attributes were filled by interpolation, implying that most of the time needed for querying the DSS went to voxels with no real data. In the current state of the DSS data from various sources (voxelized lithoclass information, surface maps (bathymetry, Top Paleogene, ...) and area maps (shipwreck locations, pipelines, windmill farms, ...), can define a 3D space which can be partitioned "on-the-fly" into new voxels of differing size. The size of these voxels is derived from the amount of information that is available in the region. As a consequence, in the DSS a voxel now reflects a box of 3D space that is considered to be homogeneous by the end-user. Research is further conducted on the most optimal form of the 3D space, hence rectangular voxels may merge into polyforms of different dimensions if this adds to a more accurate representation of an area.

Suitability mapping

Suitability scores are calculated for each voxel, reflecting how well the encapsulated area is able to satisfy a set goal. The goal needs to be entered by a set of criteria and the way they relate to each other (e.g., : "where are areas with a low amount of clay, within 5 m of the seabed, where Holocene medium sand is the dominant lithological class, not near pipelines or military training areas?"). On general terms, each voxel is then rated with a suitability score between 0 (=unacceptable) and 1 (=perfect). If a detailed querying of information is desired, a tiered approach is proposed where maps are generated to quickly discover regions of interest, which are further studied in detail afterwards, without having to generate a detailed map of the entire region.

Results and discussion

In this section only few results are shown to demonstrate the methodology and potential of the TILES workflow. The models are still in refinement and sensitivity analyses are carried out on the parameterisation of the geostatistical model. A higher resolution model of the upper seabed is in development; this one will contain more detailed sediment characteristics, as well as sediment transport parameters.

Sediment mapping of the seabed

Based on the new grain-size distribution database, seabed sediments were mapped following the Folk classification (5, 7 and 16 classes). The maps are publically available through the EMODnet-Geology data portal (www.emodnet.eu). In combination with depth zonation, tidal and wave energy data, and level of light penetration they were further translated into predominant habitats of relevance to the Marine Strategy Framework Directive (Figure 4). These habitat maps are publically available via the EMODnet-Seabed habitats data portal.

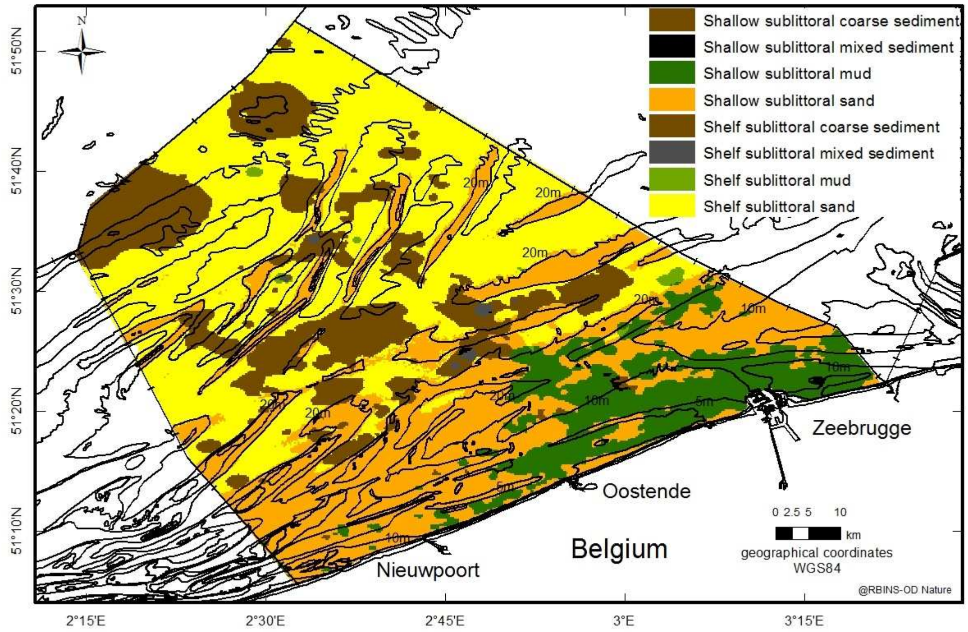

Figure 4: Most commonly occurring habitat types (EUNIS Level 3) based on a mapping of substrate type (RBINS SediCURVE@SEA_v2016 database) combined with physiographic characteristics (depth zonation and wave energy) (EMODnet Seabed Habitats project (www.emodnet-seabedhabitats.eu), funded by the European Commission's Directorate-General for Maritime Affairs and Fisheries (DG MARE)).

Geological layer modelling

A renewed Top-Paleogene surface has been published (Declercq et al., 2015). It is an important reference layer for the future extraction of marine aggregates. Within the Quaternary, three geological layers were distinguished being a proxy of the main lithostratigraphic units. All of the layers were transferred to FPS Economy for further valorization in terms of defining a new reference surface for future marine aggregate extraction (Degrendele et al., this volume).

Voxel modelling

A first portfolio of resource-distribution maps has been created for each Wentworth class (Clay to Silt; Fine, Medium to Coarse sand; Gravel), taking into account the layered model of the Quaternary. These were transferred to FPS Economy to provide first insight into the aggregate quality of the sandbank volume above a potential new reference surface (Degrendele et al., this volume). Figure 5 is an example of such a map.

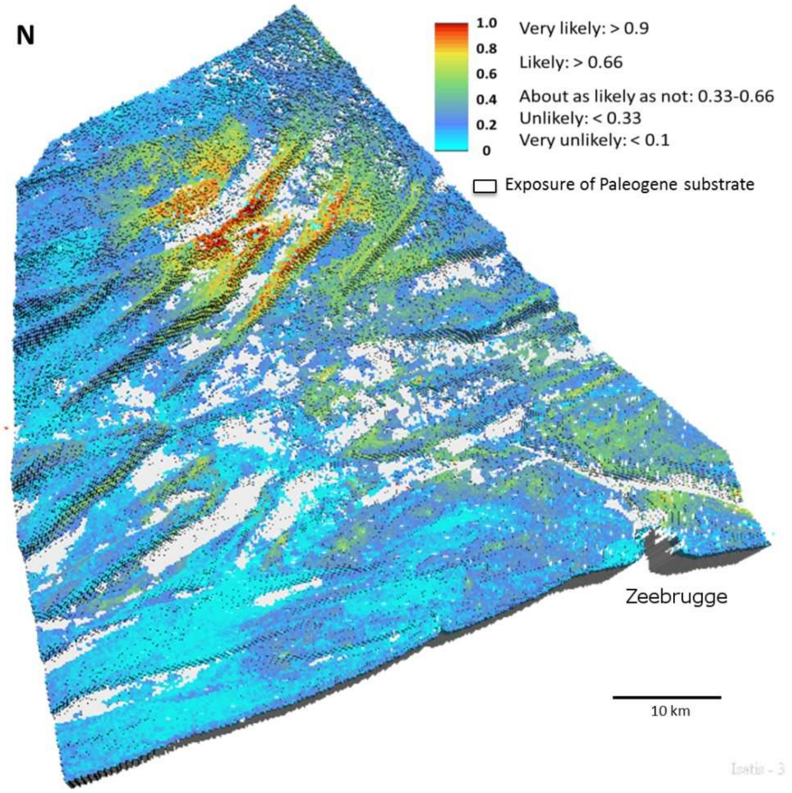

Figure 5: Probability of occurrence of medium sands in the upper Holocene layer (here seabed representation only), based on 3D interpolation of lithological descriptions within geological units (voxel dimensions of 200 x 200 x 1 m). Within the 12 nm zone, this lithoclass is only present locally; more offshore this class is more widespread available.

Figure 6 combines results from a mapping of the lithoclass occurring with highest probability, together with the entropy of the model as a measure of uncertainty when combining all probabilities of lithological classes.

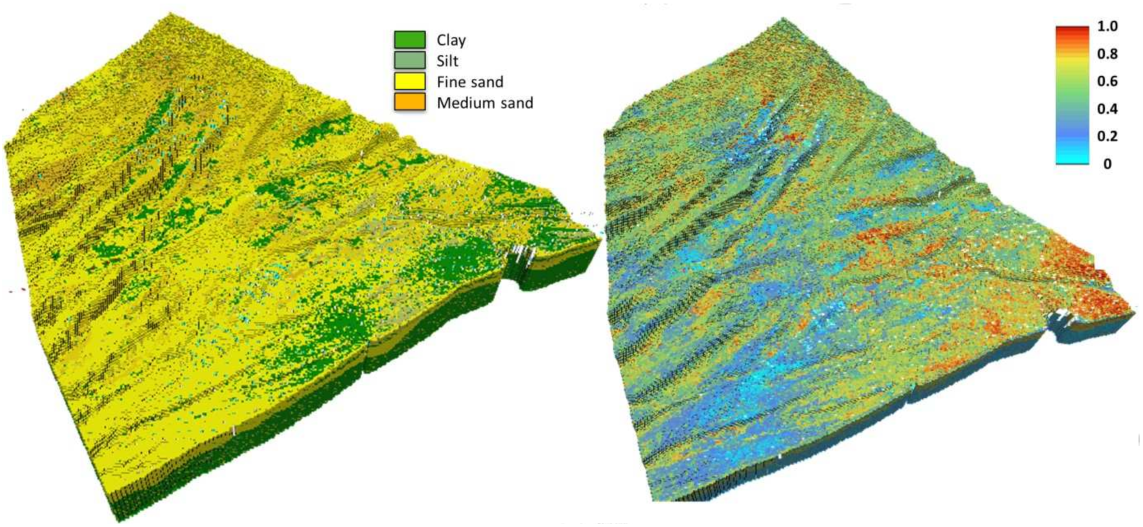

Figure 6: Left: Representation of the lithoclass occurring with the highest probability. Right: Entropy of the model. Entropy is highest, hence uncertainty in the mapping is highest in the red areas. Near Zeebrugge, and in the coastal zone, this is caused by the highly varying nature in lithoclasses at small spatial scale. To the north of the BPNS, the red colouring is merely indicative of areas with low data density.

It is important to highlight that uncertainty originates from various sources (diverse geological nature within layers, differences in data density, differences in the geostatistical interpolation), including the way the data were collected and under which circumstances (quantified from metadata).

Clearly, mapping of probabilities instead of static values of resource occurrences shows much more restrictions in where most appropriate resources for certain applications can be found. It is up to the user which uncertainty can be accepted.

First resource assessments

Figure 7 shows the volumes of the lithoclasses silt and clay, fine sand, medium sand, and coarse sand based on a query of the 200 x 200 x 1m voxel model. As mentioned, sensitivity analyses are now carried out to quantify the influence of the voxel resolution on the volumes. It is expected that the order of magnitude will be similar from a large- and long-term perspective. For detailed resource volume projections, it is likely that the voxel resolution needs up-scaling. For these, the constraints imposed by the sandbank morphology (e.g., slope areas) will also matter. However, it is clear that the majority of the available resource is fine sand. Importantly to note also is that the geological units do not have a uniform lithology. Hence, geological units, as derived from geophysical surveying, will always need ground-validation if a high certainty on a specific resource quality and quantity is desired.

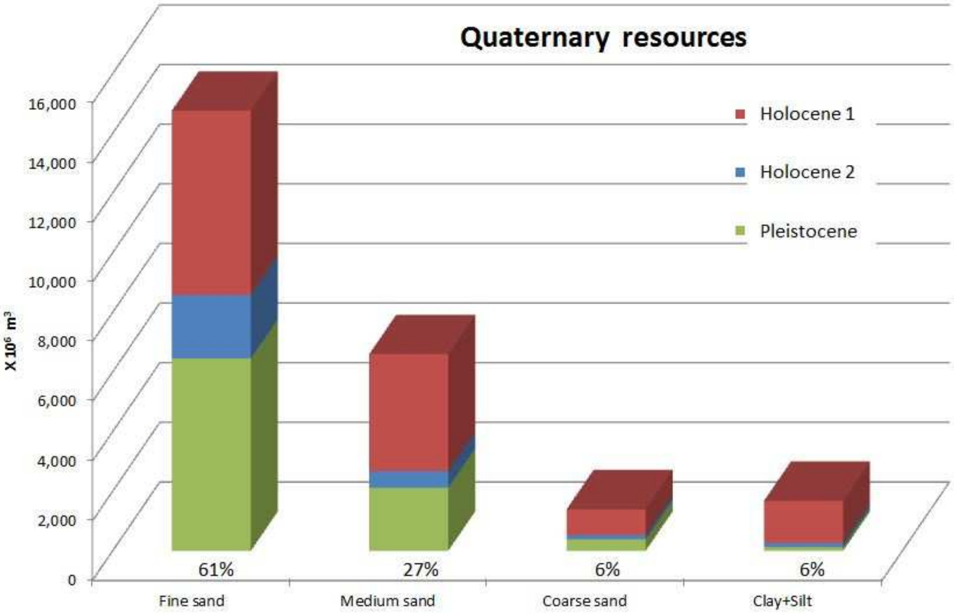

Figure 7: Volumes of the different lithoclasses in the Quaternary, and the geological unit they belong to.

Adding the 4th dimension

The coupling scheme between the 3D voxel model and the 4D environmental impact models, as presented in materials and methods, is in a testing phase. For some results on the application of 16-years hindcast of sediment transport parameters, reference is made to Francken et al. (this volume).

Decision support system

Currently, the voxel model can be queried following user-defined flexible combinations of criteria on the resource quality. In a first step the fixed-dimension geological voxel model is therefore queried. Following extra criteria from the end-user, the original voxels of 200 x 200 x 1 m are partitioned into smaller or bigger voxels. This partitioning can be based on data density as shown in Figure 8, right, but also on the other uncertainty layers that have been produced on the basis of the metadata (Figure 8, left). Experiments are now taking place on how to combine the different uncertainties into a single score that can be visualized together with the resource quality. The scoring will be fully transparent for the user.

The flexible querying of the DSS, combining resource quality with a series of uncertainties, will provide clear insight where resources can be exploited within a margin defined by the end-user. It will also become evident where existing knowledge and data are largely insufficient to support any management or exploitation advice.

Importantly, for the last phase of the project, input of end-users is critical, e.g., on improving the functionalities of the DSS, on desired qualities of resources, and exploitation strategies. For long-term predictions and management practices, it is important to gain insight into future supplies and needs. Any information on these aspects is welcome.

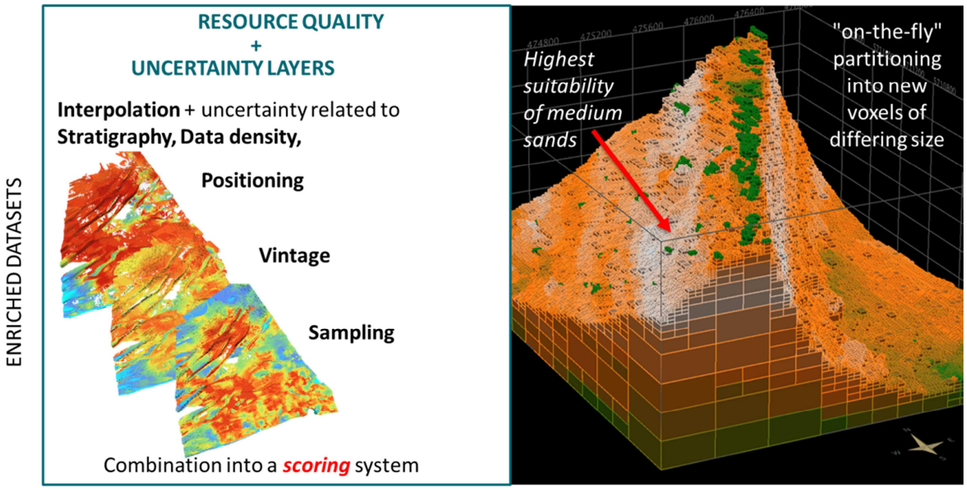

Figure 8: DSS showing a variable-size voxel model of a sandbank, based on the combination of resource suitability and an attribute of uncertainty. Here, the colour indicates suitability for medium sands (greyish: highest suitability; green: lowest suitability). Voxel size provides a broad indication of data uncertainty. Small voxel sizes at the surface are here indicative of the highly detailed bathymetrical data layer representing the seabed; voxel sizes in the subsurface are here a function of borehole density.

Conclusions

A transnational, harmonized geological knowledge base is being developed as a critical platform for the exchange of resource-related data, information and knowledge. This involves pioneering research, which is challenging in many ways: e.g., first subsurface voxel model of a marine area, accommodating voxels of varying dimensions, quantification and propagation of complex data uncertainties through the models, coupling of the voxel model with 4D numerical impact models, the development of a voxel-based decision-support system, and last but not least the many data visualization challenges. Importantly many of the developments were steered through interaction with stakeholders and their varying needs.

Sediment and borehole data have been standardised following European guidelines, allowing cross-border harmonisation in the mapping process. To facilitate this standardisation, borehole data were mapped from text-based descriptions to code. For the subsurface, a conceptual lithostratigraphic framework was set up, comparing and reconciling BE and NL subdivisions of the Neogene and Quaternary sequence.

For the BPNS, geological layer models were further refined. For the Top Paleogene a new very-high resolution digital terrain model was published. A tuned methodological workflow now exists for the creation of 3D voxel models, and is based on a four-layer voxel model distinguishing between the Top Paleogene, Pleistocene and two Holocene units. A first portfolio of resource-distribution maps for each main lithological class (Fine, Medium to Coarse sand; Clay to Silt) is created. For the BPNS, preliminary resource volume estimations of Holocene medium to coarse sands, of most interest for exploitation purposes, account for 21 % of the total available sediments in the Quaternary.

Anticipating on defining sustainable thresholds of exploitation, 4D resource modelling is performed accounting for geological boundary conditions, i.e., level of exploitation without major sediment and hydrographic changes. Additionally, an existing long-term hindcast modelling study of sediment-dynamics-related parameters was extended to 16 years, covering the time span of available monitoring data on marine sand extraction. The resulting knowledge is needed to quantify the envelope of natural and man-made variability of seabed processes. A methodological workflow is now ready for the calculation of depletion and regeneration rates.

A prototype of the decision support system is finished. It allows calculating suitability-reliability maps with scores that account for expert knowledge and data uncertainty. Results are stored in a format readable by subsurface viewers and are displayed in 2D and 3D. The result is traceable: for each voxel, it is possible to do a step-by-step analysis of how the final scores were calculated.

To conclude an efficient tool is provided to target <user-defined> suitable areas for extraction and allowing estimation of resource volume and quality. It is a flexible product of which the outcome can be coupled to other models (e.g., sediment transport, habitats, marine spatial planning).

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

Acknowledgements

The Brain-be project TILES (Transnational and Integrated Long-term marine Exploitation Strategies) is funded by Belgian Science Policy (Belspo) under contract BR/121/A2/TILES. The research is fully supported by the ZAGRI project, a federal Belgian programme for continuous monitoring of sand and gravel extraction, paid from private revenues. The progress of TILES benefits from synergies with other projects, nationally and internationally. Pivotal to the project progress has been the synergy with the IWT-SBO project SeARCH (IWT Project 120003) leading to the uptake of best available data and knowledge on the geology and stratigraphy of the Belgian part of the North Sea. Furthermore, the Belspo INDI67 project (BR/143/A2/INDI67) assists in making the project results more relevant in the framework of EU's Marine Strategy Framework Directive. Contributing EU projects have been EMODnet Geology (MARE/2008/03; MARE/2012/10; EASME/EMFF/20I6/1.3.1.2 - Lot 1/SI2.750862), Geo-Seas (FP7, Grant 238952) and ODIP (FP7, Grant 312492). Also, the EMODnet Lot on Ingestion and safe keeping of marine data regarding uptake of third party data will further strengthen the project outcomes. Underlying data have been acquired during numerous campaigns on RV Belgica, RV Simon Stevin, and many Dutch research and monitoring vessels. For Belgian waters, shiptime was granted by Belspo / RBINS OD Nature and Flanders Marine Institute.

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New limits for the sand extraction on the Belgian part of the North Sea?

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Introduction

Responding to the central question of this 2017 study day for sand extraction "Is marine sand a rare resource?" is not an easy task. It requires a scientific evaluation of the resources available for sand extraction, and based on this evaluation, a prognosis of how long the sand industry can continue its activities at the present rate. Under the current legislation, the sand reserve can be calculated by simply multiplying the total area where extraction is allowed with the maximum extraction depth. Compared to this reserve evaluation, the scientific evaluation of the available sand resource is a complex assignment, requiring knowledge of the structure and nature of the seabed. The latest attempt to produce a global and useful knowledge base of the sediments on the entire Belgian part of the North Sea is made in the framework of the Tiles project (Van Lancker et al., this volume). This article focusses on the ongoing project to combine legal restrictions, scientific criteria, and practical issues to define new limits for the extraction. Based on these well-considered limits an analysis can be made of the durability of the sediment extraction, and a prognosis of the future prospects for the sector becomes realistic.

At this moment, the limit for extraction is laid down in legislation at 5 meters below a reference area defined by the Continental Shelf Service (Law of 13 June 1969 on exploration and exploitation of the non-living resources of the territorial sea and the continental shelf, amended By the laws of 20 January 1999 and 22 April 1999). To date, this is a detailed seabed terrain model of the extraction areas, measured during extensive MBES surveys in the first half of the previous decade (in this report, this surface will be referred to as the BAS surface). Based on this limit, three areas in Zone 2 (KBMA, KBMB and BRMC), where the extraction led to a deepening of more than 5 meters, were closed. Currently, this limit is approached on some areas within Zone 1 (TBMAB) and 4 (HBMC), which in a medium term can lead more closures.

This legal constraint does not take into account the nature and structure of the seabed and the resulting differences in the extraction impact. In addition, the sustainable character of the exploitation is compromised. The sub-regions of the extraction areas with the highest quantities of the most requested quality of sand (medium to coarse sand) are closed irrespective of the still available volumes on site, while areas with economically less interesting quality of sediment (fine sand) remain open.

To address these problems, the Continental Shelf Service started a project to determine a new reference surface based on scientific and legal criteria. The purpose of this new surface is to limit the impact of extraction in the most sensitive areas of sediment and habitat and to increase economic sustainability by taking into account the available volumes and quality of sand. The introduction and application of these criteria will require a more proactive management of the sector's activities, and a closer cooperation and exchange of information between government and industry.

Procedure and assumptions

When designing the new surface, a number of considerations are taken into account:

1. In the preparation of the Marine Spatial Planning Plan (MRP) in 2014, the control zones where sand extraction was authorized were adapted: the Gootebank (then zone 1b) and the ecologically valuable gullies between the Kwintebank, the BuitenRatel and the Oostdyck inside zone 2 are no longer available for extraction (Figure 1). Only the sandy areas on the sandbanks themselves remain and the Sierra Ventana, as a source of recycled material. These are the areas that have the lowest ecological value. Furthermore, Control Zone 2 now falls completely within the newly demarcated habitat directive area (Figure 1). Within zone 2, the extracted volumes should now decrease by 2% annually to preserve and protect the habitats present in the western part of the Belgian part of the North Sea.

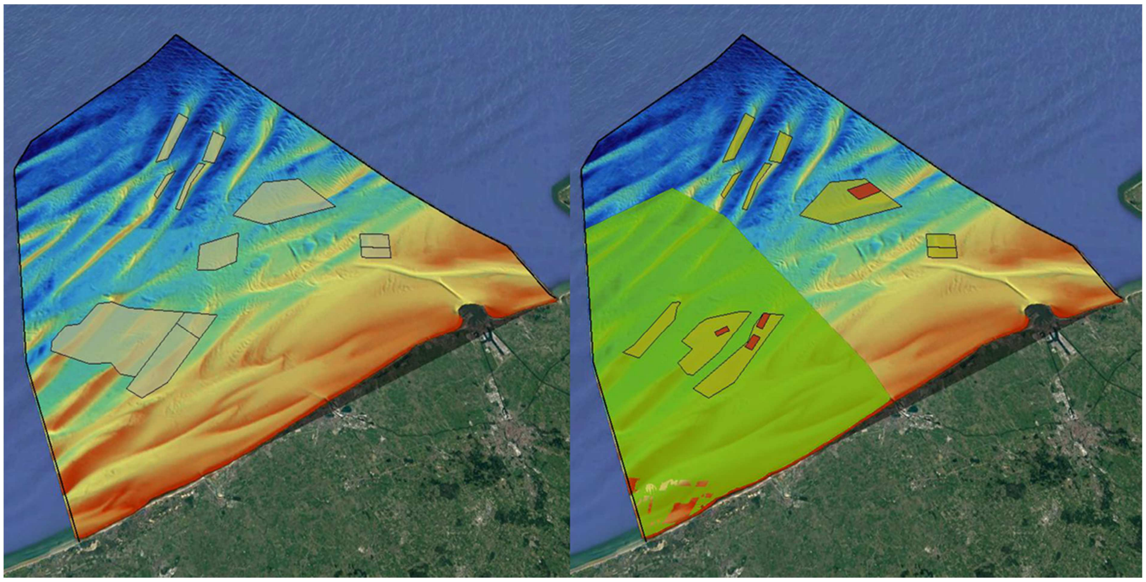

Figure1: Changes in the definition of the control zones for sand extraction in the Marine Spatial Plan (MSP). On the left the situation before (the control zones are marked in brown), on the right the situation since the implementation of the MSP. The control zones are indicated in yellow, the subareas closed for extraction in red and the habitat directive area in green.

On the basis of these recent measures and the conclusions of the biological monitoring by ILVO (De Backer et al., this volume), no new spatial restriction is introduced in this project. Thus, the current boundary of the zones is used in the further calculation of the new reference area.

2. To protect the integrity of the seabed as much as possible, the extraction should be limited to the top homogeneous package of sediments. Within this layer, the sand quality remains more or less constant. Further extraction down to the underlying layers, would change the nature of the sediments at the surface of the seabed and, consequently, the quality of the available sand. Under the European Marine Framework Framework Directive (MSFD) and its implementation in Belgian law (Royal Decree of 23 June 2010), Member States are obliged to maintain the integrity of their seabed to a maximum. This criterion therefore fully meets this specification of the directive.

To determine this limit, a complete and detailed geological (seismic) mapping of the Belgian part of the North Sea (BPNS) is required. With the collaboration of the SeArch and Tiles projects, the most recent and accurate modeled seismic surfaces are implemented: Top Paleocene (Upper Paleocene), Top Pleistocene and Top U4 (Figure 2). The presence and thickness of these geological layers vary throughout the Belgian part of the North

Sea. For this study, the lower limit of the homogeneous Holocene package is important, less the nature and age of the underlying layer. Therefore, a new surface area is defined by the Continental Shelf Service: SDS (Shallowest Discordant Surface). For each point of the new grid the corresponding value from the shallowest seismic surface (Figure 2) is selected. The result is a surface for the entire BPNS with the depth of the first found heterogeneity in the seabed composition.

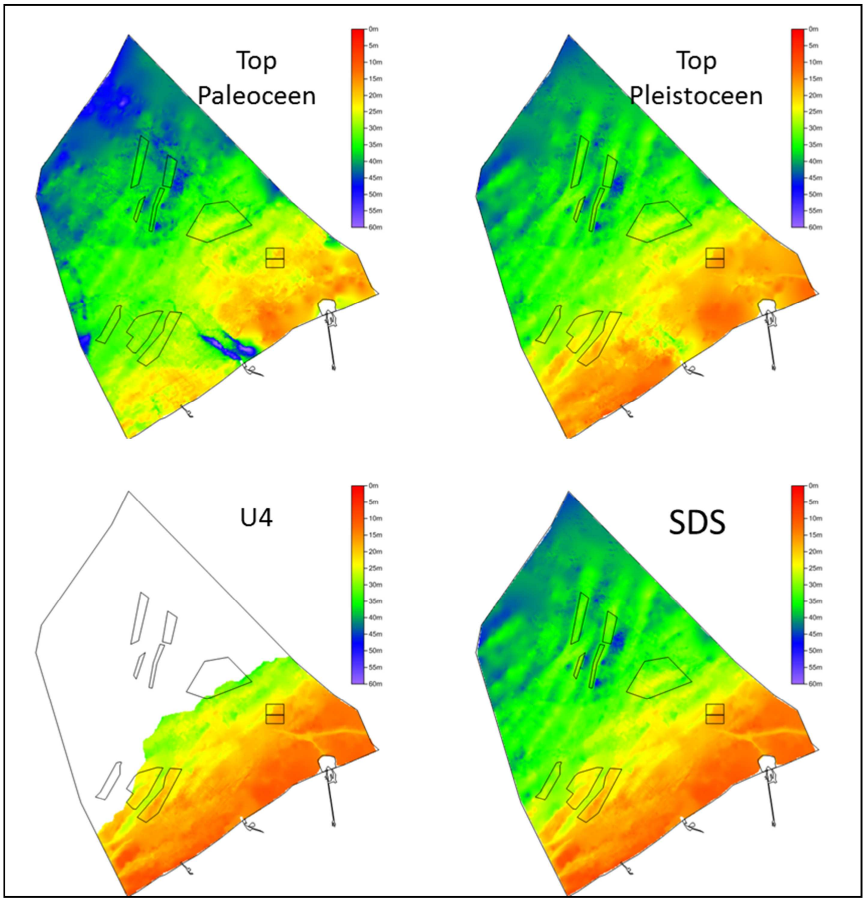

Figure2: The different seismic surfaces (courtesy ofSeArch and Tiles projects) and the resulting SDS.

The SDS becomes the absolute lower limit for the exploitation in the new reference. Taking into account the inaccuracy and possible error on seismic measurements and their interpretation, an additional buffer of 1m was added to this surface. The extraction is thus limited to a depth of 1 meter above the SDS.

3. Based on the role played by the sand banks in the protection of the Belgian coast, the maximum preservation of the morphology of the banks is introduced as a precaution. The impact of the banks' partial disappearance on coastal erosion has already been studied (Verwaest & Verelst, 2006), but the potential impact of a deepening up to the level of the new reference surface will be re-examined by the Directorate Natural Environment (OD Nature) of the Royal Belgian Institute of Natural Sciences. Within this project, maintaining the basic form of the sand banks is therefore an important criterion. However, maintaining only the basic form of the sandbank, opens up the important volume of sand in the sand dunes, the mobile part of the bank, for exploitation.

The modeling of the basic form of the various sandbanks within the control zones is an important challenge. The Continental Shelf Service approach passes by a filtering of the sandbank bathymetric data (BAS) based on the slope and local depth difference eliminating the measurement points of the grid located on the sand dunes.

With the remaining bathymetric points, a new grid is computed using an inverse distance weighted algorithm resulting in a basic form model which defines tangentially quite well the base of the dune pattern of the bank. in 2016, in collaboration with the Continental Shelf Service, researchers from ENSTA Bretagne and IMT Atlantique Télécom Bretagne have develop specific algorithms to approach the "osculatory – envelop surface" of a sandbank as closely as possible on the base of its bathymetric model (Debese & Jacq, 2016). In this contribution, the basic form of the sandbanks within the control zones (ECOS) are based on a mixed approach, merging the Continental Shelf Service approach with an intermediate osculatory model from ENSTA (Figures 3 and 4).

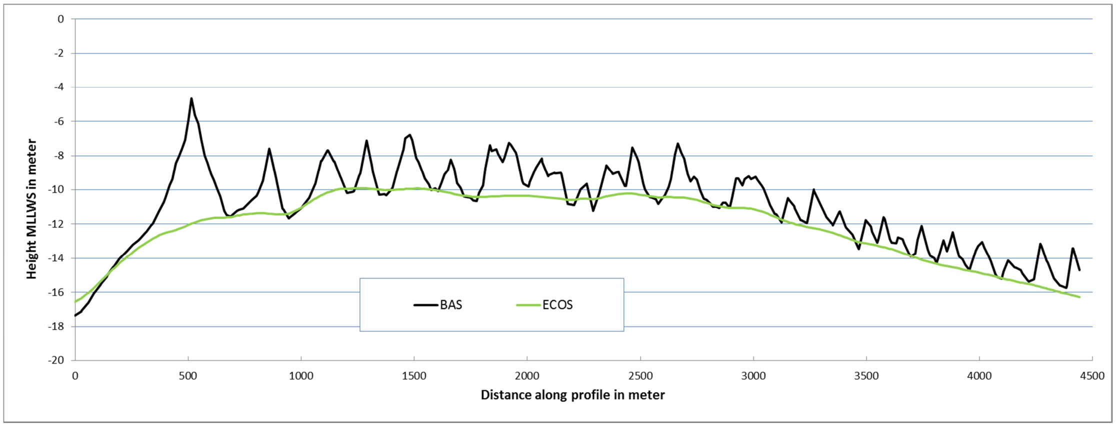

Figure 3: Cross section along profile AB (see figure 4) through BAS and ECOS surfaces for the Oostdyck. Depth in meter MLLWS.

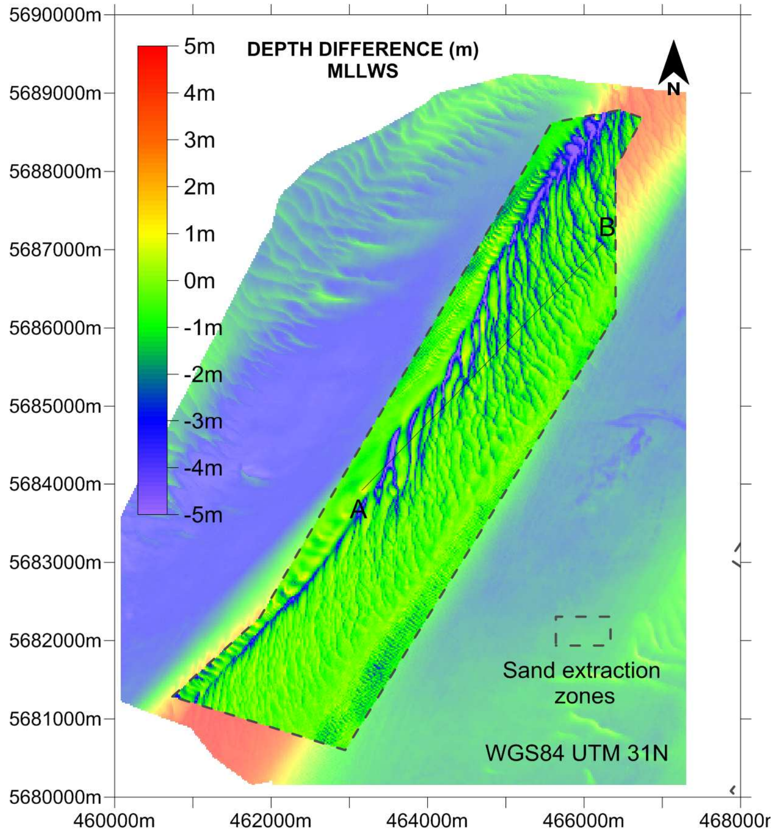

Figure 4: Depth difference between bathymetry (BAS) and basic form (ECOS) of the Oostdyck (sector 2od). A-B: profile from figure 3.

Improved modeling of the sandbanks basic forms by taking into account the latest generation of ENSTA models is under way. The new reference area will approach this resulting ECOS model for the different banks and control zones as closely as possible, taking into account economic sustainability.

Development of scenarios

Based on the SDS area (criterion 2) and the detailed bathymetric model of the control zones (BAS) or the modeled bank form (ECOS), a number of scenarios are elaborated (Figure 5). The total reserve of homogeneous Holocene material (BAS minus SDS) and dynamic sediments, or the volume of the sandwaves (BAS minus ECOS), are calculated and compared with the current legal reserve and reserves in the various scenarios. By limiting ourselves to the current control zones, all scenarios are assumed to meet the first criterion, namely minimizing environmental impact.

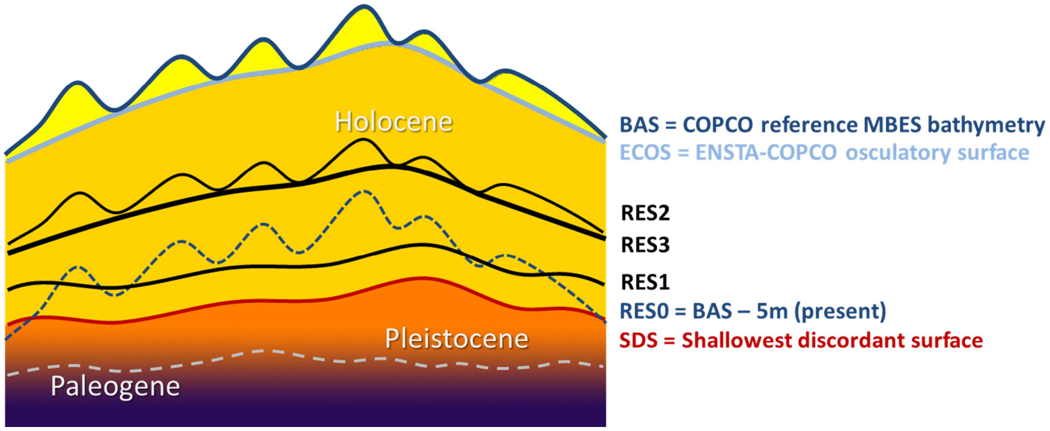

Figure 5: Overview of the different scenarios by means of a schematic cross section of a sandbank.

1. The base scenario (RES0) is the current situation with a reference area that is 5m below the bathymetric model. The nature of the sediment present is not taken into account, allowing in principle the extraction to go deeper than the upper homogeneous package (lower than SDS).

RES0 = BAS – 5m

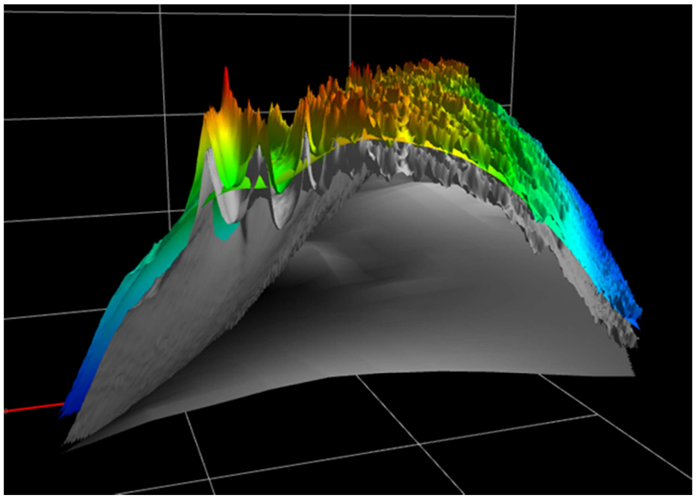

Figure 6: 3D-cross section of the Oostdyck with RES0 in grey (BAS-5m).

2. The maximum scenario in volume (RES1) does not take into account criterion 3 (retention of the bank form). The reference here becomes the SDS surface so that we remain sedimentary in the same homogeneous package. An additional 1m buffer is provided to capture the inaccuracies of the seismic models.

RES1 = SDS + 1m

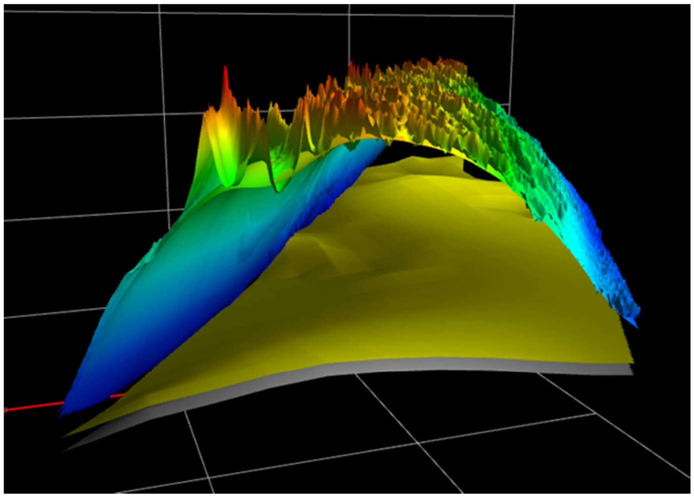

Figure7: 3D cross section of the Oostdyckwith RES1 in yellow (RES1 = SDS + 1m).

For Zone 3 (Sierra Ventana) only this scenario has been withheld. Both BAS and ECOS are useless because of the specific nature of this area: the alternation of dumping and extraction results in a constantly changing seabed. Thus, the only possible scientific criterion is to maintain a similar sediment type at the seabed surface.

3. The second new scenario takes into account the conservation of the bank form (criterion 3). The new reference area is located halfway between SDS and Bathymetry (BAS), but remains at least 1m above SDS. In this option, the morphology of the bank is partially maintained.

RES2 = (SDS + BAS)/2 with RES2 ≥RES1

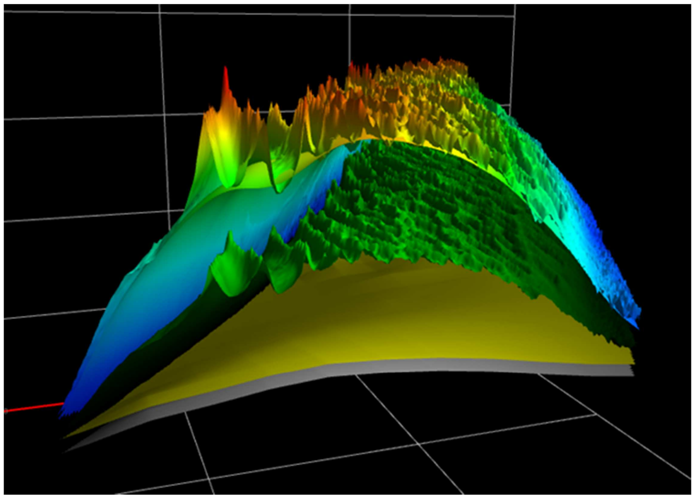

Figure 8: 3D cross section of the Oostdyck with RES2 in green (RES2 = (SDS + BAS)/2 with RES2 ≥ RES1).

4. By replacing the detailed bathymetric model of the control zones with the modeled bank shape, the volume in the sand dunes (dynamic volume) is added to the total available volume. The new reference area is thus halfway between SDS and ECOS. AS in the previous scenario, the morphology is partially maintained.

RES3 = (SDS + ECOS)/2 with RES3≥RES1

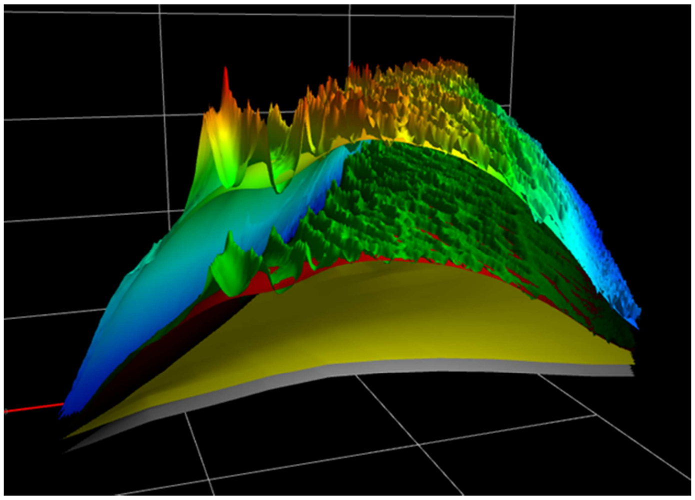

Figure9: 3D cross section of the Oostdyck with RES3 in red (RES3 = (SDS + ECOS)/2 with RES2 ≥ RES1).

Further scenarios where the volume of the bank (criterion 3) is more maintained, will not be considered for the moment, as this would significantly reduce available volumes and endanger economic sustainability. For the various proposals, the volumes available for extraction can be estimated.

SECTORS	Holocene reserve BAS-SDS	Dynamic volume BAS-EOS	Legal volume BAS-RES0	Scenario 1 BAS-RES1	Scenario 2 BAS-RES2	Scenario 3 BAS-RES3			
S1	224	72	392	166	104	125		🟩	+
S2	485	56	430	412	210	259		🟨	+/-
S3	61		83	46				🟧	-
S4	393	42	228	349	195	215		🟥	--
TOTAL	1164	170	1133	973	508	599			

Table 2.Comparison of the available volumes for extraction associated with the scenarios with the current available legal volume: red = strong decrease, orange = decrease, yellow = stable, green = increase. Volumes in $10^6 m^3$.

In zone 1, each new scenario strongly reduces the available volume (Figure 10 and Table 2). This is the consequence of the shallow location of the SDS. Extraction seems only possible in the eastern part of this zone. In the western part, the Holocene material has already largely disappeared or is not present.

In zone 2 there are big differences between the three sandbanks present (Figure 11). At the Kwintebank and Buiten Ratel there is a clear decrease in the operable volume. Only on the southern and eastern part of the Buiten Ratel the available layer remains comparable to the current situation in each scenario. This loss is partially compensated by the greater volume available on the Oostdyck.

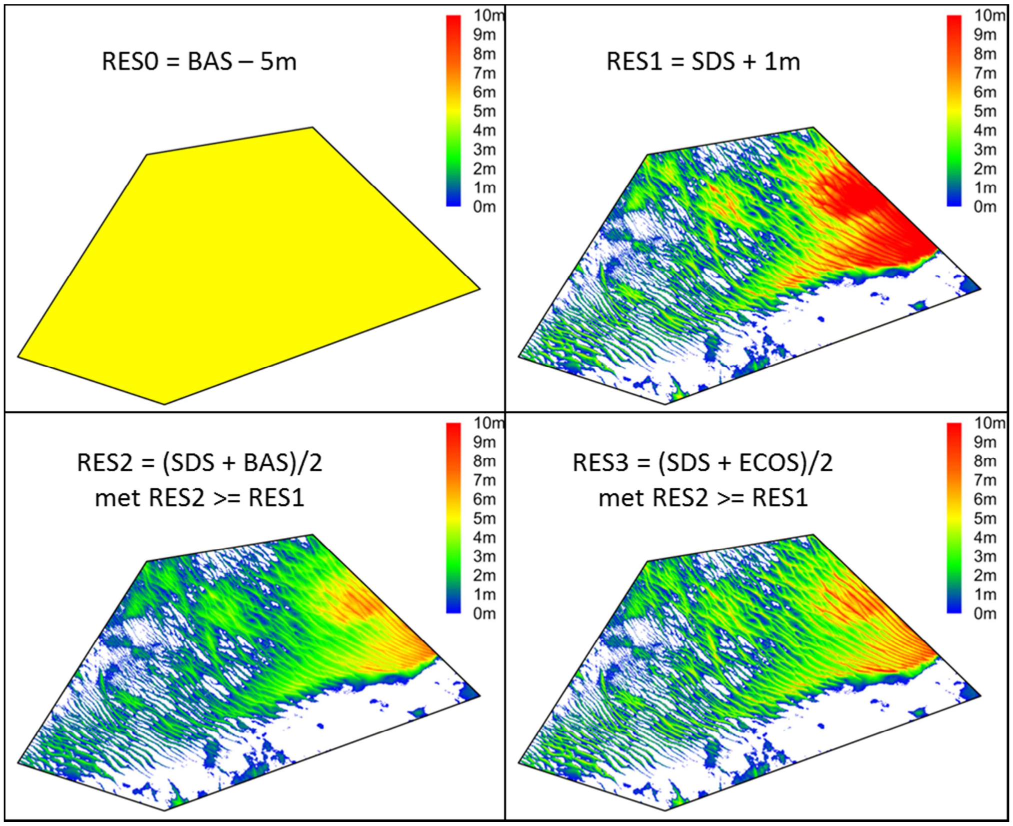

Figure10. Comparison of the thickness of the available layer of sediment in zone 1 on the basis of the different scenarios.

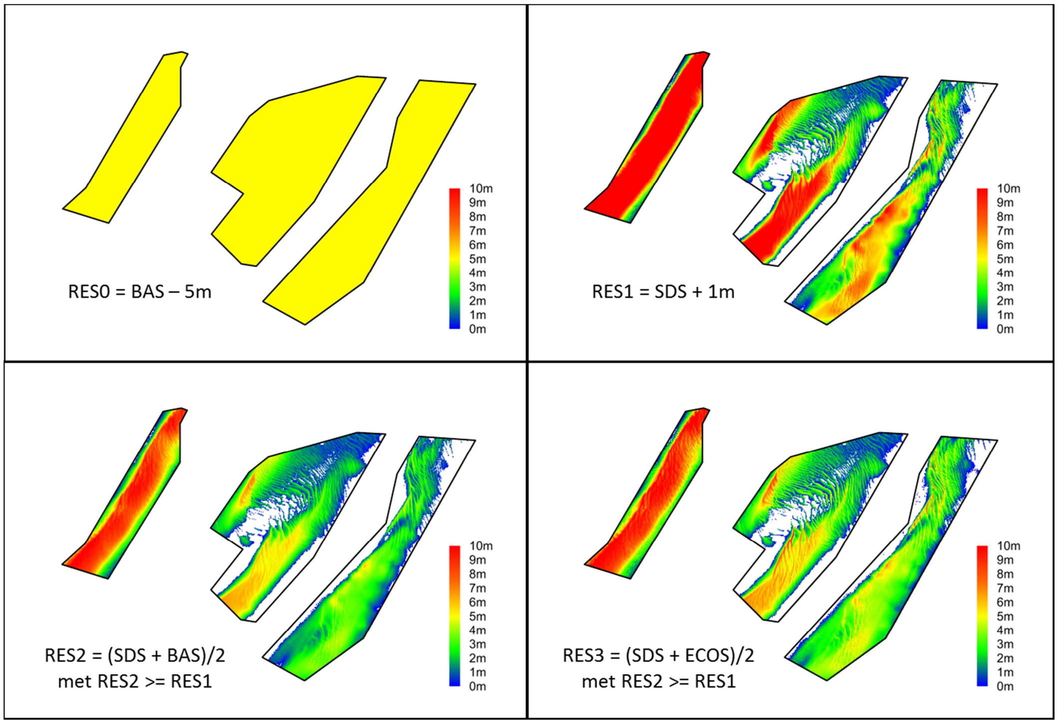

Figure 11.Comparison of the thickness of the available layer of sediment in zone 2 on the basis of the different scenarios.

At the Hinder banks, the total volume decreases less (Table 2 and Figure 12). In scenario 1, which amounts to almost the entire sandbanks in the 4 sub-areas, there is even a strong increase. For scenarios where the form of banking endures a bit more, the volume concentrates on the central upper sections of the banks, with a thickness of up to 10m.

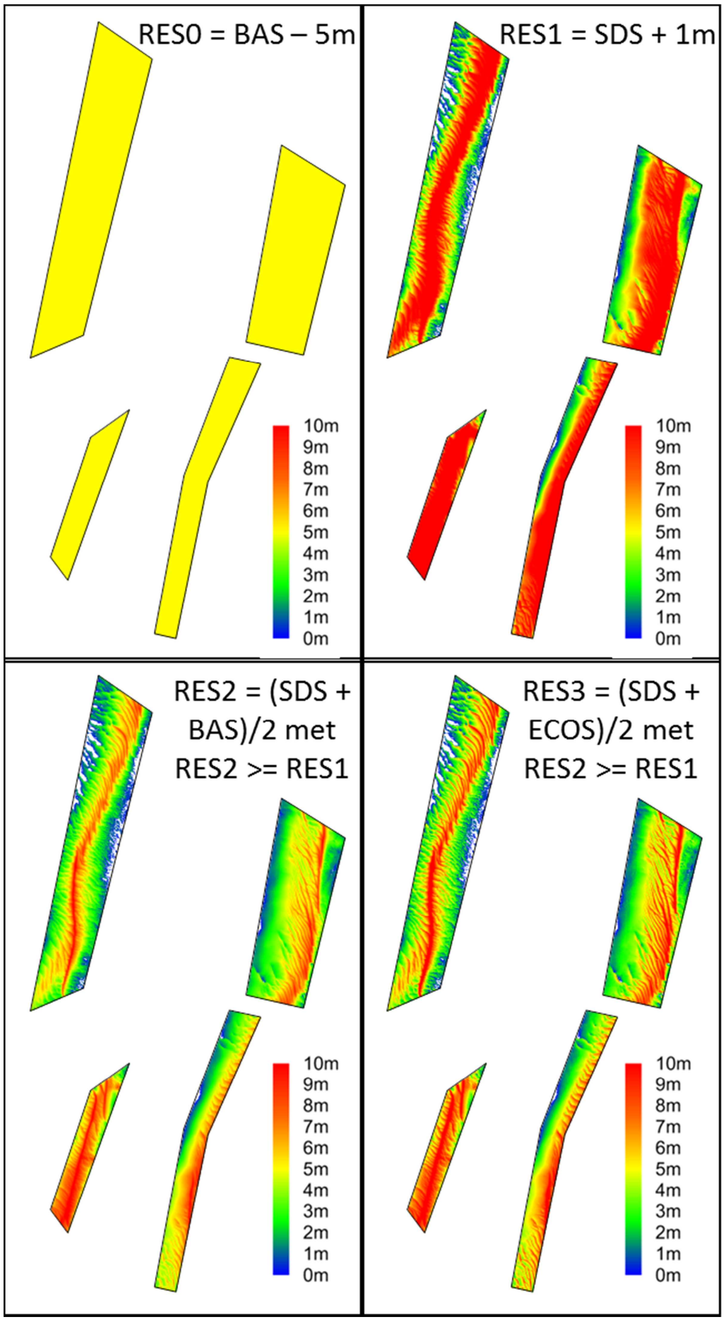

Figure 12.Comparison of the thickness of the available layer of sediment in zone 4 on the basis of the different scenarios.

In general, a shift of available volumes to the Oostdyck, the eastern part of the Thorntonbank and the Hinderbanken is observed in all three scenarios.

Selection and impact of scenarios

Based on the comparison, scenario 3 was selected as the ideal compromise between the criteria. For zone 3 scenario 1 was selected, based on the specific regulation for this area. However, the Belgian implementation of the MSFD provides an additional restriction: the resulting bottom shear stress change has to remain inside a 10% interval (see Vandeneynde et al, this volume). The third scenarios was evaluated and all area's except sector 2od (Oostdyck) complied with this condition. On the Oostdyck the impact on the seabed would exceed this threshold. The scenario was adapted to fulfill the requirements with the maximum of volume. If the surface from scenario 3 (RES3) is raised by 4m, it would comply with the MSFD specification (see Vandeneynde et al, this volume). The impact on the available volume amounts to 58 10^6m^3 (more than half of the volume in scenario 3), resulting in an important drop in the overall available sediment reserve.

The different volumes are listed more detailed (per sector) in Table 3. The available volumes for the present situation (legal volume) and for the new reference surface are corrected for the extracted quantities of sand in the period 2003-2016 (-EMS) and the area currently closed for extraction: KBMA, KBMB, BRMC and the reference area in zone 1 (-EMS -CLOSED). Zone 3 (Sierra Ventana) is included in the table, but since the model for this zone is based on recent bathymetric data, no corrections are applied (these uncorrected values are in italic).The biggest drop in available volume is situated in zones 1 and 2. On the Thorntonbank the volume would drop from 337 10^6m^3 to 87 10^6m^3, or 74%. On zone 2 this amounts in a decrease from 390 10^6m^{3}to 178 10^6m^3, or 54%. Considering the reopening of the closed areas in both zones, would reduce the decline in zone 1 to 64% (to 120 10^6m^3) and in zone 2 to 52% (to 187 10^6m^3).

SECTOR	**Legal Volume RES0**	**Legal Volume RES0 -EMS -CLOSED**	**New Volume**	**New Volume RES -EMS**	**New Volume RES - EMS -CLOSED**
S1a	392	337	125	120	87
S2kb	163	140	66	61	53
S2br	187	173	85	77	76
S2od	79	77	51	50	50
S3	83	*83*	46	*46*	*46*
S4a	96	96	79	79	79
S4b	69	69	62	62	62
S4c	42	38	41	37	37
S4d	22	22	33	33	33
TOTAL	**1133**	**1033**	**587**	**564**	**522**

Table 3. Comparison of the available volumes for extraction per sector associated with the preferred scenario with the current available legal volume. Volumes in 10^6m^3.

All these values represent the maximum volume that is available inside the limits of the sectors. How much of these volumes are really extractable is not easy to define. The spatial distribution is fragmented, not evenly distributed over the area as in the present situation (RES0). Especially in zone 1 (figure 10) this will largely reduce the extractable quantities. Furthermore, the sand is not extracted up to the border of the area. Doing so would result in infractions on the regulation (overpassing the limit of the zone) and cause direct impact on the seabed outside the allowed extraction areas. In case the impact exceeds the new limit, the impacted areas will be closed, as in the present situation. This doesn't result in closed areas where 100% of the legally accessible volume was extracted. In the closed area on the Buiten Ratel (BRMC), the average deepening is only 2.5 m, although it exceeds the 5m limit for a large part.

Based on the listed arguments and the experience up to now, an extraction of 50% of the available volume seems realistic. This would amount to a total of 260 10^6m^3, or a possible 80 years extraction at the present rate (3 10^6m^3/year). However, this doesn't take into account a further rise in the extraction figures or extra volumes for special projects (for coastal defense or offshore construction), which would decrease the forecast, and the replenishment of the available volume on zone 3, which could increase the forecast slightly.

Conclusions

The economic sustainability of the sand extraction can be augmented by ensuring the long-term availability of available stocks of economically valuable aggregates. Based on the demarcation of the control zones and the 5m limit, we can calculate the total available stock of sediments for extraction, but this does not take into account technical constraints (e.g. impossibility to extract the full volume without direct impact on the surrounding area) and the suitability of the sediments for extraction. For this latter, extensive knowledge of the sediment present is required, both on the surface of the seabed and in the subsoil.

The Tiles project (Van Lancker et al, this volume) attempts to formulate an answer to this important question. Based on the preliminary results, a 3-dimensional mapping (by means of voxels), in cooperation with Ghent University and OD Nature, of the sediments in the different control zones has been made (see Figure 13). In this case, the third scenario (halfway between SDS and the model of the bank – ECOS) is always used as the lower limit.

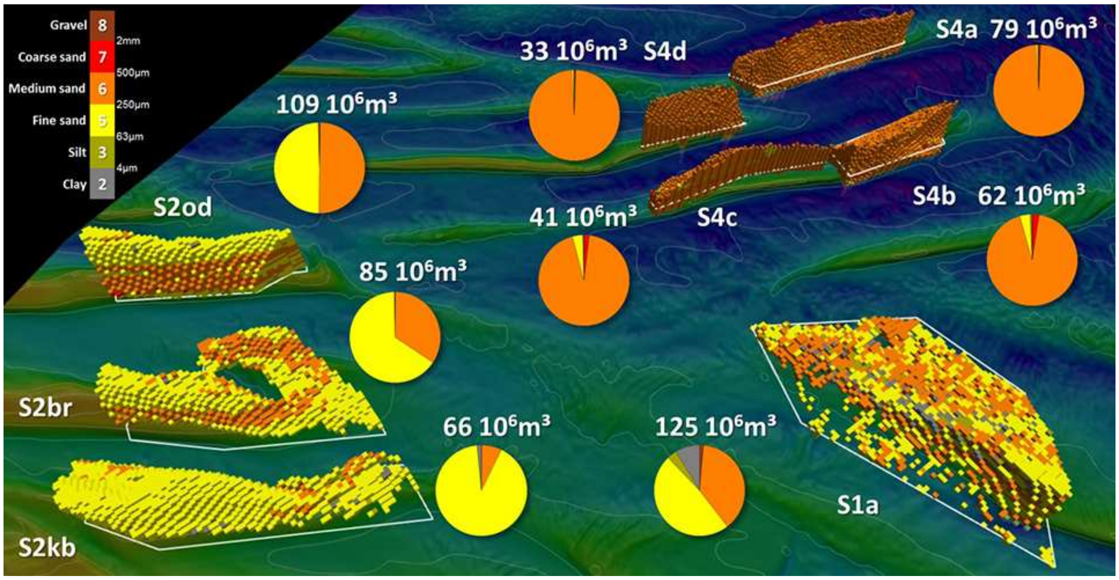

Figure13: Voxel-model for extraction zones 1, 2 and 4, based on the intermediate results of the Tiles project. Sediment types are distinguished. The quota for each sediment type is presented in polar-wedge diagram for each sector.

On the Hinderbanks (control zone 4, with sub-areas 4a, 4b, 4c and 4d) the concentration of medium coarse sand is highest (Figure 13). At the Kwintebank (zone 2kb) the available stock of the same type of sand is the lowest. The intermediate sectors (2br, 2od and 1a) present a mix of both fine and medium sand. The Voxel model shows where the most valuable sediments for mining are present and the available volumes, from an economic point of view, should be maximized.

In the next phase of the project the information from the Voxel model will be combined with maps of the seabed surface sediment type and information on the quality of sand made available by the extraction firms.This will allow a further evaluation of the economic sustainability of the different scenarios. One of the principles of this project is the transition from theoretically exploitable and undifferentiated sand stocks to realistic and useful volumes per type of sediment. This must lead to a more future-oriented and thus more sustainable management of the sand extraction on the Belgian part of the North Sea.

Acknowledgements

Nathalie Debese and Jean-José Jacq from ENSTA Bretagne and IMT Atlantique Télécom Bretagne are acknowledged for their contribution to the development of the sandbanks basic forms – osculatory surfaces. The members of Zeegra are thanked for their input of valuable information, the excellent cooperation and feedback. The colleagues from ILVO and OD Nature are thanked for the collaboration in the testing and evaluation of the different scenarios and feedback. This is an ongoing project that greatly depends on the collaboration of all the involved institutes and the sand extraction industry.

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EXTRA CONTRIBUTIONS

Application of a large dataset of sediment transport parameters: variability in sediment transport in the HBMC area

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Introduction

Distinguishing naturally- from anthropogenically-induced variability of the seabed is very difficult, as the range of natural variation is hard to quantify. 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; Roche et al., this volume), or are derived from newly acquired current and turbidity data. Still, in many cases the regional context is missing, and sound interpretations on the driving forces are not possible. Nevertheless the quantification of both naturally and man-made changes are needed for the definition of acceptable thresholds for alterations to the seabed (e.g., aggregate extraction, Van Lancker et al., this volume). Also, to assess the recovery potential of impacted areas after extraction, a critical parameter within Europe's Marine Strategy Framework Directive (MSFD), natural system variability needs to be quantified. This can be approached through statistical analyses of long-term databases on seabed evolution (cf. Dalyander et al. 2013). For the Belgian part of the North Sea, a 12-year long hindcast (1999-2010) on the main sediment transport parameters (i.e., bottom stress, bottom geometry, total load and bottom evolution) was therefore produced (Francken et al., 2014) and has now been expanded, and applied to case studies for validation.

In this case study we evaluate the natural variability of the total load sediment transport from a long-term database, as it directly impacts the bottom morphology.

Material and methods

Model data

Results from a subset (2012-2014) of the 16-year long hindcast (1999-2016) were used to assess the variability of sediment transport in the Hinder Banks. Purpose was to provide regional context to sediment processes in the monitoring area HBMC, being a subarea of the aggregate sector 4C (see Roche et al., this volume).

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 finer resolution 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 (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 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

Yearly averages of the X and Y vectors of the total load were calculated at every grid node. The same routine was also used for every season, i.e., winter (January-March), spring (April-June), summer (July-September) and autumn (October-December), but is adaptable to cover any desired period. See Francken et al. (2014) for more details on the analysis.

Results and discussion

The results from the yearly averaging of the total load in the HBMC area are presented in Figure 1.

Comparing the mean transport in 2012, 2013 and 2014 (Figure 1) it is clear that the depth-averaged sediment is mostly NE-directed. Most striking is the magnitude of transport along the SE flank of the Westhinder sandbank, but also the local variation in the Hinder Banks region. In the northern part of the study area, the general transport direction is mainly SW-directed, except for 2014 where the mean transport was near zero. In this year, NE-directed transport dominated on average over the whole area.

To investigate the underlying reasons for this distinct year-to-year variability in total load sediment transport, all data was regrouped into seasonal averages and cross-related to atmospheric data coming from the measuring pile at the Westhinder Bank (MOW7) (Meetnet Vlaamse Banken, Agentschap Maritieme Dienstverlening en Kust). Averaged wind speed at 10m above the sea surface and averaged wind direction were combined in wind roses and compared to the total load sediment transport in the Figures 2 to 5.

Figures 2 and 3 show for 2013 overall predominant winds blowing from the SW and less frequent and less strong winds blowing from the NE, which is a normal regime for the Belgian part of the North Sea (Meetnet Vlaamse Banken). However, in winter, winds were predominantly blowing from the NE sector and were much stronger than in spring and summer. They were often equally strong than the SW winds that occurred less frequent. This had a clear effect on the total load. In the northern part of the area, as well along the deeper southern part of the Oosthinder sandbank, the mean transport was directed S to SW. In autumn, SW sector winds were predominant, but showed a large spread. Almost no wind came from the NE sector. This resulted in a predominant SW to NE oriented total load transport.

The next two figures (Figs. 4 and 5) show the wind roses and averaged total load sediment transport for the four seasons of 2014.

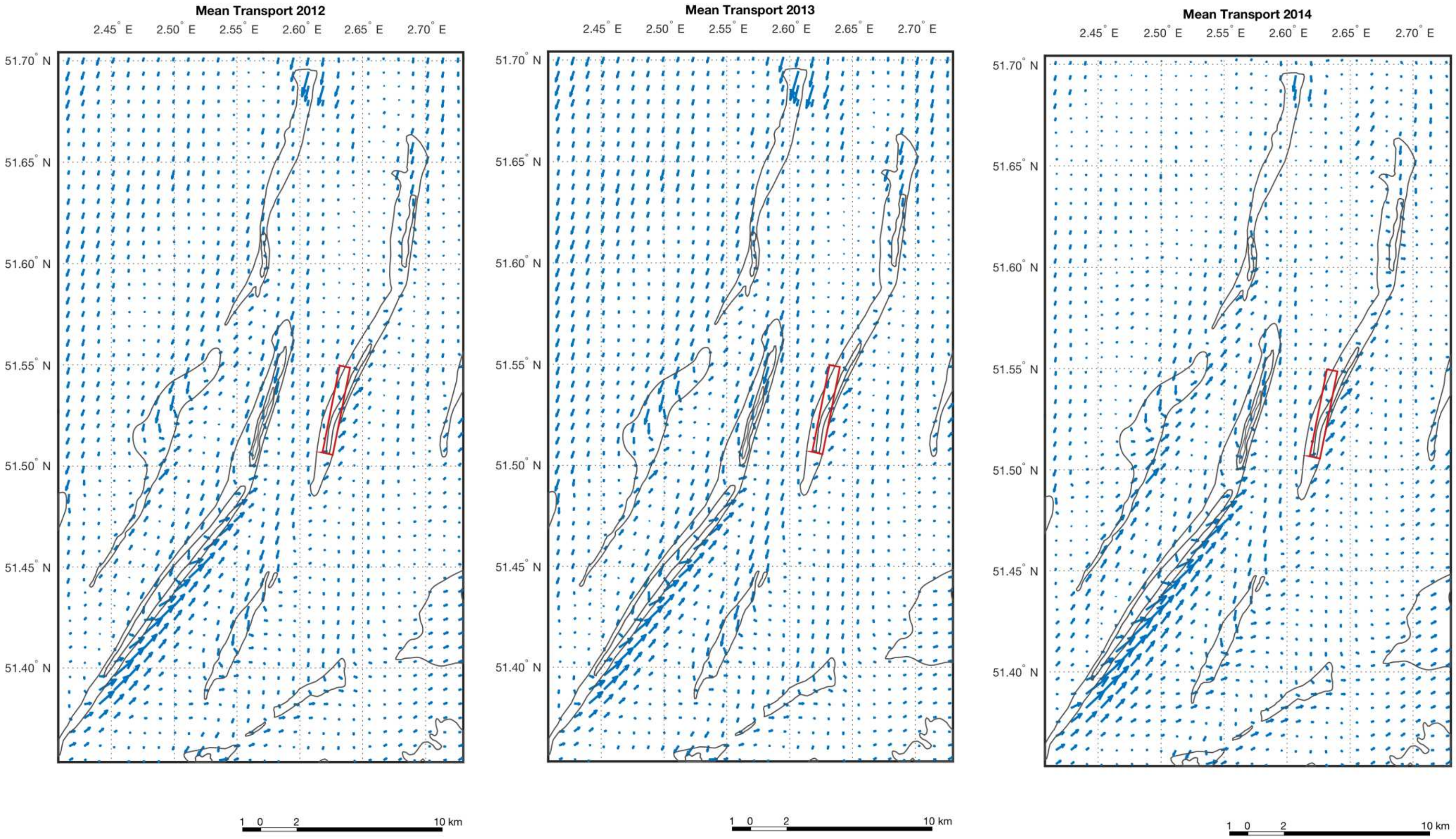

Figure 1: Yearly (2012-2013-2014) averaged direction of the total load sediment transport in the region of the Hinder Banks. HBMC area is shown in red.

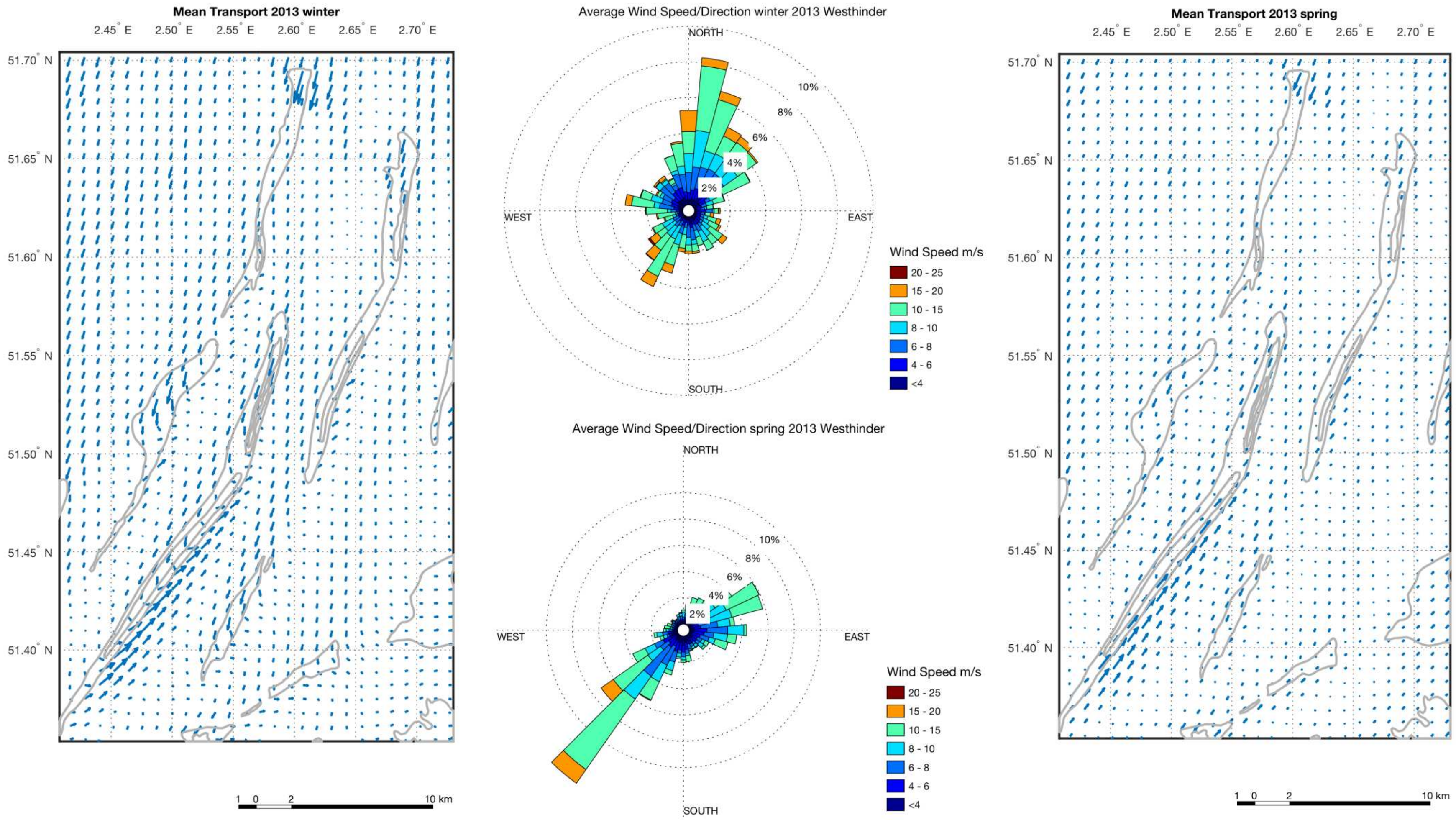

Figure 2: Seasonal averaged total load sediment transport and wind roses for winter and spring 2013.

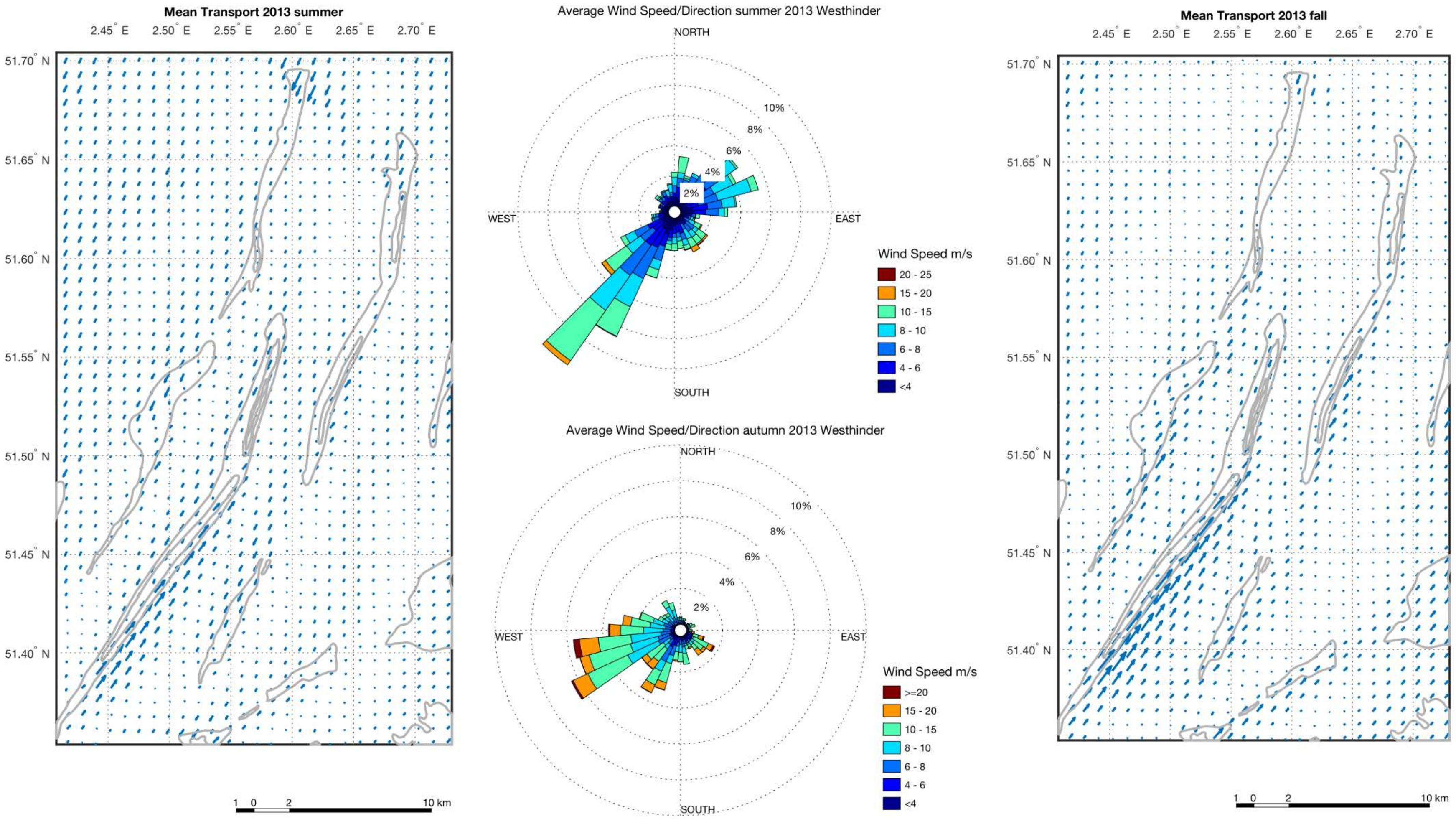

Figure 3: Seasonal averaged total load sediment transport and wind roses for summer and autumn (fall) 2013.

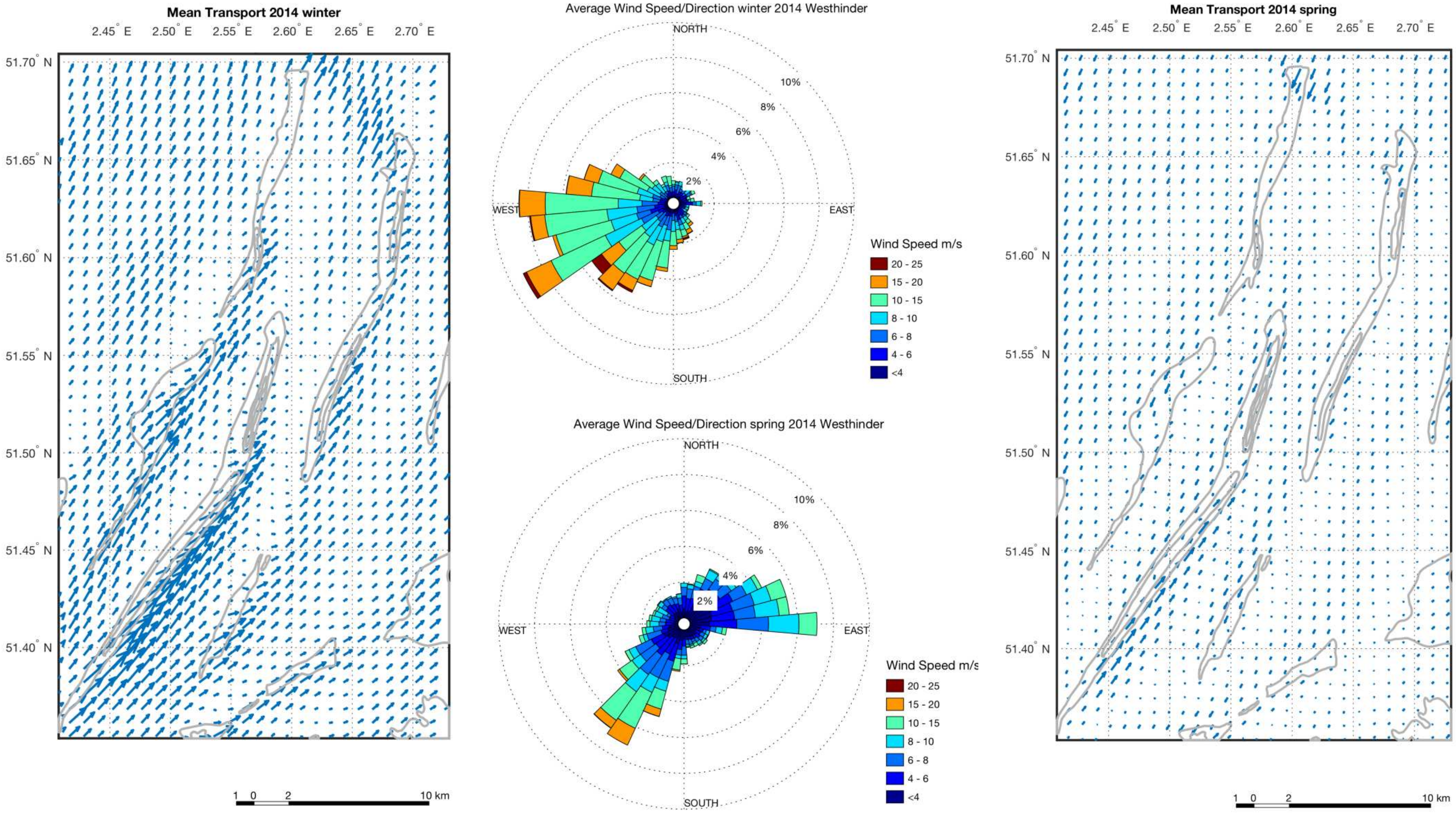

Figure 4: Seasonal averaged total load sediment transport and wind roses for winter and spring 2014.

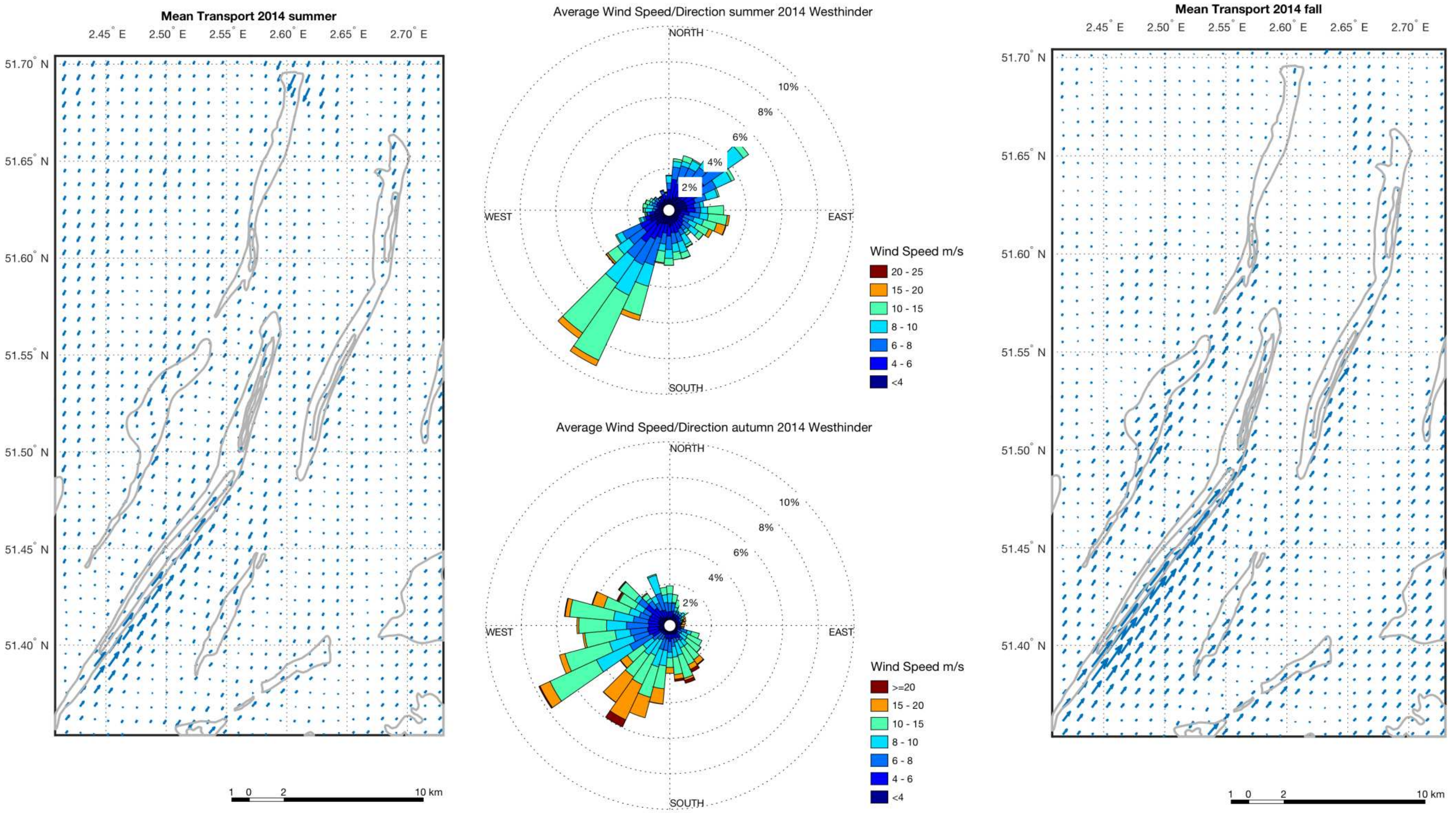

Figure 5: Seasonal averaged total load sediment transport and wind roses for summer and autumn (fall) 2014.

Figure 4 shows the winter of 2014 characterised by strong and very frequent winds blowing from the W and SW sector. Almost no wind originated from the N or the NE. The effect on the average total load transport direction is obvious. The global transport over the entire study area was SW-NE oriented. Spring and summer showed comparable patterns as in 2013. Both winds from the SW and NE sectors, giving rise to the same transport patterns as the previous year. Autumn 2014 again showed winds predominantly blowing from the W and SW sector, showing strong winds and wide spread.

It is clear that the winter of 2014 differed from the one of 2013. Model results show a distinct overall transport from the SW to the NE, which is at least partly explained by the meteorological conditions at that time. For the validation of the model results, measurements were sought on the depth and morphological evolution in the area. To this end FPS Economy, Continental Shelf Service provided a set of monitoring data (multibeam datasets) of the HBMC area on a 1m by 1m grid, for the years 2012 – 2014, each year containing two datasets.

In the SW part of the monitoring area a 2D profile was selected for the analysis of the morphological evolution (Figure 6).

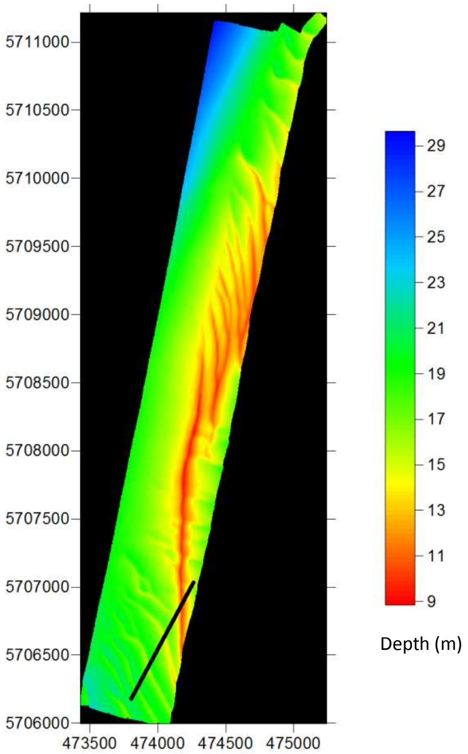

Figure 6: Digital elevation model of the HBMC area in 2012. Superimposed (south) is a profile along which depth data were extracted for comparison in time. Data courtesy FPS Economy, Continental Shelf Service.

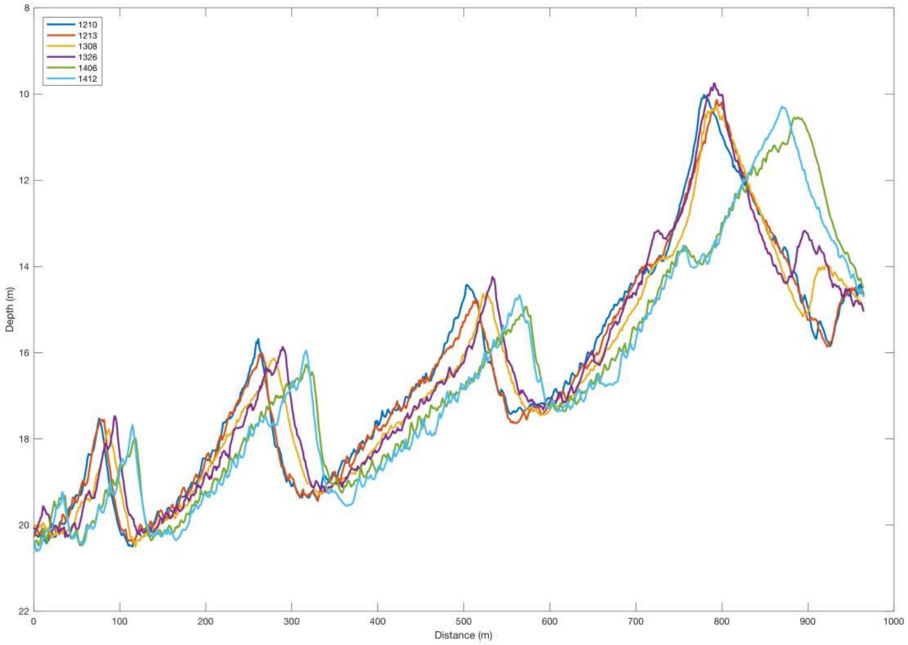

Figure 7: 2D profiles extracted from the digital elevation model time series. Dark blue and orange are profiles in 2012, yellow and purple in 2013, green and light blue in 2014.

Figure 7 shows the time series of the selected 2D profile. The dunes at the beginning of the profile (deeper water parts) show a yearly progressive migration. Most striking is the migration of the very large dune at the NE extremity of the profile, being located nearest to the top of the sandbank. The position of the dune was quasi stable in the years 2012 and 2013, but clearly a large bedform migration occurred at the end of 2013, beginning 2014 (winter 2014). In a period of several months, the top of the dune shifted for 80m in a NE direction and reduced in height. This testifies that also in the offshore area, dunes have dynamic behaviours and respond to changing hydro-meteorological conditions.

Conclusions

The previously created on-demand queryable sediment transport database (spanning 1999 – 2010) was expanded with four more years (2011 – 2014). From this, a subset (2012 – 2014) was selected to study variations in the total load sediment transport in the hinder Banks region. At first sight aberrant model output could at least be partially explained by deviant atmospheric conditions and the effects were validated by time series of a digital terrain model of the HBMC monitoring area in the aggregate sector 4C. 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.

Acknowledgements

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Marine aggregate mining in the Hinder Banks: on-board sampling of the turbid dredging overflow

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Monitoring of the effects of marine aggregate mining is needed to reach good environmental status of the marine environment (EU Marine Strategy Framework Directive). For example, changes in seafloor integrity or hydrographic conditions could adversely impact on benthic ecosystems. In the region of the Hinder Banks, the dredging overflow plumes associated with mining activity within aggregate sector 4c potentially reach ecologically valuable gravel areas in a Habitat Directive Area just south of it. Part of the effort in the monitoring programme intends to examine the characteristics of these overflow particles, such as concentration and size distribution. On-board of a trailing suction hopper dredger, 1 l sampling of the sediment-laden overflow was executed in intervals of about 10 minutes for a total overflow duration of 54 minutes. The collected overflow water was analysed with a turbidimeter and laser diffraction instrument. These revealed an overflow concentration of up to 1 g/l and a size distribution centred around 21 µm. These fine-grained overflow plumes likely remain in suspension for many hours and are systematically transported southward, due to the consistently low tide conditions of these extractions. These plumes are being observed in satellite imagery with deriving sea surface plume concentrations of 0.01 g/l. In the period February to April 2017, intensive sand mining took place within sector 4c with a frequency of up to 4 trips per day as two hopper dredgers were simultaneously in operation, just before low tide. Importantly and for the first time, both ships were commissioned to combine both sand mining and harbour maintenance operations. As a result, dredged matter having much higher silt-clay content is likely to remain inside the hopper enriching the fine particles in the overflow plumes during sand mining.

Towards a DNA (meta)barcoding approach to assess changes in seabed ecosystems related to sand extraction activities

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Biodiversity is influenced by a wide range of environmental and human-induced pressures. Physical disturbance of the seabed is probably the best known pressure to affect benthic ecosystems. The aim of this work is to evaluate the potential of DNA (meta)barcoding to assess human-induced changes in the seabed ecosystem. We focus on two benthic ecosystem components: bacteria and macrobenthos, in relation to sand extraction in the Belgian part of the North Sea.

The bacterial community composition in the sediment was assessed by amplicon sequencing of the V3-V4 fragment of the 16S rRNA gene using Illumina technology. Disturbance of the seabed due to sand extraction activities on the Buiten Ratel sand bank revealed a significant impact on the bacterial communities.

Macrobenthos is recognized as a good biological indicator to measure changes in marine ecosystems. Excellent morphological identification tools exist, but these are time-consuming. DNA barcoding (species) and DNA metabarcoding (communities) may provide a fast alternative. However, accurate DNA-based species identification is lacking.

Therefore, COI and 18S fragments of 70 macrobenthos species were amplified using several barcoding primers and Sanger sequenced to evaluate which amplicon provides the best taxonomic resolution. The 18S and COI barcode sequences were added to our DNA reference library. We developed a DNA metabarcoding method using Illumina MiSeq technology and amplicon sequencing was executed using the 18S target regions and DNA extracts both on individual species, and on pooled samples in which tissues or DNA extracts of different species were mixed. This setup allowed us 1) to check the effectiveness of the primers to detect species in both single and pooled samples; and 2) to investigate the relationship between read counts per species and the relative proportion of species in mixed samples.

This work is ongoing and will be used to establish a complete North Sea DNA barcode reference database for bacteria and macrobenthos, in close cooperation with other institutes along the North Sea.

Keywords: DNA (meta)barcoding; macrobenthos; bacteria; amplicon sequencing; biodiversity

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