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.

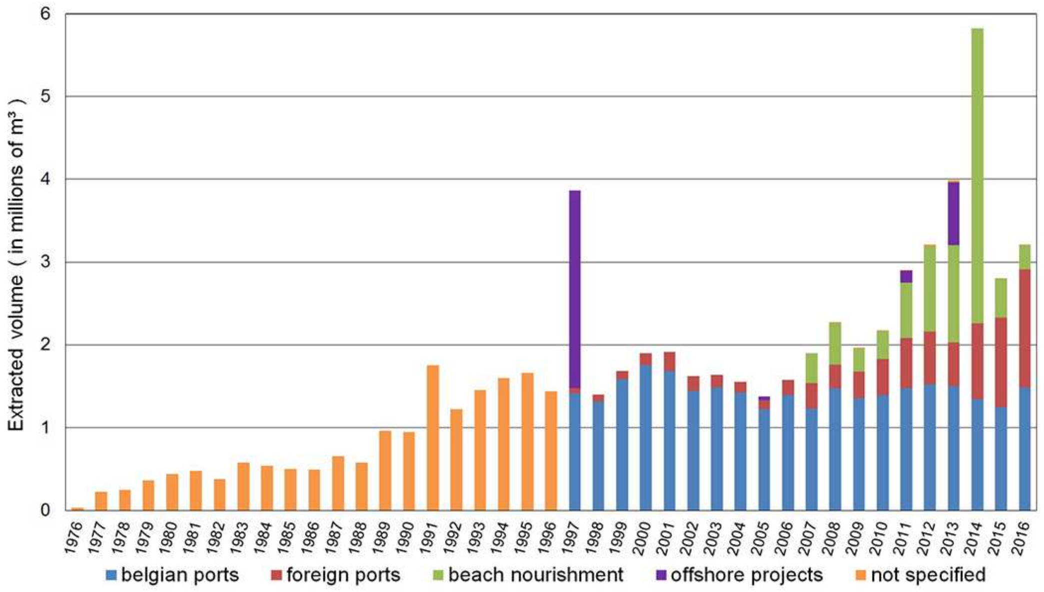


Figure 1: Evolution of the sand extraction in the BDNS from 1976 to 2016.
Statistics based on extraction registers.

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 10^6m^3	REGISTER 10^6m^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.

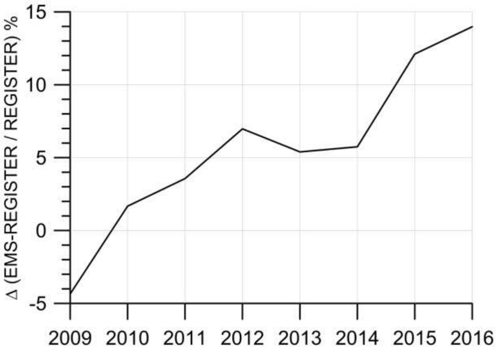


Figure 2: Evolution of discrepancies between the cumulative volumes reported in the registers and the cumulative volumes estimated from the EMS data from 2009 to 2016.

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 10^6m^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 10^6m^3 in 2008 and increased gradually to exceed 2 10^6m^3 in 2011; from 2012 to 2016, the volume of sand dredged on S2br decreased progressively, reaching 10^6m^3 in 2014, and arriving at the current level of 0.2 10^6m^3. In total, 11.6 10^6m^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 10^6m^3 in 2012 to more than 210^6m^3 in 2016. For S1a, the cumulative volume reaches 10 10^6m^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 10^6m^3 in 2013 to increase strongly in 2014, with a substantial extraction peak of 2.6 10^6m^3— more than half of this volume extracted in 2 months time— for sector 4c and above 10^6m^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.

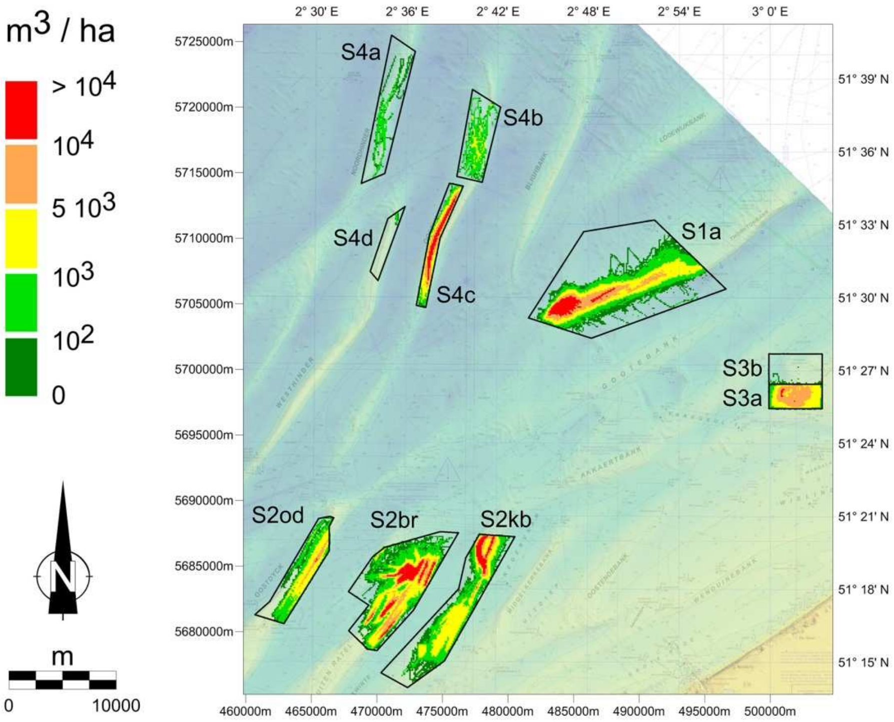


Figure 3: Cumulative volumes extracted per unit area of the extraction sectors sensu MSP 2014). Volumes from EMS data from 2003 to 2016.

Note: 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

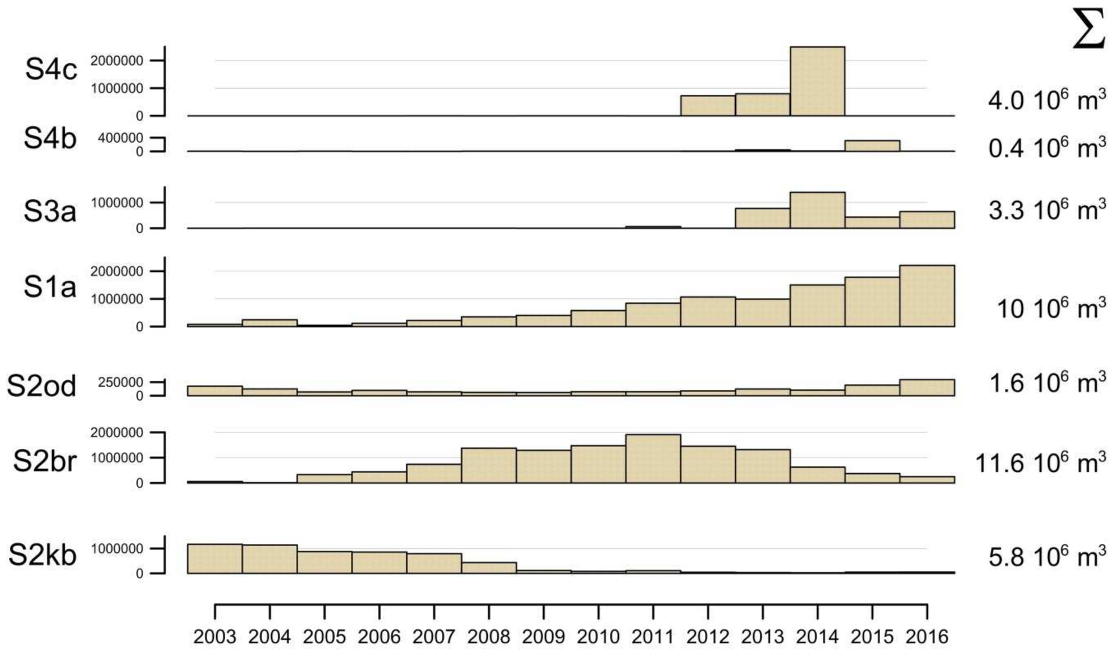
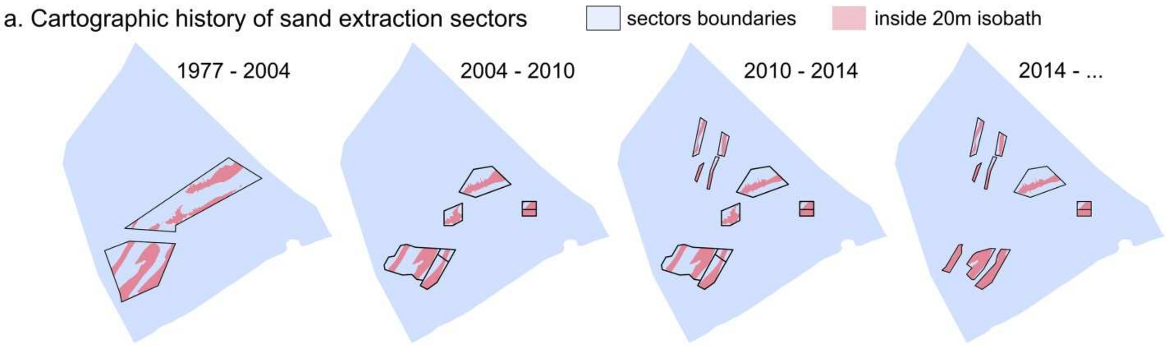


Figure 4: Evolution of sand extraction with total volumes extracted in sectors as defined in the Marine Spatial Plan (2014) from 2003 to 2016. The right column provides the cumulative volume per sector.

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.



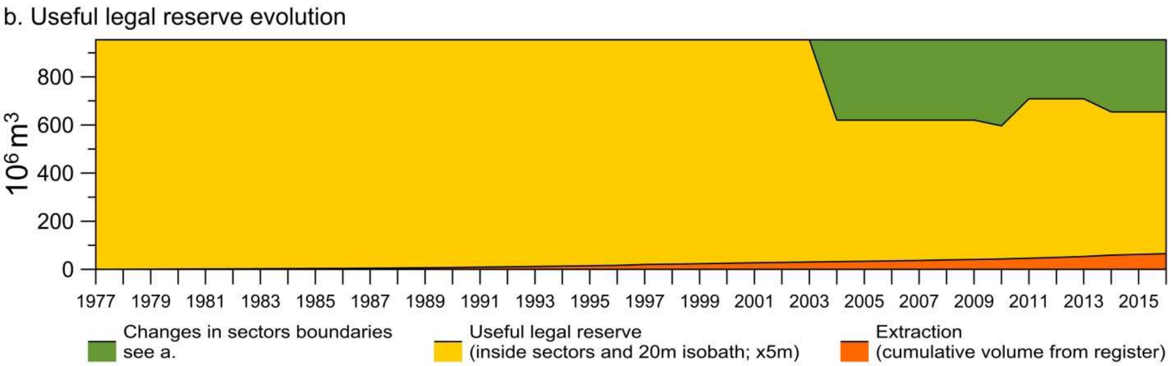


Figure 5: a. Cartographic history of the sand extraction sectors in the BPNS from 1977 to 2014.
b. Useful legal reserve evolution from 1977 to 2016. Cumulative extracted volume is based on register data.

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.

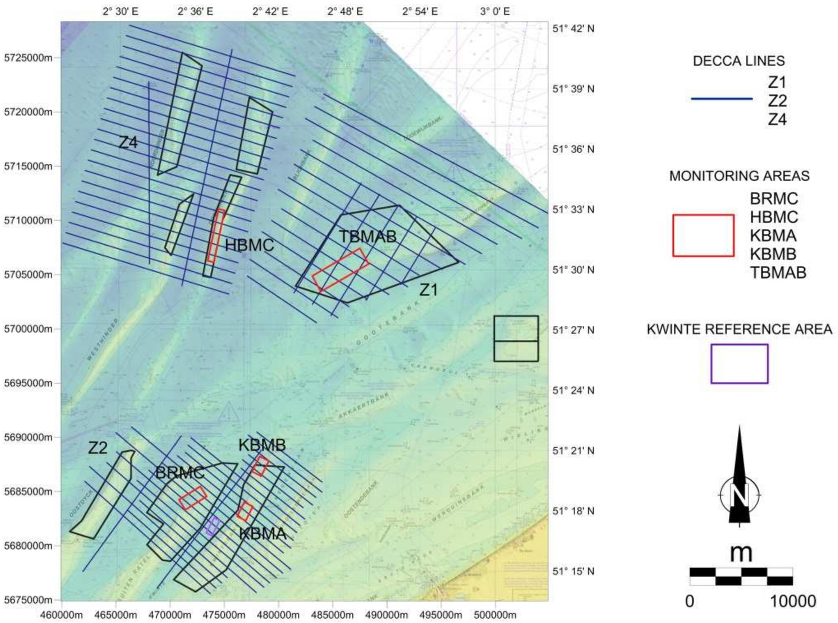


Figure 6: Location of the reference area, monitoring areas and DECCA lines used in this contribution.

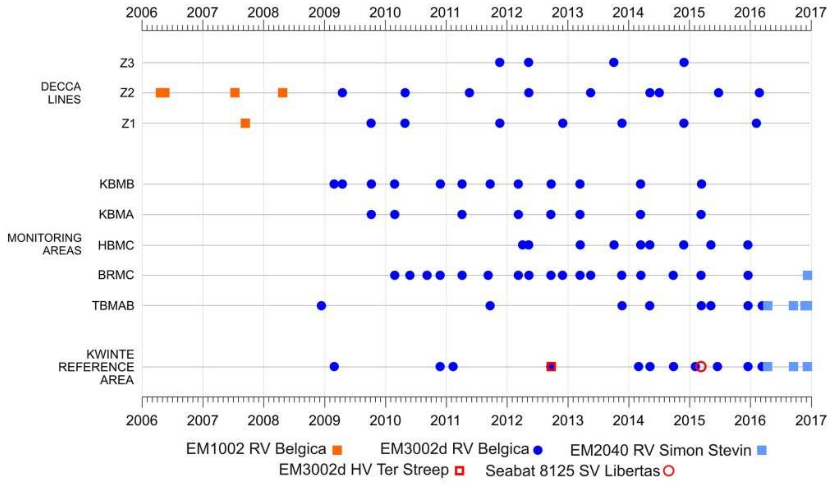


Figure 7: Time line of the data set and MBES considered in this contribution (location Figure 6). All MBES datasets are used for bathymetry analysis. Only data from the RV Belgica EM3002d are considered for backscatter analysis. Data from HV Ter Streep and SV Libertas are courtesy of the Agency for Maritime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

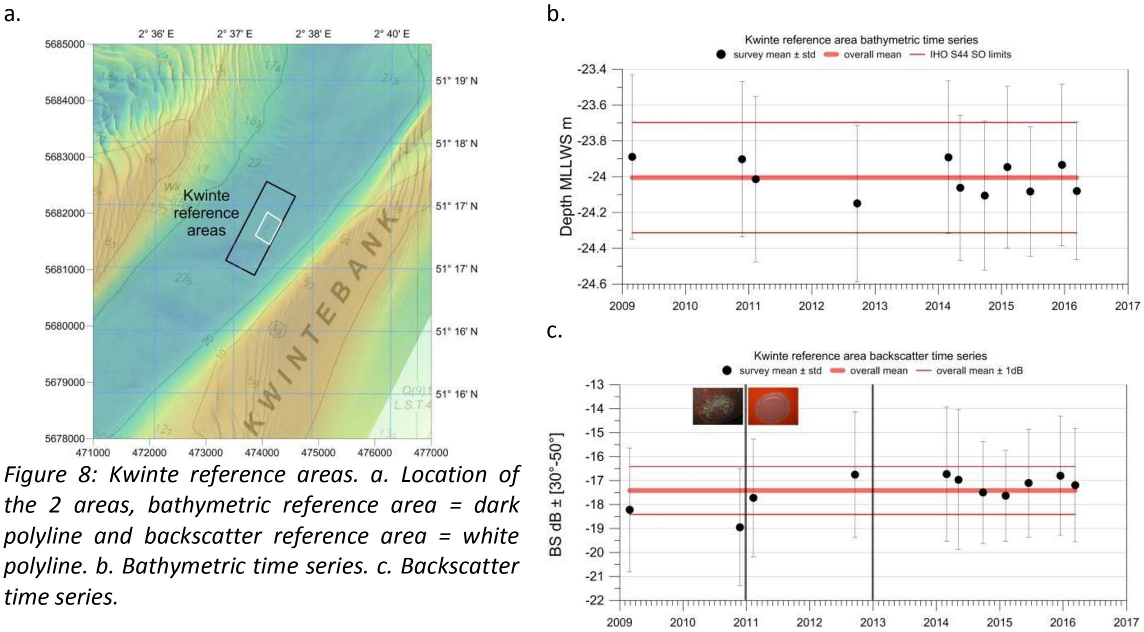


Figure 8: Kwinte reference areas. a. Location of the 2 areas, bathymetric reference area = dark polyline and backscatter reference area = white polyline. b. Bathymetric time series. c. Backscatter time series.

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).

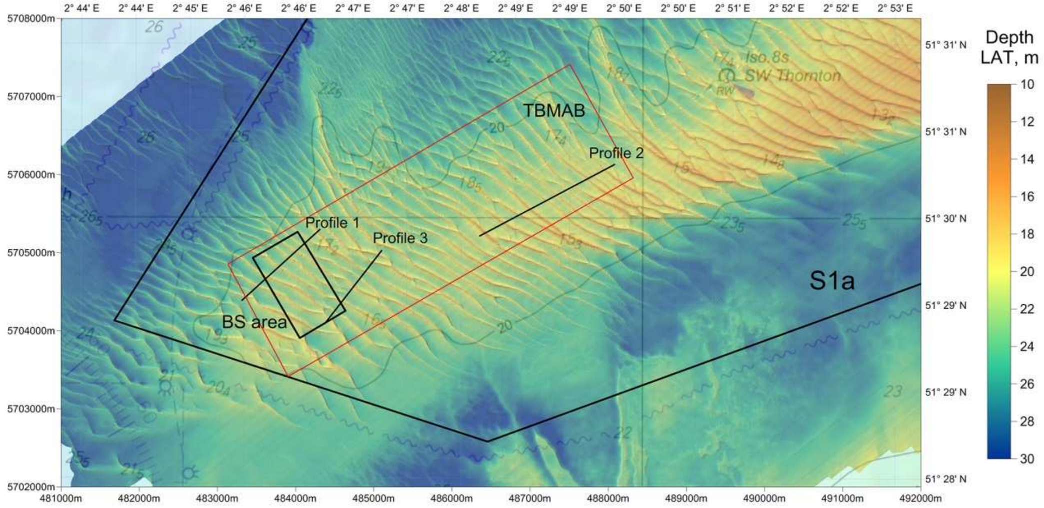


Figure9: Reference model of S1a (2001-2004), location of the profiles and the BS area for specific backscatter analysis inside TBMAB area.

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.

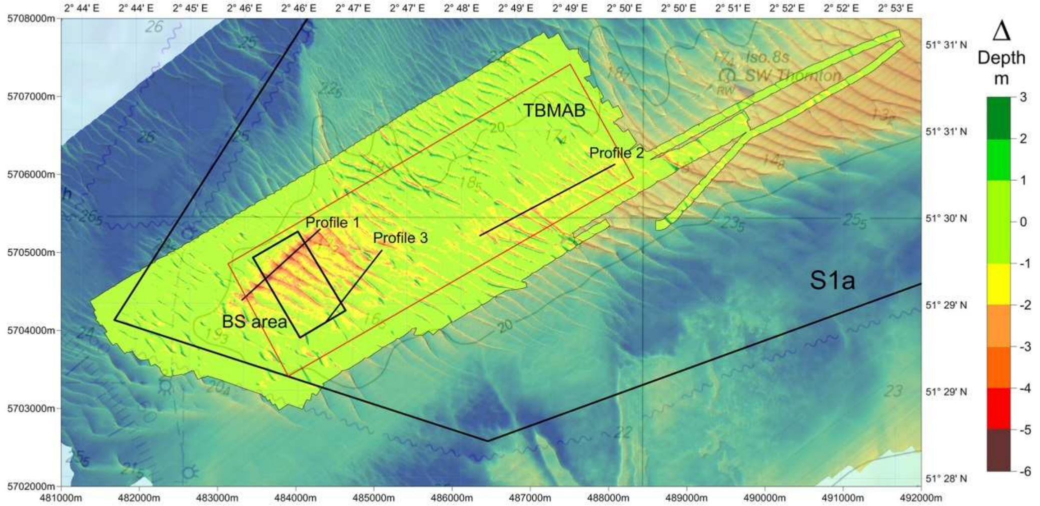


Figure10: Depth difference between the most recent surveys (Belgica EM3002d c1533 - 16/12/2015; Simon Stevin EM2040 c16900 - 23/11/2016 c16930 – 07/12/2016) and the reference model of S1a (2001-2004).

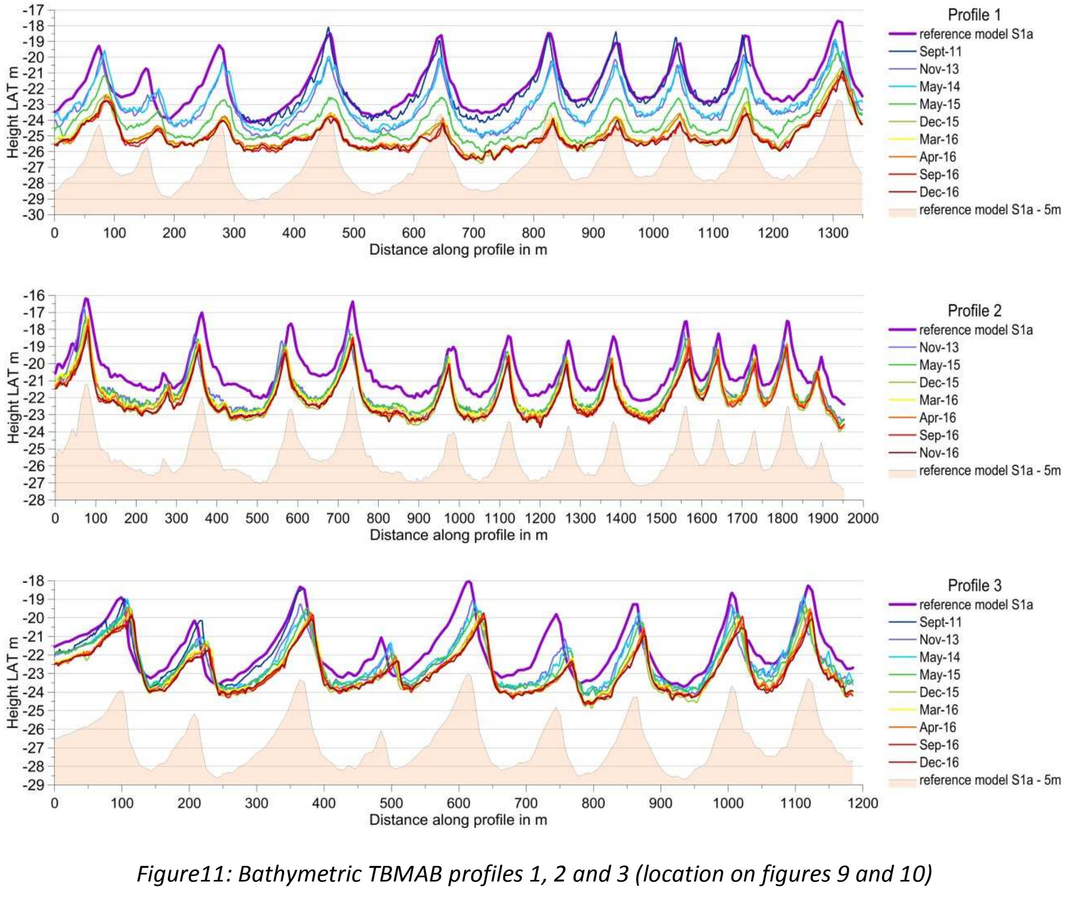


Figure11: Bathymetric TBMAB profiles 1, 2 and 3 (location on figures 9 and 10)

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.

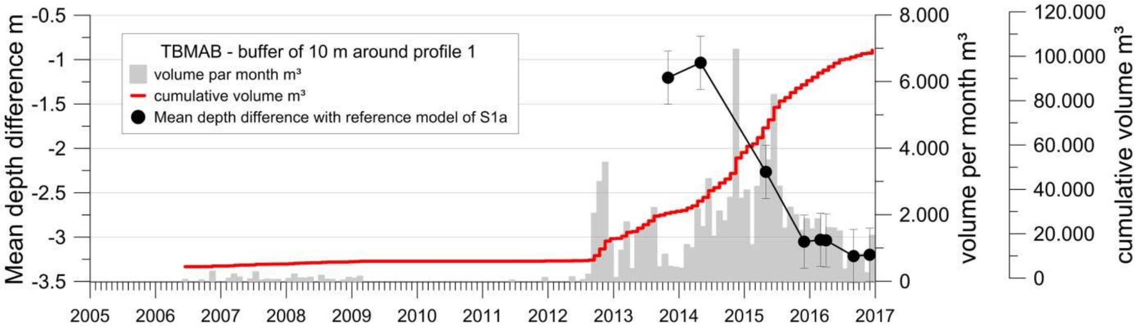


Figure12: Extracted volume per month, cumulative volume and mean depth difference with reference model of S1a (2001-2004) inside a buffer of 10 m around the TBMAB profile 1 (location on Figures 9 and 10).

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).

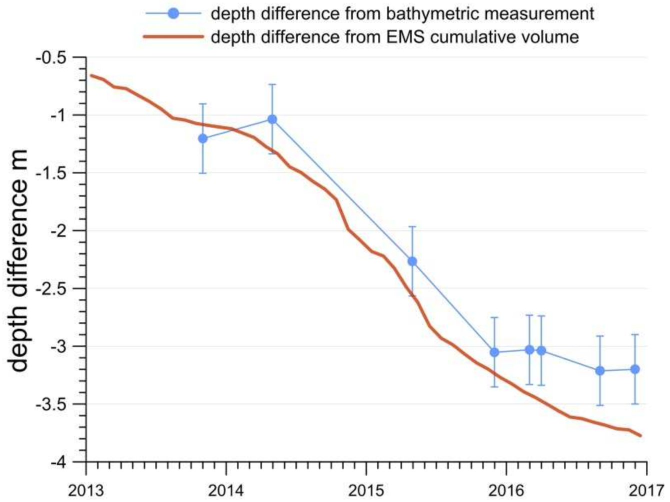


Figure13: Evolution of the mean depth difference with reference model of S1a (2001-2004) and the derived depth difference from EMS cumulative volume inside a buffer of 10 m around the profile 1 (location on Figures 9 and 10).

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.

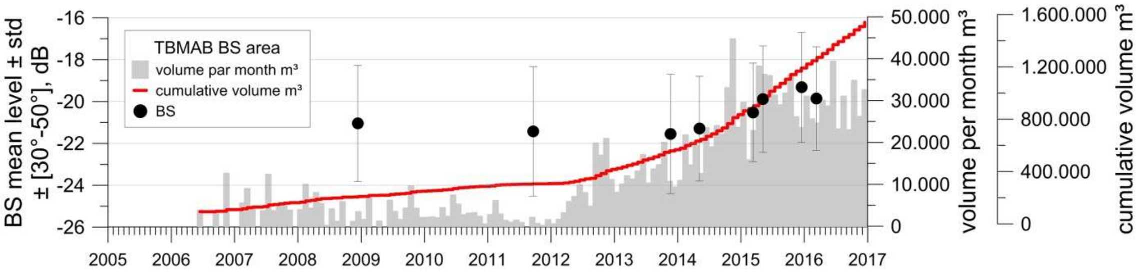


Figure14: Extracted volume per month, cumulative volume and backscatter evolution inside the BS area of TBMAB area (location on Figures 9 and 10).

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.

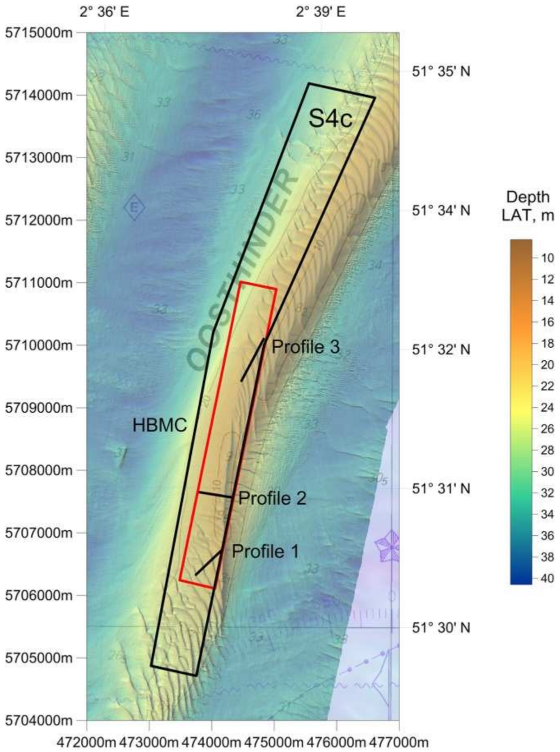


Figure 15: Reference model of S4c (2004-2006), location of HBMC monitoring area and the reference profiles.

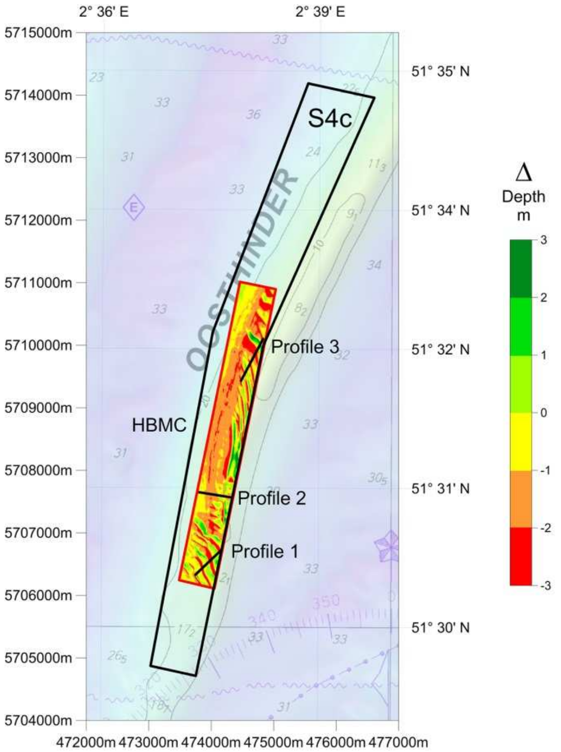


Figure 16: Depth difference between the most recent survey (Belgica EM3002d c1533 - 16/12/2015) and the reference model of S4c (2004-2006).

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.

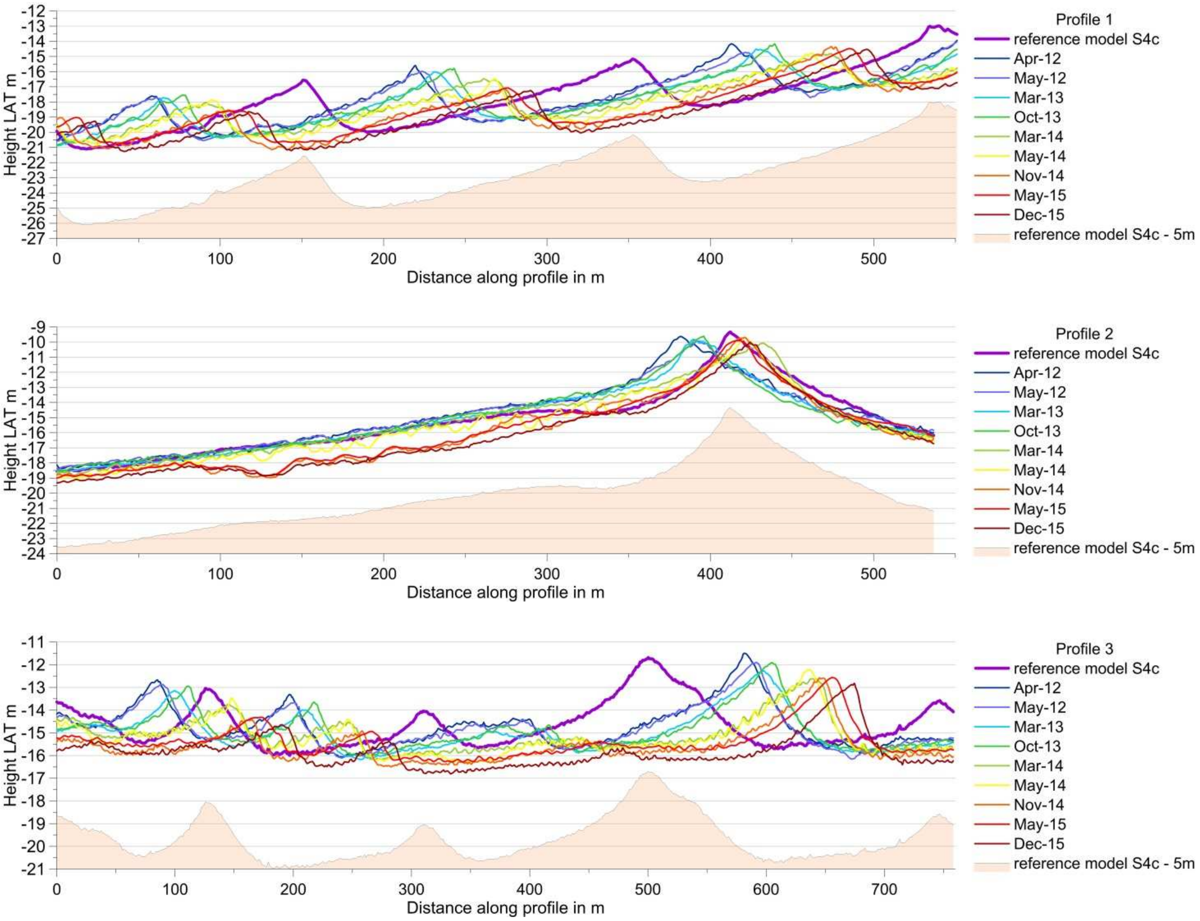


Figure 17: Bathymetric HBMC profiles 1, 2 and 3 (location figures 15 and 16).

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.

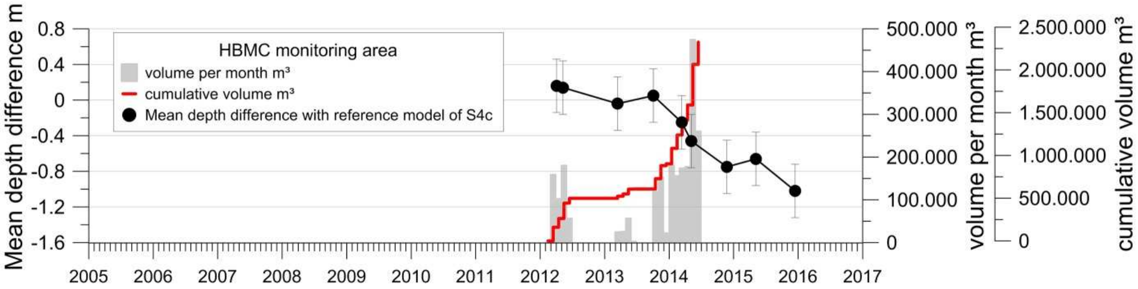


Figure 18: Extracted volume per month, cumulative volume and mean depth difference with S4c reference model (2004-2006) of HBMC monitoring area (location Figures 15 and 16).

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.

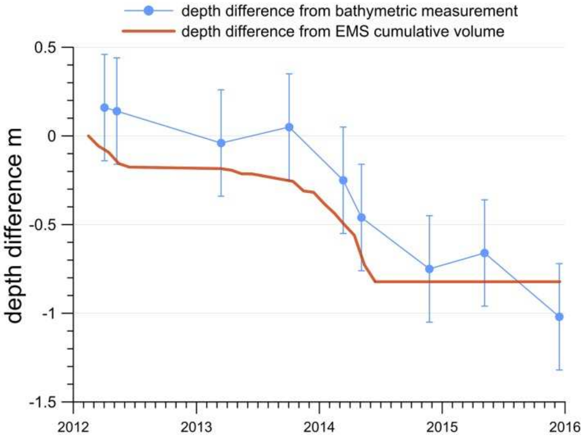


Figure 19: Evolution of the mean depth difference with reference model of S4c (2004-2006) and the derived depth difference from EMS cumulative volume of HBMC reference area (location figures 15 and 16).

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.

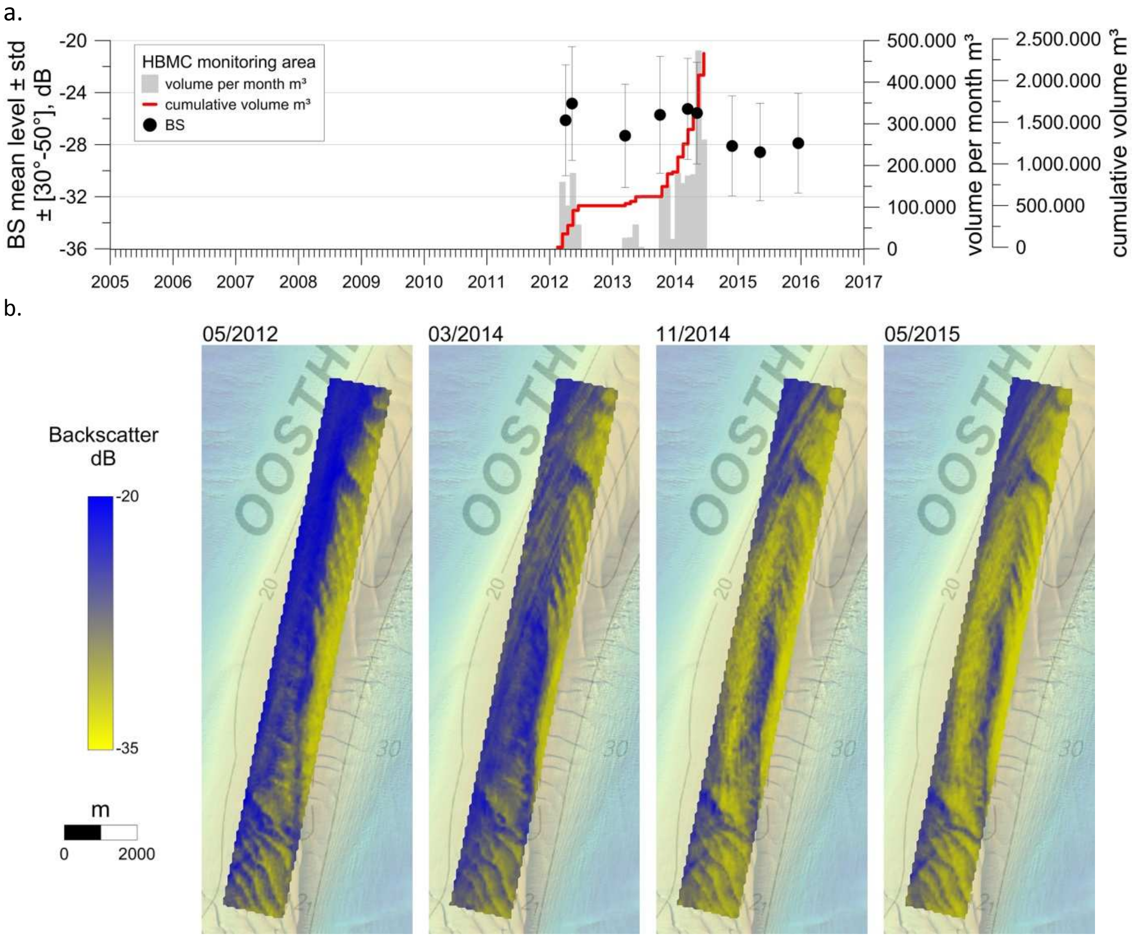


Figure 20: a. Extracted volume per month, cumulative volume and backscatter evolution ofHBMC area. b. Backscatter mosaics (mean level in 10x10m grid) of HBMC area (location figures 15 and 16).

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.

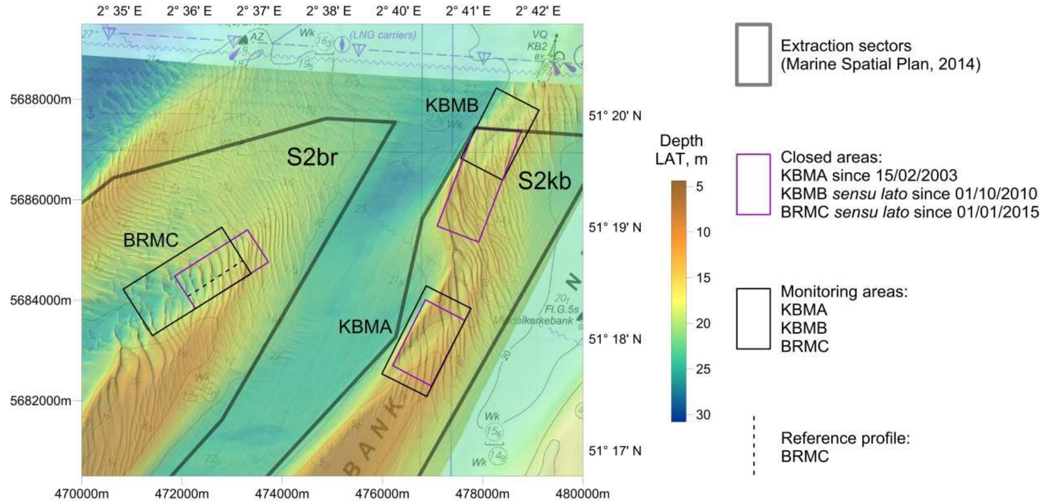


Figure 21: Reference model of sectors S2kb and S2br (2000-2003), location of BRMC, KBMA, KBMB monitoring areas, closed areas and BRMC reference profile.

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).

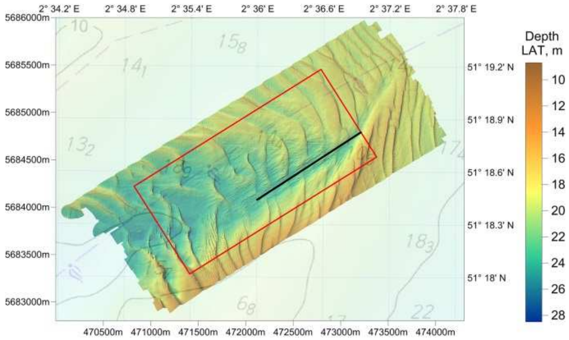


Figure 22: High resolution bathymetric model of BRMC monitoring area (RV Simon Stevin EM2040 survey - 07/12/2016). Surveyed 23 months after the closure for extraction.

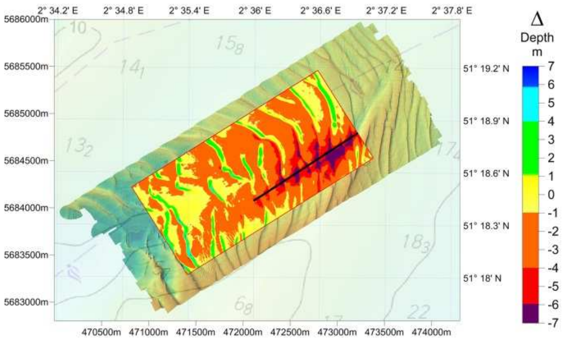


Figure 23: Depth difference between the most recent survey (RV Simon Stevin EM2040 - 07/12/2016) and the reference model of S2br (2000-2003).

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.

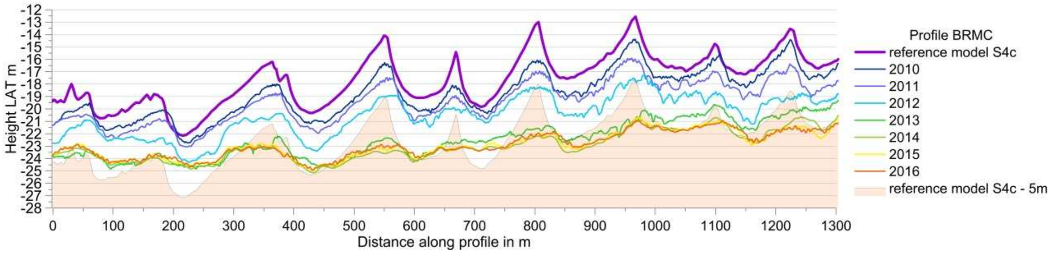


Figure 24: Bathymetric BRMC profile (location figure 20)

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).

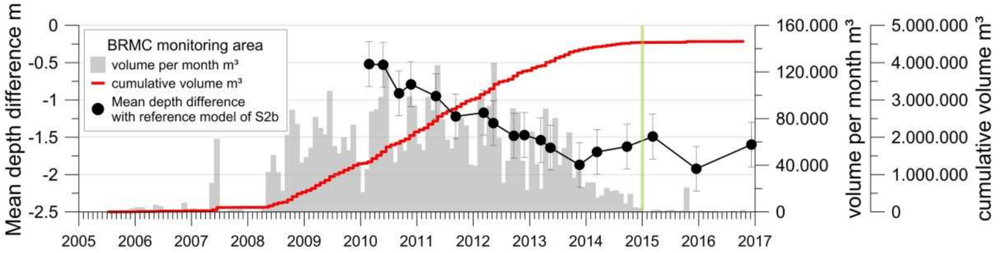


Figure 25: Extracted volume per month, cumulative volume and mean depth difference with S2br reference model (2000-2003) of BRMC monitoring area (location figure 21).
Light green line indicates the closing date of this area.

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.

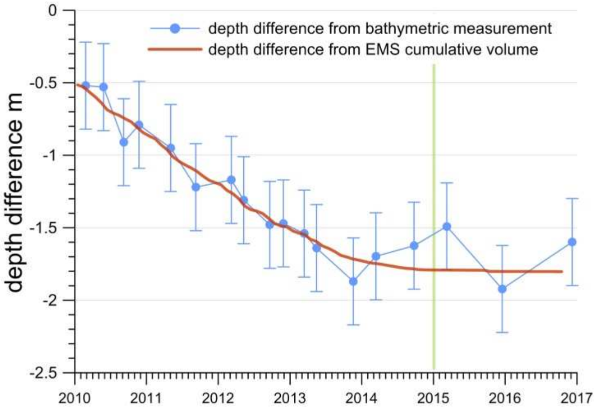


Figure 26: Evolution of the mean depth difference with reference model of S2br and the derived depth difference from EMS cumulative volume of BRMC reference area (location figure 21). Light green line indicates the closing date of this area.

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).

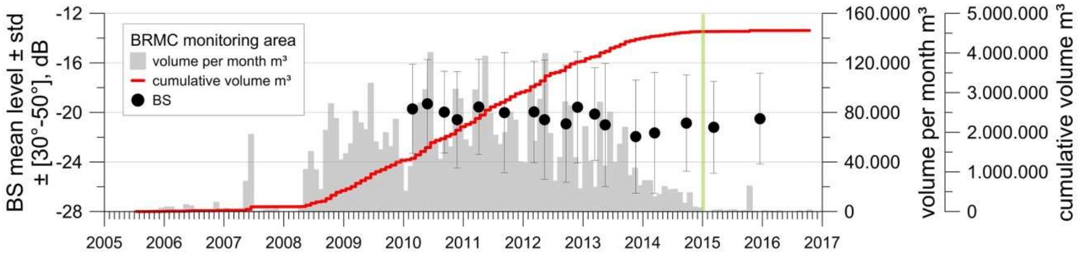


Figure 27: Extracted volume per month, cumulative volume and backscatter evolution of BRMC monitoring area (location figure 21). Light green line indicates the closing date of this area.

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.

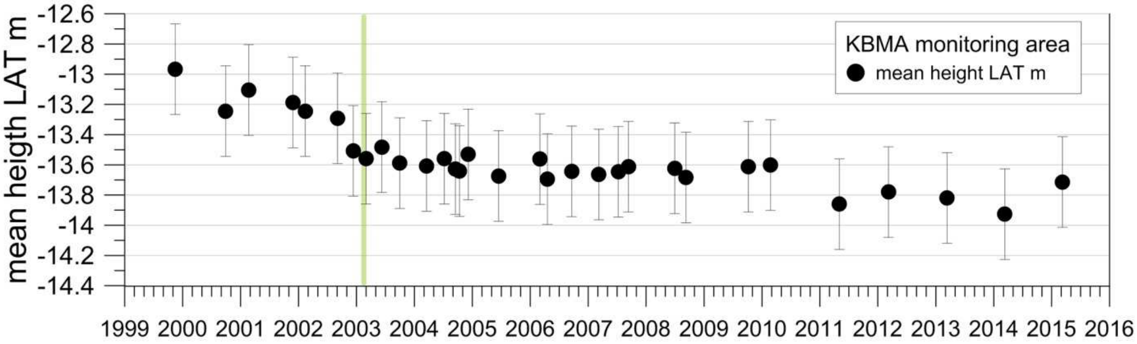


Figure 28: Bathymetric evolution of KBMA monitoring area (location figure 21). Light green line indicates the closing date of this area.

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.

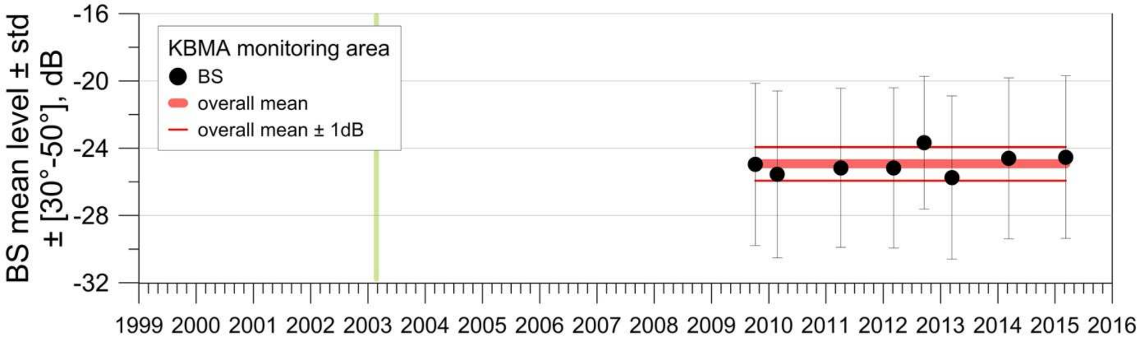


Figure 29: Backscatter evolution of KBMA monitoring area (location figure 21). Light green line indicates the closing date of this area.

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.

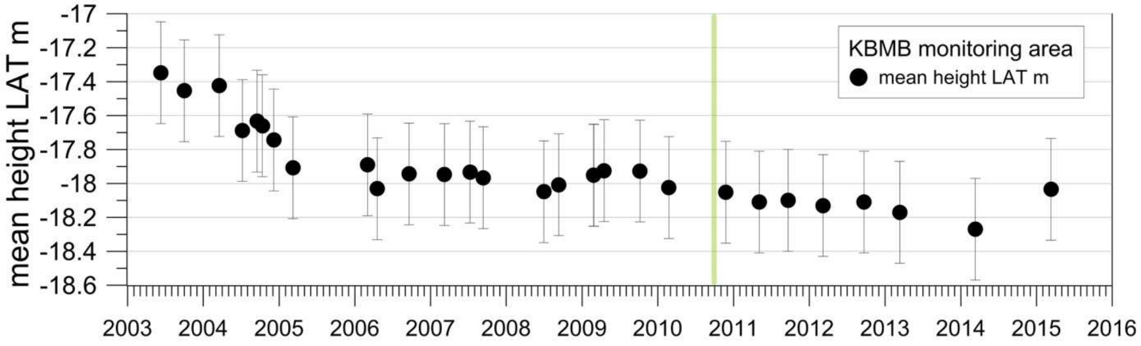


Figure 30: Bathymetric evolution of KBMB monitoring area (location figure 21). Light green line indicates the closing date of this area.

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

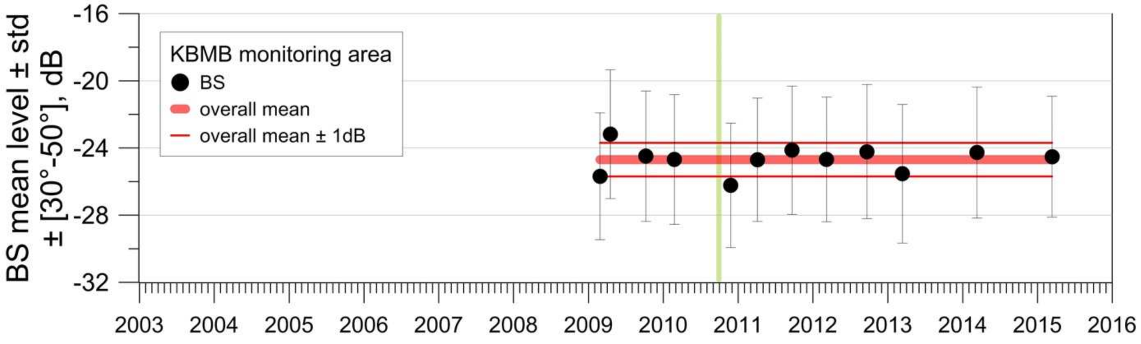


Figure 31: Backscatter evolution of KBMB monitoring area (location figure 21). Light green line indicates the closing date of this area.

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.

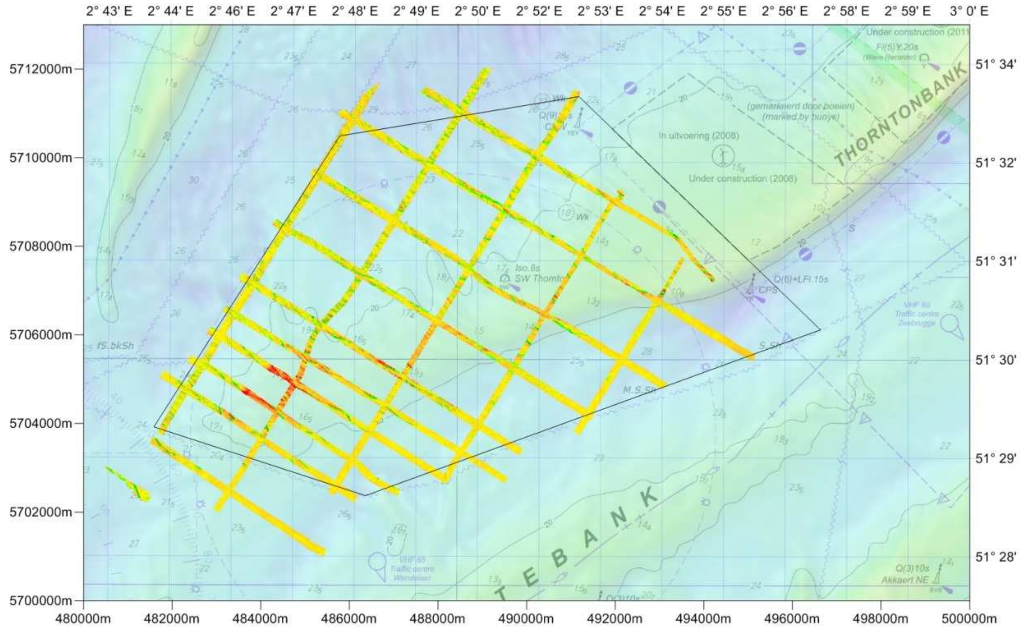


Figure 32: Measured depth difference between the most recent DECCA survey (Belgica EM3002d c1605 - 04/02/2016) and the reference model for zone 1.

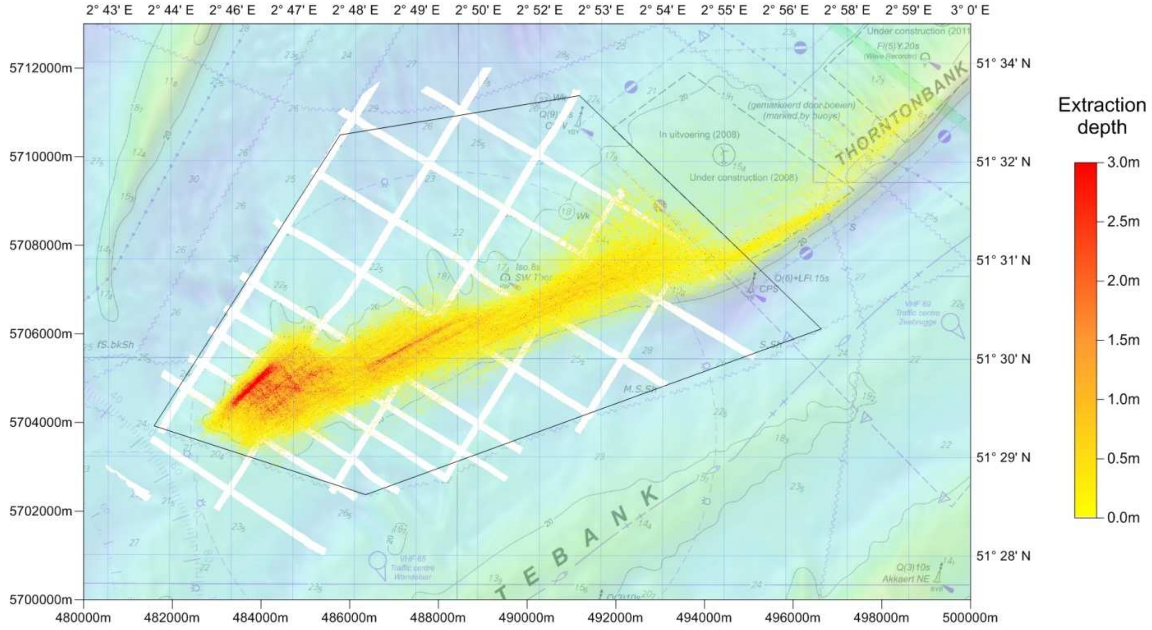


Figure 33: Extraction depth between 04/02/2016 (Belgica EM3002d c1605) and 2003 (reference model for zone 1). The part of the MBES covered area along the DECCA lines with no extraction is shown in white.

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.

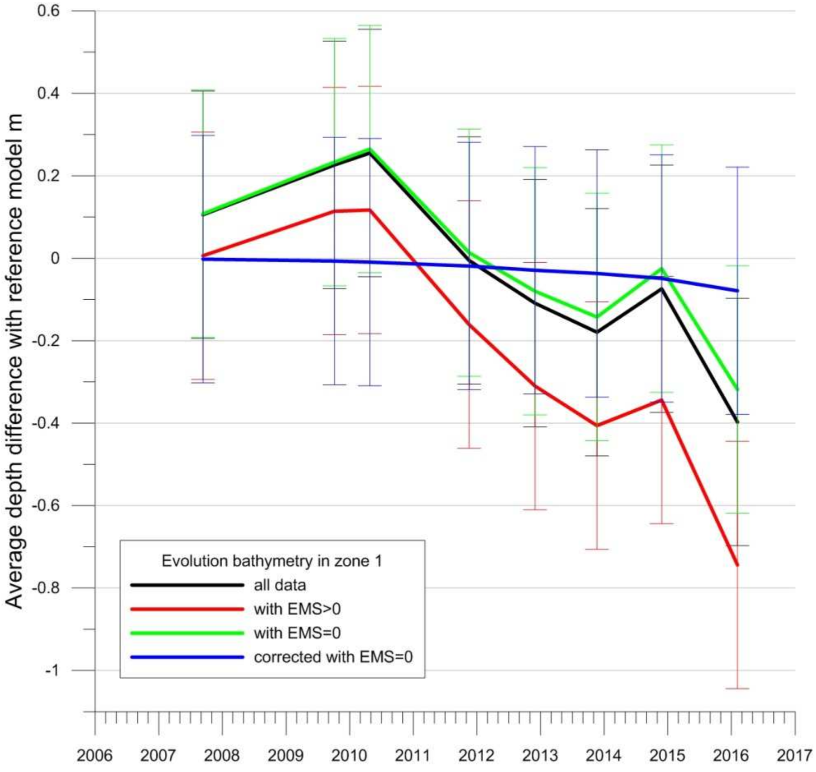


Figure 34: Bathymetric evolution along DECCA lines in zone 1.

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.

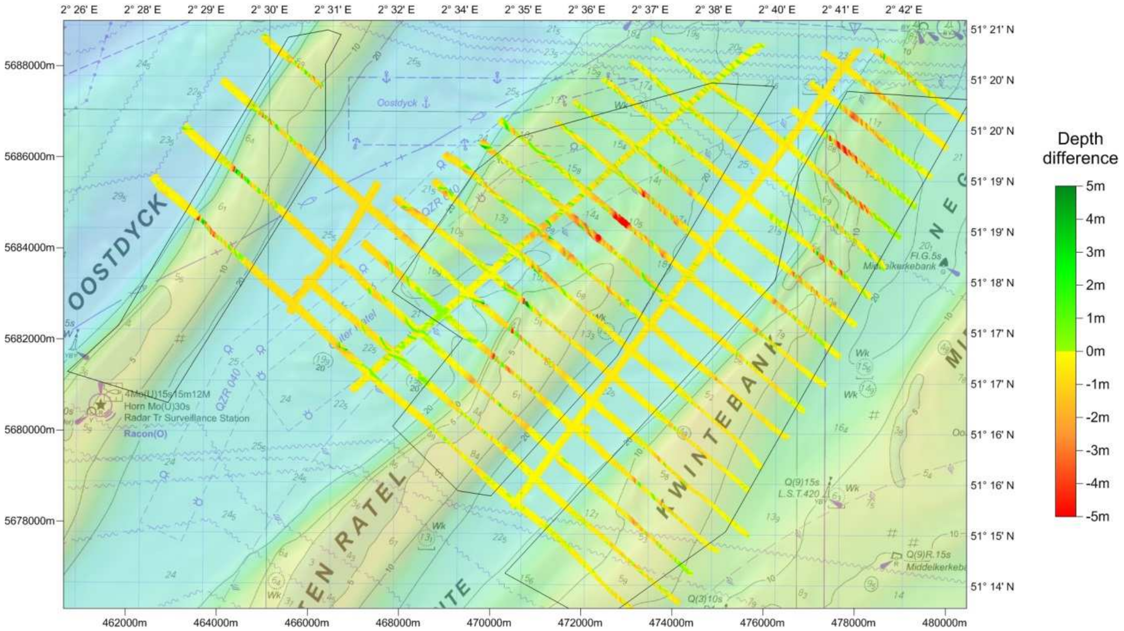


Figure 35: Measured depth difference between the most recent DECCA survey (Belgica EM3002d c1608 - 22/02/2016) and the reference model for zone 2.

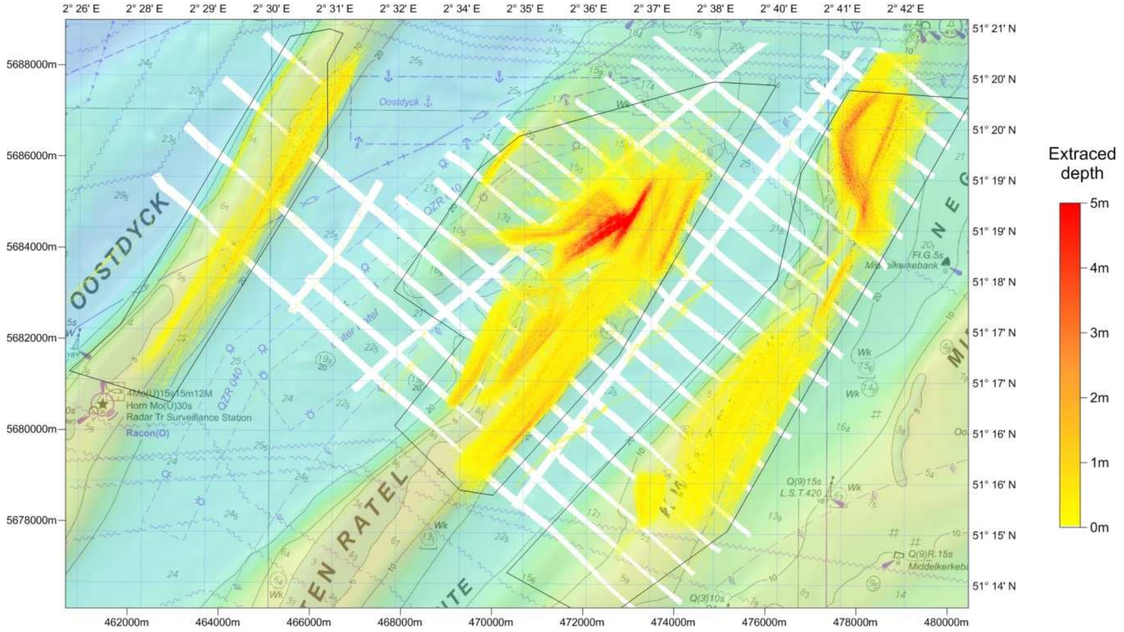


Figure 36: Extraction depth between 22/02/2016 (Belgica EM3002d c1608) and 2003 (reference model for zone 2). The part of the MBES covered area along the DECCA lines with no extraction is shown in white.

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 $10^{6}m^{3}$total extracted volume in the covered areas and 2.6 $10^{6}m^{3}$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.

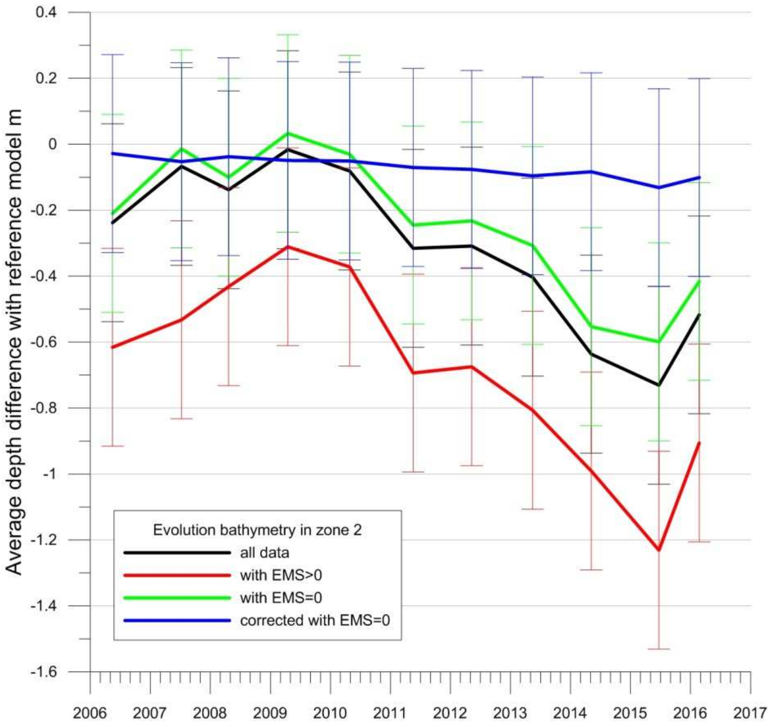


Figure 37: Bathymetric evolution along DECCA lines in zone 2.

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.

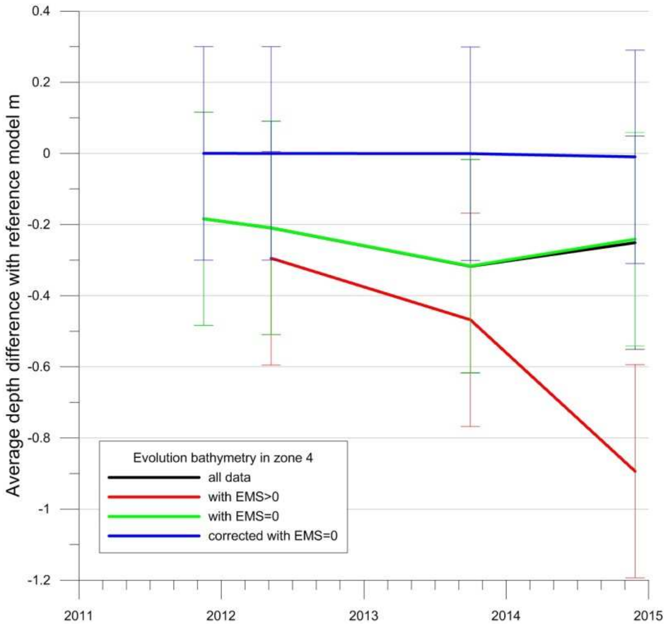


Figure 38: Bathymetric evolution along DECCA lines in zone 4.

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.

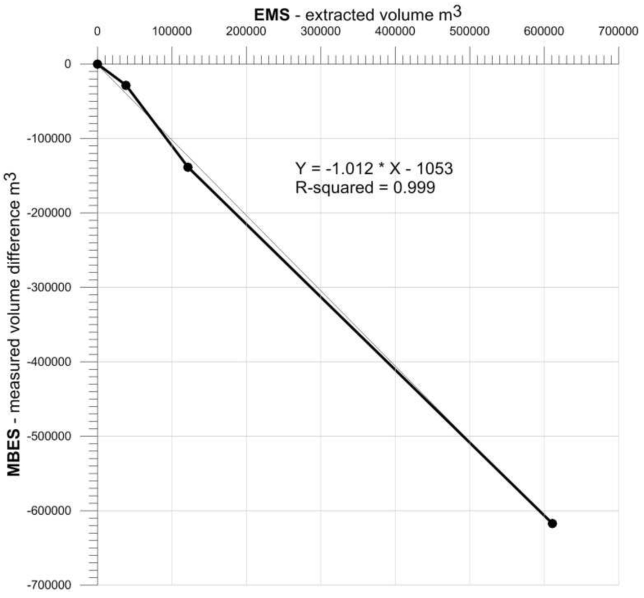


Figure 39: Correlation between MBES measured volume differences and the extracted volumes on the areas of the DECCA surveys on zone 4 with extraction (EMS>0).

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.

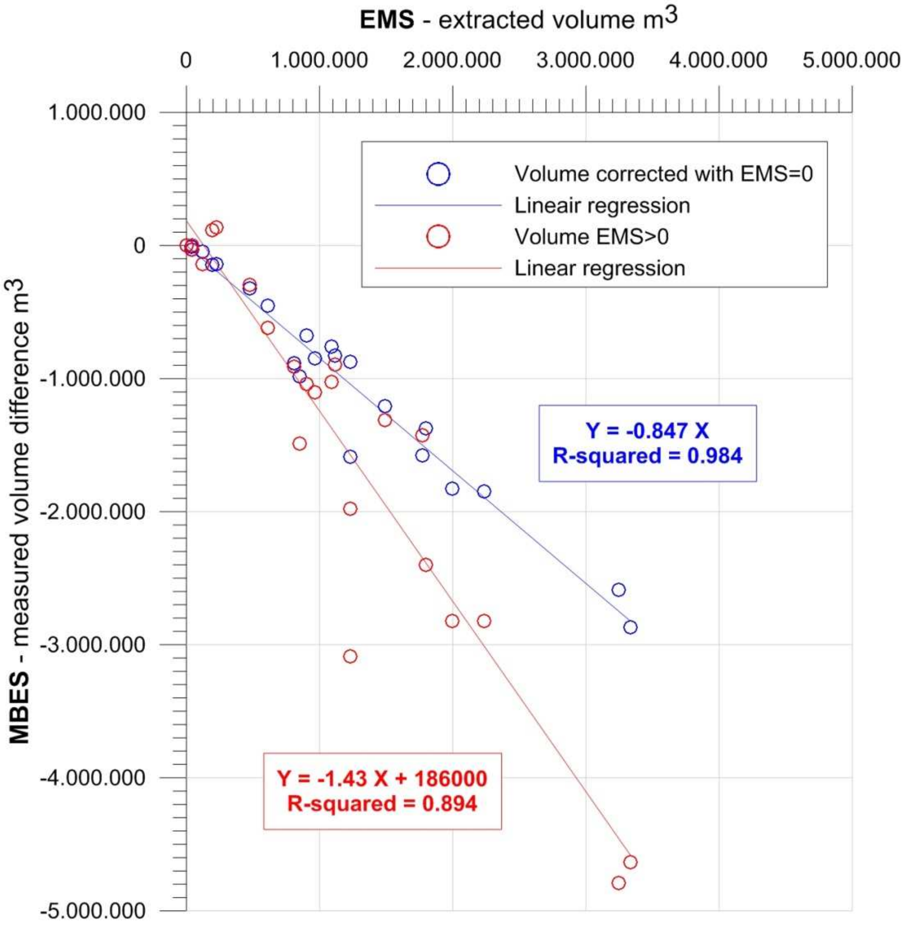


Figure 40: Correlation between MBES measured volume differences with the reference model for all DECCA surveys and the extracted volumes during the same time period and on the same area.

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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