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A 360° PERSPECTIVE ON SEA SAND

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CONTENT

REGULAR CONTRIBUTIONS

1. Near-field changes in the seabed and associated macrobenthic communities due to marine aggregate extraction on tidal sandbanks: a spatially explicit bio-physical approach considering geological context and extraction regimes

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Abstract

Based on data from Multibeam Echosounders (MBES) and Van Veen grab samples, near-field effects of marine aggregate extraction by trailing suction hopper dredgers in the Belgian part of the North Sea were assessed on a decadal scale. The combined approach allowed to investigate and compare seabed and macrobenthic community characteristics for three extraction areas with similar ecological settings, but with a different geological context and each subjected to a different extraction regime. MBES measurements detected slight alterations of the seabed for areas exposed to a continuous, low extraction regime (monthly average volume = 17 to 83 x 10^3 m^3). However, no significant changes in sediment composition nor the macrobenthic community could be attributed to this low extraction regime. High and continuous extraction in the most intensely extracted area (monthly average volume = 164 x 10^3 m^3) increased surface heterogeneity and created a local depression, hereby exposing clay and gravel from the underlying geological layer. In this area, the highest environmental impact was observed, as the physical changes in the seabed triggered a shift towards a more heterogeneous, transitional macrobenthic community including opportunistic species and species typically associated with muddy sands. Together with the species already present, this resulted in a local increase in macrobenthos density, species richness and biomass. A high but periodic extraction without screening activity on the most offshore located extraction area (monthly average volume = 230 x 10^3 m^3, averaged for those months where extraction took place) led to a redistribution of the medium to fine sand fraction and a winnowing of coarse sediment and shell fragments. The decreased median grain size induced a shift in the macrobenthic community from a typical medium to coarse sand *Hesionura elongata* community towards medium to fine sand representatives of the *Nephtys cirrosa* community, although the overall macrobenthic density and biomass in this extraction area remained stable. Based on these results, we conclude that extraction regime and local geological context are important factors driving the near-field environmental impact of marine aggregate extraction on tidal sandbanks.

1.1. Introduction

Marine aggregate extraction has increased spectacularly over the past 40 years in the North-East Atlantic, from a few hundred thousand m^3 of sand extracted per year in 1970 to tens of millions m^3 in recent years (ICES WGEXT, 2019). Extraction activities have the potential to adversely affect the marine ecosystem (Cooper et al., 2008; Desprez, 2000; Froján et al., 2011; Krause et al., 2010; Waye-Barker et al., 2015). For trailing suction hopper dredgers, the most frequently documented alterations include: sediment removal, disturbance of the seabed by the drag head (Boyd et al., 2004; Phua et al., 2002) and redeposition of material through screening activity and overspill (Cooper et al., 2011a; 2011b; Tillin et al., 2011). These processes can cause (long-lasting) changes in seabed characteristics and bathymetry (Boyd et al., 2004; Desprez, 2000; Mielck et al., 2019; Newell et al., 1998), in sediment composition (Crowe et al., 2016; De Backer et al., 2014a; McCauley et al., 1977; Van Lancker et al., 2010; Van Lancker et al., 2019) and in faunal community composition (Cooper, 2013a; De Backer et al., 2017; De Jong et al., 2015b; Vanaverbeke et al., 2007). The extent of the extraction impact is related to site-specific characteristics of the seabed, sediment composition and local hydrodynamics, next to the resilience and recovery potential of the macrobenthic community (Cooper et al., 2011b; Foden et al., 2009; Whomersley et al., 2010). Extraction intensity and frequency also influence the impact (ICES, 2016), although little is known on their cause-effect relationship with the ecosystem response. An increased understanding of such relationships can lead to mitigation measures and recommendations (eventually embedded in policy instruments) to minimize the environmental impact, which is key for a sustainable management of marine sand extraction activities (Van Lancker et al., 2010).

A major policy driver is Europe's Marine Strategy Framework Directive (MSFD, 2008/56/EC, European Commission Directive, 2008), aiming for a good environmental status (GES) of marine waters. Eleven GES descriptors are defined, each associated with indicators to be monitored by the Member States. Consequently, each Member State has set-up a six-year cycle monitoring programme. Seabed integrity is the major descriptor to be assessed when it comes to the regulation of marine aggregate extraction. Since physical loss and disturbance are often the precursor of changes in biodiversity, integrated monitoring of both the physical and biological nature of the seabed will provide a more complete view of the situation and is therefore highly recommended.

Whilst GES assessments of the macrobenthos require point sampling (e.g. Rehitha et al., 2017; Seiderer & Newell, 1999; Waye-Barker et al., 2015), cause-effect relationships best rely on a spatially-explicit investigation and characterisation of the seabed. The latter is increasingly done by means of Multibeam Echosounder (MBES) (e.g. Kenny et al., 2003), which allows to study the relief and nature of the seabed by simultaneously acquiring bathymetry and backscatter data at high resolution. The backscatter measures the intensity of the acoustic energy scattered back to the receiving sonar antenna. It depends on the frequency of the acoustic signal used and for a given angle of incidence, the backscatter strength varies with the nature of the seabed: hard, rough bottoms made up of coarse sediments return much more energy than weakly rough, soft bottoms made up of fine sediments. For this reason, over the past two decades, the backscatter has been used more and more as a proxy to characterize the seabed nature and monitoring its evolution makes it possible to evaluate sedimentary changes (Lurton et al., 2015). Embedding MBES technology in monitoring programmes combined with macrobenthos point sampling is the fundament for more thorough GES assessments (Gaida et al., 2020; Lucieer et al., 2018; Mestdagh et al., 2020, Montereale-Gavazzi et al., 2018), ultimately leading to a better extrapolation of point sampling.

Extraction activities in the Belgian part of the North Sea (BPNS) are currently restricted to four concession zones (Royal Decree 19 April 2014). The monitoring of these activities is fourfold: (1) an Electronic Monitoring System (EMS) is installed on all aggregate extraction vessels active in the BPNS and provides information on the location and extraction activity of these vessels (Van den Branden et al., 2014; 2017); (2) regular bathymetric measurements allow to check that the extraction remains within the depth limits authorized by the regulations; (3) the official declarations with respect to extraction activities and volumes are controlled; and (4) the ecosystem impact is assessed through a legally obliged environmental monitoring programme considering seabed integrity (Law of 13 January 1969 and Royal Decree of 23 June 2010 transposing the EU MSFD). The latter includes mapping changes in seabed composition and structure using MBES bathymetry and backscatter data, and the analysis of changes in the soft-sediment associated benthic communities (Belgische Staat 2020; Roche et al., 2017).

The current study integrates data from EMS, MBES, sediment, and macrobenthos samples gathered between 2010 and 2019 at three sand extraction areas (EAs) in the BPNS. The EAs are located on top of three tidal sandbanks and have similar ecological settings and macrobenthic communities, but each of them differs in terms of extraction regime, local geological and morpho-bathymetrical context. This study focuses on direct effects in the near field of extraction. Investigations of indirect and far-field impacts are on-going. See Van Lancker et al. (2020) for a synthesis.

1.2. Study area

From a Habitat Directive perspective, the entire BPNS is considered habitat type 1110, being 'sandbanks slightly covered by seawater at all times' (Degraer et al., 2009). Depending on the location with respect to the coastline and former paleo valleys, the sandbanks have different sediment types, compositions of shell fragments, and gravel and clay, with the latter typically occurring in the troughs in-between the sandbanks (Hademenos et al., 2019; Kint et al., 2021). The offshore Upper Holocene deposits, representative of the present-day hydrodynamic regime, consist mostly of medium sands (250 – 500 µm) with a median grain size (MGS) around 300 – 400 µm (Verfaillie et al., 2006). From a biological perspective, medium sands are mainly inhabited by the *Hesionura elongata* community (average MGS around 350-400 µm), characterised by interstitial species (Breine et al., 2018). Similar ecological settings prevail in terms of temperature, salinity, timing and magnitude of organic matter production (Franco et al., 2008).

1.3. Material & methods

1.3.1. Estimation of extraction intensity

Extraction intensities over the period 2010 - 2019 were estimated in this study based on data derived from the Electronic Monitoring System (EMS); an automatic registration system used for control- and monitoring purposes that is located on each aggregate extraction vessel that is active in the BPNS. The EMS provides detailed, point-based information on the vessel location and pump status (on average every 30 seconds when extracting aggregates), together with an estimation of the extracted volume at that location (Van den Branden et al., 2014; 2017). The latter is calculated in this study as the ratio between the hopper capacity (i.e. the volume of the hopper) and the number of EMS records identified as extraction for a particular extraction trip. The estimation of the extracted volume at each location thus assumes that (1) the total extracted volume during one trip equals the hopper capacity and that (2) the extracted volume at each point-based observation is identical. For a given period, surface and spatial resolution, grids of the extracted volume and depth can be created (e.g. if the extracted volume in a grid cell equals 100 m^3 over an area of 100 m^2, the extracted depth equals 0.01 m), allowing us to properly define targeted acoustic monitoring zones and grab sample locations (see Fig. A1, supplementary figure).

1.3.2. Extraction areas and extraction history

This study focuses on three aggregate extraction areas (EAs) located on top of three tidal sand banks: EA1 on the Thorntonbank, EA2od on the Oostdyck, and EA4c on the Oosthinder sandbanks (Fig. 1). The EMS data revealed that the extraction regime largely differed between the EAs, both in terms of intensity and frequency of extraction (Fig. 2) (Roche et al., 2011b; 2017). EA1 and EA2od were extracted continuously throughout the year, predominantly for industrial purposes. Extraction rates increased since 2010 in both areas, albeit in highly different magnitudes. EA1 became the epicentre of industrial sand extraction in the BPNS in 2015, as yearly extraction rates almost quadrupled from 0.5×10^6 m^3 in 2010 to 1.8×10^6 m^3 in 2019. EA2od is much less intensively exploited, with yearly extraction rates between 2010 and 2019 not exceeding 0.4×10^6 m^3 of sand. The third zone EA4c was mainly exploited for coastal protection purposes and as such the extraction regime here was irregular, characterized by intense extraction events over short time periods (Fig. 2). For EA4c, the activities started in March 2012 and have been irregular throughout the years. In 2014 extraction activity peaked as 2.6×10^6 m^3 of sand was removed that year, all within six months (Roche et al., 2017).

Figure 1: Overview map with (a) location of the Belgian exclusive economic zone (EEZ) within the North Sea; (b) the Belgian extraction areas (EAs), monitoring zones (MZs) and extraction intensities (cumulative m³ of sand extracted per hectare from 2010 to 2019); (c, d, e) detail of macrobenthos sampling (indicating REFerence, IMPact and HIGH-IMPact samples) and vertical profile locations, for resp. EA1 Thorntonbank, EA2od Oostdyck and EA4c Oosthinder, plotted on top of the extraction intensity maps.

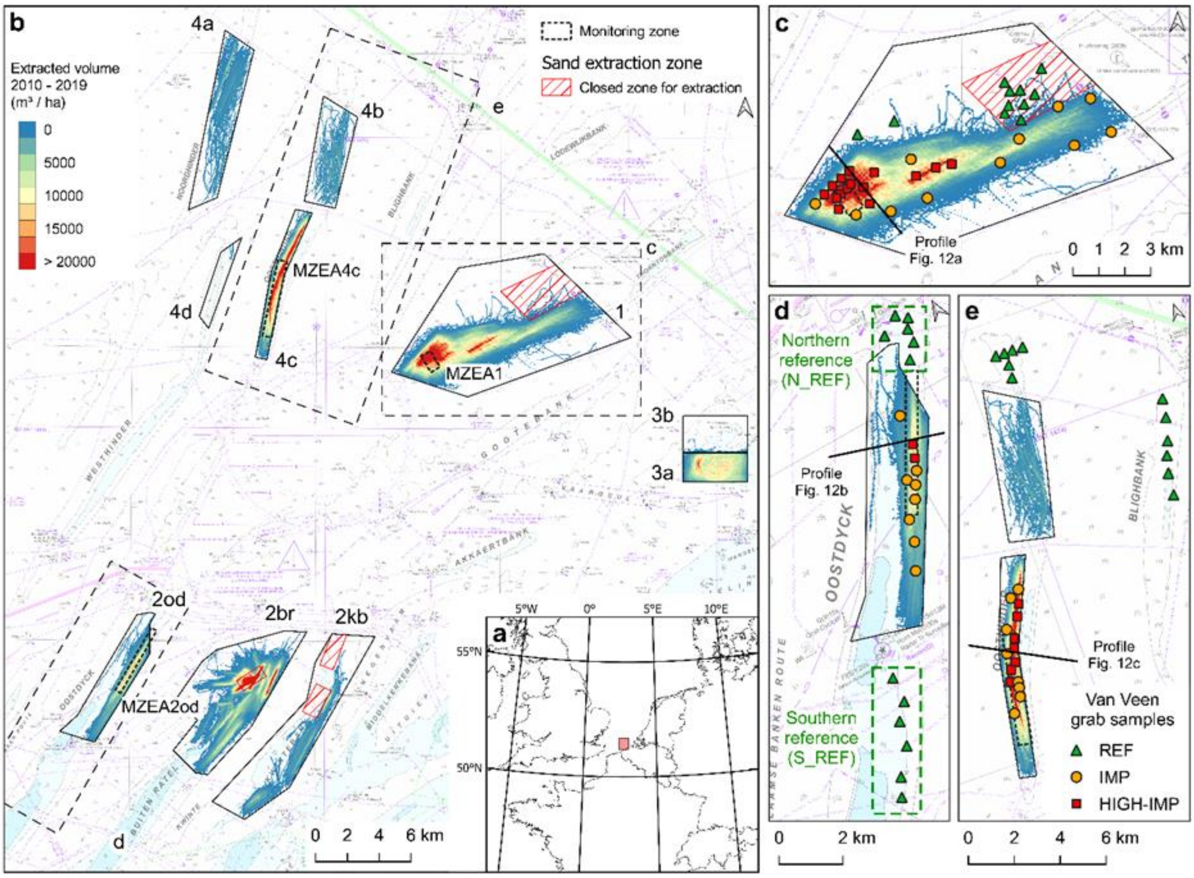
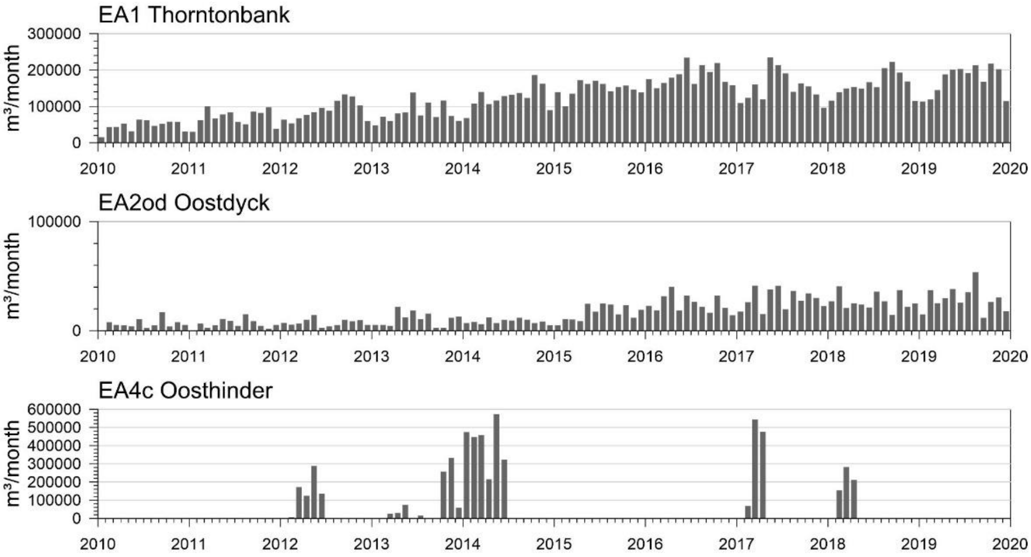


Figure 2: Extraction regimes in the three extraction areas (EA1 Thorntonbank, EA2od Oostdyck and EA4c Oosthinder) illustrated by monthly volumes extracted (m³) between 2010 to 2019.

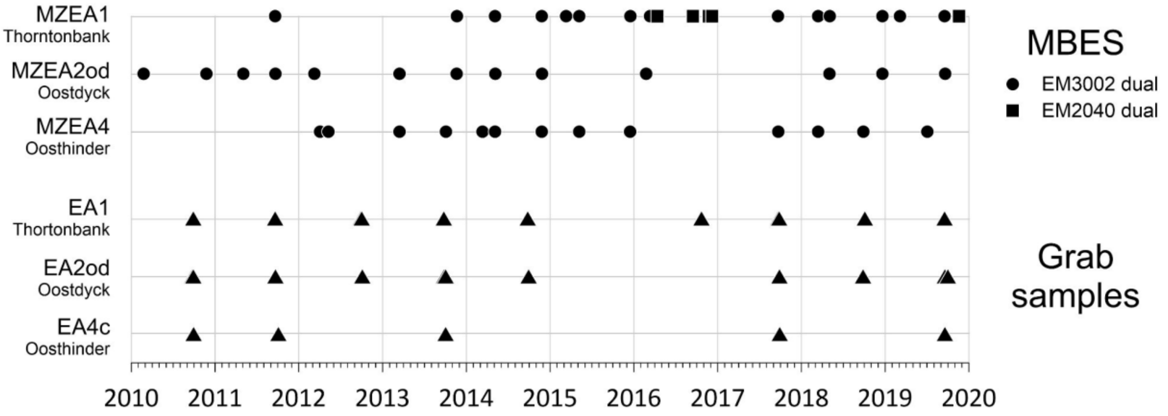


1.3.3. Sampling strategy and data analysis

Multibeam Echosounder (MBES) derived data

For each EA, MBES bathymetric and backscatter measurements were carried out regularly in dedicated monitoring zones (MZs) to control and evaluate the impact of marine aggregate extraction on the seabed integrity. The MZs considered in this study were MZEA1, MZEA2od and MZEA4c (Fig. 1). Three MBES datasets were considered, each acquired with different sensors. In the initial phase of the monitoring program, between 2000 and 2005, a bathymetric and backscatter exploration mapping of the EAs was carried out with a 100 kHz Kongsberg Maritime (KM) EM1002 installed on the RV Belgica (Degrendele et al., 2014; Roche et al., 2011a; 2017). The resulting bathymetric model was used in this study as reference level (time 0) to derive subsequent bathymetric changes based on the other MBES datasets. Simultaneously, MZs were defined and surveyed frequently. From 2009 onwards, bathymetric and backscatter time series have been acquired with a 300 kHz KM EM3002 dual MBES for each MZ at a periodicity of two to three surveys per year. These MBES time series constitute the main dataset to assess the bathymetric, morphological and sedimentary evolution in the MZs (Fig. 3). For MZEA1, additional bathymetric time series have been acquired since 2016 at 300 and 400 kHz with a KM EM2040 dual RX MBES installed on the RV Simon Stevin.

Figure 3: Data time series: Multibeam echosounder (MBES) data acquired on the monitoring zones (MZs) inside the extraction areas (EAs) (See fig. 1 for locations) and grab samples collected within the EAs. Bathymetry was analysed for MBES EM3002 dual and EM2040 dual, backscatter only for MBES EM3002 dual.



Between 2010 - 2019, the MBES KM EM3002 dual was subjected to a rigorous control of the acquisition parameters. The pulse length, which determines the instantaneous insonified area that is critical for the backscatter level calculation (Clarke, 2012), was kept at the same level in order to ensure data comparability. Secondly, the repeatability of the MBES KM EM3002 dual was verified by regular measurements on the nearby Kwintebank reference zone (Deleu & Roche, 2020; Roche et al., 2018). This backscatter time series recorded at 300 kHz produced a homogenous time series, comparable from one survey to another, which may be used as a proxy to detect significant changes in seabed characteristics. Due to the differences in frequency, beam geometry and pulse length, the data obtained with the other MBES systems were not considered in the analysis of temporal variations in the backscatter data in the different MZs. KM EM1002 backscatter data were only considered as a qualitative indicator describing the initial situation of the seabed in each of the EAs and MZs.

The MBES bathymetric dataset follows a standard hydrographic processing workflow using QPS-Qimera® (Version 2.3.1, 2020), which includes tide reduction to Lowest Astronomical Tide (LAT), correction of residual offsets and outlier soundings filtration. For each MZ, the resulting Digital Terrain Models of the successive surveys composed the bathymetric time series. The average depth difference with the reference model (time 0) was considered to assess the overall change in bathymetry and compared with the volume of sand extracted during the same time interval. For each MZ and a given time interval, the average bathymetric variation could be estimated by dividing the EMS-based extracted volume within that MZ and time interval with the area of the MZ considered. Hence, for the same time interval and MZ, the average bathymetric variation derived from the MBES and EMS data was compared. An overall uncertainty of 0.3 m for the RV Belgica KM EM3002 dual MBES bathymetric data was estimated (Roche et al., 2017).

The processing of MBES backscatter used the following approach implemented in Ifremer-SonarScope® (Version 20210107, 2021): for each survey, after suppression of the correction introduced by the manufacturer (*in casu* Kongsberg), the backscatter mean level was estimated from the raw uncompensated backscatter signal corrected for (1) the real time attenuation and (2) the instantaneous insonified area based on the incidence angle measurement provided by the Digital Terrain Model. This processing corresponds to the code A4 B0 C0 D0 E5 F0 of the nomenclature of MBES backscatter processing levels (Lamarche & Lurton, 2018). The incidence angular sector that best discriminated against the different types of sediment is the oblique-incidence sector often forming a plateau within ±[30°- 50°] (APL, 1994; Lamarche et al., 2011). The average backscatter level within the incidence angular sector of ±[30°- 50°] was used as a proxy to derive sediment change over time. To complete this approach with a cartographic visualization of the backscatter time series fluctuation, a grid of the average backscatter levels at the resolution of 10 x 10 m was computed with QPS-FMGT® (Version 7.9.5, 2020) for each survey for each MZ.

Pearson's correlation coefficient (r^2) was used to quantify the level of correlation between data derived from MBES and EMS. The detection and evaluation of time series trends was performed with a Mann-Kendall rank-based test (Rock, 1988).

Grab sample derived data

Van Veen grab samples were taken within each EA to evaluate the impact of extraction on the sediments and their associated macrobenthic communities. This was done on a yearly basis between 2010 and 2019 in September and/or October, to reduce seasonal variation within the samples (Fig. 3). With some exceptions, yearly samples from 15 to 30 different sampling locations were collected for each EA (Table A1, supplementary table). Based on an overview of the extraction intensity mapped for each area, impact locations (subjected to extraction activity) and reference locations (where no extraction has taken place) were allocated for each EA (Fig. 1). The number of locations per EA varied over the years depending on changes in extraction regime or improvements of the sampling design.

Macrobenthos was sampled by means of one Van Veen grab (sampled surface area 0.1 m^2) per location at every sampling event. 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 weighing (blotted wet weight) to the nearest 0.01 mg. All analyses were performed in a NBN EN ISO/IEC 17025 regulated environment, certified for macrobenthos species identification (BELAC T-315 certificate).

Sediment samples used for granulometric analyses were taken with a sediment core (3.6 cm diameter) from each grab sample. The fraction >1600 µm was sieved a priori, followed by the analysis of the <1600 µm fraction by means of a Malvern Mastersizer 2000G hydro version 5.40 (Malvern, 1999). Grain size fractions were determined as volume percentages according to the Wentworth scale: clay to silt (<63 µm), very fine sand (63-125 µm), fine sand (125-250 µm), medium sand (250-500 µm), coarse sand (500-1000 µm) and very coarse sand (1000-1600 µm). The fraction >1600 µm was considered as gravel, since it constituted entirely of shell hash. In addition to the sediment percentage fractions, total median grain size (MGS) was calculated.

Subsequently, the EMS-derived extraction intensity data were used to calculate the local ‘sample extraction intensity’ for each grab sample. This was done by calculating the amount of sand extracted within a 50 m buffer (i.e. an area of 7800 m^2) around the sample location using the cumulative extracted volume from 2009 up to the sampling date. A second extraction parameter, ‘number of days between last extraction activity and time of sampling’ (maximum value 366 days) was also derived from these data. Grab samples were further subdivided into three different impact groups based on sample extraction intensity: reference (REF; sample extraction intensity = 0 m^3), impact (IMP; sample extraction intensity

<7000 m^3) and high impact (HIGH-IMP; sample extraction intensity ≥7000 m^3). The threshold of 7000 m^3 sand extracted was objectively determined based on a visual inspection of a graph where sample extraction intensity for all samples and all EAs was plotted against macrobenthic S, N and W, which showed a substantial increase in outliers and between sample variance around 7000 m^3 of sand extracted.

Further analyses were performed per EA. For EA1, we discerned two extraction periods: a low extraction period (LEP; 2010 - 2014) without HIGH-IMP samples and a high extraction period (HEP; 2015 - 2019) including HIGH-IMP samples. EA2od only contained 2 HIGH-IMP samples at the end of the considered time period, therefore only IMP and REF were statistically compared. Additionally, for EA2od a distinction between reference samples taken north (N_REF) and south (S_REF) of the EA was made, to reduce spatial variation within the reference group (Fig 1d). In EA4c, a before-after control-impact (BACI) design was used since sampling started two years prior to the first extraction activities in 2012, introducing an extra time factor 'before' (B; 2010 – 2011) and 'after' extraction (A; 2012 – 2019), besides the factor 'impact group' (REF, IMP, HIGH-IMP).

Three biological univariate measures were calculated for each sample: macrobenthos species richness (S), total density (N, $N.m^{-2}$), and total biomass (W, $gWW.m^{-2}$). Additionally, sediment size class and median grain size (MGS) were also used as univariate parameters. To test for differences in these univariate measures, linear mixed effect regression models (lmer) were performed, with only 'impact group' as fixed effect for EA1 – LEP (2 levels), EA1 – HEP (3 levels) and EA2od (3 levels), while for EA4c 'impact group' (3 levels), 'B/A' (before/after) (2 levels) and their interaction factor were used. 'Year' and 'sampling location' were included in all models as random effects. If needed, the response variable was transformed to meet linear regression model requirements. A type III ANOVA, using the Wald F test with Kenward-Roger approximation of denominator degrees of freedom, was used to test for significance. If significant, differences were situated with Tukey's post hoc analysis test. When linear model assumptions could not be fulfilled, the data were square root transformed and analysed using PERMANOVA (Permutational analysis of variance) based on a Euclidean distance resemblance matrix with factors 'year' (random) (or 'B/A' (fixed) for EA4c) and 'impact group'. If significant differences were detected ($p < 0.05$), pairwise tests were conducted. A complete overview of the specific treatments used on each univariate parameter for each EA and sandbank can be found in supplementary Table A2.

Multivariate analyses were further performed on a square root transformed species-abundance matrix using the Bray – Curtis similarity index, which is most commonly-used and best suited for biological community data (Clarke & Warwick, 2001). To test for significant differences in community composition between the impact groups, PERMANOVA was applied with 'impact group' as fixed factor and 'year' as random factor for EA1 and EA2od, and 'B/A' and 'impact group' as fixed factors for EA4c. When a significant effect was found, pairwise tests were performed to situate the differences within 'impact groups' for EA1 and EA2od or within the interaction term for EA4c. PERMDISP analyses were used to test for significant differences in variance. If the PERMDISP was significant ($p < 0.05$) the PERMANOVA results were interpreted with care. A SIMPER procedure (80% abundance cut-off level) was used to investigate which species contributed most to the differences in community composition. Relationships between the multivariate data cloud and the environmental variables (sediment and extraction parameters) were investigated through DISTLM (Distance-based linear models) analysis using forward selection and AICc criterion, and visualised using a principal coordinate analysis (PCO) plot with vector overlay. This plot is a spatial representation of the similarity between samples based on their macrobenthic communities, and thus allows to have an overview of the differences within and between impact groups. Sediment based parameters (size classes, median grain size) and extraction-based parameters (sample extraction intensity, number of days between last extraction activity and time of sampling) were grouped and DISTLM was performed both on the groups and with the individual parameters. Before running the DISTLM, environmental data were square root transformed and normalised. Collinearity amongst parameters was examined using Spearman rank correlation coefficients. If a linear dependency was detected ($r > 0.8$) only one of the two parameters was kept in the analysis. For all three EAs the 'sample extraction intensity', 'number of days between last extraction activity and time of sampling' and all but one grain size fractions (very fine sand for EA1 and EA2 and clay to silt for EA4c were excluded) were kept in the analyses. Lmer models were performed using R version 4.0.3. For SIMPER, PERMANOVA, PERMDISP analyses and PCO plots we used Primer v7 with PERMANOVA add-on software (Anderson et al., 2008). A significance level of $p = 0.05$ was used in all tests. Throughout the text, averages are always given together with their standard deviation (SD).

Additional datasets

In support of the discussion, some additional datasets have been analysed per EA. They relate to: (1) local geology, based on a subsurface voxel model of the BPNS (Van Lancker et al., 2019); and (2) sediment dynamics based on systematic analyses of all bathymetric monitoring data used in the current paper. More explanation on approaches and methodologies can be found in Hademenos et al. (2019) for (1) and in Terseleer et al. (2016) for (2). For sediment dynamics, only the dune migration rate estimates are presented here, standardized in m per Spring-Neap tidal cycle of 15 days (Van Lancker et al., 2020). The full analyses on sediment dynamics in the BPNS will be published elsewhere.

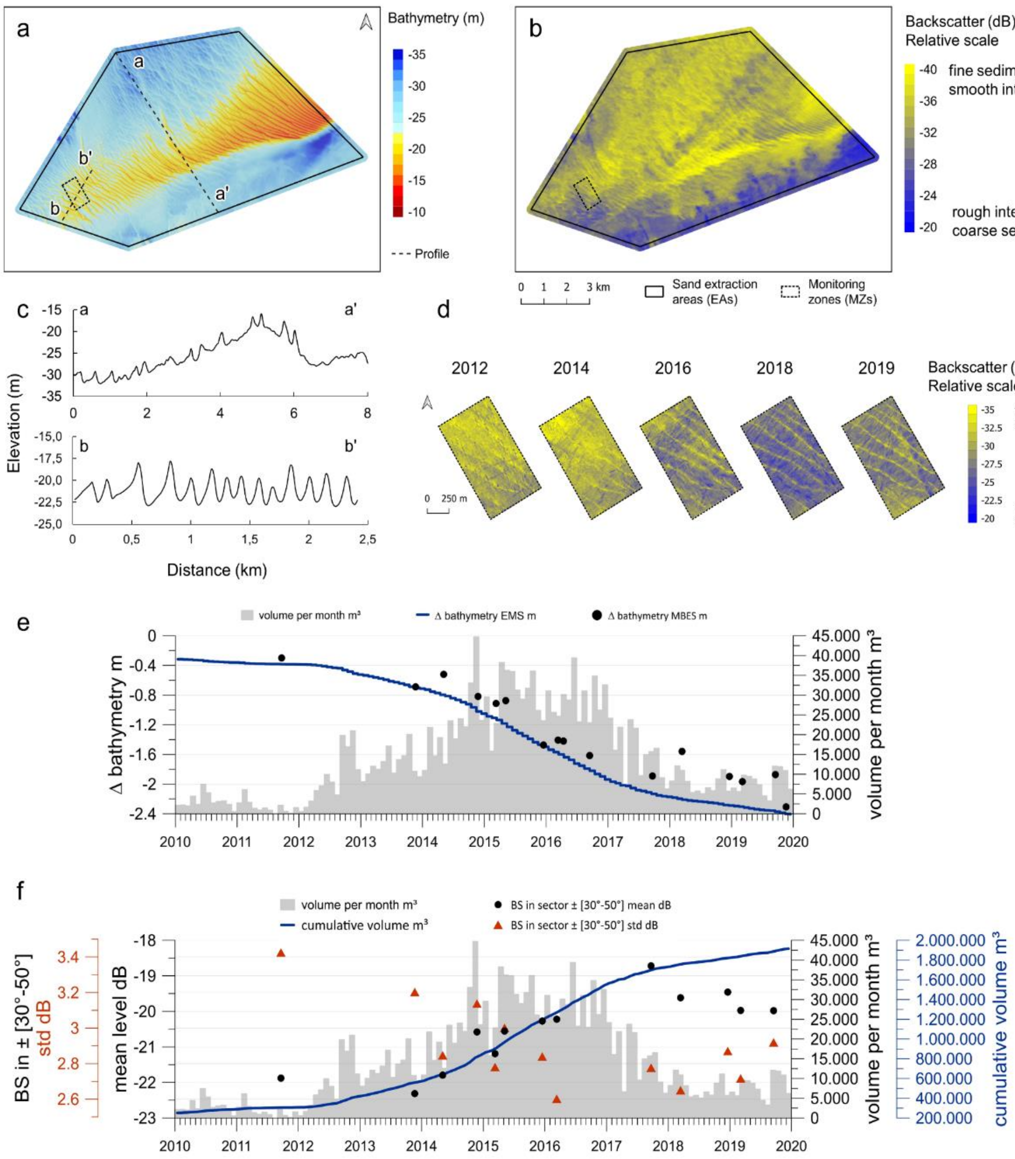
1.4. Results

1.4.1. Thorntonbank – EA1 – MZEA1

From 2010 to 2017, most of the extraction took place in the south-western part of the bank (where MZEA1 has been located). From 2018 onwards, the extraction has moved to the central part of the bank. The top of the Thorntonbank, i.e. where the extraction takes place, shows a relatively flat bathymetry, gently sloping towards the edges with an average depth level of around -22.7 m LAT (Fig. 4a, c). The seabed is shaped by a regular and stable dune pattern, with very large dunes according to the definition given in Ashley (1990), 50 to 300 m wavelength and 1 to 7 m amplitude. Dune migration rate has been estimated at 0.04 m per Spring-Neap tidal cycle of 15 days (Van Lancker et al., 2020).

Figure 4: Bathy-morphology and backscatter synthesis for EA1 and MZEA1 on the Thorntonbank:

(a) Reference bathymetric model (10 x 10 m) based on 100 kHz KM EM1002 2000-2001 dataset; (b) Backscatter model (10 x 10 m, processing QPS-FMGT®) based on 100 kHz KM EM1002 2000-2001 dataset; (c) Cross sections aa' and bb' of the reference bathymetric model; (d) MZEA1 grids (10 x 10 m, processing QPS-FMGT®) averaged per year of 300 kHz KM EM3002 dual backscatter time series; (e) MBES Bathymetric and EMS extracted volume time series on MZEA1; (f) MBES backscatter (processing Ifremer-SonarScope®) and EMS extracted volume time series on MZEA1.



Bathymetry data

The difference in depth between the MBES measurements carried out between 2010 and 2019 and the reference model (MBES data acquired in 2000) in MZEA1 on the Thorntonbank showed a highly significant decreasing trend between 2012 and 2019 (Mann-Kendall test p-value <0.0001). The bathymetric level dropped by 2.4 m on average, but local differences up to 5 m were recorded on the top of the sand dunes. The decrease in bathymetry measured by MBES was strongly correlated with the bathymetric variation deduced from the estimated extracted volumes based on EMS-data ($r^2 = 0.91$, p-value <0.0001) (Fig. 4e). Also for the whole EA1, the bathymetric variation measured by MBES showed a close spatial correlation with extraction intensity (Degrendele et al., 2014; Roche et al., 2011b; Roche et al., 2017).

Backscatter data

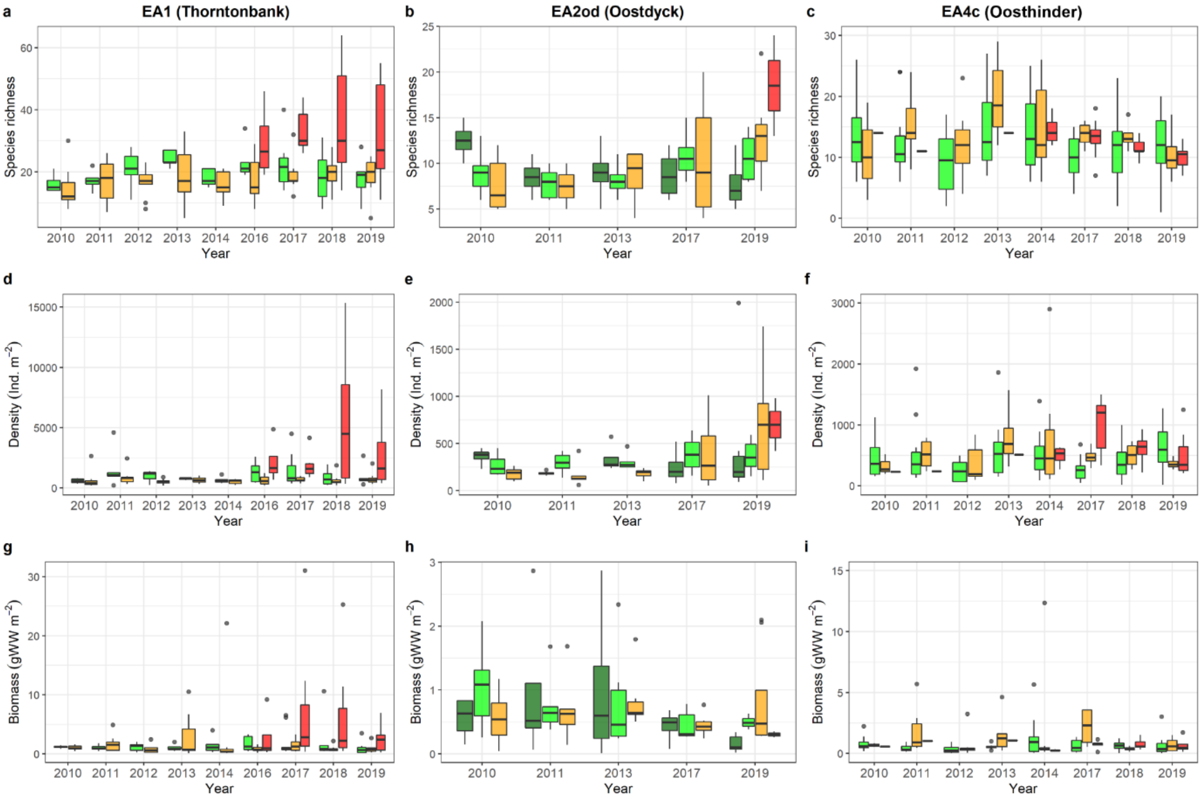
In MZEA1 on the Thorntonbank, the average backscatter level in the angular incidence interval ± [30°, 50°] showed a significant positive trend (Mann-Kendall test p-value = 0.0003), ranging from -22 dB in 2014 to -19 dB in 2018 (Fig. 4f). This increase was negatively correlated with the bathymetric decrease deduced from EMS extracted volume data (r^2 = -0.75, p-value <0.001). After 2018, the average backscatter levels stabilized between -19 and -18 dB, linked to a substantial drop and a stabilization around 16 x 10^4 m^3 per month of volumes extracted in MZEA1. As can be seen from the standard deviations, the spatial variation of the backscatter level decreased from 2011 to 2015 (Mann-Kendall test p-value = 0.03) and then stabilized around 2.8 dB from 2016 to 2019 (Fig 4f). The gradual evolution between 2012 and 2019 towards a more reflective seabed is also illustrated by the successive backscatter models (Fig. 4d).

Figure 5: Relative sediment composition (%) for the three EAs for each impact group, i.e. REFerence, IMPact, HIGH-IMPact, N_REF and S_REFerence samples (the latter respectively north and south of the extraction hotspot in EA2od). For EA1 (Thorntonbank) and EA2od (Oostdyck) sampled years are shown, while for EA4c (Oosthinder) ‘before’ and ‘after’ extraction periods are shown. Legenda: Gravel >1600 µm, Very coarse sand 1600 - 1000 µm, Coarse sand 1000 - 500 µm, Medium sand 500 - 250 µm, Fine sand 250 - 125 µm, Very fine sand 125 - 63 µm, Clay to silt 63 - 0 µm.

Sediment data

The IMP samples in EA1 on the Thorntonbank had a slightly higher medium sand fraction (average ± SD: 64.04 ± 9.82%) compared to the REF samples (54.37 ± 11.31%) (p_{Anova} = 0.048). Even so, IMP and REF samples did not differ for any of the other sediment classes (p_{Anova} >0.2) during the low extraction period (EA1-LEP) (Fig. 5a). Also during the high extraction period (EA1-HEP), sediment composition did not differ between IMP and REF. However, HIGH-IMP did have significantly higher fractions of gravel (2.69 ± 1.01%) compared to IMP (1.29 ± 0.70%) and REF (1.29 ± 0.90%) (p_{Anova} <0.0001) during this HEP. Also, clay to silt fraction percentages were generally higher for HIGH-IMP locations in EA1, while nearly absent in IMP and REF locations in both LEP and HEP (Fig. 5a). Median grain size (MGS) did not differ significantly between the three impact groups over the whole study period.

Figure 6: Macrobenthos species richness (S), density (N) and biomass (W) per year for the three EAs and for each impact group, i.e. REFerence, IMPact, HIGH-IMPact, N_REF and S_REFerence samples (the latter respectively north and south of the extraction hotspot in EA2od). For EA1 only the high extraction period (HEP, 2016 – 2019) included HIGH-IMP samples.

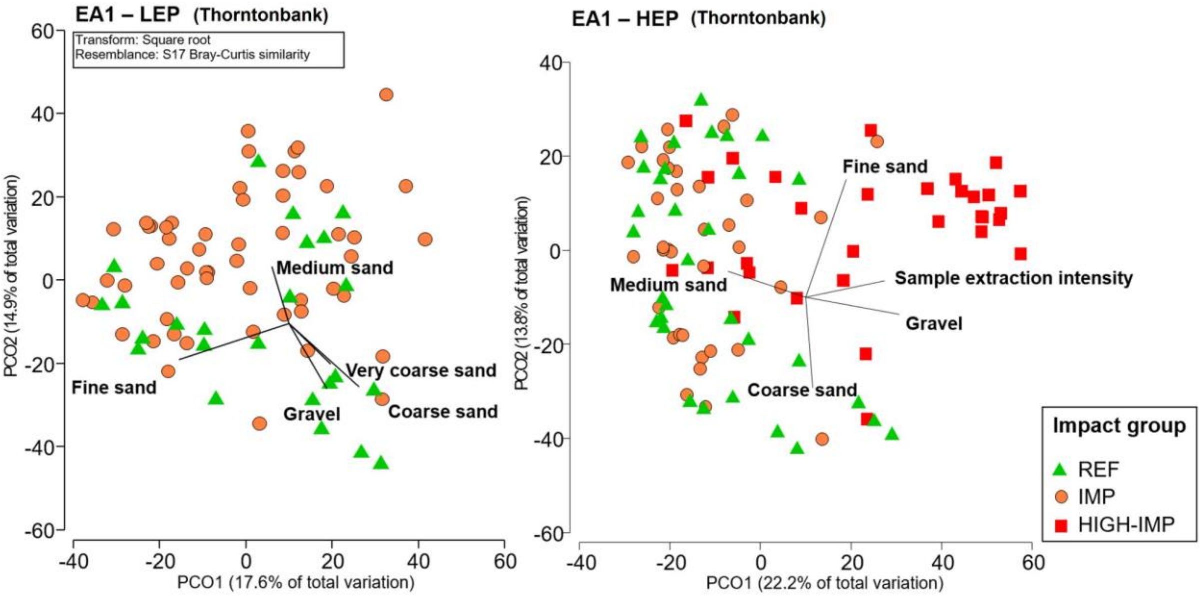


Macrobenthos data

Macrobenthos density (N) and biomass (W) did not differ between impact groups during the LEP in EA1 on the Thorntonbank, but species richness (S) was slightly higher (p_{Anova} = 0.03) in REF compared to IMP samples (Fig. 6a, d, g). Community composition differed significantly between REF and IMP (p_{Perm} = 0.01) (Fig. 7, left) with no significant dispersion between impact groups ($p_{Permdisp}$ = 0.8081). SIMPER revealed that the main dissimilarity was due to higher densities of oligochaetes and *Hesionura elongata* in the REF area. Despite these density differences, IMP and REF are both characterized as *H. elongata* community (Breine et al., 2018). Sediment parameters (size classes and MGS) explained 27.5% of the observed multivariate pattern, while only 2.6% was explained by the extraction parameters (grouped DISTLM marginal test results).

During EA1-HEP on the other hand, N, S and W strongly differed between impact groups (resp. p_{Anova} <0.0001; p_{Anova} <0.0001; p_{Anova} <0.001), with significantly higher and more variable values for HIGH-IMP (S = 32.6 ± 13.8; N = 3257.4 ± 3537.9 ind.m^{-2}; W = 5.1 ± 7.3 g.m^{-2}) compared to IMP (S = 17.3 ± 6.0; N = 650.7 ± 420.5 ind.m^{-2}; W = 1.5 ± 2.6 g.m^{-2}) or REF (S = 19.9 ± 6.2; N = 1041.4 ± 897.9 ind.m^{-2}; W = 1.5 ± 1.8 g.m^{-2}), where IMP and REF did not differ significantly ($p_{Post\ hoc}$ >0.05 for N, S and W) (Fig. 6 a,d,g). Community composition differed significantly between impact groups (p_{Perm} = 0.007) with slightly significant differences in dispersion ($p_{Permdisp}$ = 0.0156) due to a higher dispersion in HIGH-IMP (Fig 7, right panel). Pairwise tests showed that the HIGH-IMP community structure differed significantly from IMP (pairwise p_{Perm} = 0.0271) and REF (pairwise p_{Perm} = 0.0272), which did not differ significantly from one another (pairwise p_{Perm} = 0.1). SIMPER analysis revealed IMP and REF were still *H. elongata* community according to Breine et al. (2018), while HIGH-IMP differed due to the presence of muddy sand species as *Kurtiella bidentata*, *Lanice conchilega, Abludomelita obtusata* and opportunists as *Poecilochaetus serpens*, *Echinocyamus pusillus*, *Spiophanes bombyx* and juvenile *Ophiuroidea*. *Hesionura elongata* community representatives were still present in HIGH-IMP samples, albeit in lower densities. During the HEP, 12.6% of multivariate sample variation could be attributed to extraction, and 31% to sediment parameters (grouped DISTLM marginal test results).

Figure 7: PCO plot based on Bray-Curtis similarity for square-root transformed macrobenthos species abundance data in EA1 on the Thorntonbank, with indication of the three impact groups (REF, IMP, HIGH-IMP). Overlay vectors (black lines) indicate direction and degree of correlation (length of vector) in which the respective environmental variables (with r >0.3, multiple correlation type) fit the dataset. Left: low extraction period (LEP, 2010 - 2014), right: high extraction period (HEP, 2015-2019).



1.4.2. Oostdyck – EA2od – MZEA2od

In EA2od, most of the sand extraction took place on the gently sloping eastern flank of the Oostdyck sandbank, i.e. inside MZEA2od, which has a mean depth of -14.9 m LAT (Fig. 8a, b). The dune morphology in MZEA2od showed a pattern of very large dunes with a wavelength of 150 m, an amplitude around 2 m and a well-marked SW-directed asymmetry, corresponding to a predominance of the ebb-tidal currents. This pronounced asymmetry corroborates the high dune migration rates in this area, which may exceed 1 m per Spring-Neap tidal cycle (Van Lancker et al., 2020).

Bathymetry data

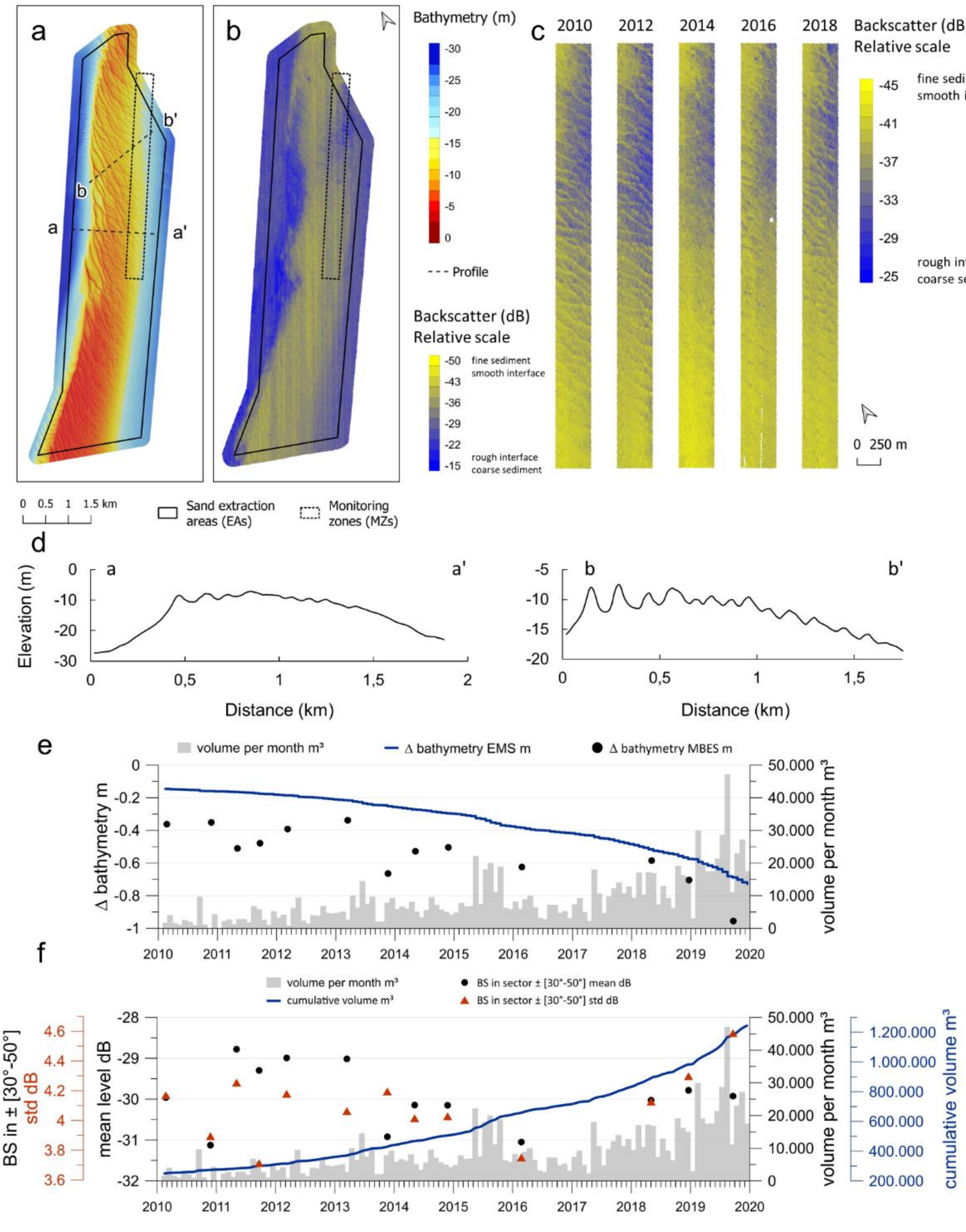
The mean bathymetric variation measured by MBES was relatively well correlated ($r^2 = 0.73$, p-value = 0.0002) with the bathymetric variation estimated from the extracted volumes based on the EMS-data (Fig. 8e). The bathymetric data recorded between 2010 and 2019 showed a significant negative trend with an average final deepening of almost 1 m. On most of the measurements, a vertical bias of on average 0.25 m was observed between the MBES and EMS data. This bias probably results from a combination of systematic errors, an underestimation of the volumes extracted in the EMS data on the MZEA2od, and/or a bias on the bathymetric reference model and the subsequent bathymetric data from the MBES.

Backscatter data

MZEA2od on the Oostdyck showed intermediate to moderately high backscatter levels, suggesting a fine to medium sand sediment cover. The average levels and standard deviations fluctuated around average values of -30 dB ± 4 dB, without a clear significant trend (Fig. 8f) nor a correlation with the extracted volumes values derived from EMS data. The successive models of the backscatter (Fig. 8c) confirmed the lack of a clear trend.

Figure 8: Bathy-morphology and backscatter synthesis for EA2od and MZEA2od on the Oostdyck:

(a) Reference bathymetric model (10 x 10 m) based on 100 kHz KM EM1002 2003 dataset; (b) Backscatter model (10 x 10 m, processing QPS-FMGT®) based on 100 kHz KM EM1002 2003 dataset; (c) MZEA2od grids (10 x 10 m, processing QPS-FMGT®) averaged per year of 300 kHz KM EM3002 dual backscatter time series; (d) Cross sections aa' and bb' of the reference bathymetric model; (e) MBES Bathymetric and EMS extracted volume time series on MZEA2od; (f) MBES backscatter (processing Ifremer-SonarScope®) and EMS extracted volume time series on MZEA2od.



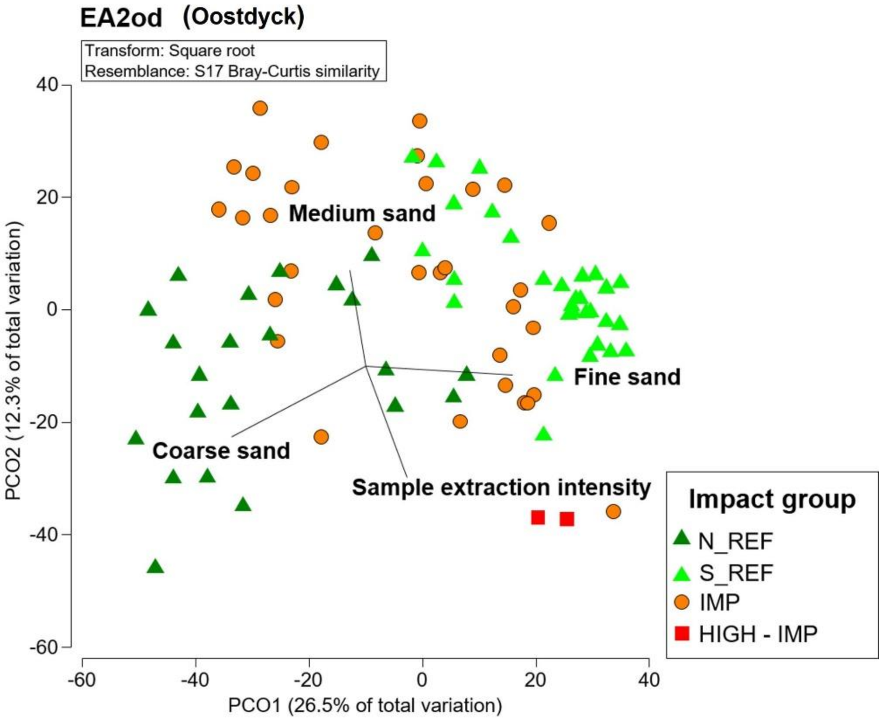
Sediment data

Medium sand was the dominant sediment fraction for all impact groups and did not differ significantly between impact groups, i.e. the impact samples *vs.* the reference zones north and south of the EA2od. On the other hand, median grain size (MGS) significantly differed between N_REF, S_REF and IMP, with all impact groups significantly different from each other (pairwise $p_{Perm} < 0.0091$). A decrease in average MGS from north (N_REF, avg. MGS = 452 ± 116 µm) to south (S_REF, avg. MGS = 311 ± 12 µm) was observed with an intermediate average MGS (343 ± 18 µm) in IMP, indicating that the Oostdyck sandbank in EA2od was still characterized by a natural gradient in sediment grain size over the ridge of the bank (De Backer et al., 2014b). Fine sand significantly increased from N_REF (3.21 ± 3.39%) over IMP (14.62 ± 7.61%) to S_REF (27.85 ± 5.33%), while coarse sand (N_REF = 29.31 ± 14.39%; IMP = 7.09 ± 3.77%; S_REF = 1.37 ± 0.77%) and gravel decreased from north to south (Fig. 5b).

Macrobenthos data

Macrobenthos species diversity, density nor biomass were affected by the impact group parameter in EA2od of the Oostdyck ($p_{Anova} > 0.2$) (Fig. 6b, e, h). However, the macrobenthic community composition differed significantly between all impact groups (pairwise test $p_{Perm} < 0.0143$) (Fig. 9), and also the amount of dispersion differed significantly for the impact groups ($p_{Permdisp} = 0.0001$), with highest dispersion found in IMP. SIMPER results matched the observed sediment gradient with N_REF containing typical coarser sand interstitial species as *H. elongata* and *Protodriloides spp.* characteristic for the *H. elongata* community, whereas S_REF displayed a medium to fine sand *N. cirrosa* community, with *Bathyporeia elegans* and high densities of *Nephtys cirrosa* as characteristic species. The IMP community composition was a transition between both, with typical *N. cirrosa* community species, but also a higher density of *H. elongata* and a lower density of *B. elegans* compared to S_REF. Two stations were classified as HIGH-IMP (in 2019) and these clustered a bit apart on the PCO plot, mainly due to the abundant presence of juvenile *Urothoe brevicornis*, *B. elegans* and *Nephtys spp.* The sample extraction intensity vector seemed to correlate with their community composition (Fig. 9).

Figure 9: PCO plot based on Bray-Curtis similarity for square-root transformed macrobenthos species abundance data in EA2od on the Oostdyck with indication of the three impact groups (N_REF, S_REF, IMP, HIGH-IMP). Overlay vectors (black lines) indicate direction and degree of correlation (length of vector) in which the respective environmental variables (with r >0.3, multiple correlation type) fit the dataset.

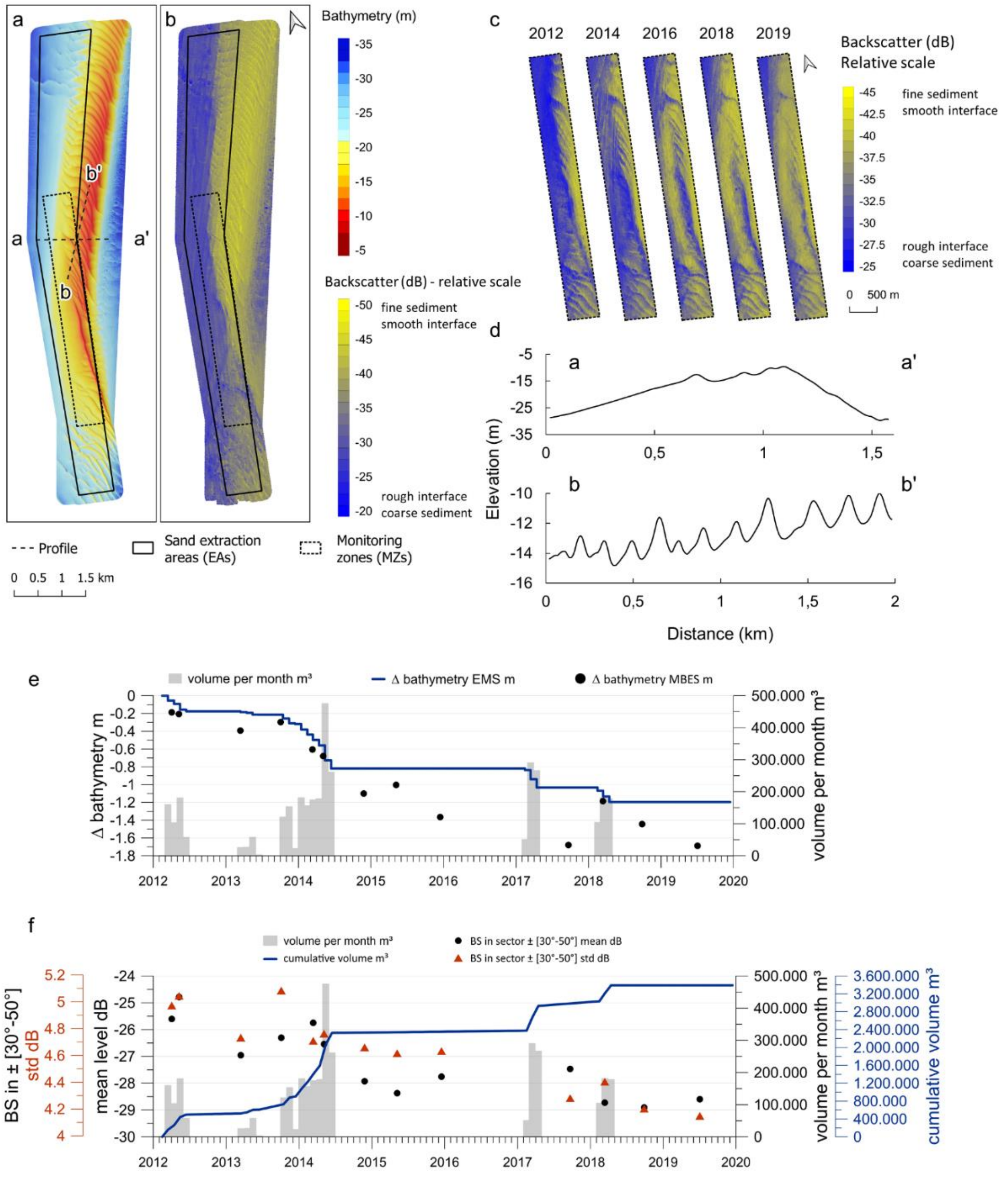


1.4.3. Oosthinder – EA4c – MZEA4c

Located in the southern part of the Oosthinder sandbank, EA4c essentially covers the less steep western flank of the bank parallel to its main ridge. The extraction was spread out over the entire length of EA4c in parallel with the crest of the bank, with a mean depth of -17.5 m LAT in MZEA4c. Very large dunes with a wavelength of 120 to 260 m and amplitudes ranging from 2 to 7 m characterize the morphology of EA4c. The median dune migration rate was estimated at 0.25 m per Spring-Neap tidal cycle of 15 days (Van Lancker et al., 2020).

Figure 10: Bathy-morphology and backscatter synthesis for EA4c and MZEA4c on the Oosthinder:

(a) Reference bathymetric model (10 x 10 m) based on 100 kHz KM EM1002 2004-2005 dataset; (b) Backscatter model (10 x 10 m, processing QPS-FMGT®) based on 100 kHz KM EM1002 2004-2005 dataset; (c) MZEA4c grids (10 x 10 m, processing QPS-FMGT®) averaged per year of 300 kHz KM EM3002 dual backscatter time series; (d) Cross sections aa' and bb' of the reference bathymetric model; (e) MBES Bathymetric and EMS extracted volume time series on MZEA4c; (f) MBES backscatter (processing Ifremer-SonarScope®) and EMS extracted volume time series on MZEA4c.



Bathymetry data

The temporal evolution of the extracted volumes estimated from the EMS data in MZEA4c on the Oosthinder showed intense extraction phases between March and June 2012, from October 2013 to June 2014, in March-April 2017, and between February and April 2018, each time followed by longer periods of no extraction (Fig. 10e). The average MBES bathymetry in MZEA4c showed a highly significant decrease (Mann-Kendall test p-value <0.0001) in the order of 2 m from 2012 to 2019 (Fig. 10e). An acceleration of the bathymetric lowering was observed each time after a period of intense extraction. A highly significant correlation ($r^2 = 0.91$ p-value <0.0001) was measured between the mean bathymetric change derived from MBES data and the trend estimated from EMS data.

Backscatter data

The average backscatter level showed a highly significant (Mann-Kendall test p-value = 0.0006) regular negative trend (Fig. 10f). The first measurements taken in early 2012 showed average levels around -25 dB, while in 2015 the average level dropped to around -28 dB, and this negative trend continued through 2019 with average backscatter levels reaching -29 dB. The correlation between the average backscatter level and the bathymetric change deduced from the extracted volumes based on EMS data was highly significant ($r^2 = 0.79$, p-value = 0.0002). The backscatter standard deviation also decreased towards 2019, and followed the same significant decreasing trend as the average level. The successive backscatter maps in MZEA4c on the Oosthinder (Fig. 10c) revealed a gradual disappearance of the zone with high backscatter levels on the western flank of the bank. In the March 2014 backscatter image, the dredging traces of the drag head underlined by weaker lower-level backscatter lineaments were unambiguously identifiable. After the most intense extraction phase in spring 2014, the highly reflective zone on the western flank had practically disappeared, revealing a bathy-morphology with acoustic properties similar to the ones covering the top zone of the bank.

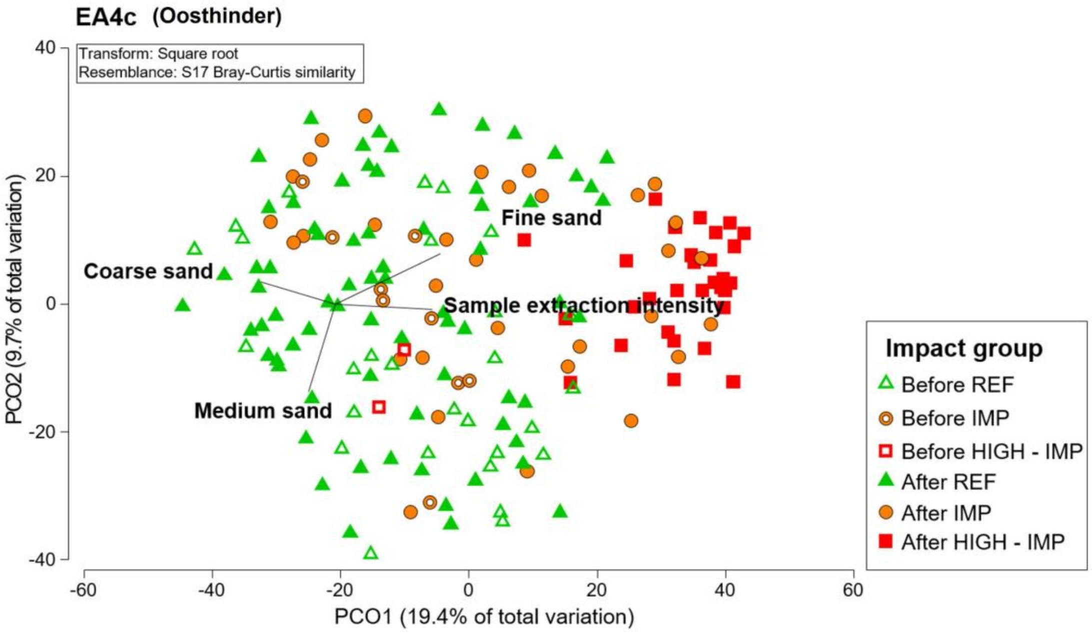
Sediment data

Sediment data in EA4c on the Oosthinder revealed a significant interaction (Before/After extraction x impact group) for median grain size ($p_{Anova} = 0.005$), caused by a decrease in average MGS in HIGH-IMP locations after the start of extraction (B: 341.1 ± 0.4 µm and A: 312.1 ± 18.5 µm). This was mainly due to a significantly larger fine sand fraction in HIGH-IMP (28.09 ± 6.30%) compared to IMP (18.31 ± 6.84%) ($p_{Post\ hoc} = 0.005$) and REF (10.62 ± 5.17%) ($p_{Post\ hoc} < 0.0001$), and a lower coarse sand fraction in HIGH-IMP (2.13 ± 2.18%) compared to IMP (11.17 ± 10.29%) ($p_{Post\ hoc} = 0.0967$) and REF (12.76 ± 6.64) ($p_{Post\ hoc} = 0.0067$) in the period after extraction started (Fig. 5c). Medium sand was not significantly affected by the extraction activities in the 'After' period. In the 'Before' period, neither median grain size nor the fine, medium and coarse sand fractions did differ significantly between REF, IMP and HIGH-IMP groups.

Macrobenthos data

Period B/A, impact group or their interaction factor did not significantly affect macrobenthos S, N, or W ($p_{Anova} > 0.05$) (Fig. 6c, f, i). Nonetheless, community composition was significantly affected by the interaction factor 'B/A x impact group'. Before extraction took place, impact groups did not significantly differ from each other ($p_{Perm} > 0.05$), while after the start of extraction, impact groups strongly differed in community composition ($p_{Perm} = 0.0001$) (Fig. 11). Dispersion also differed significantly ($p_{Permdisp} = 0.0001$) between impact groups as REF and IMP had a higher dispersion compared to HIGH-IMP after the start of extraction, partly because only few HIGH-IMP samples were available before extraction (Fig. 11). SIMPER results revealed that in the 'Before' period, all impact groups could be classified as *H. elongata* community, whilst for the 'After' period, the REF group still represented the *H. elongata* community, but IMP shifted towards the *N. cirrosa* community and HIGH-IMP clearly resembled the *N. cirrosa* community according to the classification given in Breine et al. (2018). This community shift in both IMP and HIGH-IMP is characterized by decreased densities of *Ophelia borealis* and interstitial species such as *H. elongata*, and increased densities and biomass of species like *N. cirrosa*, *Urothoe brevicornis*, *B. elegans* and *Magelona johnstoni* (SIMPER results). Grouped DISTLM attributed 13.9% of the observed multivariate pattern to extraction parameters, and 23.1% to sediment parameters (marginal test results).

Figure 11: PCO plot based on Bray-Curtis similarity for square-root transformed macrobenthos species abundance data in EA4c on the Oosthinder, with indication of the three impact groups (REF, IMP, HIGH-IMP), and whether the sample was taken 'before' or 'after' (B/A) the start of extraction activities. Overlay vectors (black lines) indicate direction and degree of correlation (length of vector) in which the respective environmental variables (with r >0.3, multiple correlation type) fit the dataset.



1.5. Discussion

The first Royal Decree regulating marine aggregate extraction in Belgian waters dates from 1974. In the period 1976-1986 around 6 x 10^6 m^3 of sand was extracted (De Moor and Lanckneus, 1992). At the time, it was believed that the natural maintenance mechanism of sandbanks would counterbalance the extraction, though already in the period 1987-1994, when cumulatively 4.5 to 5 x 10^6 m^3 of sand was extracted in the top zone of one sandbank alone, it was concluded that the extraction had surpassed the recovery potential (De Moor, 2004). Van Lancker et al. (2010) synthesized the findings of the subsequent period during which the creation of extraction-induced depressions was evidenced and the impact these had on the hydrodynamics, morphology, sedimentology and biology.

Our results now indicate that extraction regime and local geological context are important factors driving the direct environmental impact of marine aggregate extraction in subtidal sandbank ecosystems. Table 2 summarizes the differences in extraction regime and the observed effects for each extraction area (EA). The observed seabed changes were not consistent for the three sandbanks and their respective EAs, with both fining and coarsening trends observed. The most drastic impact was observed when a high and continuous extraction regime coincided with a varying nature in local geological layers and sediment types. The macrobenthic community response always matched changes in the seabed and especially changes in sediment characteristics, highlighting once more the strong association between both as has been noted by other studies (Cooper, 2013b; Creutzberg et al., 1984; Snelgrove & Butman, 1995; Van Hoey et al., 2004).

In the following paragraphs, we discuss the relevance of considering the local geological context in environmental impact assessments, and the consequences that bathy-morphological and sedimentary changes may have on the biological (macrobenthic) responses, considering differences in exposure to low continuous, high continuous and high irregular extraction regimes. We conclude with some recommendations concerning the environmental impact monitoring in relation to marine aggregate extraction and seabed integrity.

Table 1: Summary of the different conditions in each sandbank, extraction regime and observed changes in relation to marine aggregate extraction in each EA (EA1 Thorntonbank, EA2od Oostdyck, EA4c Oosthinder). Mean backscatter level estimated in angular range ± [30°-50°].

*Legenda: Increase (+); Decrease (-); No change (=), with Intensity of change from Moderate (1 symbol) over Strong to Very Strong (3 symbols). Sections marked with an * are based on the MBES monitoring zones MZEA1, MZEA2od and MZEA4c within the respective EAs. **LEP and HEP refer to the Low (2010 – 2014) and High (2015 – 2019) extraction periods for EA1.*

Extraction area			**EA1 (Thorntonbank)**		**EA2od (Oostdyck)**	**EA4c (Oosthinder)**
			LEP**	**HEP****		
Dune characteristics *	Wavelength (range & *median*; m)		50–300 *(130)*		50–220 *(130)*	120–260 *(200)*
	Amplitude (range & *median*; m)		1-7 *(4)*		0,5-4 *(2)*	2-7 *(2.5)*
	Dune migration rate (avg. m per Spring-Neap tidal cycle)		0.04		0.75	0.25
Extraction regime	Avg. depth of extraction area (m LAT)		-22		-12	-15
	Monthly average volume (m^3) (only months when extraction took place considered)		83 x 10^3	164 x 10^3	17 x 10^3	230 x 10^3
	Yearly average volume (m^3) (idem)		996 x 10^3	1969 x 10^3	197 x 10^3	1150 x 10^3
	Frequency of extraction		continuous	continuous	continuous	periodic
Effects of marine aggregate extraction	Bathy-morphological evolution*	Mean depth	+	+++	+	++
		Mean backscatter level	+	++	=	---
	Sediment characteristics	Median grain size	=	=	=	--
		Coarse fractions	=	++ Gravel	=	- Coarse sand
		Fine fractions	=	+ Clay to silt	=	+++ Fine sand
	Macrobenthos	Species richness	=	+++	=	=
		Density	=	+++	=	=
		Biomass	=	+++	=	=
		Species community	No effect on community structure	Attraction of muddy sand species and opportunistic species	No effect of extraction; Natural sediment gradient determines species community	Transition from coarse sand community to medium sand community

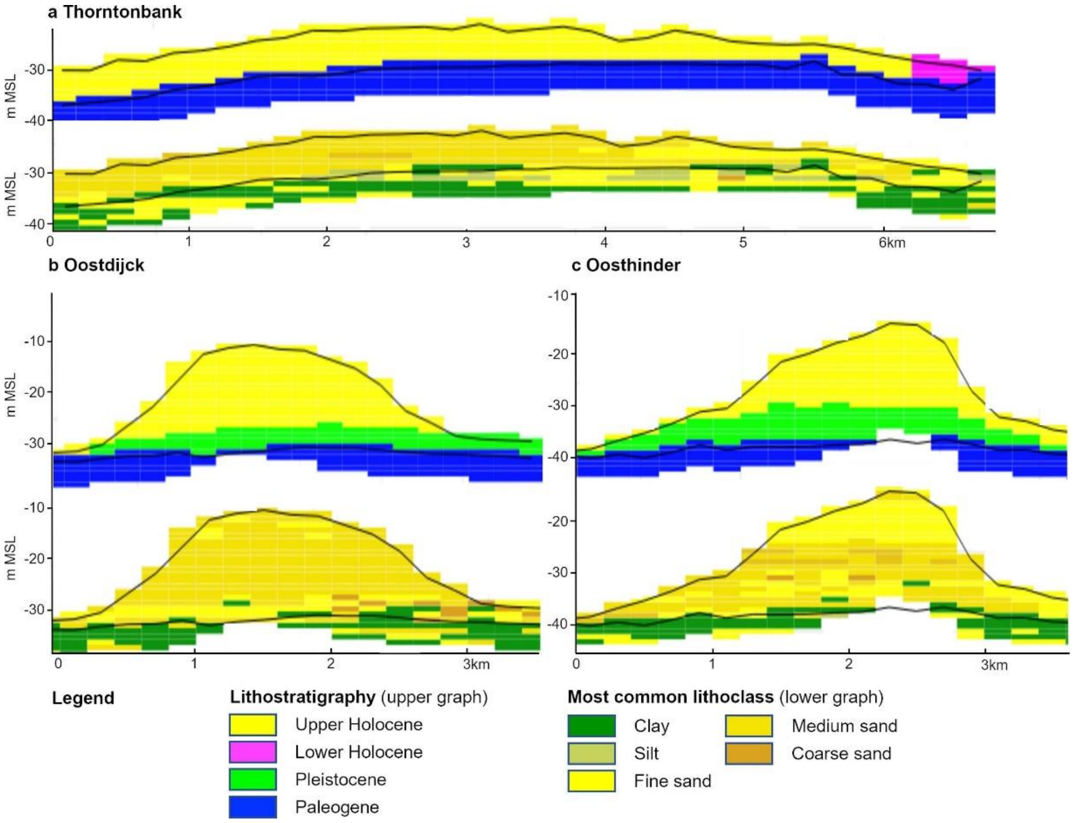
1.5.2. Local geology of the EAs

Figure 12 provides an overview of the differences in local geology for the three EAs. For the entire Belgian part of the North Sea, four main litho-stratigraphic units can be differentiated, each with different sediment characteristics (so-called lithoclasses). From old to young these units are: (1) Paleogene, composed mainly of stiff clay with local gravel occurrences; (2) Pleistocene, varying in sand composition, shell fragments and silt/clay percentages; (3) Lower Holocene, also highly varying in sediment composition; and (4) Upper Holocene, mostly representative of the present-day hydrodynamic regime, with a more uniform sediment composition (Hademenos et al., 2019; Van Lancker et al., 2019).

The southwestern part of EA1 has a relatively thin Upper Holocene cover (Fig. 12a). The high extraction rates make EA1 on the Thorntonbank prone to depletion of this thin top layer. Moreover, sediments are more heterogeneous in nature near the Paleogene/Quaternary transition, and depletion of surface sediments may locally result in the surfacing of Paleogene clay together with increased gravel and shell occurrences. EA2od (Oostdyck) and EA4c (Oosthinder) have similar sequences of Paleogene, Pleistocene and Upper Holocene sediments, but the Holocene cover of EA2od is more extensive homogeneous compared to EA4c (Fig. 12b, c). At EA4c, extraction took place at the lower flanks of the sandbank, where Pleistocene medium sands outcrop. Compared to the other EAs, the top zone of EA4c is composed predominantly of sands with a lower grain size, i.e. fine to medium sands.

Figure 12: Vertical profile sections presenting the local geology for the three EAs (see Fig. 1. for location of the different cross sections): (a) south-western extremity of the Thorntonbank EA1; (b) north-eastern part of Oostdijck EA2od, and (c) south-west part of Oosthinder sandbank EA4c (c). The upper figures show the litho-stratigraphic units, the lower figures the main lithoclasses (sediment types).

Figures extracted from TILES Consortium (2018), http://www.bmdc.be/tiles-dss/#). The subsurface models are represented by voxels of 200 x 200 x 1 m. MSL: Mean Sea Level.



1.5.3. Effects of continuous but low extraction

In areas exposed to continuous, low extraction intensities, such as EA1 (Thorntonbank) during the low extraction period (LEP, 2010 - 2014) or EA2od (Oostdyck), only limited changes in sediment composition and macrobenthic community were observed, which were rather similar to changes that may be expected from natural variations. The low extraction intensities, continuous migration of the underwater sand dunes (Boyd et al., 2004; Van Lancker et al., 2020) and the resilient nature of the macrobenthos (Boyd et al., 2004) are probably the main reasons why biological responses were not directly evoked. This is also evidenced by the absence of a significant trend in the mean backscatter level in MZEA2od. The latter may be attributed to continuous dune migration as well as to the homogeneous Upper Holocene sand cover in that area, but also to reduced screening activities during extraction.

Although the extraction intensity is low, direct bathy-morphological effects of continuous extraction are clearly visible: the average bathymetric deviation of -0,8 m in MZEA2od has not been refilled by the migrating dunes, which means that the natural processes cannot compensate for the extracted sand volumes. Deepening may cause local alterations in physical processes (e.g. erosion and sedimentation rates or changes in bed shear stress), which in turn structure the macrobenthic (De Jong et al., 2015a) but also meiobenthic communities (Vanaverbeke et al., 2007). However, no clear environmental responses were observed in EA2od nor EA1-LEP. Most likely, the continuous extraction only caused a gradual physical abrasion of homogeneous sediments. Macrobenthic communities in high energetic sandy areas are expected to have a lower sensitivity to extraction or bathymetric changes (Cooper et al., 2011b; Foden et al., 2009). In conclusion, limited changes in the soft sediment associated macrobenthic communities are expected (at least in the BPNS where extraction takes place on top of the sand banks) when extraction intensity is low to intermediate.

1.5.4. Effects of continuous and periodic high extraction

In areas exposed to continuous (EA1-HEP from 2015 onwards) or periodic (EA4c) high extraction intensities, the aggregate extraction activities clearly altered the bathy-morphology and the associated macrobenthic community. However, different responses were observed, mainly related to local variations in sandbank geology and differences in extraction practices (screening versus non-screening).

The continuous aggregate extraction of 20 x 10^3 to 40 x 10^3 m^3 per month over the period 2015 - 2018 in MZEA1 on the Thorntonbank created a local depression with an average bathymetric difference of 2.4 m compared to the reference level , with local differences up to 5 m. Formation of local depressions have been observed earlier as well for the BPNS e.g. on the Kwintebank (Degrendele et al. 2010). The continuous high excavation on the Thorntonbank most probably removed the Upper Holocene medium sands, exposing the older geological layers, which consist of muddy and gravelly sediments (Van Lancker et al., 2019). The gravel fraction significantly increased in the HIGH-IMP samples, but also the silt to clay fraction increased for samples taken during the high extraction period (HEP) in the centre of the EA1 depression. Additionally, processes such as screening and overflow also contributed to the increase of both fractions. When screened, the larger sediment fractions fall more or less directly to the seabed, within a 300 – 600 m range from the point of discharge (Cooper, 2013a; Newell et al., 1998; Poiner & Kennedy, 1984). As a result of overflow, fine fractions can disperse up to several kilometres depending on local hydrodynamics (Van Lancker & Baeye, 2015). As such, overflow not only contributes to the local fine particle enrichment, but also down current of the extraction activity (Le Bot et al., 2010; Robinson et al., 2005). Changes in seabed characteristics are also evidenced by an increase in the average backscatter level through time. This may be explained by an increase in seabed roughness due to the mechanical impact of the dredge head and the local concentration of the coarse sand fraction and shells due to screening during the HEP. Furthermore, the seabed surface inside a depression is often subjected to a lower bed shear stress compared to the natural surface (De Jong et al., 2016). These local slower bottom currents can reduce the degree of sand transport and allow mud to settle (Mielck et al., 2019), which corroborates our finding of increased fine sediments near the extraction hot spot in EA1.

Also, the macrobenthic community showed a clear biological response to the high and continuous aggregate extraction activity. In the EA1 depression, all biological parameters (species richness, densities and biomass) strongly increased. The density and numbers of typical *H. elongata* community representatives slightly reduced, while *Spiophanes bombyx* densities increased. The latter is a typical r-strategist often found in unstable habitats such as extraction areas (Ager, 2005; Coates et al., 2015; De Backer et al., 2017). The increased fine sediments further attracted species typical for fine to muddy sediments, such as *Abludomelita obtusata*, *Kurtiella bidentata* and the reef builder *Lanice conchilega*. Furthermore, opportunistic species such as juvenile *Ophiuroidea* and *Echinocyamus pusillus*, also colonised the area, likely due to an increased availability of organic matter (De Jong et al., 2015a). An observation very similar to the latter has been described by Bonne et al. (2010) concerning the 5m deep excavation depression on the Kwintebank. Several studies showed that extraction activities can increase the organic matter content through release, resuspension and settlement of organic matter and fine sediments in relation to drag head disturbance (Cooper et al., 2011a; Newell et al., 1998; Snelgrove & Butman, 1995). Secondly, extraction-induced trawl marks increase the patchiness and heterogeneity of the seabed surface area (Boyd et al., 2004; Cooper, 2013b; Phua et al., 2002). In MZEA1 this is reflected by the increased mean backscatter levels, increased between-sample variance of grab samples and significantly higher species richness, density and biomass values of the associated macrobenthic communities. An enhanced macrobenthos production due to extraction has been reported before (De Backer et al., 2014b; De Jong et al., 2015b; Gubbay, 2003; Newell et al., 1998). De Backer et al. (2014b) found similar physical and ecological responses to extraction for another extraction zone in the BPNS, located on the Buiten Ratel, a sandbank east of the Oostdyck (see Fig. 1). Both the increase in fine sediments and organic matter, which attracts opportunists, and the increased seabed surface heterogeneity, which provides more niches to colonise, likely contributed to the observed enhancement in macrobenthos species richness, density and biomass.

In contrast to EA1, EA4c is subjected to periods of very high extraction intensities alternated with longer periods without extraction. For EA4c, a gradual change in sediment composition was observed, without abrupt shifts as seen in EA1 during the HEP. The Upper Holocene cover on the Oosthinder EA4c is thicker, and also the estimated dune migration rates were higher than for EA1 (Van Lancker et al., 2020). The coarse sediment fractions in EA4c mainly comprised fragmented shells, which have been gradually removed from the area through extraction, as the vessels usually do not screen when dredging for beach nourishment purposes. This may have caused the gradual decrease of the backscatter level from ca. -25 dB in 2012 to ca. -29 dB in 2017 in the western part of MZEA4c, although the change in backscatter may also reflect a redistribution of the predominantly occurring fine sands in the top zone of the sandbank.

As a response to this sediment transition, the macrobenthic community shifted from a medium to coarse sand *H. elongata* community towards a typical medium to fine sand *N. cirrosa* community in the high impact (HIGH-IMP) samples. In contrast to EA1, the densities of opportunistic species did not increase in EA4c, and species richness, densities and biomass of the local macrobenthic community remained constant. This response is very similar to what Vanaverbeke et al. (2007) observed for meiobenthic communities after long-term intensive extraction on the Kwintebank, where diversity parameters also were not altered, while community composition responded to changes in sediment characteristics with more small-sized species after disturbance. Although the settlement of fine sediments due to extraction is normally associated with a local influx of organic matter, it seems that the easy resuspendable material seems less prone to settle in EA4c compared to EA1. Likely, the local hydrodynamics and high dune dynamics in EA4c evoked a faster resuspension of organic matter, in contrast to the situation in EA1, where the extraction depression acts as a fine sediment trap due to local conditions of reduced bed shear stress.

1.5.5. Recommendations for monitoring seabed integrity

Specific environmental and biological responses to sand extraction are highlighted when comparing EAs of highly similar ecological settings located on tidal sandbanks. These responses depend on both the geological context and the extraction regime. High extraction regimes can lead to depletion of the Upper Holocene aggregate resource layer, as such exposing older geological layers with different sediment characteristics. This may lead to physical loss of the upper sediment habitat, which may lead to drastic changes in the main macrobenthic community parameters. Up until now, this might be seen as a rather local effect of aggregate extraction (e.g. in EA1 and EA4c). However, this will become a more frequent threat with increasing allocations of EAs, especially in regions with a relatively thin Quaternary cover like the BPNS. This implies that in order for extraction to be sustainable from an ecological point of view, it is critical that the physical seabed integrity is maintained in order to prevent changes in biological communities or to at least enable recovery towards original communities. It is not possible to determine a maximum sustainable exploitation rate in this context, since this will depend on the capacity and production rate of the dredging vessel and on the extraction practice as well. In-depth knowledge on geological layers does enable us to determine a maximum depth limit for extraction in order to maintain seabed integrity. To enforce accounting for this depth limit, the Belgian regulators on aggregate extraction provide, since 2021, a maximum extraction limit or reference surface (FPS Economy, 2021). It is based on resource thickness and sediment characteristics criteria extracted from a newly built Quaternary geological knowledge base (Van Lancker et al., 2019), and further fine-tuned with criteria related to minimizing changes in bottom shear stress (Van den Eynde 2017). Previously, extraction was limited to 5 m below initial bathymetric surface for all extraction areas, possibly leading to exposure of older geological layers as shown in this study. With the new extraction surface, major changes in seabed integrity and hydrographic conditions should be prevented. Provided that a regular monitoring of environmental and biological responses is maintained, a more sustainable exploitation of the aggregate resources is envisaged.

Besides analysing the physical characteristics of the EA, an ecological assessment of the area is crucial, as this allows to identify sensitive communities and important habitats that need to be conserved (Van Lancker et al., 2010). The biological impact assessments in this study focused on active extraction areas, where we accounted for progressive impacts over multiple years by using cumulative extraction intensities over the study period, thereby excluding a potential recovery factor in the analyses. A degree of recovery is very likely present and should be accounted for in future ecological impact assessments. Moreover, as in other traditional ecological impact assessment studies (e.g. De Backer et al., 2014a; Rehitha et al., 2017; Seiderer & Newell, 1999; Waye-Barker et al., 2015), we compared macrobenthic community parameters for the EAs with those from nearby reference areas. Changes in the macrobenthic community structure have proven to be a reliable indicator when analysing the ecological status of a certain site (Dauer, 1993). However, more recent publications revealed that structural impact and recovery trajectories of benthic communities do not always match their functional counterparts (Bolam et al., 2016; Hussin et al., 2012). Physical changes of the habitat, whether naturally or induced by human activities, may change the biological community structure and the functional traits expressed by the community, thereby affecting ecosystem functioning and its services (Toussaint et al., 2021). In general, structurally diverse communities express more functional traits compared to structurally poor communities (Hillebrand & Matthiessen, 2009; Reiss et al., 2009; Snelgrove et al., 2014), but the strength and direction of this relationship is highly variable (Lam-Gordillo et al., 2020). From an ecosystem management perspective, it is necessary to improve our understanding of how the quality and quantity of ecosystem services provided by coastal marine ecosystems may change in relation to potential disturbances (Hillman et al., 2020; Snelgrove et al., 2014). Therefore, gathering empirical information on the impact of aggregate extraction on the functional diversity and benthic ecosystem functioning is the way forward.

This study presented a spatially explicit and integrated bio-physical approach by combining Multibeam echosounder (MBES) and Van Veen grab (sediment and macrobenthos) data. The integration allowed us to substantiate our findings and to present a more holistic impact assessment of marine aggregate extraction. Still, both datasets were acquired during different monitoring campaigns, implying potential spatio-temporal lag effects and a suboptimal sampling design. In tidal-dominated sandbank ecosystems, multi-scale morphological surface patterns prevail, ranging from sand ripples to entire sandbanks, resulting in nested levels of habitat heterogeneity (Mestdagh et al., 2020). Such patterns have seldom been accounted for in past ecological assessments, even though a high degree of heterogeneity in macrobenthos samples has often been described (e.g. De Backer et al., 2014b; De Jong et al., 2015b; Gubbay, 2003; Newell et al., 1998; this study; Phua et al., 2002). Therefore, combining MBES measurements with physical and biological sampling from the start of the monitoring, allows for a better selection of grab sample locations whilst considering the spatial heterogeneity of the seabed (cfr. Amiri-Simkooei et al., 2019; Haris et al., 2012; Mestdagh et al., 2020; Montereale-Gavazzi et al., 2019).

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2. Advances in DNA-based monitoring to study the effects of marine aggregate extraction on benthic communities

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Marine aggregate extraction activities alter the seafloor through sediment removal and sediment (re)suspension and these seafloor changes in turn affect the benthic communities (de Jong et al., 2015). Understanding whether and how benthic organisms are affected by aggregate extraction provides critical information to safeguard a sustainable exploitation of marine aggregate resources while simultaneously reducing detrimental effects for the marine benthic system. These benthic communities encompass bacteria and archaea, small-sized fauna such as nematodes and copepods (meiobenthos) and animals larger than 1 mm (macrobenthos). In environmental impact assessments (EIAs), benthic metazoan species identification is typically based on morphological characteristics, a time-consuming and labor-intensive process for which specific taxonomic knowledge and experts are needed. DNA-based approaches such as DNA metabarcoding may provide a faster and cheaper alternative to morphological identification.

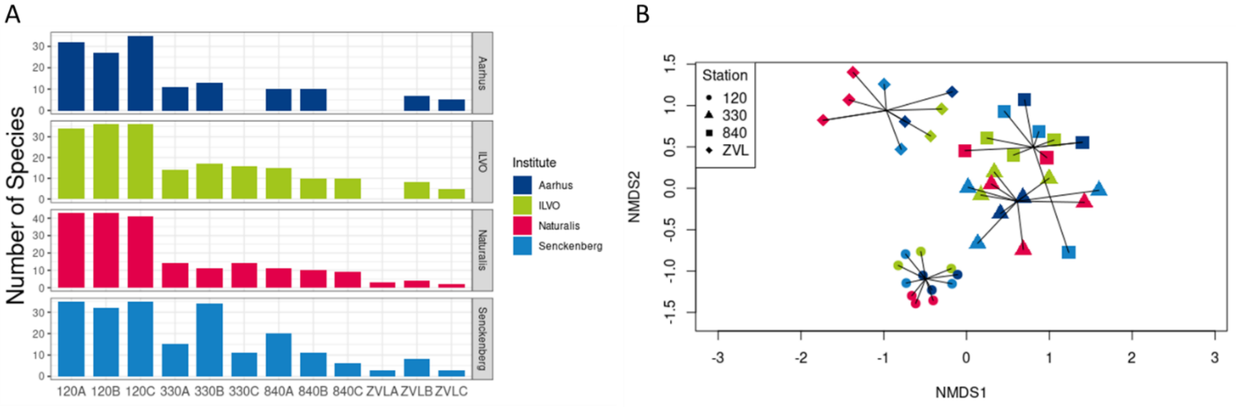
DNA metabarcoding of macrobenthos starts with blending the organisms on a per sample basis to achieve a homogeneous soup from which bulkDNA is extracted. This bulkDNA is used to PCR amplify a portion of the mitochondrial COI gene using general primers and primer specific amplification conditions. The resulting PCR products are sequenced using high throughput sequencing technologies (Baird and Hajibabaei, 2012). Since multiple species in many samples can be sequenced in a single instrument run, processing time of samples is substantially reduced compared to morphological identification (Aylagas et al., 2018). After data analysis, the obtained sequences are linked to species names by comparing them to DNA sequences of morphologically identified specimens in private or public reference databases. Within the North Sea region project GEANS, we tracked time and costs associated with the morphological and DNA-based identification of macrobenthos from the same samples collected in aggregate extraction sites in the Belgian part of the North Sea (BPNS) and showed that DNA-based identification can speed up the identification of macrobenthos samples by 45% while reducing the cost with 27%.

In view of the many laboratory steps in the DNA metabarcoding method, a standardized protocol that allows for reproducible and reliable DNA metabarcoding results is a prerequisite for the adaption of the DNA-based method by policy and stakeholders. Using macrobenthos communities differing in species density and diversity from the BPNS, we first determined the best primer set to PCR amplify as many macrobenthos species as possible using DNA metabarcoding and showed that the DNA-based approach adequately distinguished the different macrobenthos communities (Derycke et al., 2021). Next to the choice of the primer set used to amplify species, the PCR process itself and the DNA extraction step can introduce bias in species detection: during the PCR step, primers may not always adequately bind to the target DNA, while during the DNA extraction step inhibitor substances may be present that affect the PCR efficiency. Therefore, as a second step towards harmonization, we aimed to reduce the stochastic effect of both processes by investigating the number of technical replicates needed in the lab protocol to detect as many species as possible with DNA metabarcoding. Our results showed that three DNA replicates were needed to pick up at least 80% of the species diversity, and at least three PCR replicates in the lab protocol were required to get a good representation of the species (Van den Bulcke et al., 2021). In contrast to general belief, larger body size or higher abundance of the species in a sample did not increase its detection prevalence among DNA replicates. Instead, the diversity in the samples influenced the detection of rare species which were less consistently detected in samples with high diversity compared to locations with less diversity (Van den Bulcke et al., 2021).

Importantly, DNA-based results should be repeatable and robust regardless of the institute that conducts the lab processing of the samples. Therefore, as a third step towards standardization, we conducted a ring test where subsamples of 12 macrobenthos samples originating from four different macrobenthos communities in the BPNS were distributed to four institutes located in Belgium, the Netherlands, Germany and Denmark. Samples were processed using the same standardized lab protocol and the resulting datasets were bioinformatically processed by one institute. Results showed that overall diversity patterns were identical between the four institutes (Fig 1). The number of species showed a similar decreasing trend across institutes from the location with high macrobenthos diversity (station 120) to the station with lowest macrobenthos diversity (ZVL) (Fig 1A). In total, 100 macrobenthos species were detected with DNA metabarcoding, of which 60 species were picked up by all four institutes. At most 14 species were recorded by only one of the four institutes and these species typically had very low abundances. Species composition patterns were also comparable between the four institutes as samples clustered based on the macrobenthos communities independent of the institute that conducted the work (Fig 1B). In addition, small changes to the lab protocol (different DNA extraction kit, different high fidelity polymerases for PCR amplification, different reagents for clean-up) resulted in only minor changes in macrobenthos species detection: similar number of species were detected as with the fixed protocol in all samples and 70 - 75% of the species were shared between the 'fixed' and adjusted protocols. These results show that DNA metabarcoding offers a highly repeatable assessment of species numbers and species composition irrespective of the lab conducting the sample processing.

Figure 1. DNA metabarcoding results of 12 macrobenthos samples that have been processed by four different institutes (indicated by different colors).

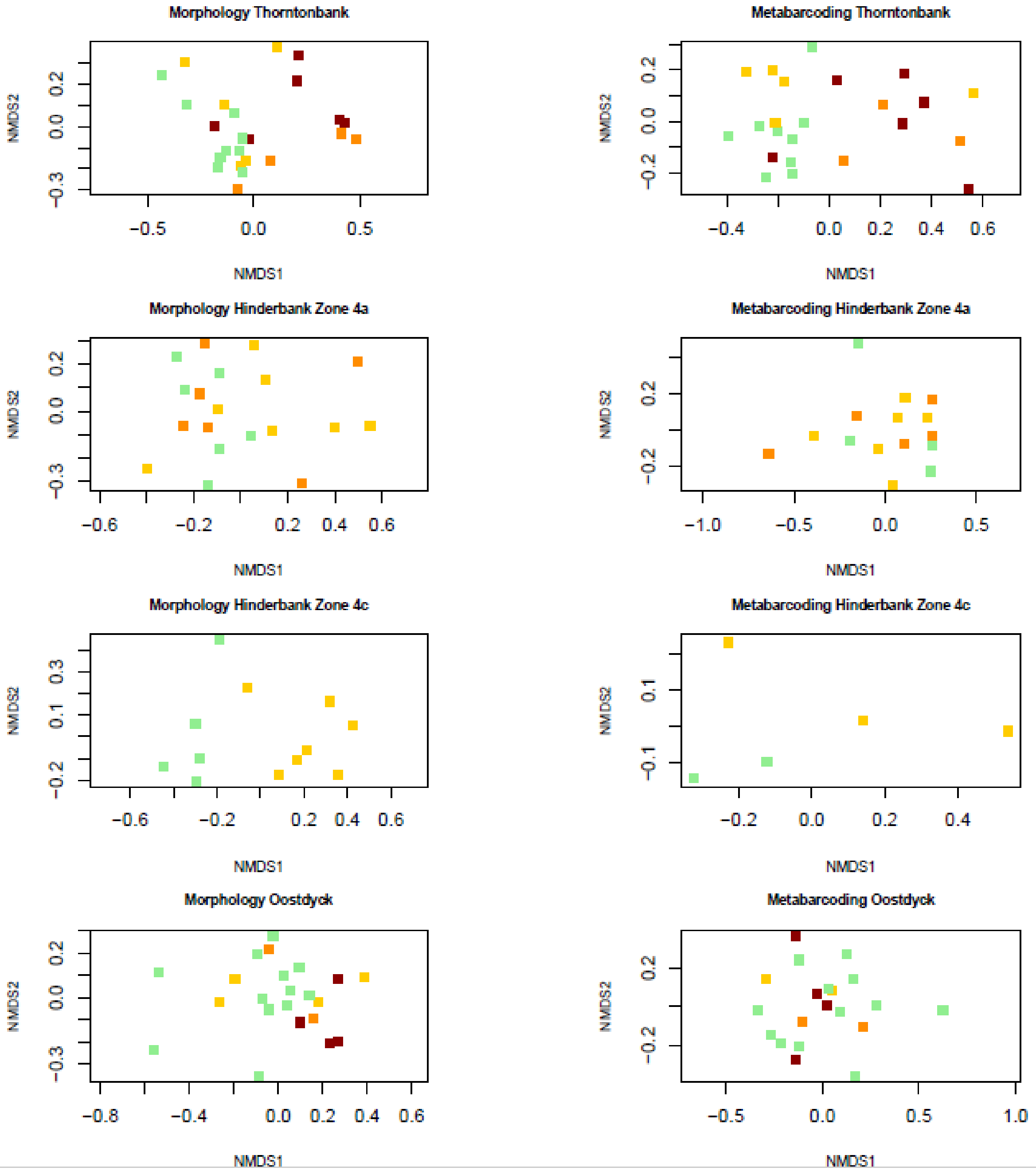
Macrobenthos was collected in station 120 (high diversity, 39 morphological species), stations 330 and 840 (intermediate diversity with 13 and 10 morphological species, respectively) and station ZVL (low diversity with only 3 morphological species). In each station, three biological replicates were collected (A, B, C). A: number of species detected with DNA metabarcoding in each of the 12 stations for each of the four institutes. B: species composition in each of the 12 samples processed by the four institutes illustrated by the nMDS plot based on Bray-Curtis dissimilarity index.



The harmonized and validated DNA metabarcoding protocol was subsequently used to characterize macrobenthos in relation to different regimes of marine aggregate extraction in the BPNS. Macrobenthos samples were collected in 2019 both inside (impact) and outside (reference) extraction areas on three sandbanks characterized by different degrees of extraction intensity: the Thortonbank, which is the epicenter of extraction since 2015 with continuous high extraction intensities of ca 150 000 m^3/month and a total extracted volume of 1.8 million m^3 in 2019, the Oostdyck with continuous but low extraction intensities of around 30 000 m^3/month and a total of 340 000 m^3 in 2019 and the Hinderbanken with periodically high amounts of extraction (sometimes up to 500 000 m^3/month) for coastal protection, where in 2019 around 600 000 m^3 was extracted in zone 4a mainly in the period February-April (Wyns et al., 2021). In zone 4c of the Hinderbanken, no extraction occurred in 2019, but this area has been extracted heavily in previous years. Depending on the amount of sand extracted in 2019, the locations in each of the three sandbanks were divided into three impact groups (high: > 2000 m^3, medium: 500 – 2000 m^3, low: < 500 m^3) and a reference group (0 m^3). Multivariate analyses of macrobenthos communities in the Thortonbank showed a significant impact of sand extraction on species composition for the two methods (PERMANOVA, $p < 0.001$ for DNA metabarcoding and $p = 0.0041$ for morphology). Reference sites were significantly different from the high ($p = 0.024$) , medium ($p = 0.024$) and low ($p = 0.03$) impact sites in the metabarcoding dataset and from the high ($p = 0.012$) and medium ($p = 0.006$) impact sites in the morphological dataset (Fig 2). For the Hinderbanken, the morphological and the metabarcode datasets were consistent and showed no significant differences in macrobenthic communities for zone 4a (Fig 2) suggesting that the recent periodic high extraction in this area has not yet affected the macrobenthos communities. For zone 4c, on the other hand, impact samples clustered separately from reference samples in the morphological and in the metabarcode dataset (Fig 2). No extraction took place in 2019, but previous sand extraction has resulted in finer sediment in the impacted areas compared to the reference areas (Wyns et al., 2021) which may explain the differences in macrobenthos communities between impact and reference samples in zone 4c. Importantly, the number of samples for the metabarcode dataset in zone 4c was reduced to only five because of the low number of DNA sequences obtained for 11 samples. These 11 samples yielded lower DNA and PCR concentrations compared to the other samples despite having a comparable number of specimens, suggesting that DNA quality was reduced and/or PCR amplification was inhibited. This illustrates that the DNA metabarcoding method may not always work for all sample types. For the Oostdyck, species composition was significantly different in the morphological dataset (PERMANOVA, $p = 0.0399$), with high impact sites significantly different from the reference sites ($p = 0.036$, Fig 2). In contrast, no significant differences in species composition were observed for the DNA-based method. This can be explained by the presence of a large number of juveniles in the high impact sites which could not be identified up to species level in the morphological dataset. SIMPER analysis showed that the higher taxon level identifications *Urothoe*, *Bathyporeia*, Echinoidea, *Corophium*, *Nephthys* and *Spio* explained 33% of the differentiation between the high and reference sites. These taxa are regarded as additional species in the morphological dataset thereby artificially inflating species diversity. In the DNA metabarcoding dataset DNA sequences from these juveniles are classified to the correct species, but information on the life stage (juvenile, adult) is lost. These results illustrate that DNA metabarcoding is a valuable method to determine the impact of sand extraction activity on macrobenthos communities and is complementary to morphological identification of macrobenthos samples.

Our next step is to further decrease time and cost associated with sample processing for impact assessment studies by using machine learning algorithms. Machine learning models are trained by using biotic indices based on morphologically identified macrobenthos samples and then use DNA sequence data of macrobenthos to predict the biotic index of new samples using only DNA sequence data. This approach excludes the need for morphological identification, and even for a taxonomic identification step of the DNA sequences thereby circumventing the problem associated with incomplete reference databases for DNA metabarcoding. Furthermore, the machine learning approach can also use DNA sequence data from other organismal groups than macrobenthos (for example bacteria or meiofauna) for which molecular processing time of samples on board and in the lab is much quicker compared to macrobenthos identification. A prerequisite to use other organismal groups to infer the ecological status of samples through machine learning is that they need to show the same response to sand extraction as the macrobenthos. Machine learning algorithms have successfully been used to assess environmental contamination using bacterial communities (Cordier et al., 2019) or foraminifera (Cordier et al., 2017). To explore the potential of machine learning to predict the environmental status of marine aggregate extraction sites, we have conducted 16S rDNA metabarcoding to characterize the bacterial communities in all locations of the three sandbanks described above. We are currently building models to evaluate how well abiotic parameters, COI profiles of macrobenthos and/or 16S profiles of bacterial communities can predict the ecological status of samples determined with morphological macrobenthos data. Our preliminary results indicate that abiotic parameters together with 16S bacterial profiles correlate well with the number of macrobenthos species in sand extraction locations. Additional models are now being built to evaluate whether the prediction of the ecological status of marine aggregate extraction sites can be further improved.

Figure 2: Illustration of macrobenthos species composition for the Thortonbank (top row), Hinderbanken zone 4a (second row), Hinderbanken zone 4c (third row) and Oostdyck (bottom row) using nMDS plots based on the Bray-Curtis dissimilarity index for the morphological dataset (left column) and the DNA metabarcoding dataset (right column). Each square in the plots represents a sample, colors indicate reference sites (green), low impact sites (yellow), medium impact sites (orange) and high impact sites (darkbrown).



In conclusion, our work shows that DNA metabarcoding is a reliable, repeatable and cost-efficient tool for monitoring macrobenthos communities in relation to aggregate extraction in the Belgian part of the North Sea. The DNA-based method decreases time and costs associated with the morphological analyses of macrobenthos samples while adequately capturing changes in macrobenthos diversity. The quick advancements in DNA sequencing technology, bioinformatic processing and machine learning algorithms generate a much higher throughput of samples compared to morphological identification and therefore biodiversity changes related to marine aggregate extraction can be picked up much faster. These methods can be a quick screening and warning tool allowing to use the traditional methods for a more targeted sampling aiming at understanding the underlying ecological processes and life-history changes. An exciting future for biodiversity monitoring in the marine environment lays ahead of us, with the promise of high resolution biodiversity data generated at unprecedented speed with the sole purpose to achieve a sustainable exploitation of the sea.

Keywords: impact assessment, DNA metabarcoding, macrobenthos, biological monitoring, DNA-based monitoring

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3. Effects of marine aggregate extraction on seafloor integrity and hydrographical conditions. New insights and developments

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3.1. Introduction

The Royal Belgian Institute of Natural Sciences is responsible for monitoring the effects of aggregate extraction on the hydrodynamics and sediment (transport) of the marine environment. Quantification of the effects of sand extraction is also needed to monitor progress towards good environmental status (GES) of the marine environment as required by the European Marine Strategy Framework Directive (MSFD; 2008/56/EC). With regard to the physical impact of aggregate extraction, this requires a follow-up of the GES descriptors seafloor integrity and hydrographical conditions. Seafloor integrity refers to the structure and functions that the seabed provides to the ecosystem (e.g. oxygen and nutrient supply), while hydrographical conditions refer to currents, turbidity and/or other oceanographic parameters, changes thereof possibly having a negative impact on benthic ecosystems. Critical to the study of changes is good baseline information whereby the characteristics of the geological substrate provide important preconditions for more sustainable extraction practices.

The RBINS monitoring framework therefore comprises three main objectives:

(1) Quantification of natural and human-induced variability of sediment characteristics and processes, with a focus on sand.

(2) Process and system modelling of the activity-pressure chain effects on the marine environment, in the near and far field.

(3) Recommendations for a more sustainable use of marine resources (i.e., sand), in line with the MSFD, and contributing to the United Nations Environmental Programme (UNEP) on a more collective management of mineral resources.

Increased process and system knowledge is required to better understand the impact of sand extraction on the environment and to characterise natural variability. In the near field, a better estimation of the recovery potential after abrasion of the seabed is important, as well as knowledge of the processes that determine the dispersion of extraction-induced suspended solids. This is important to better predict the probability of deposition of these particles in the gravel-dominated areas having a potential to host high biodiversity. This also requires a better understanding of seabed mobility and sand dynamics in particular. Such knowledge building is all the more critical when exploitation takes place within or near a Habitat Directive area (HD, 92/43/EEC, requiring appropriate assessments of all stressors) as is increasingly the case in the Belgian part of the North Sea (BPNS). Besides striving for minimal impact of the activity on the environment, a good knowledge of the geological resource remains crucial, in quality and quantity, arguing for a further digitalisation of the geological knowledge base. Combining all objectives remains a challenge but is necessary to understand cause-effect relationships and better estimate recovery at the system level. It should be emphasised that the above contributes to a larger monitoring framework, i.e., complementing the research of FPS Economy COPCO and ILVO (see Wyns et al., this volume), respectively.

Furthermore, the MSFD framework leads to a more coherent environmental monitoring on an (inter)national level (e.g., MONIT.be, https://odnature.naturalsciences.be/msfd/nl/assessments/2018/).

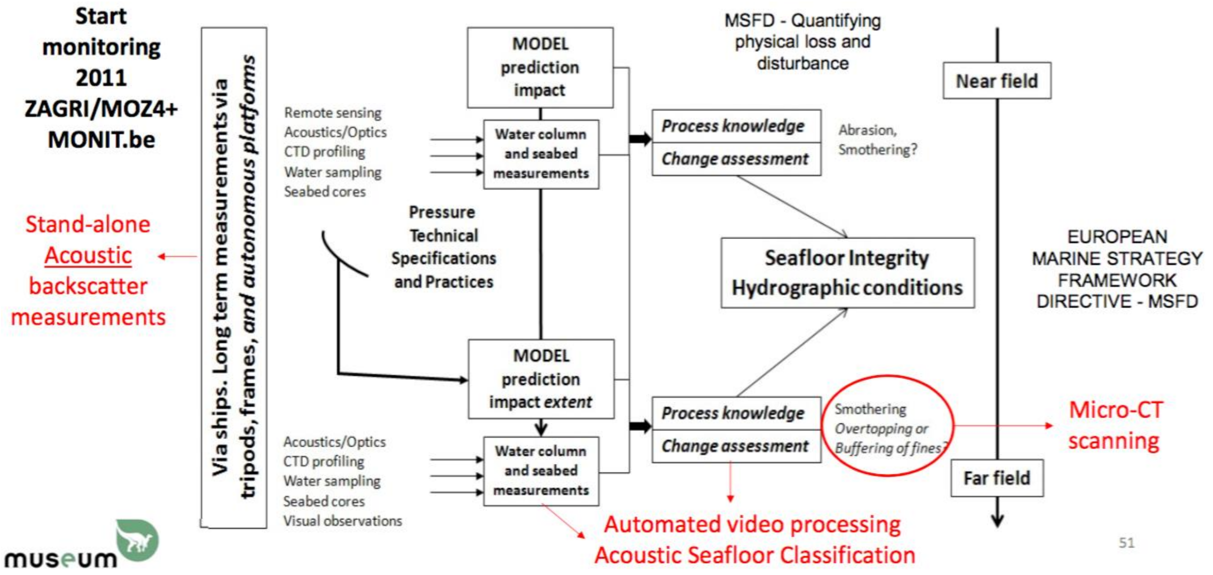
3.2. Methodology

3.2.1. Quantifying natural and human-induced changes in sediment characteristics and processes

Measurements are essential for quantifying the natural and man-made variability of sediment characteristics and processes. They are currently mainly carried out in the region of the Hinderbanks under the umbrella of the monitoring programme MOZ4 (Flemish Government). Limited information was available for this area, yet sand extraction is increasing steadily. The measurements are in line with the objectives of the MSFD, i.e., the assessment of changes in seafloor integrity and hydrographical conditions (Belgian State, 2018). They include: (1) characterising the spatial and temporal variability of the nature of the seabed; (2) building knowledge of sediment processes in the Hinderbanks; and (3) testing impact hypotheses (Van Lancker et al., 2016).

Figure 1. Integrated monitoring approach to study the effects of marine aggregate extraction on hydrodynamics and sediment (transport).

The monitoring focuses on compliance with the Marine Strategy Framework Directive, with a focus on seafloor integrity and hydrographical conditions, two key descriptors of good environmental status. In red, some innovations developed in the period 2017-2020.



With regard to aggregate extraction, measurements of the water column are important to predict changes in the seabed. To this end, various instruments were used, including optical and acoustic sensors, in combination with water sampling. Sediment samples were also obtained from a trailing suction hopper dredger (TSHD). Sea-going campaigns were organised with RV Belgica where measurements are typically carried out over a period of 13 hours to determine tide-induced variability. Two strategies were followed: (1) the ship is anchored, and measurements are carried out over the water column; (2) the ship sails back and forth along the same sandbank transect. In both cases, the concentration of suspended solids is measured; in the first case, locally and at a higher time resolution; in the second case, the spatial variability, i.e. sand bank versus channel, can also be included. These measurements are often combined with the deployment of bottom frames equipped with various optical and acoustic sensors and which measure *in situ* over a longer period of time. Optical backscatter sensors are typically more performant in characterising fine-grained material, while acoustic backscatter sensors are better for sand measurements. The aim is to record the variation over a series of consecutive tidal cycles. In the period 2017-2020, long-term series were thus obtained that also allow studying spring tide-neap tide variation (e.g. south of Sector 4a, Noordhinder in 2019, 2021).

Seabed properties were studied using multiple methodologies. In the near field of the aggregate sectors, Reineck box cores were taken in the sandy sediments of the sandbanks. The aim was to sample the upper seabed in detail to increase the chance of detecting changes in sediment properties. Shallow cores were taken and sampled on board at 1-cm resolution and then frozen. In the laboratory, grain-size analyses were performed with a laser diffractometer, and organic matter and carbonate content were measured using the loss-on-ignition method. In the Habitat Directive area, south of concession zone 4, further efforts were made to map the substrate using multibeam technology (depth and backscatter values). The further translation of these data into sediment types was part of PhD research specifically aimed at seabed classification in a monitoring context and automated detection of sediment changes (Montereale Gavazzi, 2019). This process goes hand in hand with a targeted site verification for which the most appropriate sampling technique was chosen per substrate type. This is most critical for gravel areas, where only Hamon grabs, retrieving a volume of sediment, allow for all sediment fractions to be captured. Additional video observations were crucial to validate the variability of the seabed at the surface. Automatic video procedures were developed to quantify the ratio of hard to soft substrates (Montereale Gavazzi, 2019). In order to quantitatively indicate sand thickness and composition, shallow cores were taken by divers (RBINS Scientific Diver Team led by A. Norro). Microcomputed tomography (UGCT lab, UGent) was used for a detailed analysis of the distribution of the sediment fractions throughout the sediment column.

For a detailed description of all techniques and analyses used, see Van Lancker et al. (2020). The different sea-going campaigns were reported in Van Lancker et al. (2017, 2020), and Van den Eynde et al. (2019a).

3.2.2. Process and system modelling for a better understanding of the activity-pressure-impact chain

Modelling of hydrodynamics and waves

A new limit of extraction was proposed based on scientific and economic criteria (see Degrendele et al., this volume for an overview). In Van den Eynde (2017) and Van den Eynde et al. (2017), this new limit was evaluated based on the Belgian implementation of the MSFD. This guideline stated that the consequences of changes in bottom shear stress should be accounted for; namely, it should not change by more than 10% (outside a buffer zone) as a result of a human activity. Given the explicit statement that this should be done with a validated numerical model, the accuracy of bottom shear stress measurements was studied at a known measurement site (MOW1) (Van den Eynde, 2016).

In a next step, the newly proposed extraction limit was further evaluated, more specifically focusing on the significant lowering of the sandbanks and the possible impact on the coast. See Van den Eynde et al. (2019b) and Van den Eynde et al. (this volume) for a detailed description.

Sediment plume modelling

Modelling of sediment dynamics is essential to quantify the effects of sand mining in the far field. In particular, the formation, distribution and deposition of sediment plumes need to be better understood. Based on measurements in trailing suction hopper dredgers and beyond (Baeye et al., 2019; Van Lancker et al., 2020), new boundary conditions have been generated that allow for the further development and validation of sand transport and advection diffusion models, thus better simulating the distribution of sediment plumes. Previous reports focused on the validation of the two-dimensional hydrodynamic model (resolution of 250 m x 250 m), the sand transport model <mu-STM> and the two-dimensional silt transport model <mu-SEDIM> (Van Lancker et al., 2014, 2015; Van den Eynde et al., 2014). The new developments concern the incorporation of mixed sediment modelling (Bi and Toorman, 2015), flocculation modelling (e.g., Lee et al., 2019; Shen et al., 2019a, 2019b), and the incorporation of three-dimensional effects. The latter is especially important for modelling near- and far-field effects of sand mining and modelling sediment plumes (e.g., Spearman et al., 2011; Decrop, 2016). Moreover, better seabed models are now available (Belspo TILES, Van Lancker et al., 2019) that generate new geological boundary conditions (see Section 1.3.3).

COHERENS V2 software (Luyten, 2016) was used for the development and validation of the three-dimensional sediment transport model. A new model train was developed with four coupled models, resulting in a model for the whole BPNS with a resolution of about 250 m x 270 m (Dulière, 2017). The validation of this new hydrodynamic modelling is now in its final phase. The sediment transport model was improved, with sand and silt transport being included separately. Furthermore, progress was made with the modelling of sediment interactions and a flocculation module was included in the model. Further improvements and validation of this new sediment transport model are planned for the next period and results will be reported later.

Automated analysis of dune migration to increase system understanding

Initiated in the Belspo TILES project (Van Lancker et al., 2019), and further investigated in the framework of the ZAGRI monitoring programme, all multibeam depth datasets of FPS Economy (COPCO) were analysed. A total of 180+ MBES campaigns were covered, spread over 10 different areas over a 20-year monitoring period. Using an automated approach, 1000+ observations on 100+ dunes were extracted and morphodynamic parameters such as dune migration, wavelengths and heights were calculated.

3.2.3. Towards a more sustainable use of marine resources

The focus is on improving knowledge of the seabed environment by: (i) extension of seabed mapping and site validation; (ii) compilation of seabed sediment databases (i.e., grain-size distribution curves); and (iii) further valorisation of the geological subsurface. Thus, efforts are continued to digitise marine resource data extending on the results of the Belspo project TILES (Transnational and Integrated Long-term Marine Exploitation Strategies, Van Lancker et al., 2019). Furthermore, efforts are being made to better educate and communicate the sustainability aspects of marine sand extraction (Belspo valorisation project Seabed4U: Seabed CommUnity Initiative: communicating sustainability challenges of marine sand use in a changing world). A community initiative is hereby initiated, aligned with the vision of the United Nations around a more collective management of mineral resources (UNEP, 2019) (see Van Lancker et al., this volume).

Synthesis of results *sensu* Marine Strategy Framework Directive

Ultimately, the results are evaluated against the environmental objectives as laid out by the European MSFD, focusing on the descriptors of good environmental status (GES): seafloor integrity and hydrographical conditions. With regard to hydrographical conditions, two indicators are included in the monitoring: (1) changes in bottom shear stress; and (2) changes in turbidity, as both can have a negative impact on benthic biodiversity. For seafloor integrity, a methodology needed to be developed to use time series of multibeam depth and backscatter values to assess changes in the major sediment types i.e., mud, sand and gravel (see Van Lancker et al., 2018, for a rationale). It should be emphasised that at the European level, monitoring methodologies and the assessment of GES descriptors are under continuous development. Regarding seafloor integrity, methodological approaches are still in development, inter alia, in the European Commission's Seabed Technical Group (TG Seabed) to which RBINS participates. To date, the quantification of physical loss and disturbance has followed a rigorous approach based on the activities themselves and taking into account literature-based impact buffers around the activities (Kint et al., 2018). In the future, this will increasingly be based on process-based modelling of far-field impacts to which the current research will contribute.

3.3. Results

The following sections show a selection of the main results of the 2016-2020 monitoring programme. See Van Lancker et al. (2020) for a more thorough overview.

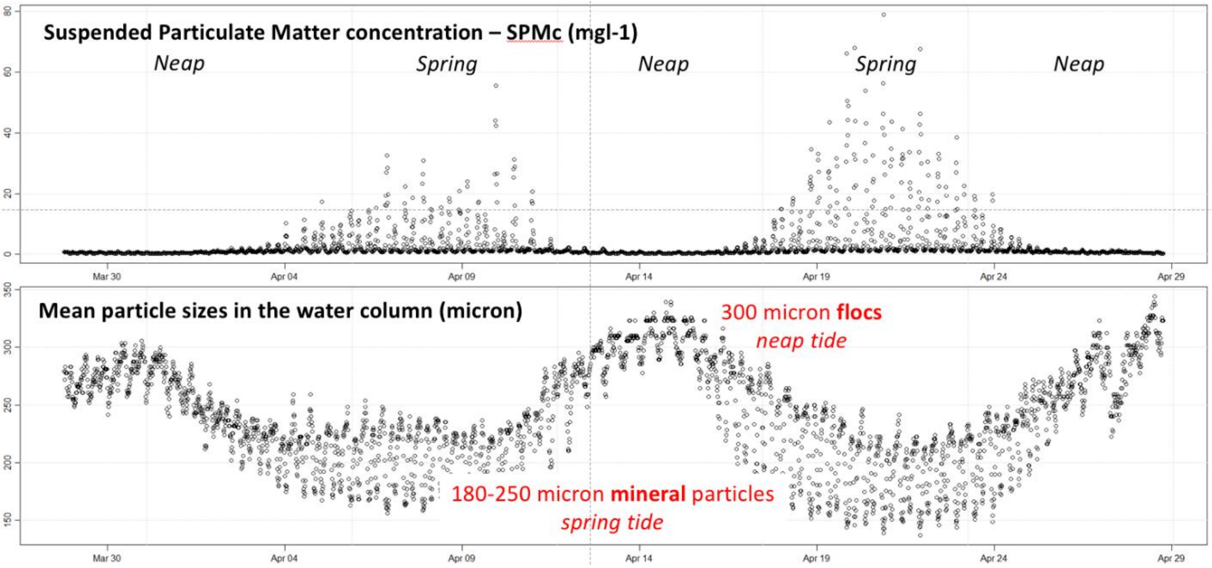
3.3.1. Quantifying natural and human-induced changes in sediment characteristics and processes

Water column properties in the near field of extractions

Grain-size distributions of the sediment samples taken in a trailing suction hopper dredger showed systematically bimodal populations with a peak at about 25 µm and one at about 300 µm, corresponding respectively to the fraction that will be further dispersed in the water and to the seabed fraction. Latest calculations estimate that per extraction event for a 12000 m^3 vessel around 16 tonnes of fine-grained material is introduced into the seawater (Baeye et al., 2019). In 2019, up to three vessels operated in Sector 4a, extracting twice a day. Figure 2 is the longest time series obtained with a measurement frame deployed at the edge of Sector 4a. Results indicate a strong variation in suspended solids concentration (SPMc) with no resuspension of material during neap tide, and concentrations above 0.04 gl^{-1} during spring tide. The time series shows a large variation in mean particle size, with the fine sand fraction (125-250 m) being most easily transported under the current tidal regime.

Figure 2. Time series (43 days) of SPMc and average particle size at 1.5 metres above the bottom.

The variation over different neap tidal cycles (March-April 2019) is shown. The measurements originate from an acoustic backscatter sensor mounted in a bottom frame at a sandbank location at the edge of Sector 4a, Noordhinder. Striking are the highest average particle sizes near the bottom during neap tide, due to flocculation, while smaller sizes are found at high current speeds. This indicates a process of flocculation at high flow velocities and aggregation into flocs at low flow velocities.



The formation of flocs (largest particle size) during neap tides indicates the importance of including flocculation in the modelling of the distribution of sediment plumes. The measurements did not allow depicting a systematic increase in SPMc due to extraction, probably due to strong variations in space (horizontal and vertical) and time. The new measurements are critical to improve sediment plume models and build up reference material for future evaluations. Since the beginning of the monitoring in the Hinderbanks region near 2500 SPMc filtrations have been carried out at various locations. They are now being analysed together with other RBINS SPMc datasets to obtain good estimates of natural variability.

Seabed sediment characteristics in the near field of extractions

Detailed sediment samples obtained from the short cores (and subsampled in 1-cm slices) on the sandbanks showed an enrichment of organic matter at extraction sites in both Sector 4a and Sector 4c (Noordhinder and Oosthinder, respectively). Furthermore, a decrease in carbonate content was measured by comparing time series samples from Sector 4c of 2014, 2018 and 2019 (Table 1). Homogenisation of the sediments and, therefore, increased sorting is most striking. No systematic enrichment of fine sand could be demonstrated from the 4c samples. See Kint & Van Lancker (2020), Van Lancker et al. (2020) for a detailed presentation of the results, and Kint et al., (this volume) for a dedicated Sector 4a analysis.

Table 1. Mean (maximum) content of organic matter (OM, %), and calcium carbonate (CC, %, grey) in the sediment of the upper centimetres for eight locations in Sector 4c, Oosthinder Sandbank, in 2014, 2018 and 2019.

Sites are coloured according to relative importance of extraction pressure (from green, yellow, orange to red). Content of organic matter is shown in a black font, carbonate content in red. There was no extraction in Sector 4c in 2019.

	Loc1	**Loc2**	**Loc3**	**Loc4**	**Loc5**	**Loc6**	**Loc7**	**Loc8**
2014 *	0.80 (1.20)	1.08 (1.40)	1.10 (1.45)	/	/	/	1.59 (2.10)	1.13 (1.75)
	6.55 (35.00)	6.72 (15.00)	7.68 (13.00)	/	/	/	7.71 (11.00)	9.74 (22.50)
2018 **	1.13 (1.84)	1.99 (2.47)	2.59 (3.93)	1.76 (2.41)	3.06 (4.04)	1.86 (3.27)	1.34 (1.96)	0.95 (2.05)
	2.53 (5.69)	0.98 (1.51)	3.78 (11.29)	1.23 (2.52)	1.52 (1.77)	1.98 (3.17)	1.47 (1.95)	1.39 (4.39)
2019 ***	1.59 (2.13)	2.02 (3.80)	2.11 (3.60)	1.28 (2.04)	1.20 (2.17)	1.50 (2.24)	1.09 (1.57)	1.17 (2.26)
	0.82 (1.08)	2.07 (5.91)	6.26 (10.69)	1.89 (2.39)	1.76 (2.20)	2.02 (2.65)	1.77 (3.10)	2.93 (3.92)

*Order of magnitude of the precision of the measurements: *0.05 %, 1.75 %; ** 0.35 %, 0.22 %; ***0.18 %, 0.18 %, for OM and CC respectively.*

The Habitat Directive area south of the extraction sectors is known to be an important gravel area, at least as far as the in-between bank channels are concerned. Multibeam measurements and mapping from the past (Van Lancker et al., 2007) showed an acoustic signature associated with the occurrence of gravel. However, recent acoustic measurements and visual observations also show the occurrence of sand ripple fields, indicating sand dynamics and a certain sand availability to develop these bedforms. Critical here is the sand thickness, and whether or not increases could lead to burial of the gravel beds. A prolonged burial is detrimental to the development of the biodiversity associated with these gravel beds. Most attempts to determine sand thickness by sampling failed, because of obstruction by larger clasts, hence preventing obtaining a representative view of the seabed composition (see also Kint et al., 2020). The use of a Hamon grab is successful, but this can only confirm the presence of sand and gravel without indicating sand thickness. Furthermore, efforts were made to take video images. These show sand and gravel, but do not allow the thickness to be determined. Video imagery, in combination with sampling, was used to classify multibeam time series in sediment types (seven campaigns in the period 2004-2015) in zones with hotspots of gravel biodiversity (see Montereale Gavazzi et al. (2018) for detailed results). These occur mostly in the troughs of barchan dunes (see also Van Lancker et al. (2016) for the process study conducted in 2011-2016). The results showed changes in the hard/soft substrate ratio with a minimum of the gravel surface in 2014, the peak period of extraction, but also an exceptional year in sediment dynamics (Francken et al., 2017). After 2014, the hard/soft ratio changed again in favour of gravel occurrence. However, the results were mainly indicative of natural dynamics and also showed significant bedform migration. Vertical depth differences fell within the margin of error of the measurements. Further thorough analysis of the multibeam backscatter in Montereale Gavazzi et al. (2018) rather indicated a loss of gravel in favour of sand. The systematics and significance of the process is currently under investigation considering historic and recent multibeam data. Short cores taken by scientific divers in areas where divers previously measured zero sand thicknesses showed a sand thickness of 8-10 cm (2019). Micro-CT scans showed that the pores of the permeable medium- to coarse-grained sands are filled with fine-grained material (see Van Lancker et al., 2020). Adverse effects on gravel-related fauna and flora are studied (e.g., Belspo FaCE-It) and will be further integrated.

For comparison, mapping and seabed assessments are also carried out in areas outside of the Hinderbanks region. Unless earlier published, results will be reported in the MSFD second cycle assessment (2024).

3.3.2. Process and system modelling for a better understanding of the activity-pressure-impact chain

Modelling of hydrodynamics and waves

Results are reported in Van den Eynde et al. (this volume). For the Hinderbanks, main conclusion is that the effects near the extraction sites themselves can be significant, but the effect of the extraction on the coastal nearshore wave climate and thus the relationship with possible coastal erosion can be considered negligible.

Characterising dune dynamics to increase system understanding

The automated analysis of all dunes in the extraction areas (datasets FPS Economy, COPCO) allowed several parameters to be calculated and further investigated in relation to other datasets. One figure is shown here (Figure 3) relating to the research question of whether dune development is affected by sand extraction. The procedure consists of: (1) assigning an extraction quantity to each dune, in a buffer of 25 m (i.e. the amount between two consecutive campaigns) by linking the dune dataset to the database with information from the Electronic Ship Monitoring System (EMS); (2) recovering the dunes with the extracted volume; (3) visualising the difference in (recovered) dune height between consecutive campaigns with respect to the extracted volume; (4) evaluating the residual evolution in dune height. This results in a decreasing trend in dune height that increases as the extraction in an area intensifies. This indicates a slower recovery and also means that long-term predictions of the decrease in sediment volumes on reclaimed sandbanks must account for more erosion than would be predicted on the basis of the extraction rate alone. Although these findings are consistent, it should be stressed that inaccuracies on the EMS extracted quantities (over- and underestimations), the vertical error on the multibeam datasets and the automated procedure itself can influence the results.

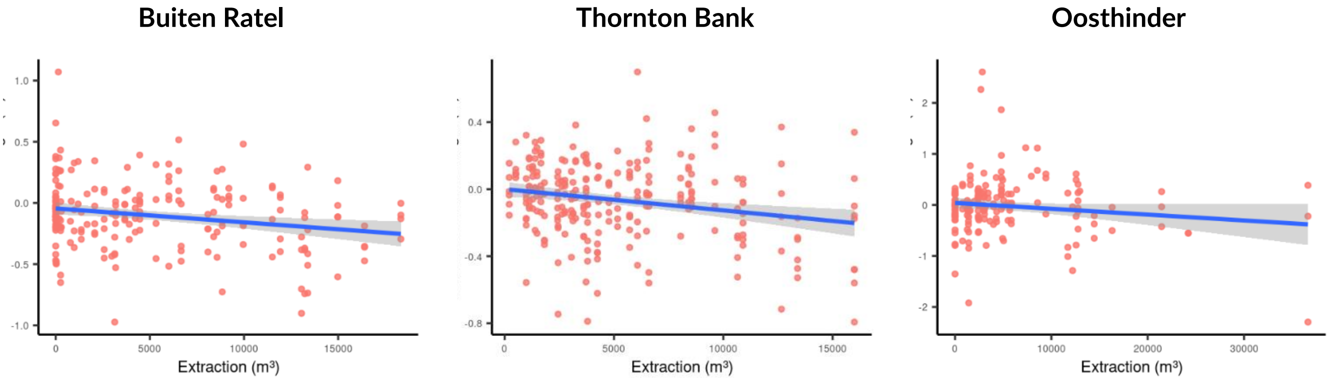
3.3.3. Towards a more sustainable use of marine resources

Increasing the knowledge base of the seabed

Two examples are given here of how the knowledge base for geological resources, as built up in the TILES project, is further valorised (Figure 4). The basis is the voxel-based geological subsurface model with xyz-dimensions of 200 m x 200 m x 1 m, and downloadable via the online available decision support system (TILES Consortium (2018); see Van Lancker et al. (2019) for more detail). Furthermore, the procedures for quantifying and qualifying all lithological descriptions that, together with the extensive seismic database of Ghent University, formed the foundation for the voxel modelling process have been published in Kint et al. (2020). See Hademenos et al. (2018) for the voxel modelling process itself and the resulting subsurface model. For an extensive discussion on the importance of uncertainty in decision support tools, see De Mol (2019).

Figure 3. Residual height evolution of sand dunes in the aggregate extraction zones.

Evolution of the difference in dune height between all consecutive campaigns and for all surveyed dunes (X-axis), after restoration of the dune height based on EMS data, plotted against the cumulative extraction amounts. Shown here for three measurement areas. See text and Van Lancker et al. (2020) for further explanation.



Synthesis of results w.r.t the Marine Strategy Framework Directive

Hydrographic conditions

Assessing changes in bottom shear stress has proven to be a practical approach in modelling scenarios of large-scale extraction practices and was also used in evaluating the impact of the new reference surface (Degrendele et al., 2017) for coastal extraction (Van den Eynde et al., 2019b for details) (see 1.3.2). The usefulness of using changes in turbidity as an indicator of good environmental status was mainly investigated in the Belspo project INDI67 (Fettweis et al., 2020). The conclusion was that only trends in SPMc can be assessed, indicating that measurements of turbidity, an optical measure, should first be converted to mass concentrations (Fettweis et al., 2019). However, monitoring has shown once more that the spatial and temporal variability of SPMc is highly variable and especially in areas with low concentrations the uncertainty of measurements is very high, making trend analyses very difficult. The INDI67 report summarises a number of newly published measurement and analysis protocols (Fettweis et al., 2020) that are further used in the impact assessment. The measurements, as described in section 1.2.1, are very new for the Hinderbanks region, hence important for future comparison of new datasets.

Seafloor integrity

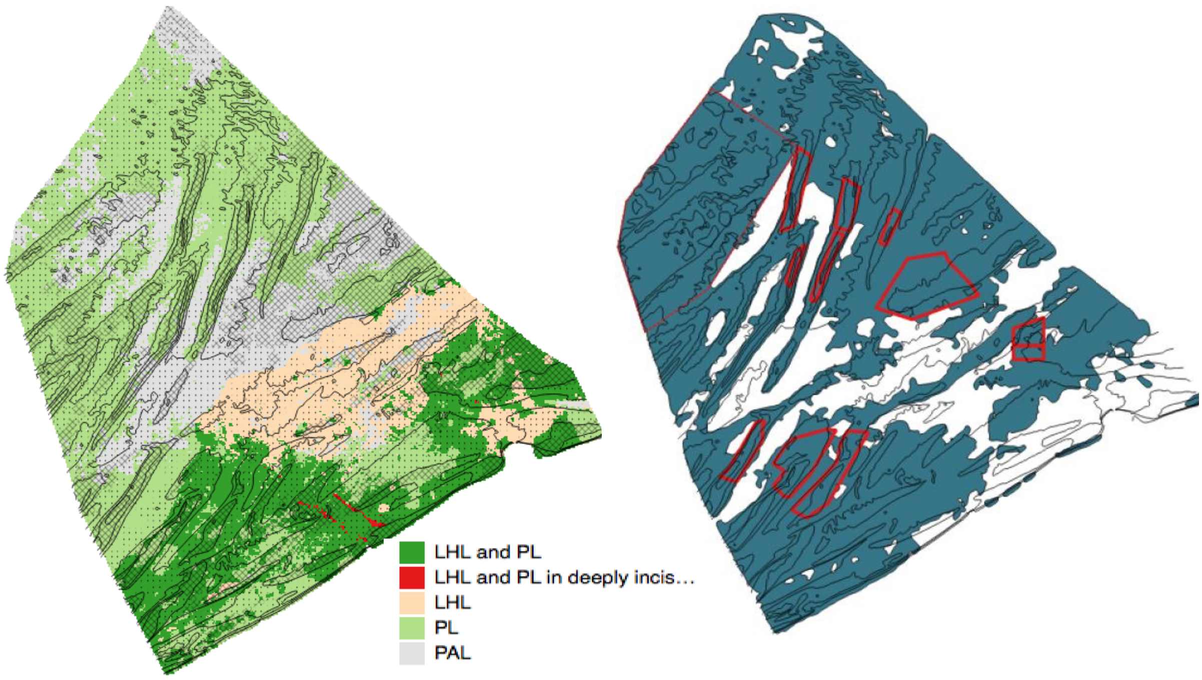
Significant progress was made in the methodological procedures for detecting and assessing changes in major sediment types using multibeam depth and backscatter values (see Montereale Gavazzi, 2019 for in-depth analyses and discussions). The study also demonstrated the continued importance of good site verification, both in terms of sampling and visual observations, as well as the importance of studying short-term processes affecting the backscatter signal (Montereale Gavazzi et al., 2019).

In the near field of the Hinderbanks sectors, no changes in seafloor integrity, i.e. changes in major sediment types, were observed. At a smaller scale, the sediment sampling time series on Sector 4c did show a decrease in carbonate content, indicating a homogenisation process. This is also shown by the monitoring of FPS Economy and ILVO and has been further synthesized in Wyns et al. (this volume).

In the far field, and in the Habitat Directive area in particular, changes were observed in the GES indicator 'ratio hard versus soft substrate' in the known biodiversity hotspots (Houziaux et al., 2008), of which the trend should be positive according to the Belgian implementation of the MSFD. The time series dataset, based on multibeam depth and backscatter values, showed a fluctuation that can be attributed to natural and human-driven influences (Montereale Gavazzi et al., 2018). Recent observations show an increase in sand thickness, extension of sand ripple fields, and siltation enrichment in these permeable sands. The nature, consistency and significance of the process is further investigated. Implications towards the structure and functions of permeable seabeds is currently being finalised in the Belspo project FaCE-It.

Figure 4. Examples of the further digitalisation of the geological knowledge base.

Left: Profile map of Quaternary deposits above the top of the Paleogene (PAL): gives an indication of the succession of geological layers below the Upper Holocene (LHL and PL: Lower Holocene and Pleistocene); red indicates that the Pleistocene deposits occur in deeply incised valleys; LHL: only the Lower Holocene occurs below the Upper Holocene; similar for PL: here Upper Holocene directly on top of Pleistocene deposits. PAL is where the Paleogene (mostly clay) is directly beneath the Upper Holocene. The overlapping shading and dotted points indicate a thick and thin Quaternary cover, respectively. This is made even more explicit in the figure on the right. Here the TILES subsurface model has been queried to indicate all areas where sand, as the main soil type, has been consistently modelled over the first five metres per voxel. In this case, no distinction is made between the age of the geological layers. The white areas roughly correspond to the silt-dominated areas in the coastal zone, and the gravel-dominated areas in the more seaward zone (derived from http://www.bmdc.be/tiles-dss/#; TILES Consortium, 2018).



In general, the mapping and assessments outside of the Hinderbanks area will be reported in the MSFD second cycle assessment (2024). The results from an area at the Belgium-UK border are near-published (Montereale Gavazzi et al., revisions subm.).

Finally, the nature and persistency of morphological changes are also important for the evaluation of seafloor integrity, yet no guidelines have been developed within the MSFD. Once an agreement has been reached at the European level (e.g., within TG Seabed), the automatic dune analysis procedures will be further valorised.

3.4. Conclusions

The RBINS monitoring framework, geared to assessing changes in seafloor integrity and hydrographical conditions (MSFD), was further developed successfully. The 2017-2020 phase focused on methodological advances to better quantify changes in these descriptors of good environmental status. It should be emphasised that change detection remains a complex matter and is sensitive to many factors that require research and wider collaboration. Changes are often minor, but can nevertheless be detrimental to the seabed environment. Therefore, it is important that measurements, in combination with models, lead to a better understanding of the processes, the scale at which they operate, and capture systemic changes. Margins of error must be known for the instruments used in monitoring, which is a study in itself. This is even more important when assessing changes in water properties of areas with low sediment concentrations. The concentrations are often too low for repeatable, good measurements. The development of robust measurement protocols and quality standards was therefore paramount, as was instrument calibration. In addition, sediment processes in sandbank environments are spatially and temporally highly variable, which necessitates flexibility in the monitoring programme. Since 2011, measurements have therefore been taken at various locations, comparative datasets have been compiled and basic information and system knowledge have been increased to gain a better understanding of the cause-effect relationships.

Until now, changes in water properties were only visible in the near field of extraction activities. Particle-size spectra show both a water-column and a seabed-related component. The sand released during extraction is deposited in the near field while the finer particles disperse further. Organic enrichment was demonstrated in areas with extractive activities, also influencing the dispersal behaviour of the finer particles. Predicting where the fine-grained particles settle and how this affects the seabed environment remains critical, especially in areas of gravel beds with richer biodiversity. In the hotspots of gravel biodiversity where no sand thickness was measured by divers in 2006-2007, a sand cover of 8-10 cm was measured in 2019. The sand consisted mainly of permeable medium to coarse material as present in the environment. However, the pores of the sand layer contained fine-grained material, which has now been clearly demonstrated for the first time by means of micro-CT scans. Whether this leads to pore clogging that may reduce the functions that the seabed provides to the ecosystem requires further investigation. Compared to historical data, seabed mapping and visual observations tend to indicate an increasing presence of sand. However, this is difficult to deduce from depth measurements since the changes fall within the margin of error of the depth measurements (+/- 30 cm in 30 m water depth). An increase in sand over gravel areas leads to a homogenisation of the sea bed, resulting in less structure for benthic and epibenthic species, and in worst case irreversible burial being lethal. In the next monitoring phase, historical multibeam datasets will be re-analysed, focusing on pattern changes. Also, different source-to-sink scenarios will be investigated, accounting for different human activities, in an attempt to find typical sediment-source signatures. Based on this, new insights into cumulative and in-combination effects are expected.

Finally, for several extraction areas, there are indications that despite the recovery of dune structures after extraction, dune height development remains slightly negative. Overall, dune heights are lower than would be expected based on the wavelength. The significance of this should be studied in a broader context, whereby the detailed and renewed multibeam EMS analyses by FPS Economy, COPCO will be leading.

3.5. Recommendations

The recommendations concern: (1) Aiming for rapid recovery of the seabed after disturbance (resilience of the system), i.e. no significant disturbance of natural processes; (2) Avoiding changes in habitat types (sediment-related); (3) Avoiding unnatural fragmentation of the seabed; and (4) Avoiding permanent alteration of hydrographical conditions.

(1) and (2) indicate the importance of limiting extraction to areas where sufficient sand with similar characteristics is present, especially avoiding areas with clayey, silty or gravelly deposits. This can best be achieved by limiting extraction to the most recently deposited geological layer (Upper Holocene). This can now be retrieved using the freely available voxel-based resource model (TILES Consortium, 2018). In areas with a thin Upper Holocene layer, it is more likely that changes in sediment types will occur

which has also been shown by the monitoring of RBINS, FPS Economy COPCO and ILVO (Wyns et al., this volume). The change may become permanent leading to physical loss of a habitat.

To avoid sediment changes in the far field of the extraction activities, it is advised to spread the activity over different sectors and to spread the timing of the extraction over the tidal cycle, whenever possible. Continuous extraction in one sector and consistently during the ebbing phase of the tide leads to preferential deposition of extraction-induced fine-grained material towards the Habitat Directive area. When combining extraction activities with harbour maintenance activities in the silt-dominated coastal zone (Baeye et al., 2019), the dredging vessel should be properly cleaned after the maintenance activities to avoid bringing coastal mud into the offshore zone.

(3) Changes in bottom shear stress should be taken into account when planning large-scale extraction activities. Although there are still many uncertainties in the calculation and modelling of this indicator of good environmental status, the modelling results provide insight into where most changes in the sediment distribution are likely to occur and how this can be better anticipated. The wave modelling under different extraction scenarios also provides guidance on how to limit the height reduction of the sandbanks and thus avoid cascading effects towards the coast.

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4. Near-real time monitoring of marine aggregate extraction using AIS data

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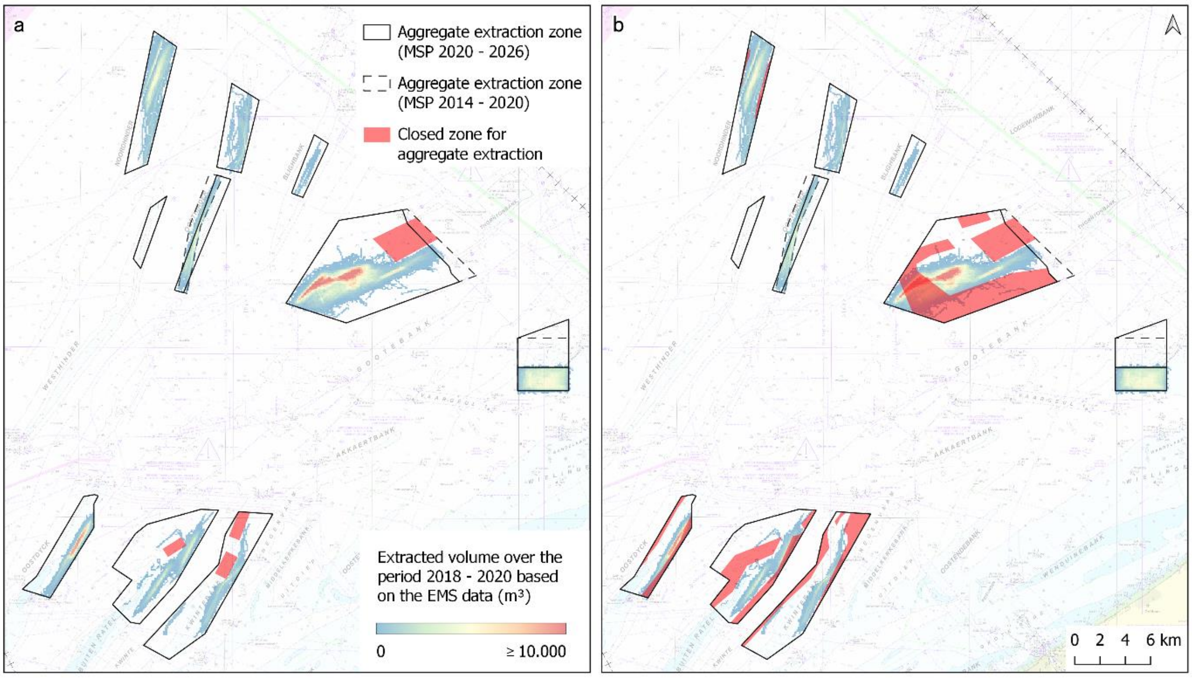
4.1. Context

On the 1st of January 2021, the new reference level for sand extraction entered into force mainly to preserve the integrity of the seabed within the framework of the Marine Strategy Framework Directive (Degrendele et al., 2021, this contribution). As a result, the closed zones for sand extraction were drastically adapted (Figure 1). This was particularly the case for the sand extraction zone located on the Thorntonbank (sector 1a), where a large part of the area that was intensively extracted over the last years was closed (see Wyns et al., 2021, this contribution). A close monitoring of sand extraction activities at the start of 2021 was required to verify the compliance of the sand extraction activities to the new closed zones, and correct the concessionaires if necessary.

Figure 1. Evolution of the closed zones for aggregate extraction. (a) Closed zones before 01/01/2021. (b) Closed zones for the period 01/01/2021 – 31/12/2021. MSP = Marine Spatial Plan.

Background: Agentschap voor Maritieme Dienstverlening en Kust - Vlaamse Hydrografie (2014).



Since more than 20 years, sand extraction activities in the Belgian part of the North Sea are controlled and monitored using an Electronic Monitoring System (EMS); a closed and sealed system onboard of the aggregate extraction vessels that automatically records, among others, the date, time, geographical position, speed, status of the dredging pump(s) and dredging activity (Van den Branden et al., 2017). The

EMS has proven its great value for the control and monitoring of sand extraction activities over the last years (e.g. Degrendele et al., 2010; Roche et al., 2017; Wyns et al., 2021). However, the time between the acquisition, processing and delivery of the data does not allow for a near-real time monitoring of sand extraction activities. The latter is particularly useful at the moment when the legislation changes (e.g. modification of closed zones or sand extraction sector), to rapidly identify and avoid infringements.

In order to closely monitor the compliance of the sand extraction activities to the new closed zones, an additional monitoring system based on Automatic Identification System (AIS) was developed. The AIS was developed in the 1990s to improve navigation safety and preventing collisions between vessels by exchanging in real-time key information such as ship identity, position, time, course, and speed between vessels and the land through the use of AIS transmitters and receivers (Spire Maritime, 2021). The applications of AIS are diverse and include among others (1) navigation safety, (2) traffic management, (3) ship behaviour analysis, (4) ship emission analysis, (5) trade analysis and (6) ship and port performance analysis (Spire Maritime, 2021; Yang et al., 2019). Within the framework of marine aggregate extraction monitoring, AIS data is used in among others Denmark and France (ICES, 2016; Miljøstyrelsen, 2021).

AIS data provides mainly information on the position of vessels. AIS data of aggregate extraction vessels therefore does not contain any information on extraction activities, in contrast to the EMS. Consequently, in order to gain insights on aggregate extraction activities from AIS data, aggregate extraction should be first inferred from the spatio-temporal information provided by the AIS data.

The aim of this contribution is to

- present an approach to infer aggregate extraction from AIS data,
- provide a first quantitative assessment of the accuracy and reliability of the proposed approach and
- present some of the applications of AIS data for the monitoring of aggregate extraction activities in the Belgian part of the North Sea, alongside with the EMS.

4.2. Identifying aggregate extraction from AIS data

Considering that aggregate extraction commonly occurs at low navigation speeds (in the order of 1 – 3 knots), a parametric model was developed to identify aggregate extraction from a detailed time-series analysis of the vessel speed (Figure 2).

The model accounts for the typical extraction speed and duration of each vessel based on historical EMS data (or an average value if no EMS data is available). The location of the AIS records is considered as well in the model to avoid the identification of aggregate extraction within the mainland (i.e. within harbours and inland waterways) and within a distance of 5 kilometres from the coast (e.g. records related to the anchorage of a vessel or beach nourishment activities). Figure 3 illustrates key elements that are considered in the model.

The results presented in this contribution are based on AIS data acquired from Marine Traffic with a temporal resolution of 2 minutes when the vessel is in movement (when the vessel is not in movement, the temporal resolution of the data is lower). The proposed approach can be applied to other spatio-temporal datasets, as long as it comprises at least (1) an identifier of the vessel (e.g. name, MMSI-number (Maritime Mobile Service Identity)- or IMO-number (International Maritime Organization)), (2) a timestamp and (3) a position (e.g. latitude-longitude or another coordinate system). The proposed approach is therefore not limited to AIS data.

The management of the AIS data, the identification of aggregate extraction and the creation and export of useful information (e.g. GIS layers, volume grids, maps, graphs and summary tables) is implemented in Python and is completely automatized to assure a simple and rapid processing of the data.

Figure 2. Characteristic speed (time series) of aggregate extraction vessels. (left) Time series of the vessel speed showing the records that are reported as extraction by the EMS (red bars) and the records located inland or within 5 kilometer from the coastline (grey bars). (right) Map showing the speed of the corresponding records.

Background: Agentschap voor Maritieme Dienstverlening en Kust - Vlaamse Hydrografie (2014).

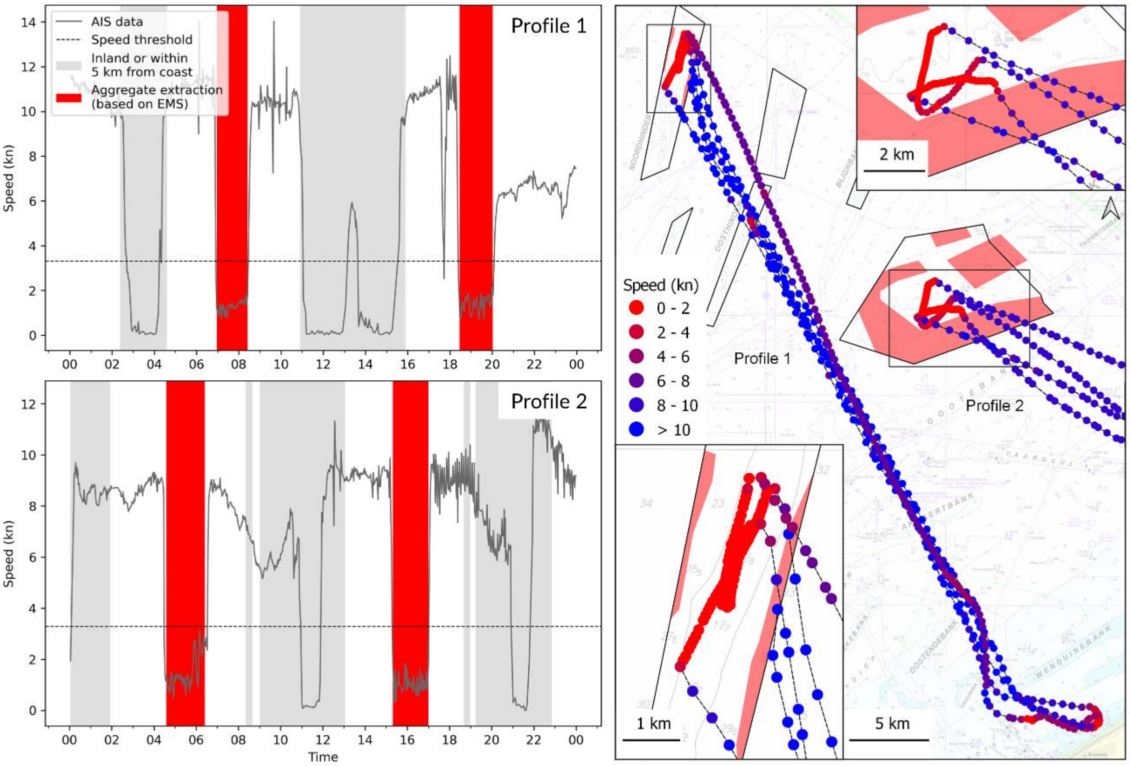
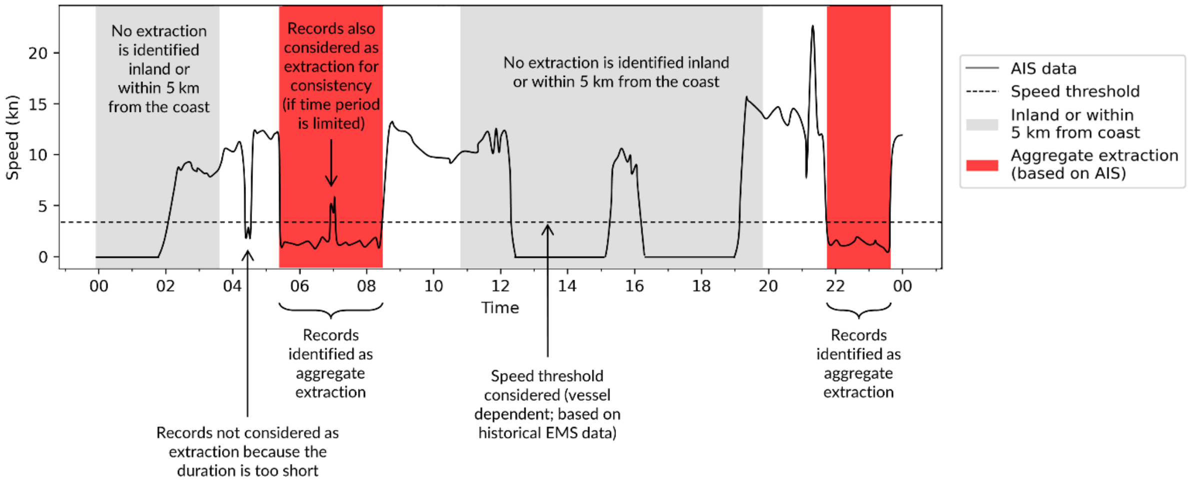


Figure 3. Overview of key elements that are considered in the model.



No extraction is identified inland or within 5 km from the coast

Records also considered as extraction for consistency (if time period is limited)

No extraction is identified inland or within 5 km from the coast

Records identified as aggregate extraction

Speed threshold considered (vessel dependent; based on historical EMS data)

Records identified as aggregate extraction

Records not considered as extraction because the duration is too short

4.3. Preliminary assessment of the model

A preliminary assessment of the model is performed by comparing the identified extractions with the extractions reported by the EMS for the period 01/11/2020 – 31/08/2021 (10 months).

Figure 4 shows the AIS and EMS records that are identified as extraction, as well as grids of the extracted volume for the period considered. Both the AIS and EMS grids of the extracted volume were obtained by subdividing for each extraction sequence the hopper capacity over the number of records. The hopper capacity of the aggregate extraction vessels is based on the values included in the EMS configuration.

The extractions identified based on the AIS data are consistent and overall comparable with the extractions reported by the EMS (Figure 4a,b). Both grids of the extracted volume show very similar patterns (Figure 4c,d), and indicate that the intensity of the extraction is also correctly captured based on the AIS data. The cumulative extracted volume per extraction zone is as well comparable (Figure 5). Two notable differences between the AIS- and EMS based extractions are indicated with the numbers 1 and 2 in Figure 4a and c. The uncommon time series of the vessel speed before and/or after the actual extraction resulted in an incorrect identification of the extraction (Figure 6).

Figure 4. AIS (a) and EMS (b) records identified as extraction for the period 01/11/2020 – 31/08/2021. Extracted volume (considering the hopper capacity) based on the AIS (c) and EMS (d) records for the same period.

Background: Agentschap voor Maritieme Dienstverlening en Kust - Vlaamse Hydrografie (2014).

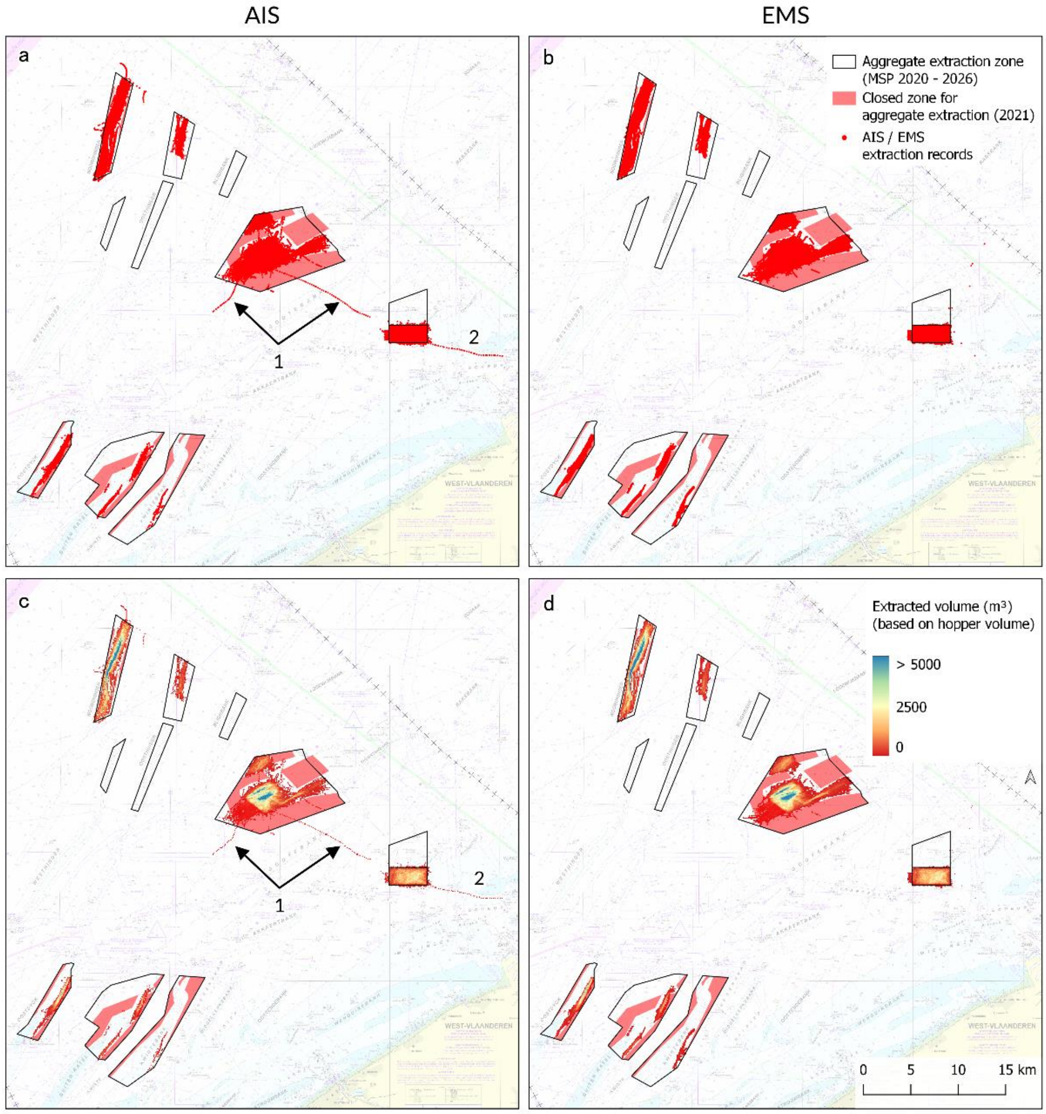


Figure 5. Cumulative extracted volume over the period 01/11/2020 - 31/08/2021 for each extraction zone. The estimation of the extracted volume is based on the hopper capacity.

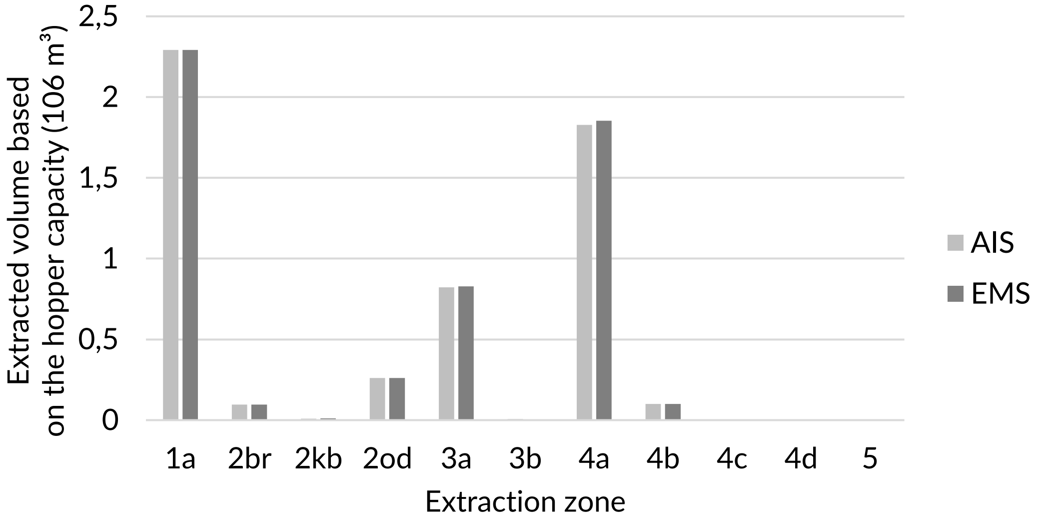


Figure 6. Incorrect identification of aggregate extraction by the model. Cases a and b correspond to extraction 1 and 2 in Figure 4 a and c, respectively.

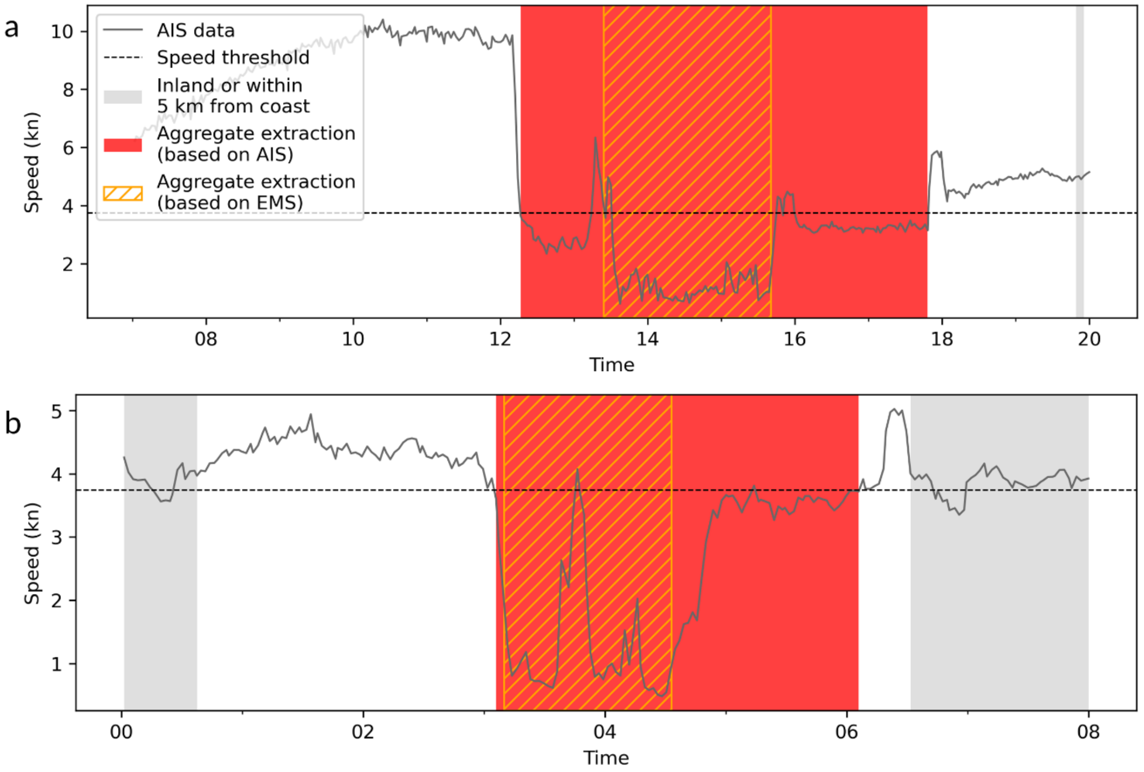
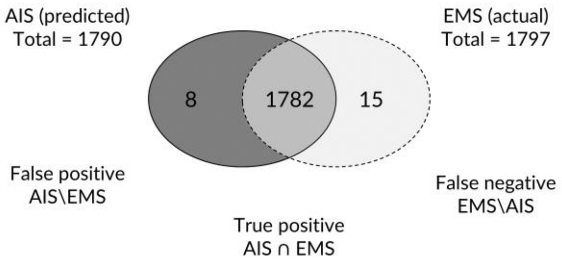


Figure 7 shows the results of the cross-validation between the extractions that were identified based on the AIS data (prediction) and the extractions reported by the EMS (reference) for the considered period.

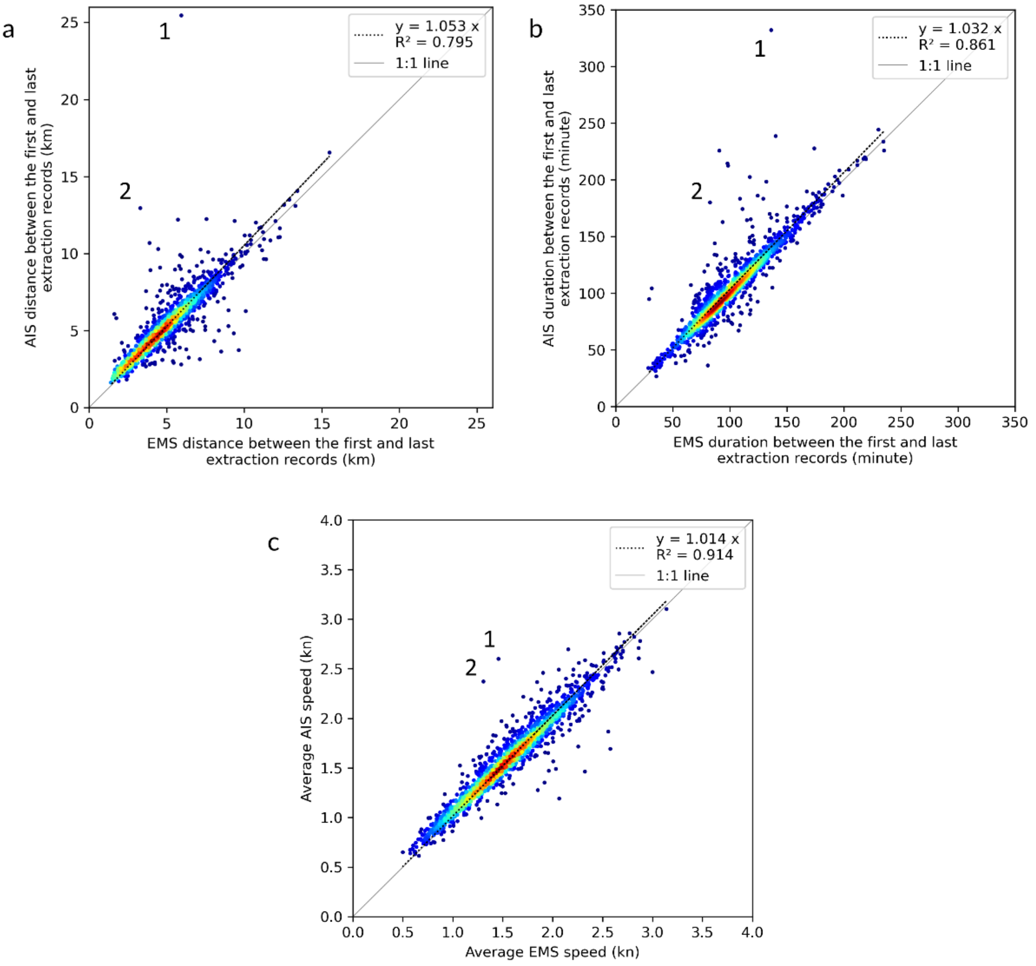
About 99.2% of the extractions reported by the EMS are identified based on the AIS data. A detailed comparison of the distance, duration and average speed between these corresponding extractions that were identified based on the AIS data and reported by the EMS indicates that a large majority of the extractions is correctly identified (Figure 8). A limited number of extractions are not correctly identified, as illustrated in Figure 6.

Figure 7. Summary of the results of the cross-validation of the identified records based on AIS data and the reported extraction by the EMS over the period 01/11/2020 – 31/08/2021.



About 0.8% of the extractions reported by the EMS are not identified based on the AIS data and proposed model (false negative cases; Figure 7). An uncommon time series of the vessel speed and the restrictions on the extraction duration implemented in the model explains why these extractions were not identified (Figure 9).

Figure 8. Scatter plots of the distance (a) and duration (b) between the first and last extraction record, and average speed (c) between the extractions trips identified based on AIS data (y-axis) and the reported extractions by the EMS (x-axis). The numbers 1 and 2 correspond respectively to case a and b in Figure 6.



About 0.4% of the extractions that were identified based on the AIS data are not reported by the EMS (false positive cases). The incorrect identification of aggregate extraction and the identification of a single extraction reported by the EMS as a series of extractions explain some of these cases (Figure 10). Some of the identified extractions are possibly related to cases where technical anomalies occurred during dredging (i.e. breakdown of a part of the dredging equipment). This is further investigated at the moment of writing.

Figure 9. Example of cases where the extraction could not be identified by the model (false negative cases).

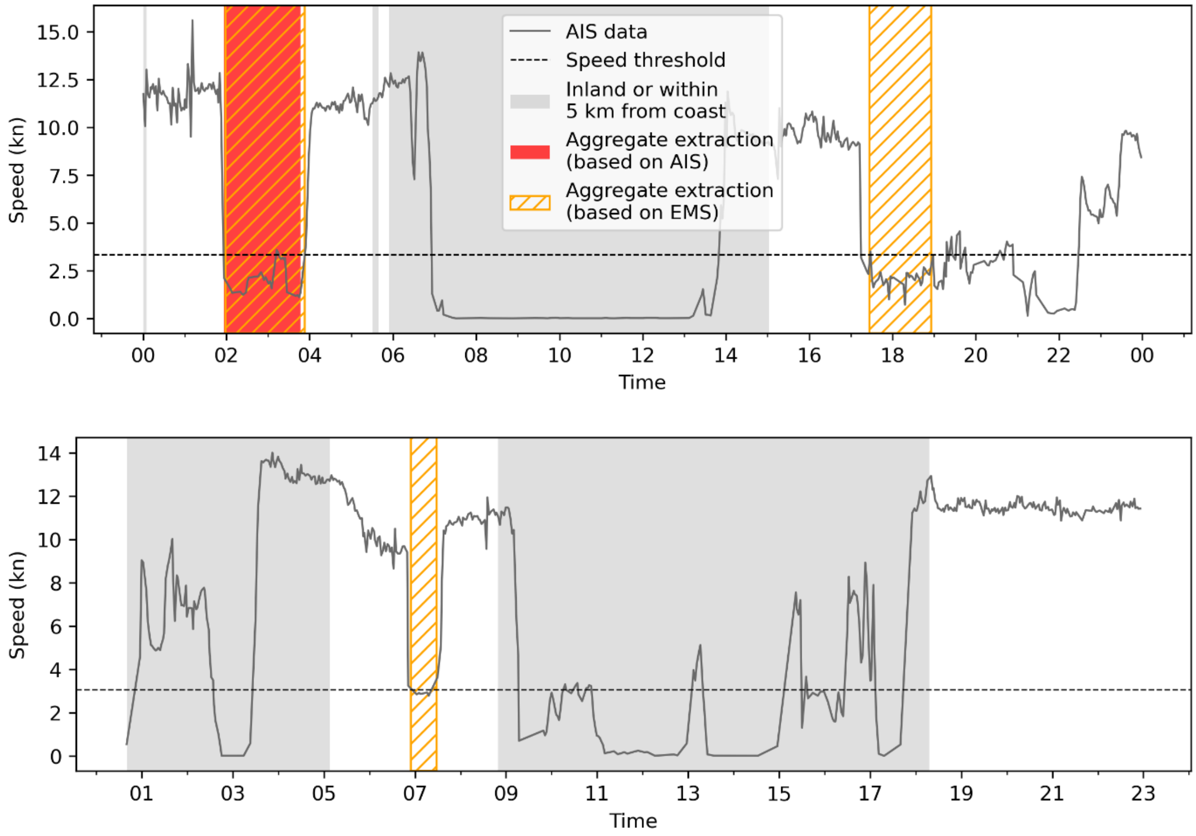
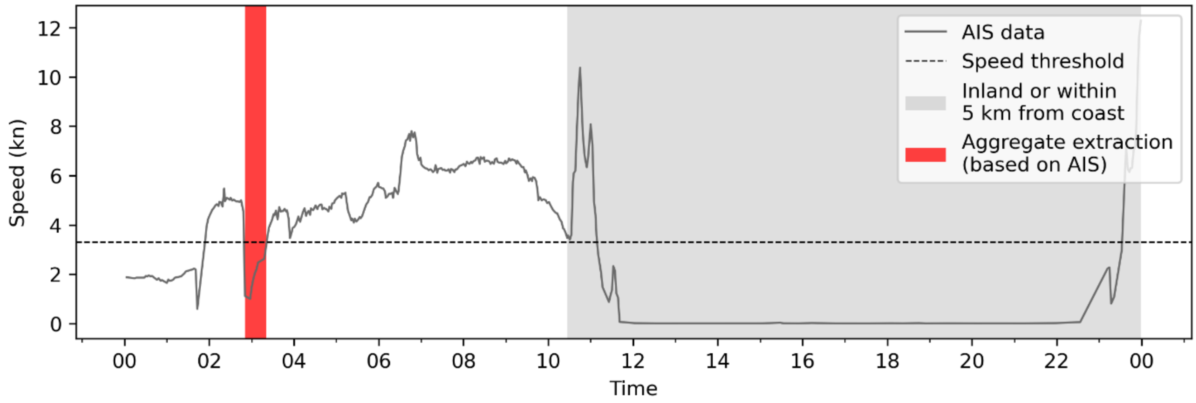


Figure 10. Example of a wrongly identified extraction (false positive case).

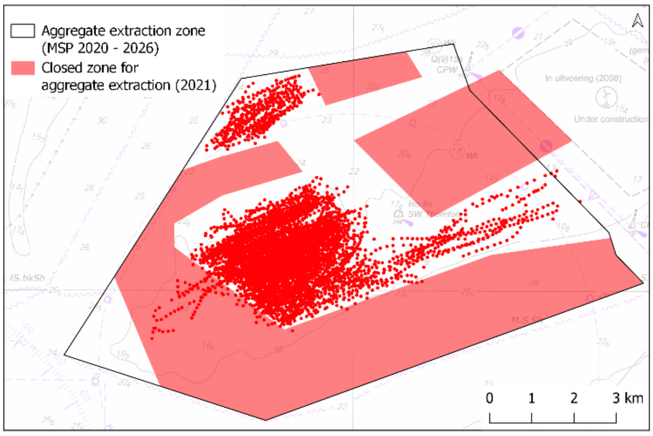


4.4. AIS: A complementary source of information for the monitoring of aggregate extraction

The previous section illustrated that AIS data can provide interesting and overall reliable insights with respect to aggregate extraction activities. The near-real time nature of the AIS makes this data particularly interesting for a number of applications. Two concrete applications of AIS data within the context of aggregate extraction are briefly described here.

AIS data is being used to closely monitor aggregate extraction activities, and in particular the control of the compliance of aggregate extraction activities to the new closed zone. At the start of 2021, the AIS data of the aggregate extraction vessels was regularly analysed to identify whether the new closed zones were well respected. The AIS data rapidly confirmed that the new boundaries were well respected, and that information on the new closed zones was well communicated (Figure 11).

Figure 11. AIS records identified as extraction over the period 01/01/2021 – 28/02/2021. Background: Agentschap voor Maritieme Dienstverlening en Kust - Vlaamse Hydrografie (2014).



The analysis of AIS data provides useful information for the organization of monitoring campaigns, such as recent information on the extraction intensity. The latter was used by researchers from ILVO to determine the location where a multibeam echosounder survey should be realized, and where sediment samples should be collected.

It is important to recognize the limitations of AIS data for the monitoring of aggregate extraction activities. First, AIS data does not contain any direct information on aggregate extraction activities, such as dredging activities or pump status in contrast to the EMS. The identification of aggregate extraction can therefore only be deduced from the spatio-temporal data, and this can be subjected to errors as highlighted in the previous section. Secondly, the AIS might be switched off, resulting in the invisibility of the vessel. Lastly, AIS might be subjected to data corruption due to for example hijacking, spoofing or maliciously corruption (Spire Maritime, 2021).

Therefore, AIS data should be seen as a complementary source of information for the monitoring of aggregate extraction activities, alongside with the EMS.

Acknowledgement

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5. The implementation of the new reference level for sand extraction on the Belgian Continental Shelf

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5.1. Historical overview

The impact of sand extraction on the Belgian part of the North Sea on the physical seabed was until the end of 2020 only limited by an arbitrary vertical boundary of 5m. When using a fixed maximum extraction depth, the nature and structure of the seabed and the sediments present, and the resulting differences in impact, are not taken into account. This method prohibits efficient and sustainable management that should consider (1) the quality and quantity of the marine sediments present, (2) the continuous demand for raw materials by the industry and government and (3) the most recent environmental legislation.

In 2014, the Continental Shelf Service started a study to define a new limit for sand extraction based on scientific and economic criteria. This new surface aims to reduce the impact of activities in the most sensitive areas in terms of sediment and habitat and to increase economic sustainability by taking into account the available volumes and quality of sand. In 2017, the results of this study were extensively presented at the triennial study day (Degrendele et al., 2017). At the request of the Consultative Commission[1], the possible impact of the new reference on coastal safety was investigated by the Royal Belgian Institute of Natural Sciences (RBINS), Flanders Hydraulics Research and Fides Engineering (Van den Eynde et al., 2019). After the presentation of the results and the report at the meeting of 18 June 2019, the committee agreed with the conclusions of this study.

Six years after the start of the research into a scientifically substantiated reference surface for sand extraction in the Belgian part of the North Sea, this project culminated in the Ministerial Decree of 28 September 2020 establishing maximum extraction depths for sand and gravel exploration on the Belgian Continental Shelf. As of 1 January 2021, the new defined references replaced the previously applicable limit for sand extraction of 5m.

5.2. Reference level

A number of criteria were taken into account when defining the new surface:

- No change in the sediments on the surface of the seabed in order to best preserve the integrity of the seabed. Taking into account the European Framework Directive MSFD (Marine Strategy Framework Directive) and its implementation in Belgian law (Royal Decree of 23 June 2010), the Member States are required to preserve as much as possible the integrity of their seabed and to limit the impact on the hydrodynamic conditions;
- The preservation of the structure of the sandbanks, based on their role in the protection of the Belgian coast;
- Maximum use of the available sand in mobile structures such as sand waves;
- Limiting the impact on hydrodynamic conditions.

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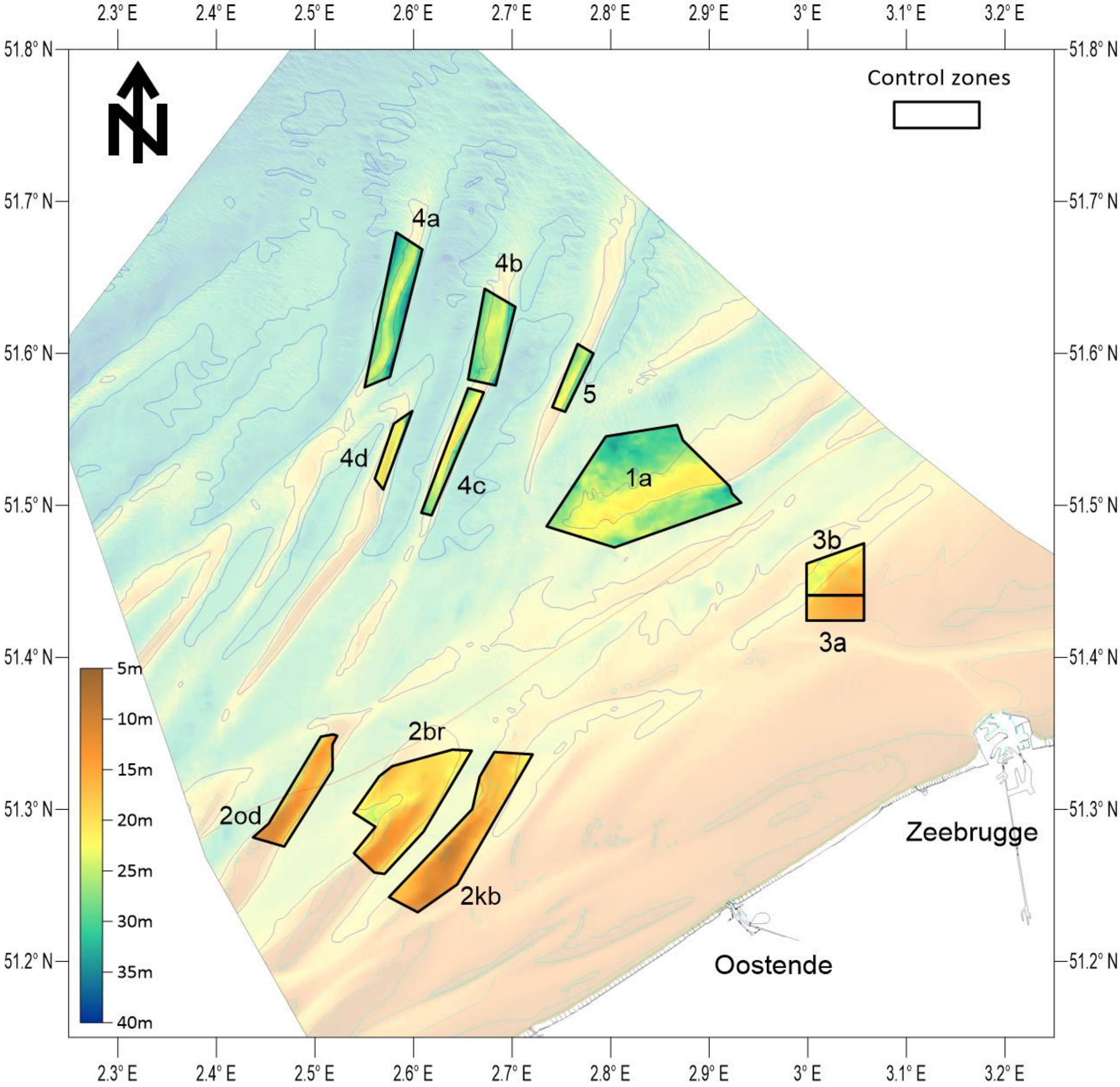
[1] Consultative Commission to ensure the coordination between the administrations involved in the management of exploration and exploitation of the continental shelf and territorial sea (RD 12-08-2000).

Based on the available geological data, reference surfaces were drawn up for each individual control zone (figure 1). These surfaces consist of the maximum depths relative to LAT (Lowest Astronomical Tide) to which the seabed may be extracted. These surfaces are available digitally in the form of grids or map layers on request from the Continental Shelf Service.

Figure 1: Reference surfaces (depth in meter LAT).

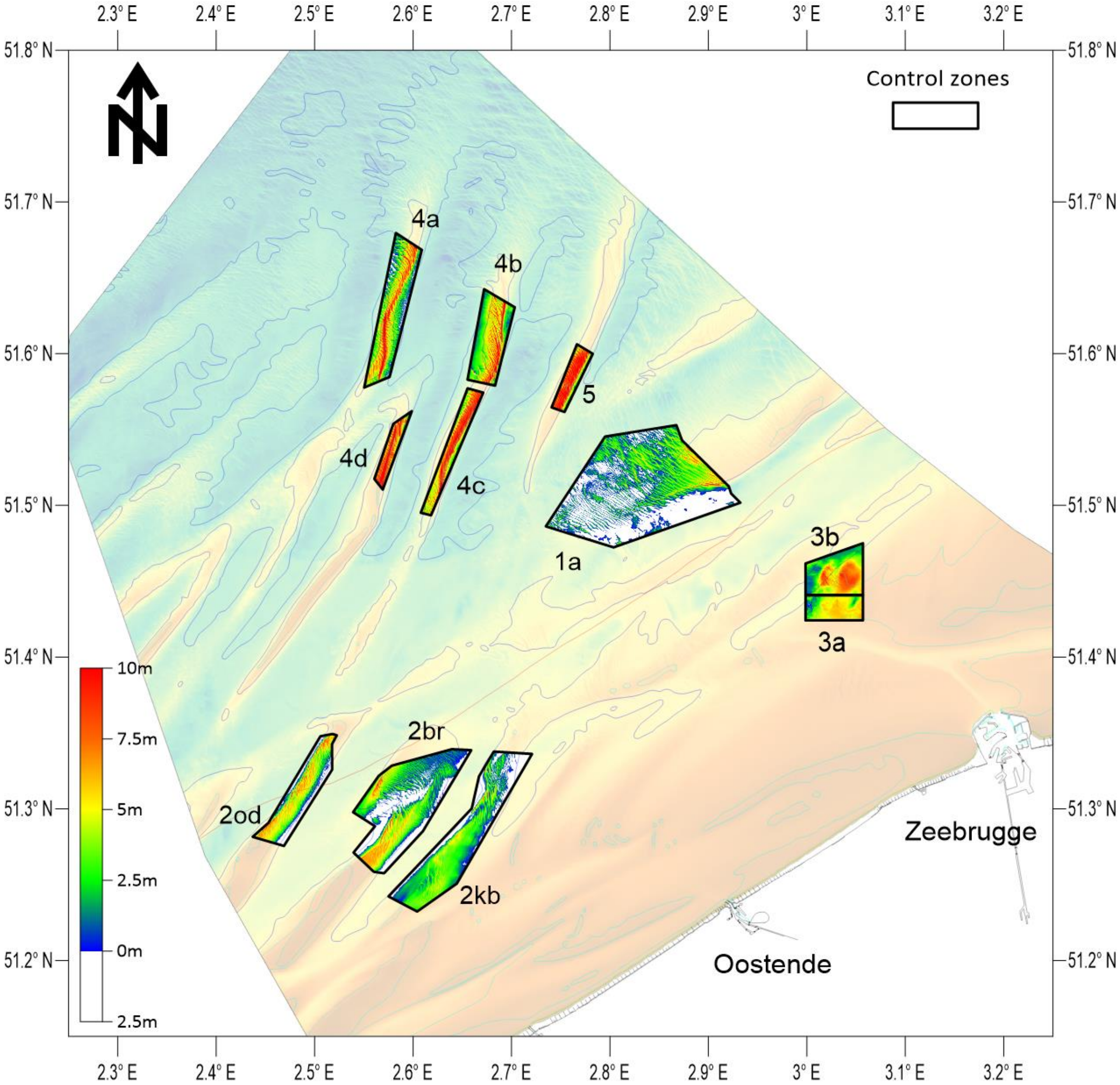
Background: Bathymetric map of the Belgian part of the North sea (Continental Shelf Service and Flemish Hydrography)



The available volume of sand for extraction is established by calculating the difference between the reference surface and the actual seabed surface (the bathymetry). Figure 2 shows the thickness of the exploitable sand layer within the various zones in 2021. The values vary from negative values, where the limit has been reached, to more than 10m in sectors 4c, 4d and control zone 5.

Figure 2: Thickness of the sand layer available for extraction (in meter).

Background: Bathymetric map of the Belgian part of the North sea (Continental Shelf Service and Flemish Hydrography)



5.3. Demarcation of closed areas

Based on the reference level in force as of 2021, subzones within the control areas are defined, where this level is globally reached or exceeded. Annually in September, the delineated zones are re-evaluated and after approval by the Consultative Commission closed for extraction as of 1 January of the following year.

Following the advice from the Continental Shelf Service (Degrendele et al., 2020), the areas KBMA, KBMB and BRMC, that were closed for extraction based on the 5m rule, are reopened as from 1 January 2021 and are taken into account in the definition of the subzones. As a result, only the Thorntonbank monitoring zone (THREF), defined in the Marine Spatial Plan 2020-2026[2], remains closed to extraction prior to the evaluation.

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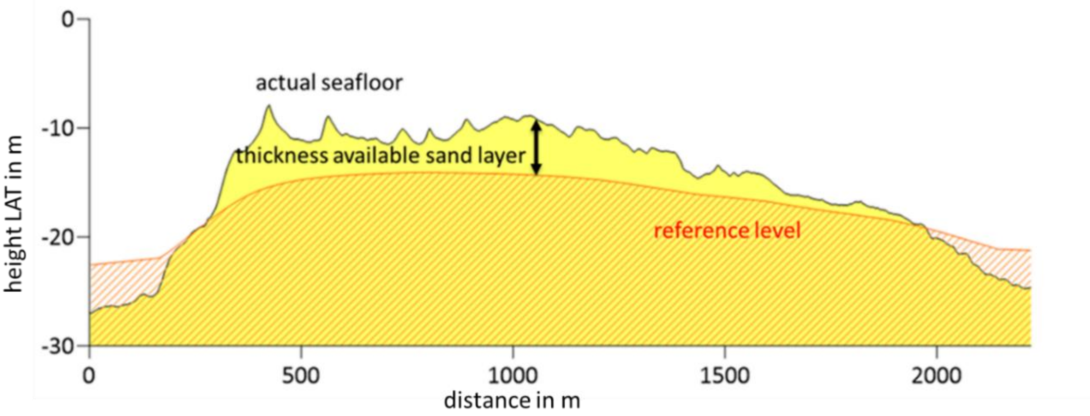
[2] http://www.health.belgium.be/en/marinespatialplan.be

Based on the difference between the most recent seabed terrain model and the depth of the reference level, the thickness of the sand layer that can be exploited, is determined. We can also describe this difference in height as the "maximum permissible extraction depth". Figure 3 illustrates that it can be both positive or negative, i.e. the actual seabed has not or has reached the reference level.

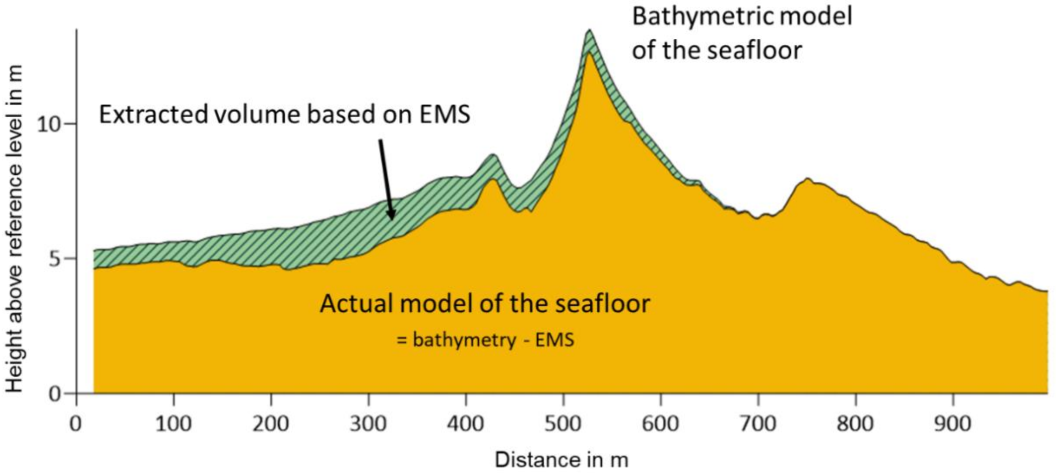
Figure 3: Example of the difference in height between the actual seabed and the reference level (profile through Sector 2od - Oostdyck), resulting in the thickness of the sand layer available for sand extraction (= maximum permissible extraction depth). This difference can be either positive (current seabed is above the reference level) or negative (current seabed is below the reference level).



The reference level is defined in the Ministerial Decree of 28 September 2020 on the maximum extraction depths for sand and gravel exploration in the Belgian marine areas, and will only be adjusted in case of important new scientific insights and/or improved quality and quantity of the geological data that are the starting point for the definition.

Due to the lack of a complete, detailed and up-to-date bathymetric model of the seabed for all zones, the bathymetric reference models build for the evaluation of the maximum extraction depth of 5m, were used in control zones 1 to 4. For each zone, these older models were corrected using the charted extracted volumes recorded with EMS (Van den Branden et al., 2017) to represent as best as possible the actual seabed (figure 4). Given the strong correlation found between the bathymetric evolution measured with an echosounder and the calculated evolution of the bathymetry based on EMS data, the latter can be used as a good approximation (Roche et al., 2017). The new control zone 5 on the Bligh Bank was fully mapped in 2018, which made the resulting model immediately usable in the calculations.

Figure 4: Example of the correction of the bathymetric model of the seabed with the extracted volumes based on EMS data. The end result is an updated seabed model that is further used in the calculations.



For each control zone, subzones are defined within which mining is prohibited, with the following criteria being pursued:

a. The average permissible extraction depth for the entire subzone is negative.

b. At least 50% of the area of the subzone is below the reference level (in other words the median is negative).

The remaining part of the control zone naturally remains open for exploitation. A number of criteria are also pursued for this part of the area:

a. The average permissible extraction depth for the entire subzone is > 1m.

b. 90% of the area of the subzone lies above the reference level.

Overall, we strive to demarcate contiguous areas, in order to guarantee exploitability. In addition, in the application of the criteria and delineation, a balance will be sought between exploitable volume in closed zones and volumes below the reference level in open zones.

5.4. First implementation in 2021

For the first evaluation and implementation, the available EMS data up to the end of 2019 were used. For the year 2020, the EMS data were only available to a limited extent, which means that the extraction in the current year could not be taken into account.

The adopted proposal from the Continental Shelf Service comprises the closure of a total of 11 subzones, spread over control zones 1, 2 and 4. Following the working method described above, several possible options were reviewed and the most appropriate ones were retained in the proposal. Inside control zones 3 and 5 the limit was nowhere exceeded, so no subzones were defined there.

We go through the defined subzones and their impact per control zone.

5.4.1. Control zone 1

The specific geological context - a limited quaternary sand layer - of control zone 1 leads to the most complex situation of the different reclamation zones (figure 5).

A large part of the zone is below the reference level. The eastern part of the zone is a continuous area with a large volume of available sand, while in the western part of the zone there is an alternation of sand waves above the reference level and troughs below the reference level (recognisable on figure 5 by the alternation of green/blue coloured crests of the waves and the white coloured troughs in between).

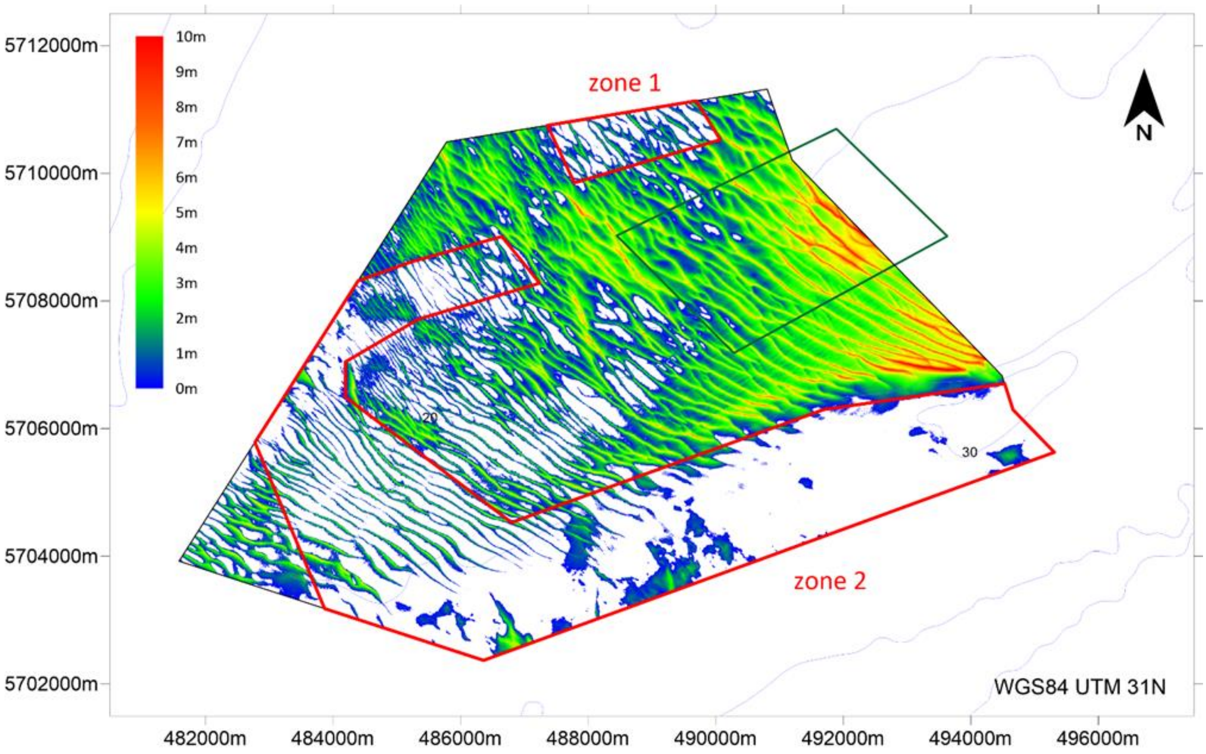
This complex situation makes the delimitation extremely difficult, taking into account the criteria established. As a solution, 2 subzones are delineated (figure 5).

Table 1: Characteristics of the delineated subzones in control zone 1: mean difference in height between the reference level and the actual seabed model (= average permissible extraction depth), and percentage of the area below and above the reference level (= limit).

Control zone 1	Average permissible extraction depth	Area of subzone below limit	area of subzone above limit
Subzone 1	-0.03m	54%	46%
Subzone 2	-0.54m	76%	24%
Open zone	+1.87m	16%	84%

Figure 5: Thickness of the available sand layer (in meter) compared to the reference level in zone 1. Negative values (reference level reached or exceeded) in white. Delimited subzones in red. Closed THREF zone in green. Boundary of the sand extraction areas as laid down in the Marine Spatial Plan 2020-2026.

Background: Hydrographic chart D11 (source: Flemish Hydrography).



Subzone 1 in the north is an obvious choice. Most of the zone is below the limit (table 1) and the zone is surrounded by a continuous area with sufficient available sand for exploitation.

Subzone 2 consists of a southern area with only sporadically available sand. The local sand deposits are too small to be exploited separately, and were therefore included in this subzone. In addition, subzone 2 also includes the western part of the large sand wave area. This is the most heavily exploited part of the bank, and the limit is already exceeded in many places. Despite the significant volume still available in this area, this subzone also broadly satisfies the criteria set (table 1).

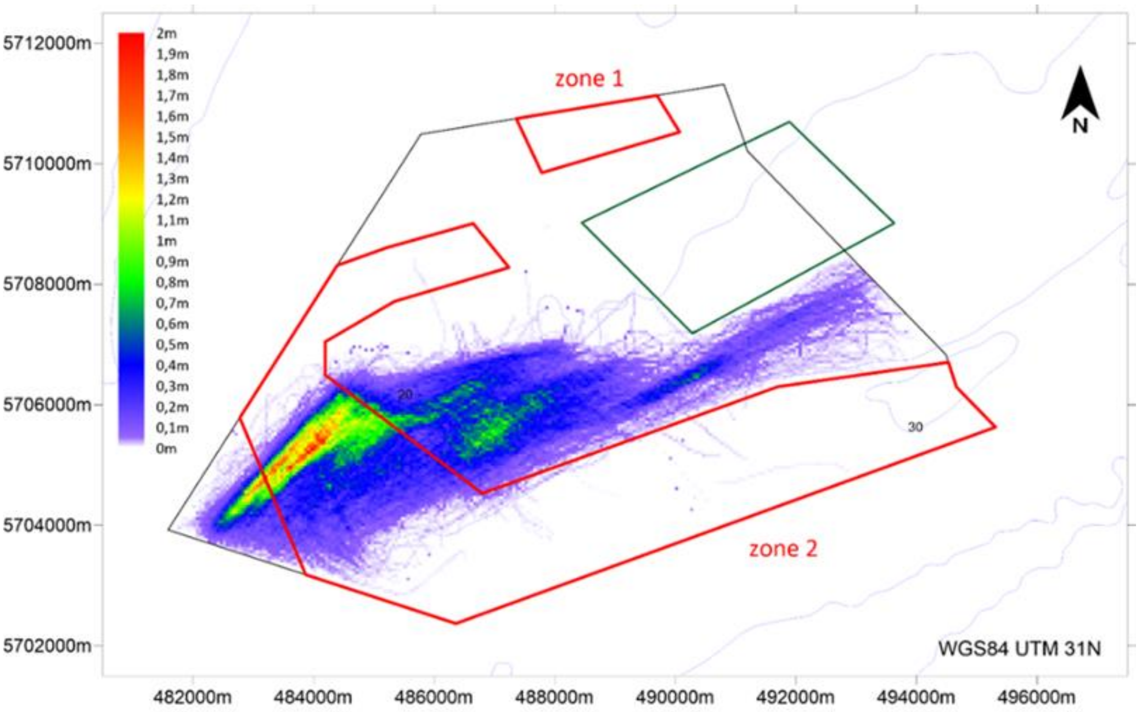
The restriction to these two subzones means that the remaining open part of the bank remains a contiguous area. Only in the extreme west a smaller area stays open. The eastern part of the sand bank area remains open for extraction and thus ensures a balance with the available volumes that are lost in both subzones. Before the delimitation, only 51% of control zone 1 was above the reference level. After the closure of the delimited zones this becomes 84%. So the 90% criterion has not yet been reached, but this gradual closure gives the sand extraction sector some time to adapt to this drastic change. This transitional situation is re-evaluated and adjusted in September 2021.

With this proposal, the mineable area of control zone 1 is limited to 40.54 km^2 or 57% of the total area of control zone 1. This loss of area is mainly at the expense of the part of the zone where the extraction limit is reached (from 29.95 km^2 to 6.35 km^2). The impact in terms of available volume for extraction is limited: it decreases from 90 to 82.5 million cubic meters.

However, the magnitude of the impact becomes particularly apparent when we map the extracted volumes based on EMS data and compare them to the delineated zones (figure 6). Subzone 1 has no impact, but 45% of the extraction that took place in control zone 1 in the period 2017-2019, lies within subzone 2. Therefore, closing this subzone will result in a very significant relocation of the extraction on the Thorntonbank.

Figure 6: Thickness of the sand layer in meters extracted in the period 2017 - 2019 in control zone 1, based on EMS data. This corresponds to the depth due to extraction for this period. Demarcated subzones in red. Closed THREF zone in green. Boundary of the sand extraction areas as defined in the Marine Spatial Plan 2020-2026.

Background: Hydrographic chart D11 (source: Flemish Hydrography).



5.4.2. Control zone 2

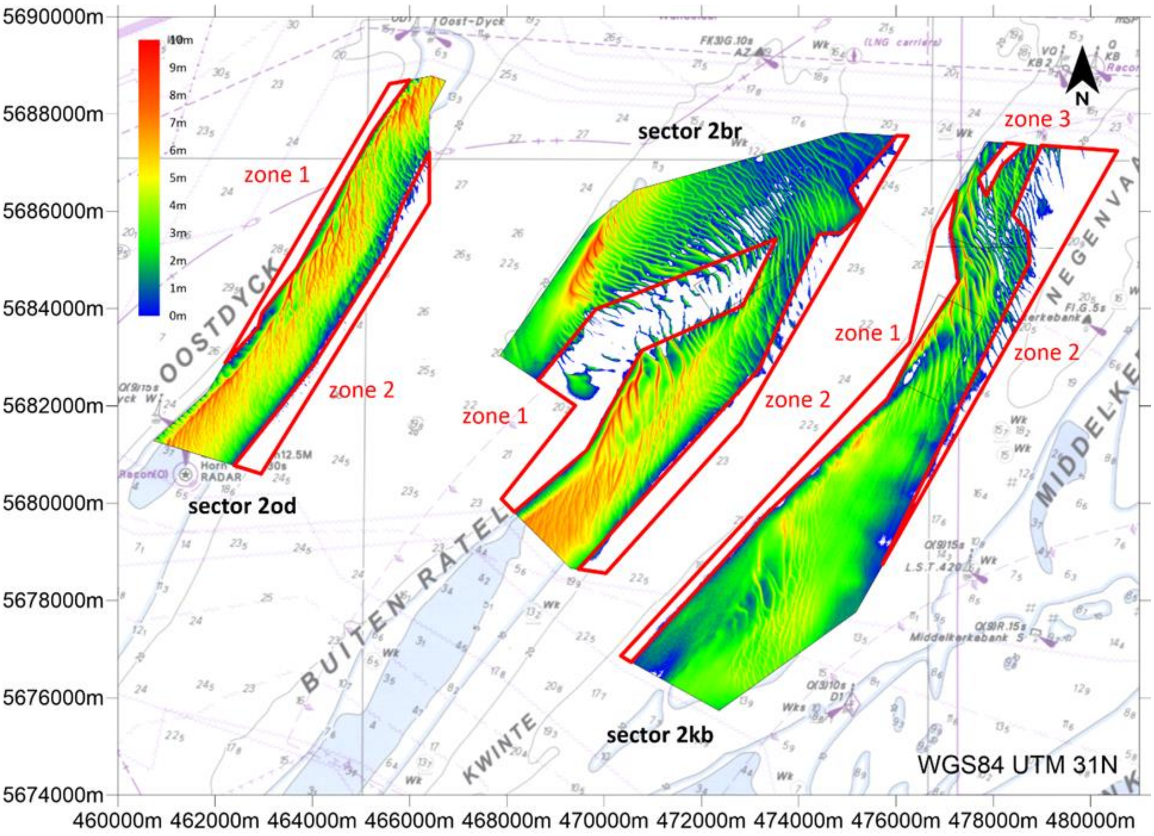
Within the different sectors of control zone 2 (2od, 2br and 2kb), a total of 7 subzones are defined (figure 7). All subzones meet the predefined criteria, and the available volumes within them are limited. Again, there is a balance between the available volumes in the closed zones and the limited presence of areas where the limit is reached in the open zones. The share of these areas below the reference surface in the three sectors is reduced from 24% in sectors 2kb and 2od, and from 28% in sector 2br to 1-3% (table 2). Thus, the target criteria for the open areas are also met.

Table 2: Characteristics of the delineated subzones in control zone 2: mean difference in height between the reference level and the actual seabed model (= average permissible extraction depth), and percentage of the area below and above the reference level (= limit).

Control zone 2		Average permissible extraction depth	Area of subzone below limit	Area of subzone above limit
Sector 2od	Subzone 1	-1.77m	94%	6%
Sector 2od	Subzone 2	-1.24m	93%	7%
Sector 2od	Open zone	+4.09m	1%	99%
Sector 2br	Subzone 1	-0.89m	78%	22%
Sector 2br	Subzone 2	-0.77m	88%	12%
Sector 2br	Open zone	+2.85m	3%	97%
Sector 2kb	Subzone 1	-1.24m	96%	4%
Sector 2kb	Subzone 2	-0.56m	79%	21%
Sector 2kb	Subzone 3	-0.82m	86%	14%
Sector 2kb	Open zone	+2.45m	3%	97%

Figure 7: Thickness of the available sand layer (in m) compared to the reference level in control zone 2. Negative values (reference level reached or exceeded) in white. Delimited subzones in red. Boundary of the sand extraction areas as laid down in the Marine Spatial Plan 2020-2026.

Background: Hydrographic chart D11 (source: Flemish Hydrography).



The impact on the available volume for extraction is limited: 2.89 million cubic meters in all subzones combined. In contrast: 29% of the extraction in the 2br sector in the period 2017-2019 took place in subzone 2. In subzone 2 of sector 2od this is even 31%. Within the other subzones, little or nothing was extracted during this period. The closure of these subzones could therefore, as on the Thorntonbank, result in a significant shift of activity in the sectors on the Buiten Ratel and Oostdyck.

5.4.3. Control zone 4

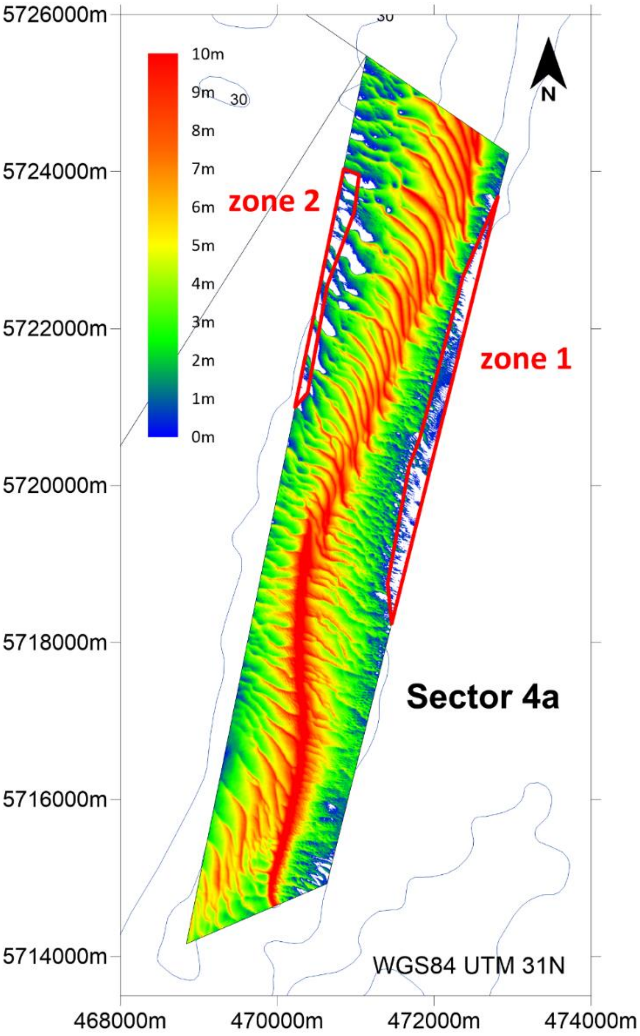
In control zone 4, the reference level is only significantly reached in sector 4a. In sector 4b, the area below the limit is negligible and located at the edge of the sector - no subzone is defined. The other sectors 4c and 4d are entirely above the reference surface. In sector 4a, the new limit is locally reached on the two flanks of the Noordhinder (figure 8).

Table 3: Characteristics of the delineated subzones in control zone 4, sector a: mean difference in height between the reference level and the actual seabed model (= average permissible extraction depth), and percentage of the area below and above the reference level (= limit).

Sector 4a	Average permissible extraction depth	Area of subzone below limit	Area of subzone above limit
Subzone 1	-0.07m	56%	44%
Subzone 2	-0.01m	57%	43%
Open zone	+4.45m	2%	98%

Figure 8: Thickness of the available sand layer (in m) compared to the reference level in sector 4a. Negative values (reference level reached or exceeded) in white. Delimited subzones in red. Boundary of the sand extraction areas as laid down in the Marine Spatial Plan 2020-2026.

Background: Hydrographic chart D11 (source: Flemish Hydrography).



The two delineated zones shown in figure 8 both meet the predefined criteria (table 3). The impact of closing these zones is very limited, both on the available volume and on the location of extraction.

5.5. First evaluation and follow-up

A first analysis of the follow-up of the new regulations was made with the available AIS data from the start of 2021. The mapping of AIS data demonstrates that the delimitation of the zones is well known and respected (Barette et al., this contribution).

In September 2021 the defined zones were re-evaluated for the first time. The bathymetry of zone 3 (Sierra Ventana) was replaced with a new model, surveyed in 2019 and 2020 (Degrendele et al., this contribution). For the other areas the bathymetric models were updated with the EMS derived extracted depths up to the end of 2020. The characteristics for all subzones are recalculated and re-evaluated according the same criteria.

The impact of the recalculation was minimal for all areas and induced no significant changes in the values for the different criteria. Based on this exercise, the subzones of 2021 could remain unchanged for 2022.

But, as mentioned above, not all criteria were met for control zone 1. In the remaining open area only 84% lies above the reference surface. This is confirmed in the new calculation: due to the intensive extraction the percentage drops further to 83%. As stated before, this was considered a transitional measure, and the criteria would be met in future evaluations. To comply with this criterium, the subzone 2 was enlarged with the most extracted central area (figure 9). The new delineation of subzone 2 augments the surface percentage of the remaining open area above the limit to 90% (table 4).

Figure 9: Thickness of the available sand layer (in meter) compared to the reference level in control zone 1. Negative values (reference level reached or exceeded) in white. Delimited subzones in red. Closed THREF zone in green. Boundary of the sand extraction areas as laid down in the Marine Spatial Plan 2020-2026.

Background: Hydrographic chart D11 (source: Flemish Hydrography).

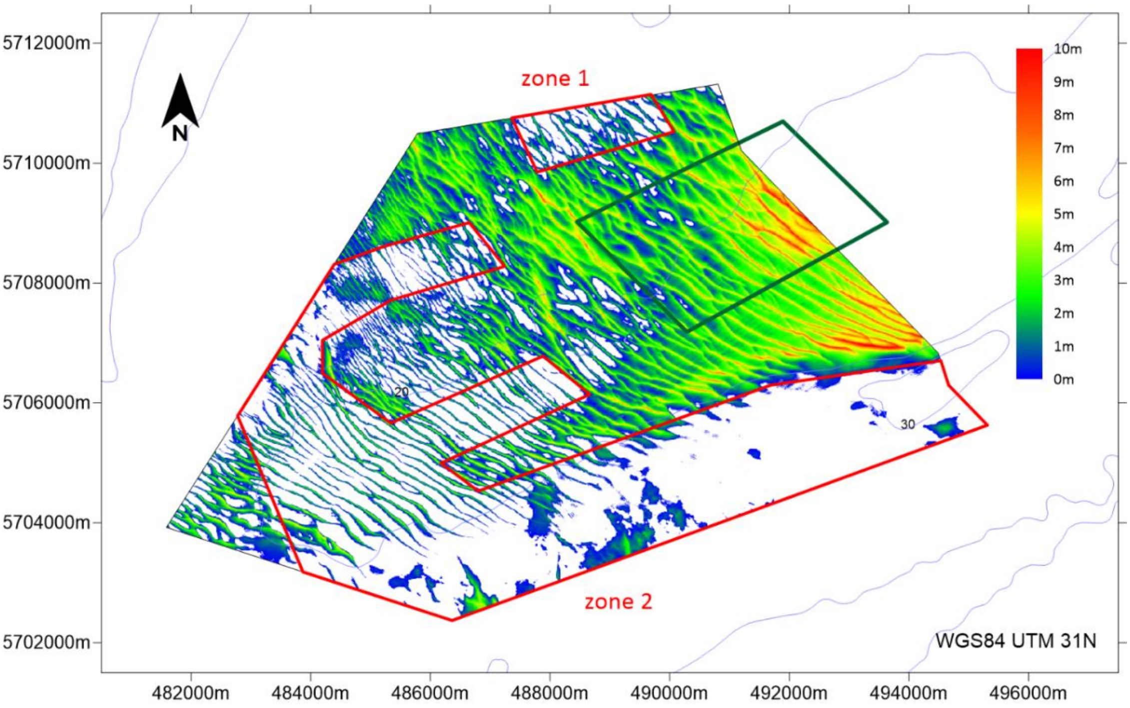


Table 4: Characteristics of the delineated subzones in control zone 1: mean difference in height between the reference level and the actual seabed model (= average permissible extraction depth), and percentage of the area below and above the reference level (= limit).

Control zone 1	Average permissible extraction depth	Area of subzone below limit	Area of subzone above limit
Subzone 1	-0.03m	54%	46%
Subzone 2	-0.55m	77%	23%
Open zone	+2.01m	10%	90%

With this expansion, the closed subzone now covers 64% of the extracted volume in control zone 1 in the period 2017 - 2020, amounting to 5 10^6 m^3 sand (figure 10). Based on the AIS cartography the enlarged subzone 2 now covers more than one quarter of the extracted volume during the first half of 2021: 0,51 10^6 m^3 of sand was extracted up to 23 August 2021 or 27% of the total volume extracted in control zone 1 (figure 11).

Figure 10: Thickness of the sand layer in meter, extracted in the period 2017 - 2020 in control zone 1, based on EMS data. This corresponds to the depth due to extraction for this period. Demarcated subzones in red. Closed THREF zone in green. Boundary of the sand extraction areas as defined in the Marine Spatial Plan 2020-2026.

Background: Hydrographic chart D11 (source: Flemish Hydrography).

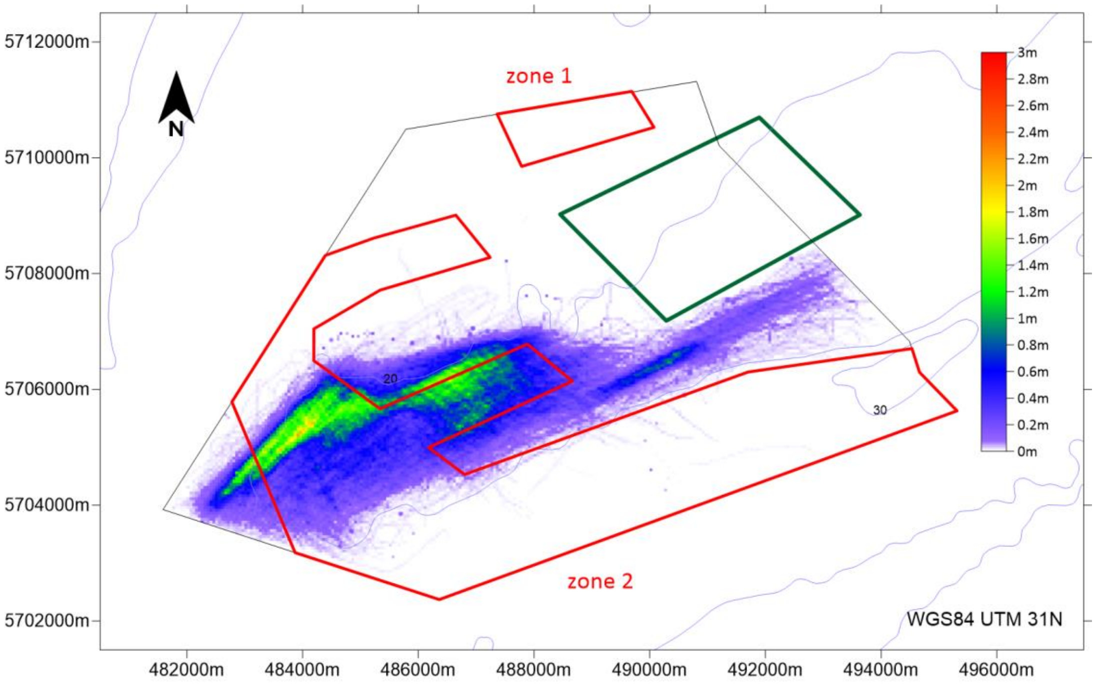
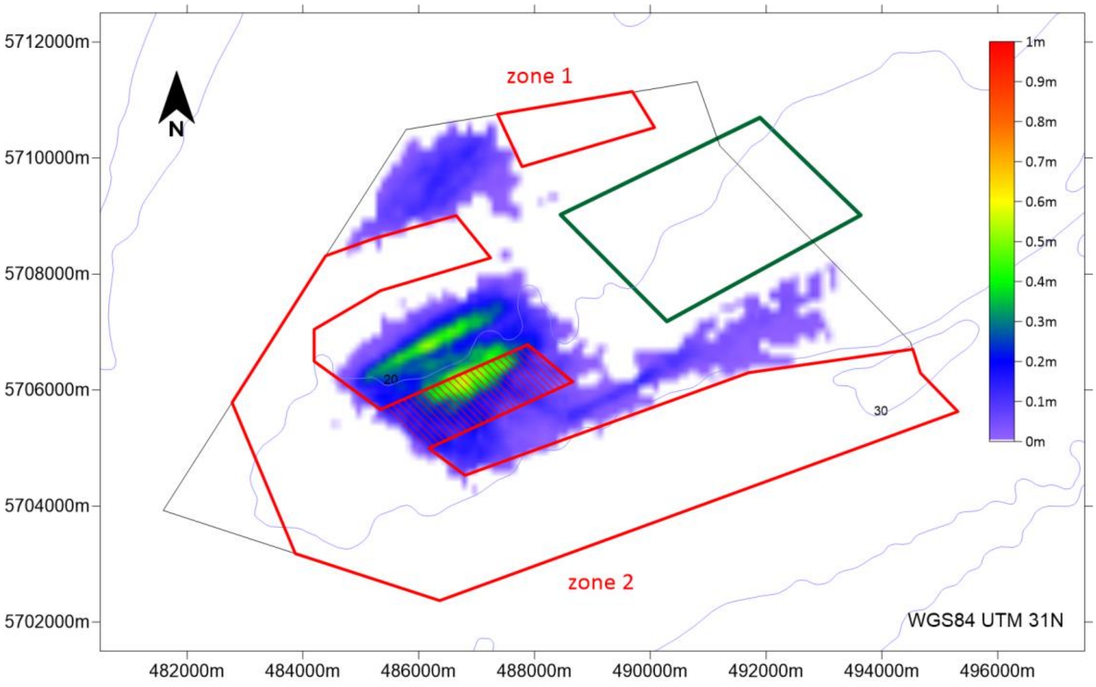


Figure 11: Thickness in meter of the sand layer extracted in the first half of 2021 in control zone 1, based on AIS data. This corresponds to the depth due to extraction for this period. Demarcated subzones in red – enlarged area of subzone 2 shaded in red. Closed THREF zone in green. Boundary of the sand extraction areas as defined in the Marine Spatial Plan 2020-2026.

Background: Hydrographic chart D11 (source: Flemish Hydrography).



Overall the impact of the implementation of the reference surface can be summarized in one figure: 25% of the total surface in all control zones is now closed based on the criteria. Compared to the 2% of the surface that was closed before the introduction, this can be considered a complete turnaround. Not only is the area directly impacted by extraction strongly reduced, the closed areas are predominantly located on the deeper parts of the extraction areas, which constitute the ecologically most valuable areas. Therefore we can already conclude that the ecological impact is clearly positive.

Although the impact on the available sand quantity is limited (amounts to 1.7% loss of the total available volume), the impact on the quantities of sand with guaranteed quality is important. The gradual but ongoing closing of the main part of control zone 1 increases the demand for alternative sources of qualitatively similar sand. The possible delineation of new zones in the exploration area and the reopening of the reference area on the Thorntonbank (for the biological monitoring of the impact of sand extraction and wind energy) thus become important future perspectives.

The use of AIS for extraction mapping will allow for more responsive and faster future annual evaluations. In addition, the possible application of a more generalized reference level for all seabed disturbing activities could be investigated, so that a positive contribution can be made to limiting the direct environmental impact on the entire Belgian part of the North Sea.

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6. The impact of sand extraction on the wave height near the Belgian coast

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6.1. Introduction

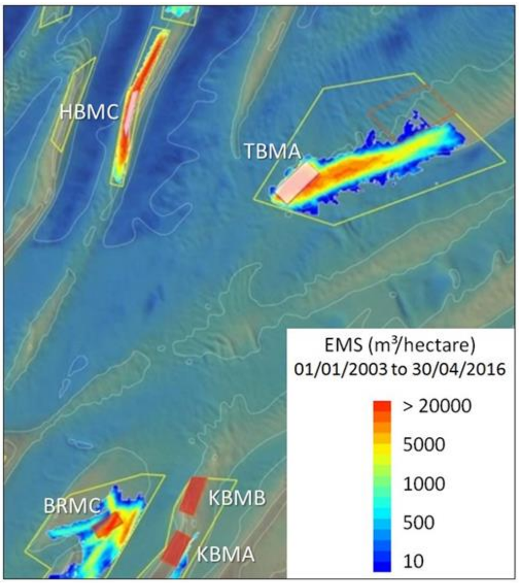
Over the last years, the extraction of marine aggregates is increasing considerable. While in the period 2003-2010, the total volume of extracted marine aggregates on the Belgian Continental Shelf stayed below 2.5 Mm^3, since 2011 the extraction increased, with peaks at 2013, with an extraction of more than 4.0 Mm^3, and 2014, with an extraction of even more than 6.0 Mm^3 (Van den Branden et al., 2016). Furthermore, since 2012, concessions were granted in the region of the offshore Hinderbanks. 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 (www.kustveiligheid.be).

The limits of the extraction in the Belgian Law was set at 5 m below the reference level, that was defined by the Service Continental Shelf of the Federal Public Service 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 20th, 1999 and April 22th, 1999). This reference model was based on a detailed terrain model of the sea bottom in the extraction zones, measured during multi-beam surveys in the first half of the previous decennium. Based on this limit, three areas in the extraction Sector 2 (KBMA, KBMB and BRMC), where extraction led to a deepening of more than 5 m, were closed (see Figure 1). In other areas in Sector 1 (TBMAB) and Sector 4 (HBMC), this limit was approached as well.

This method however didn't take the structure of the sea bottom and the differences in impact into account. Furthermore, the sustainable character of the marine aggregate extraction became at risk. The areas with the best quality sands (median size to coarse sands) were being closed while zones with economically less interesting quality (fine sands) remained open. Therefore, COPCO defined a new extraction limit level, which was based on scientific and economic criteria (Degrendele, 2016; Degrendele et al., 2017; Degrendele et al., this volume). The goal of this new extraction limit level is to limit the impact of the extraction in the most sensitive areas for sediment and habitat and to increase the economic sustainability, by accounting for the available volumes and the quality of the sands. Using the new extraction limit, the total volume of the reserves, i.e., the total volume that can be extracted, decreases from about 1050 Mm^3 to 599 Mm^3. However, the extraction will happen on a more sustainable way and taking into account the economic interests.

In Van den Eynde (2016; 2017), the effect of this new proposed extraction limit level on the changes in the bottom stress were evaluated, according to the Belgian implementation of the European Marine Strategy Framework Directive (Belgian State, 2012; 2018). In this Directive, it was stated that human impacts need consideration when the bottom shear stress, calculated with a validated numerical model, changes with more than 10 % at a specified distance of the activity. The impact of extraction of marine aggregates, up to the new proposed extraction limit levels, was evaluated with this respect. Simulations were executed with numerical models to test whether the three newly proposed extraction limit levels were within these constraints. Some small changes were suggested to adapt the new extraction limit to assure that no violation of this regulation would occur.

Figure 1: Areas, closed for extraction (red) and areas where the limit is almost reached (rose).



Source: Degrendele, 2016.

In this article, the effect of the change of the extraction level limit on the wave propagation on the Belgian continental shelf is investigated. This is done using the SWAN wave model. From these results the effect of the extraction on coastal protection is evaluated.

Remark however that in the current report the Sector 4a is not considered anymore and a new extraction Sector 5 is being defined (see Figure 2). The simulations are executed for these extraction sectors. Remark also that in the current article Sector 3 (Sierra Ventana) is out of scope. This extraction section is considered an area where sand is extracted that was previously deposited there and is therefore not taken into account.

In the first section the numerical model is shortly presented. The second section discusses the setup of the model grid. In the third section, the simulations are presented, while a discussion is presented in the next section. A conclusion is formulated in the last section.

6.2. Numerical model

For the propagation of the waves over the shallow Belgian coastal waters, different models can be used. For the operational forecasts of the waves on the Belgian coast, the third generation WAM model is used (WAMDI Group, 1988; Günther et al., 1992). The local grid however has only a resolution of 0.033° in latitude and 0.022° in longitude, which is more than 1.5 km.

Therefore, for this study the SWAN model (e.g., Ris, 1997; Booij et al., 1999; Holthuijsen et al., 1989, 1993, 2003) is used. The SWAN model is a third-generation wave model that computes random, short-crested wind-generated waves in coastal regions and inland waters. The model calculates in time and space, the generation of waves, their propagation and shoaling, non-linear wave-wave interaction, white-capping, bottom friction and depth-induced breaking. In comparison with the WAM model, the model is more suited to calculate the propagation of the waves in the nearshore area. The main disadvantage is that the models is preferably used in stationary mode. The SWAN model is implemented (see next session) on a grid of 250 m x 250 m, better representing the sand banks. This is needed to evaluate the effect of sand extraction on the wave propagation.

In the current project, the SWAN cycle III version 40.51 is used (SWAN, 2006a, 2006b), with most of the default values. The wave spectra in the model are described for 37 frequencies within the frequency range of 0.025 Hz to 0.85 Hz. The frequencies are logarithmic distributed. The full directional range is covered with a resolution of 10°. The model uses the 3th generation source terms, including linear and exponential wind growth, white capping, non-linear 4-wave interactions (so-called quadruplets), depth-induced wave breaking, bottom friction and non-linear shallow water 3-wave interactions (so-called triads). The triads and bottom friction, non-active by default, were activated.

The model was run in stationary mode, with default accuracy parameters and with maximum 40 iterations. Normally around 7 iterations are used in the current calculations.

While recent research by Zijlema et al. (2012) showed that in older versions of SWAN (like the 40.51 version) wave growth by wind was overestimated, which was compensated by larger bottom friction for wind sea, the lower bottom friction was not included here, because the new wave growth formulations were not included in the 40.51 version of the model.

6.3. Bathymetry

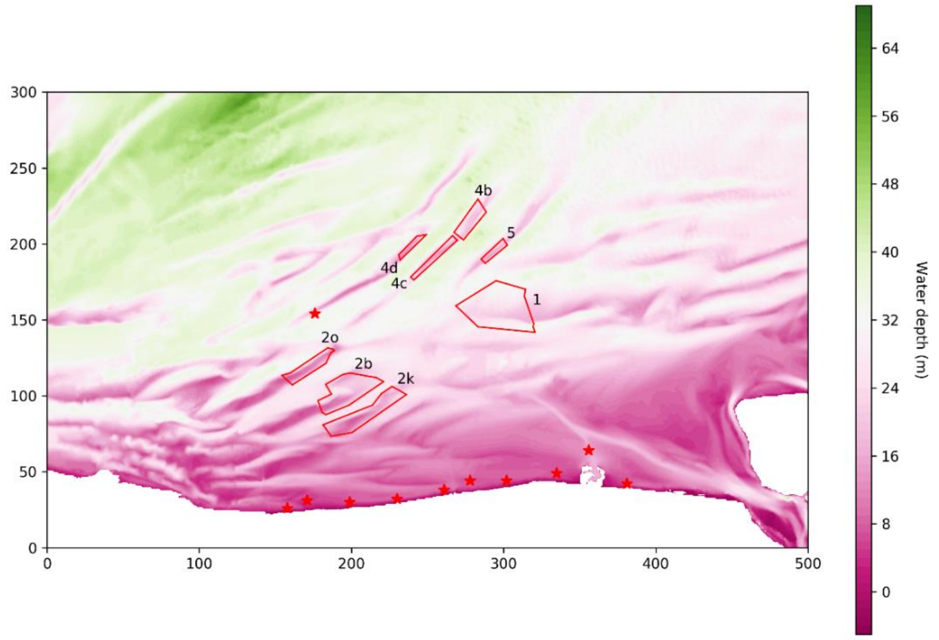
6.3.1. Extended SWAN bathymetry

In the framework of the CLIMAR project (Van den Eynde, 2011; Van den Eynde et al., 2011), the SWAN model was used to simulate the propagation of the waves from offshore to the Belgian coast and to investigate the effect of sea level rise on the wave propagation. For that application, the model was implemented on a Cartesian grid, rotated over 25.5° anti-clockwise, along the Belgian coast, with a resolution of 250 m x 250 m, a grid that was prepared by KULeuven & FHR (2004). The rotation is needed to assure that the distance from the coast to the offshore boundaries are similar. This assures that the time of the waves, travelling from the offshore conditions to the shore takes the same time, which is useful, using the model in stationary mode. The lower left point of the grid had the co-ordinates (50°54’00”, 2°07’12”). For the current application, a more extended model grid was set up, based on the new bathymetries that were developed for the new hydrodynamic model train, based on the COHERENS software, that is being installed at the RBINS-OD Nature (Dulière, 2017).

The bathymetry is shown in Figure 2. In the figure, also 10 possible output points before the Belgian coast are shown where the output could be used by coastal models such as the XBeach model (Roelvink et al., 2009; 2015) and the UNIBEST-CL+ model (https://www.deltares.nl/en/software/unibest-cl/). The XBeach model is operated by Flanders Hydraulics Research (FHR) to evaluate the changes of the beach profiles during storms (De Roo et al., 2015; Kolokythas et al., 2016). The UNIBEST-CL+ model is operated to simulate larger scale coastline dynamics. These points were taken from IMDC (2009) to represent the wave climate for the 10 coastal municipalities.

Figure 2: New extended SWAN grid.

Reference levels is Mean Sea Level. Points are output points at the coastal municipalities and the wave buoy at Westhinder (offshore). The extraction zones are indicated. Coastal points from West to East: DPa: De Panne, Kok: Koksijde, Nwp: Nieuwpoort, Mid: Middelkerke, Oos: Oostende, Brd: Bredene, DHn: De Haan, Bla: Blankenberge, Zbr: Zeebrugge, Knk: Knokke. Offshore point Whi: Westhinder.



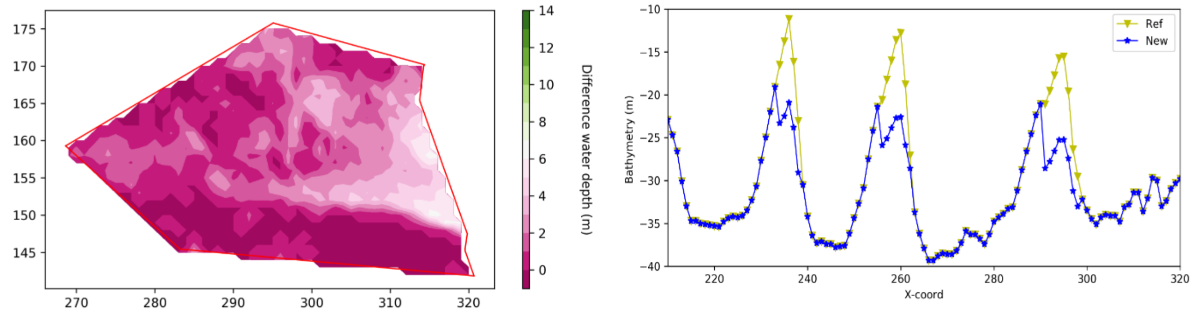
6.3.2. Inclusion of the new reference level

To check the influence of the sand and gravel extraction, the bathymetry of the SWAN grid is adapted in the extraction zones to the new extraction level. For the present bathymetry and for the new extraction limit level, bathymetrical files were received on a grid of 5 m x 5 m for the different sectors from COPCO. To make the inclusion of these data consistent, both data sets were included in the SWAN bathymetry. A similar procedure is used, as was used in Van den Eynde (2016; 2017).

It can be noted that small differences between the reference bathymetry provided by COPCO and the bathymetry of the new SWAN grid, ranging between +0.17 m and -0.75 m were observed. To make the calculation of the effect of the change in bathymetry, due to extraction, more consistent, the COPCO bathymetries were corrected.

After the preparation of the new reference bathymetry, the same procedure was followed to prepare the new bathymetry, where the bathymetry in the extraction zones was lowered to the new extraction limit. In Figure 3, the difference between the reference bathymetry and the extraction limit bathymetry is shown for sector 1. Also the difference between the reference bathymetry is shown for a cross-section of the bathymetry at model coordinate Y=195, where the sectors 4c, 4d and 5 are cut.

Figure 3: Left: Difference between the reference bathymetry and the extraction limit bathymetry for the sector 1. Right: Difference between the reference bathymetry and the extraction limit bathymetry at Y=195.



Sector 1 is clearly the largest zone, with a size of 73 km², while sector 4d and the new sector 5 are the smallest ones, with a size of only 5.2 km² and 6.2 km² respectively. The largest amount can be extracted in sector 1, namely about 93 Mm³. In the other sectors, the extractable amount varies between 35.7 Mm³ (sector 4d) and 85.4 Mm³ (sector 2b). Remark that in the sector 1 only 1.28 m can be extracted on average over the entire sector, while in sector 5, more than 7 m can be extracted on average over the zone. In total a volume of 508 Mm³ can be extracted in the different sectors.

6.4. Effect of extraction on wave propagation

6.4.1. Effect of boundary conditions

Simulations were executed for winds to the shore, covering the wind directions from South-West (SW) over North (N) to North-East (NE) with a resolution of 22.5°. Remark that the winds from NNW is almost a wind perpendicular to the shore. At the boundaries a JONSWAP spectrum is applied with a peak enhancement parameters γ of 3.3, representing a (fully developed) wind sea spectrum. The directional width is set to 30°, in agreement with the results of the tests by IMDC (2009). The waves are characterised by a significant wave height *Hs*, a peak period *Tp* and a wave direction *Dir*. A constant wind was applied with a wind speed *Ws*. The wave direction at the boundary was assumed to be the same as the wind direction.

In IMDC (2009) some tests have been executed to check the influence of applying boundaries at the northern boundary alone or at the northern and western boundary of the model grid. It was stated that applying waves at the eastern boundary was not important, due to the limited effect of these boundaries at the Belgian coast, as they used the model grid, set up by KULeuven and FHR (2004), which was limited offshore to Westhinder. The results showed that for the Belgian coast, the effect of the boundaries was not too important. Since the model grid has been extended considerable to the North in this project, some initial test to check the influence of the boundary conditions on the results at the Belgian coastal stations were carried out. Results showed that the differences in this case are mainly at the western and eastern boundaries and that the difference at the Belgian coast is limited.

6.4.2. Simulations for normal climate

For the effect of the extraction of sand at the propagation of the waves to the Belgian coast, a total of 108 simulations have been executed. Three different wave heights were applied at the boundaries of the model, i.e., *Hs* = 2 m, 3 m and 4 m. In Verwaest et al. (2008), a wave climate for the Belgian coast, based on measurements at station Westhinder was derived. They estimated that around 9.4 % of the time, wave heights of 2 m or higher were encountered at Westhinder with wind/wave direction between SW, N and NE. Waves with significant wave height of 3 m and 4 m are already more extreme cases.

Furthermore, in Verwaest et al. (2008) a relation was proposed between the wave height and the peak period and between the wave height and the wind speed for the waves with significant wave height of 2 m, which are peak period *Tp*= 7 s and wind speed *Ws* = 14 m/s. Based on these relationships, values were proposed for significant wave heights of 3 m and 4 m as well. Simulations were performed for 9 different wave and wind directions, going from SW to NE, with a resolution of 22.5°. Furthermore, simulations were executed for low waters and high waters. Low water was set at 0 m TAW, i.e. at -2.33 m below MSL, while high water was set at +2.33 m MSL. To test the effect of the extraction of sand, simulations were of course executed for the reference bathymetry and for the bathymetry with the new proposed extraction limit level. As such, a total of 108 simulations have been executed.

Results at the coastal stations

For the significant wave height of 2 m at the boundaries, the difference at the coastal stations is limited to 0.02 m or less, both for the HW and the LW water levels, except for station Middelkerke, where a decrease in wave height is expected for HW water level and for waves from WSW of -0.03 m (Figure 4). The effects at the coast are therefore limited. Overall, a small decrease in significant wave height could be expected for some western stations (Nieuwpoort, Middelkerke), while a small increase is expected for some central stations (Oostende, Bredene, De Haan). The effects are slightly larger for the HW water level than for the LW water level.

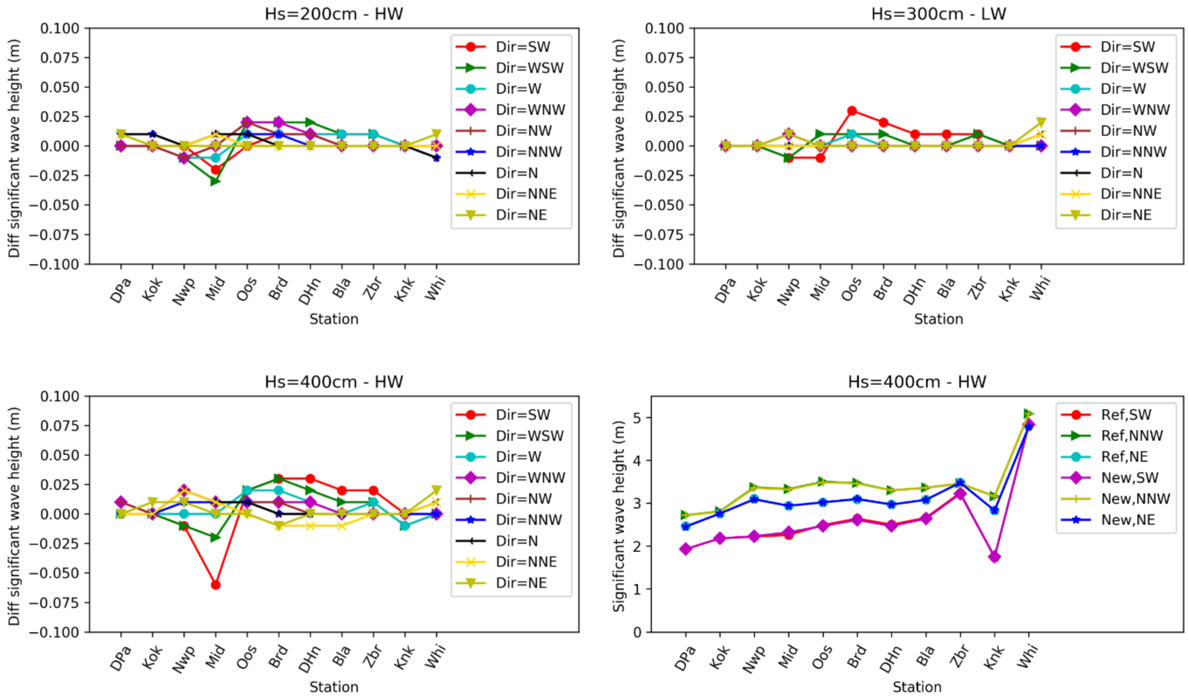
Similar results are found for a significant wave height of 3 m at the boundaries (Figure 4). At stations Middelkerke, a decrease is found of significant wave height of -0.04 m for winds coming from WSW and SW and for HW. On the other hand, an increase of +0.03 m is found for station Oostende for wind from SW. Also here, for the rest, the differences remain limited to 0.02 m.

For significant wave heights of 4 m at the boundaries and wind speeds of 22 m/s, the changes remain limited (Figure 4). The decrease at station Middelkerke for HW and winds from SW is -0.06 m now, while for the same wind direction, the increase in significant wave height at stations Bredene and De Haan is +0.03 m now. For the rest the results are limited to 0.02 m. Although there are differences for the difference coastal stations and for the wind direction, the influence of the sand extraction is limited (Figure 4). Remark that also at station Westhinder, the changes remain very limited. Only for winds from NE and wave height of 4 m at the boundaries, an increase in wave height is found of +0.04 m.

One can conclude that the highest effects are to be expected at HW water levels, that in the area Nieuwpoort-Middelkerke a small decrease is expected and in the area Oostende-Bredene-De Haan a small increase is expected. Furthermore, the highest changes are expected for the largest waves and for the winds from SW and WSW. Overall, however, the effects remain very limited.

The changes to the mean period near the coast remain limited to less than -0.09 s or +0.07 s, and are the largest for winds coming from SW. Also the changes in wave direction remain limited to less than +1.7 degrees or -1.4 degrees.

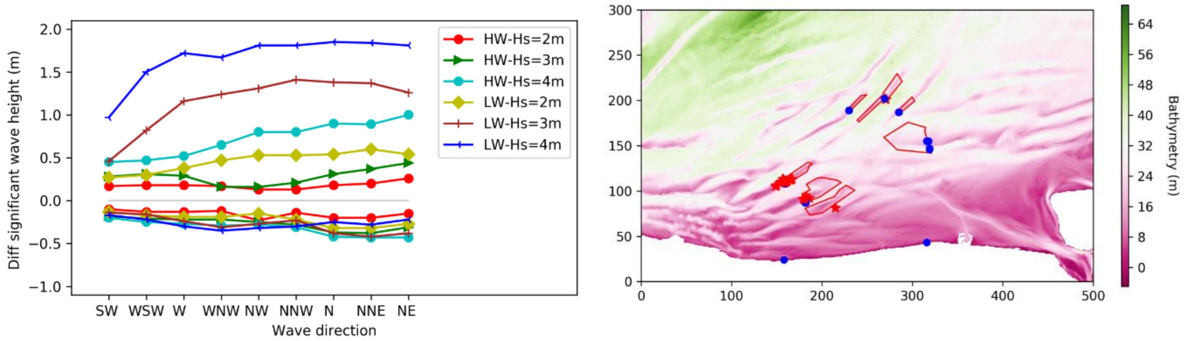
Figure 4: Upper left and right and bottom left: Increase of significant wave height at coastal stations and Westhinder for simulation with the new extraction limit compared to without extraction. Upper left: waves at boundary with significant wave height of 2.0 m, wind speed = 14 m/s, different wave and wind directions, HW situation (MSL +2.33 m). Upper right: waves at boundary with significant wave height of 3.0 m, wind speed = 18 m/s, different wave and wind directions. LW situation (MSL -2.33 m). Bottom left: waves at boundary with significant wave height of 4.0 m, wind speed = 22 m/s, different wave and wind directions. HW situation (MSL +2.33 m). Bottom right: significant wave height at coastal stations and Westhinder for simulation with the new extraction limit (NEW) compared to without extraction (REF). Waves at boundary with significant wave height of 4.0 m, wind speed = 22 m/s, different wave and wind directions. HW situation (MSL +2.33 m).



Results on entire Continental Shelf

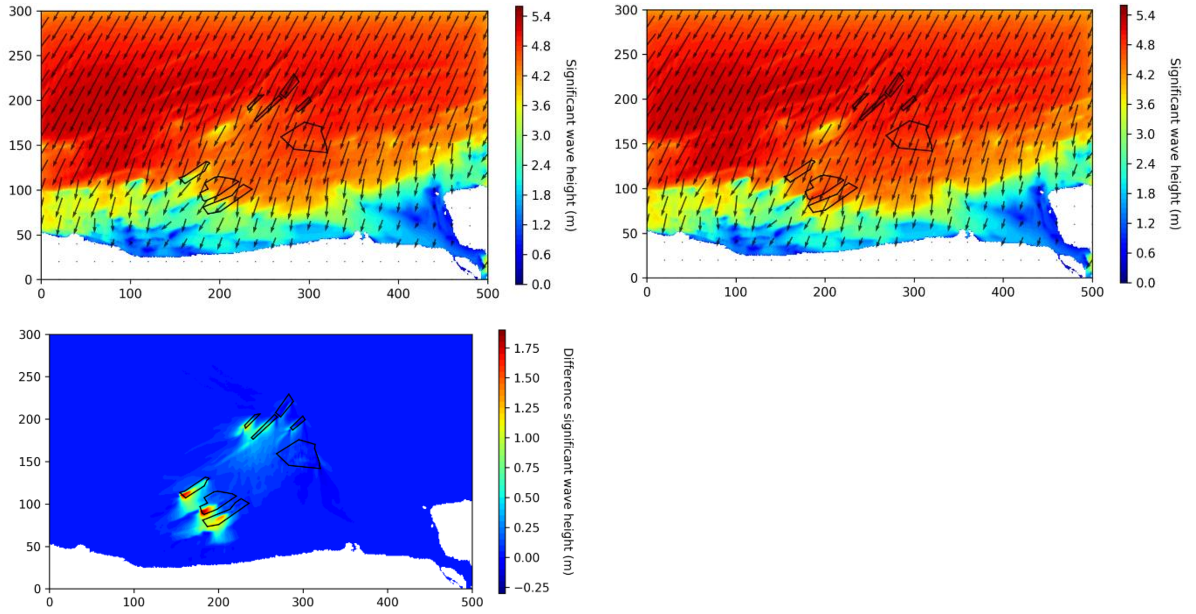
On the entire model grid, the differences can be of course larger, certainly near the changes in the bathymetry. The largest decrease in wave heights is limited to -0.43 m (Figure 5). The decrease is larger for the waves coming from N to NE. The maximum increase in wave height is more variable. The difference are larger for higher significant wave heights at the boundaries, but also the water level is of great importance. The maximum increase for low water (MSL -2.33 m) and for wave heights of 3 m at the boundaries is much larger than the maximum increase for high water (MSL +2.33 m) and for wave heights of 4 m at the boundaries (Figure 5). The largest decreases are for waves coming from NNW (perpendicular to the coast) to NE and are found south or east of the extraction zones 1, 4 and 5, and at two points near the coast. The decrease of wave height is possibly due to the less shoaling. The maximum increase during HW is +1.0 m for waves coming from NE, raising to +1.85 m during LW for winds coming from N. The largest increases are mostly found southwest or south of the extraction zones 2, around the extraction zone Oostdyck. This is mainly due to the fact that the waves are less breaking, due to bottom friction.

Figure 5: Right: largest increase and decrease in significant wave height at the model grid for simulation without extraction and with the new proposed extraction limit as a function of the wind direction, for three different wave heights at the boundaries (Hs=2 m – Ws=14 m/s; Hs=3 m – Ws=18 m/s; Hs=4 m – Ws=22 m/s) and for HW and LW water levels. Left: Position of the points were highest increase (red stars) and highest decrease (blue dots) in significant wave height are found for all simulations.



The effect in the neighbourhood of the extraction zones can be quite considerable, with an increase in significant wave height south of the extraction zone 2at the Buitenratel up to +1.85 m, but that the effect at the Belgian coast is negligible (Figure 6).

Figure 6: Results for simulation with waves at boundaries: Hs=4.0m, Dir=N; wind speed Ws=22 m/s. Upper left: Significant wave height with original bathymetry. Upper right: Significant wave height with extraction limit bathymetry. Lower left: Difference in significant wave height.



6.4.3. Simulations for 1000 yearly storm

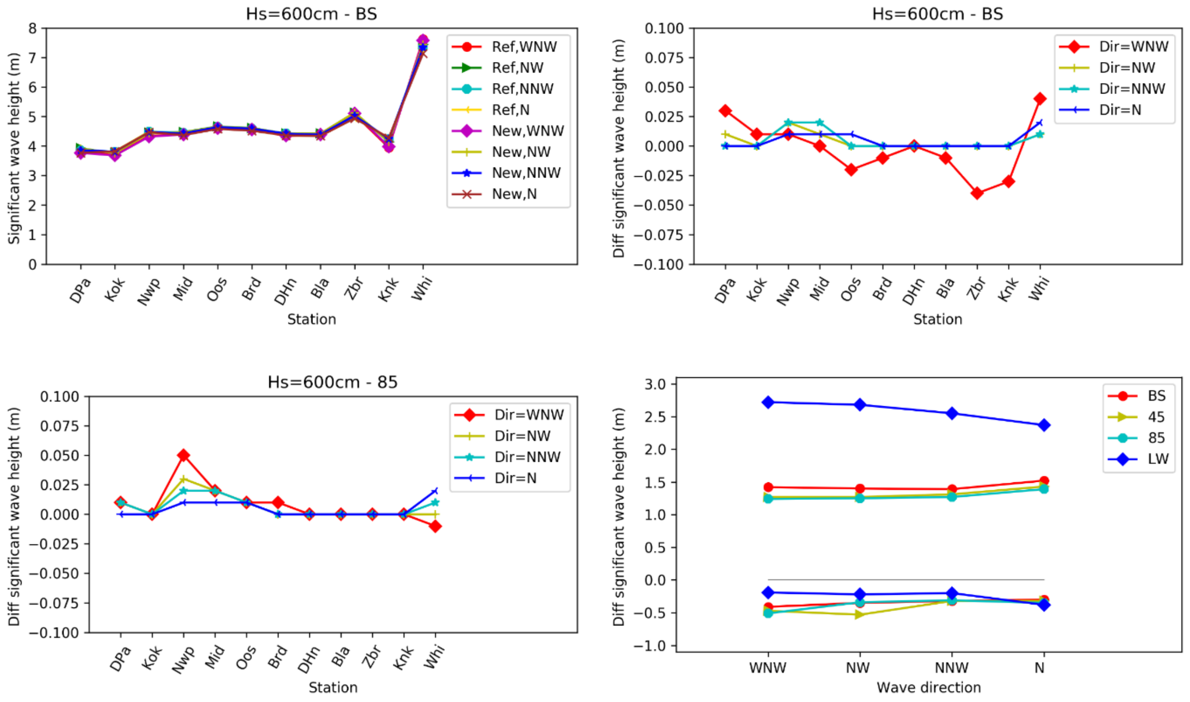
Also simulations were executed for the so-called 1000 yearly storm. In this case waves of 6 m are applied at the boundaries, the water level is set at 7 m above TAW (i.e., at 4.67 m above MSL). The peak frequency is set at 10.5 s and the wind velocity is put at 30 m/s (De Roo et al., 2014). Normally these boundary conditions are taken at station Westhinder. In this case the same boundary conditions were taken at the boundary of the new grid, which is extended more to the North. The simulations were done for 4 wind directions, which are N, NNW, NW and WNW since these directions contribute to the resulting extreme wave height near the coast and depending on the location, one direction can have more impact due to sand mining than the other. To take into account possible sea level rise on a longer term, reference was taken to the report of CREST and Coastal Project Coastal Vision (2019), were four common climate change scenarios for the Belgian coast were proposed. For the current study, the values based on the IPCC (2013) RCP4.5 and RCP8.5 were selected, using a sea level rise of +0.60 m and +0.85 m respectively for the year 2100.

Although it is very unlikely that a 1000 yearly storm with waves with significant wave height up to 6 m at the boundary occur with no storm surge, the simulations were also done with a very low water situation, namely with water level at MSL -2.33 m as reference. The simulations were executed for the reference bathymetry and for the bathymetry with the new extraction limit for extraction.

Results at the coastal stations

During this 1000-yearly storm, the significant wave height at De Panne and Koksijde remains below 4 m, while at the coastal stations from Nieuwpoort to Blankenberge, the significant wave height varies around 4.5 m (Figure 7). At Zeebrugge, the station a little bit more offshore, a significant wave height of more than 5 m is reached. At Westhinder, a significant wave height of more than 7.5 m is reached for winds from the WNW. Overall the highest wave heights are obtained for winds from the NW. The simulated wave heights at the coastal stations correspond well with the characteristic values given for the 1000 yearly storm conditions along the coastline in De Roo et al. (2014).

Figure 7: Upper left: Significant wave height at coastal stations and Westhinder for simulation with the new proposed extraction limit (New) compared to without extraction (Ref). Waves at boundary with significant wave height of 6.0 m, wind speed = 30 m/s, water level at 4.67 m MSL (1000 yearly storm). Results for different wave and wind directions. Upper right: Increase of significant wave height at coastal stations and Westhinder for simulation with the proposed extraction limit compared to without extraction, water level at 4.67 m MSL. Lower left: Increase of significant wave height at coastal stations and Westhinder for simulation with the proposed extraction limit compared to without extraction, water level at 5.52 m MSL (1000 yearly storm + sea level rise RCP 8.5).



The effects at the coastal stations and at Westhinder remain limited also for this case (Figure 7). Most effects are seen for waves and winds coming from NW and especially WNW. Only in these cases changes of more than 0.02 m are expected. The largest increase in significant wave height is for a sea level rise of +0.85 cm, where the increase in significant wave height is +0.05 m at station Nieuwpoort. For the current sea level, at station Zeebrugge and Knokke a decrease of significant wave heights is found of -0.04 m and -0.03 m respectively. Overall the effects are negligible.

For the situation with the 1000 yearly storm during low water level, the changes at the coastal stations are even less and are always below 0.02 m. Only for winds from N, an increase in significant wave height of +0.02 m is found for station De Panne. The differences are less than 1% of the obtained wave height in the considered points.

Results on entire Continental Shelf

The results at the Belgian Continental Shelf, more offshore, near the extraction zones are much higher, as expected. The maximum decrease in wave heights is again limited to -0.53 m, in this case for RCP 4.5 and for waves from NW. The maximum increase in wave heights for the 1000 yearly storm is +1.52 m for the waves coming from the North. This maximum increase is slightly lower when sea level rises of +0.60 m or +0.85 m are taken into account. For the 1000 yearly storm during low water (MSL -2.33 m) the maximum increase in significant wave height is much higher, up to +2.72 m, in this case from waves coming from the WNW.

6.5. Discussion

To evaluate the effects on coastal protection one considers the normal wave climate as well as the wave conditions during 1000 yearly storm conditions. The water levels can be assumed to be unaltered by the extraction scenarios due to the small size of the extraction zones compared to the southern North Sea area at which scale tides and storm surges are generated.

The normal wave climate drives changes in the coastline position. Positive gradients in alongshore transport and net cross-shore transport which is off-shore directed induce erosion of the coastline. The intensities of these transports are proportional with the significant wave height. From the SWAN model results, one observes very small changes of the significant wave heights along the coast, less than ±1 % on average. The impact of these changes on coastline erosion can be considered negligible.

The conditions during a 1000 yearly extreme storm determine the coastal safety level. Higher wave heights will result in larger erosion of dunes and dry beaches and in more overtopping of sea dikes and structures in the harbours. From the SWAN model results, one observes a very small increase of the wave height, 0.05 m maximum. However, this increase is so small that it can be considered negligible for the evaluation of the coastal safety level. This is confirmed by results of an earlier evaluation of sand extraction at the Kwintebank from coastal safety perspective (Verwaest and Verelst, 2006).

It can be concluded that the effect on coastal protection of the sand extraction scenarios considered is negligible. This conclusion is attributed to the large distance from the extraction sectors to the coastline, namely more than 10 km.

6.6. Conclusions

In the present study, the effect of extraction of marine aggregates on wave propagation to the Belgian coast was studied. More specifically, the impact of a newly extraction limit levels (Degrendele, 2016; Degrendele et al., 2017, this volume), on the wave propagation was investigated.

For the current climate 108 different simulations were executed with different significant wave heights at the boundaries (2 m, 3 m and 4 m), for different water levels (high water and low water) and for different wind and wave directions from SW to NE with an increment of 22.5°. The results showed that the effect of the extraction on the significant wave height at the coastal stations is very limited. Although in the neighbourhood of the extraction zones, an increase of significant wave height is possible up to +1.85 m, the effect at the coastline is negligible. Therefore, it can be concluded that the impact of the extraction scenarios considered on coastline erosion can be considered negligible.

For 1000 yearly storm conditions, some simulations were executed, including the effect of possible sea level rise (up to +0.85 m) until 2100. It was clear that large effects on the wave heights can be expected near the extraction zones, especially during low water situations, but that the effect at the coastline remains very limited to an increase of +0.05 m maximum (less than 1% increase). It can be concluded that the impact of the extraction scenarios on the coastal safety level is negligible.

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7. Impact of the Marine Spatial Plan 2020-2026 and the new reference surface on sand extraction in Belgium

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ZEEGRA is the Belgian federation of importers and producers of dredged sea aggregates. Its 10 member companies are all active in the extraction, production and marketing of marine aggregates to be used in the construction industry. The marine aggregates are extracted from various licensed areas in the North Sea. All members of ZEEGRA have a license to dredge sea sand on the Belgian Continental Shelf (BCS).

The fleet active in the Belgian part of the North Sea consists of ca. 15 dredgers with an average hopper volume between 2.000 and 3.000 m³

The total yearly extraction volume of marine construction sand from the BCS is at a maximum level of 15,0 million m³ over 5 years or on average 3,0 million m³ per year.

In order to qualify as a suitable sand-source for the construction industry, there are a number of key requirements to be fulfilled in terms of quality, quantity and cost.

1. Quality of the sand has to be good/sufficient and constant. Main quality parameters are grain size distribution, (absence of) organics, (low) shell content and colour.
2. Sufficient volumes have to be available now and in the future.
3. As in any economic activity, cost is an important aspect. Main parameters that drive costs in this case are sailing distances, dredging depth and the ability for in-line separation of oversize (>8mm).

Over the past fifty years, the use of Belgian marine sand in construction has gradually increased thanks to its own merit i.e. good and very constant quality, as a welcome substitute for the diminishing alternative (on shore) resources.

The legally imposed maximum level of 3,0 million m³ per year is now reached. Whether or not to increase this level is a political choice, whereby the balance is considered between current and future availability. Although sand can be extracted in a sustainable way, it is a non-renewable resource.

From the perspective of sustainability, the introduction in 2021 of the new reference surface as the bottom-limit for extraction is a major step forward. Reference is made to the presentation on this subject by the previous speaker, Mr. Koen Degrendele. The new reference surface is based on scientific principles and by respecting it, the following very important boundary conditions are automatically met:

1. The integrity of the seabed is best preserved as sand extraction is limited to the top sediment layer only.
2. The structure of the sandbanks are preserved, thereby ensuring their continued role in the protection of the Belgian coast.
3. The use of the available sand in mobile structures such as sand waves is maximised.
4. The impact on hydrodynamic conditions is limited.

The above boundary conditions are crucial to enable sustainable sand extraction over the long term. Neglecting any of these conditions, can very easily result in unacceptable impact of sand extraction, which in turn would undermine the economic activity.

Sand extraction is just one of the many activities taking place in the Belgian part of the North Sea. Other activities involve (in random order) shipping, green energy, the installation of cables and pipelines, nature conservation, fishing, military activities,… A Marine Spatial Plan (MSP) is an absolute necessity to reconcile these various (economic, ecological and social) interests and to provide every activity with an appropriate place in the rather limited space that is available in the Belgian part of the North Sea. Belgium was a pioneer in Europe and even in the world with its very first MSP for the period 2014-2020. The MSP covers a six year period. For the new cycle (2020-2026), it entered into force on 20th March 2020.

In Belgium, the MSP provides for sand extraction in legally defined areas called 'control zones'. There are currently five control zones where sand extraction is allowed, labelled with a number from 1 to 5. The quality and nature of the sand vary across the control zones as does the cost to extract the sand depending in function of dredging depth and sailing distance.

With the increased activity in the Belgian part of the North Sea, especially the increase of green energy, and the installation of additional cables and pipelines, very large volumes of good quality construction sand have been (temporarily) blocked from immediate access. This is no problem in the short term, but over the long term this definitely has to be a point of attention in marine spatial planning. Good quality construction sand is a vital and non-renewable resource. The extensive studies leading up to the new reference surface have confirmed the availability of very large sand resources outside the currently active control zones. These resources have to be safeguarded as a future reserve. Appropriate legislation is required with regard to the design and installation of offshore infrastructure, to enable the complete removal of all obstacles from the seabed at the end of the technical/economical lifetime of such infrastructure (e.g. foundations, cables, etc.). This will enable future spatial planning to make these reserves available again for sand extraction, whilst the control zones that by then will be extracted down to the defined reference surface, can then be made available for other seabed users. This long term dynamic interaction will have to be introduced more and more in the future spatial planning in order to safeguard and optimally use the scarce but very good quality sand reserves that Belgium possesses on its Continental Shelf.

In conclusion, both the new reference surface and the Marine Spatial Plan are very important for the long term sand extraction in Belgium – to the point that both are a condition sine qua non. Despite their relatively recent coming into existence, both the new reference surface and the MSP have already become part of a solid foundation that can continue to support the future of this economic activity for generations to come.

Keywords: Zeegra, marine aggregates, sand extraction, sand-source, sand quality, dredge, licensed area, availability, reserve, construction, industry, new reference surface, Marine Spatial Plan 2020-2026

8. SAND AND CIRCULARITY

Aiming at a symbiosis between the Geosphere and the Anthroposphere

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Natural sands and, in a broader sense fine aggregates under 4 mm, are the building blocks of our modern society. Their role is of utmost importance in the granular assemblage forming the internal structure of concrete, to ensure both optimal mechanical performance and long term durability.

Sand can no longer be considered as a renewable resource as our extraction rate from riverbeds such as the Rhine, far exceeds our annual consumption. Alternative materials have to be sourced either from industrial residues (ex. residual filler fraction from lime operations) or from crushed demolition waste.

In this paper, we will review the characteristics of available non-natural sand sources and analyse how they impact on physical properties of granular assemblages. In particular, we will consider the opportunities to achieve optimal mixes of both natural and non-natural sands and how this impacts on compactness, flowability, etc.

Particle size distributions and particle shape distributions clearly differentiate natural and non-natural sand fractions but they are not the only ones. Differences in mineralogy, particle porosity and trace elements purity are also important. They have to be carefully analysed before considering the possible, partial or total, substitution of natural sands by crushed materials.

As a conclusion the highly celebrated circular economy paradigm also applies to sand resources, but the reality is closer to the one of a spiral economy, where the initial functional value of a natural material is progressively lost. The challenge being to slow down this functional degradation and make sure that future generations will still have access to a unique resource called SAND.

Keywords: circular economy, aggregates, mineral

9. Circular economy in the construction sector – sand in an eternal cycle?

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9.1. Sand: a finite but not (yet) scare ressource for the construction sector?

The construction sector uses sand in many applications: concrete, mortar, building blocks, glass, foundation layers, …. Distinction is made between the 'fine' sand or filling sand, used in landscaping and 'coarse' sand, coming from rivers, the sea, sand pits and manufacturing processes in quarries.

Currently, the excavation and use of sand worldwide is twice as big as the natural production : 40 vs. 20 billion tonnes.[3] Also in Belgium, about 30 million tonnes of sand is used each year in construction, whereas Belgium only produces half of that amount (2 million tonnes form the sea, 6.8 million tonnes in Flanders and 7 million tonnes in Wallonia) – about 15 million tonnes are imported each year. It is assumed that the upcoming 25 years, no real import and supply problems are to be foreseen. However, incidents like long dry periods in the summer can cause temporal problems. In the upcoming period of 30 years, no real changes in the need for sand for the construction sector are expected – conjuncture may fluctuate, but will remain more or less on the same level.

Although quite stable for the moment, it is important the construction sector looks and thinks ahead, and tries to assure the possible use of qualitative sands in the future. Two main concepts are presented in the following paragraphs as a framework to work out solutions for the use of sand in eternal cycles.

9.2. Circular economy in the construction sector

A concept that is gaining importance and attention in the construction sector is circular economy. "The circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended. In practice, it implies reducing waste to a minimum. When a product reaches the end of its life, its materials are kept within the economy wherever possible. These can be productively used again and again, thereby creating further value. This is a departure from the traditional, linear economic model, which is based on a take-make-consume-throw away pattern. This model relies on large quantities of cheap, easily accessible materials and energy."[4]

Translated to the construction sector, the concept of circular economy can be structured according to 3 main axes:[5]

- Circular design & construction : creating building from which the materials can be easily recovered at the end and buildings with a long service life, allowing flexibility and adaptability to changing needs & demands.
- Urban mining : using the existing building stock as a source ('mine') of new construction materials, focussing on reuse and recycling.
- Business models : creating an added value throughout the service life of a building or product (eg. through sharing, waste as resource or product-as-a-service).

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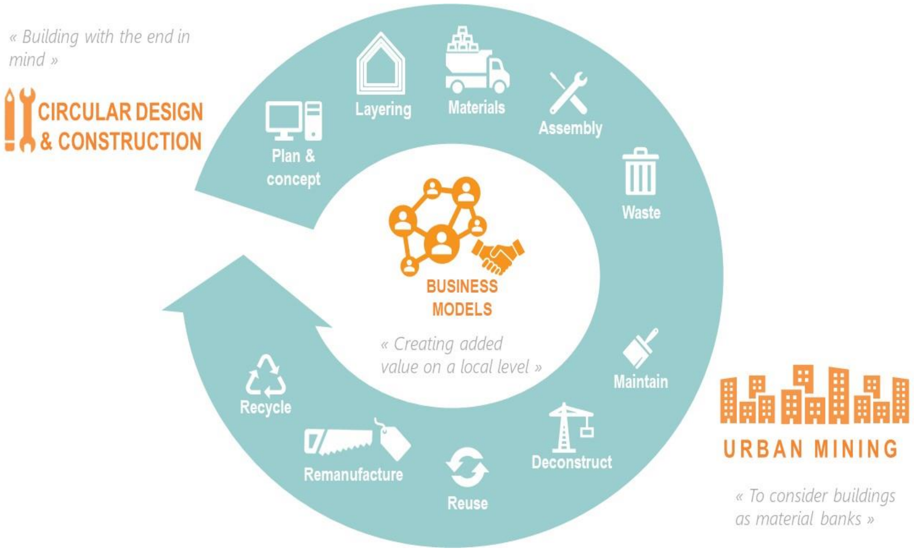
[3] https://wedocs.unep.org/bitstream/handle/20.500.11822/8665/GEAS_Mar2014_Sand_Mining.pdf?sequence=3

[4] https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits

[5] https://www.wtcb.be/publicaties/monografieen/28/#:~:text=Deze%20monografie%20geeft%20een%20overzicht,nieuwe%20markten%20...).



9.3. Trias materialis: solutions for sand in the construction industry

While in theory there is enough sand available in the mid-long term in Belgium, some factors are and will be limiting in the future, like the availability of excavation sites and the negative impacts of excavation to the environment. Thus considering the 'limitedness' of sand in the future, several options are available (and to be combined) to face the upcoming challenges. In analogy with the energy question, solutions can be developed according to 3 axes – the "trias materialis":

- Reducing the need or demand for sand
    - In principle, reducing construction activities as a whole could be an option; although a growing population and a densification in combination with a renovation wave don't make this scenario plausible
    - Realising a shift from mineral materials to other materials, eg. using PU-glue instead of mortar, or using wood (CLT, …), steel, plastics, … instead of concrete
    - Improving soil and geotechnical constructions instead of using sand and/or concrete constructions, using technologies like soil-mix, geocomposites, ….
    - Reusing materials and structures by renovation rather dan demolition, and reusing bricks, concrete elements, tiles, …

- Using renewable and alternative resources replacing natural sand
    - Upgrading/using fine sands like dessert sand, however this faces a lot of technical challenges
    - Using different types of soil, for eg. rammed earth applications[6]
    - Using construction and demolition waste, or rather the recycled aggregates produced from them. Many research is done and ongoing to realise the potential of using recycled sands in concrete. An important remark to make is that the availability of recycled sands is limited in comparison to the need for sand in Belgium each year.
    - Using other waste flows like cellular concrete, glass, ashes and slags, … where attention must be paid to the effects on the so called third life (recyclability) and the availability of these material flows in the future.

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[6] https://www.bcmaterials.org/concept-nl.html

- Using sand more efficiently where it is needed
    - Efficiency can be found in a better design of concrete structures, a more precise and qualitative execution and using more innovative building concepts.
    - Efficiency can also be found in creating more value with less materials, eg. smaller houses, less infrastructure through densification.

9.4. Conclusions

Many technological developments are ongoing to address the potential scarcity of construction sand in the future. Concepts like the circular economy and the trias materialis can help in the future to use sand efficiently and integrate alternatives in practice.

In order to do so, some non-technical barriers will need to be addressed as well, ranging from more systemic problems in the construction sector (e.g. focus on lowest investment cost, lack of confidence and cooperation throughout the complex construction chain, …) to societal and political factors (eg. trading off the ability to fulfil in the own material needs against the effects on the environment or the importance of other societal or political goals).

10. Substitution sand in road engineering, a product from the recycling of Shredder Residues of Metallic wastes Sand: recycled more efficient than the natural

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Born from the recycling dedicated to ferrous and non-ferrous materials, the COMET group has developed different expertise and innovations in the recycling professions, with new highly technological plants.

Awarded in 2016 by the Belgian Circular Economy Prize, the Mons plant produces artificial sand that has physical properties superior to natural sand for the formulation of bituminous asphalt.

Today, the COMET Group has about thirty companies in Belgium and France and employs nearly 400 people. It treats more than one million tons of metal waste per year (construction scrap, light scrap, end-of-life vehicles and household appliances depolluted, solar panels dismantled, scrap from recycling parcs, etc.). With these volumes, the COMET Group has become an important supplier in terms of secondary raw materials for industry.

With regard to the mineral fraction from photovoltaic panels, end-of-life vehicles or WEEE, the R&D teams of Comet Traitements, in collaboration with the University of Liège and a road infrastructure manufacturer and supported by the General Directorate of Economics of the SPW (Public Service of Wallonia), have implemented a concentration and purification process that makes it possible to obtain a technical sand that combines several undeniable advantages:

- Physico-chemical properties superior to natural marine sand that improve the strength of bituminous asphalt;
- An environmental gain, by reducing the pressure exerted on a scarce natural resource;
- A contribution to the challenges of mobility and reduction of CO2 emissions related to transport, given the local circularity solution.

Thanks to these undeniable qualities, after several strict field analyses, the Public Service of Wallonia has included this sand as a possible official component in bituminous mixtures for Walloon public roads (Specifications-type "Qualiroute").

In general, the COMET group is thus involved in a long-term solution research for the new products reaching the end of their life, with the maximum possible circularity (currently 97.8% recycling rate based on inputs). It should be noted that the COMET Group, associated with the social economy company RECMA, has just been awarded a large multi-year contract for the treatment of photovoltaic panels in France.

Since solar panels are made of 75% glass, the deposit in question here (20,000 tons by 2026) will inevitably contribute to the technical sand replacing even more its natural cousin, for the greater good of our environment.

Keywords: metals, recycled sand, bitumen

11. Climate change adaptation and circular economy – the role of the European marine aggregates industry

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Large quantities of building materials such as gravel and sand are needed to adapt to the impacts of climate change. The marine aggregates industry can play a crucial role in implementing necessary coastal protection measures and coastal infrastructure projects, as well as in the construction of renewable energy plants and environmentally friendly, energy-efficient buildings. Especially in coastal regions where local, land-based sand and gravel deposits are increasingly scarce or non-existent, marine deposits play an important role in the supply of raw materials. For certain coastal protection measures and projects, they are without alternative.

To fill supply gaps, large quantities of sand and gravel can be delivered by sea close to where the product is needed. This reduces traffic and transport distances, thus lowers transport related CO2 emission.

Primary aggregates, such as marine gravel and sand, are essential to cover the entire demand for construction materials, as recycled materials and biomass products are insufficient or unsuitable to cover demand. Nevertheless, the products made from marine aggregates, such as concrete, can be recycled later and fed into a sustainable material cycle.

Marine aggregates should be considered as a key element for climate change adaptation and the supply of raw materials to the building materials industry.

Keywords: marine aggregates, climate change adaptation, circular economy, EU Green Deal

12. Marine sand and coastal safety

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The impact of climate change on the coastal region and by extension the province of West Flanders, the Flemish region and the federal state is particularly large. Extensive statistical analysis of the measured water level at sea already showed a linear long-term sea level rise of +2 mm per year (Oostende 1925-2014). In addition to the water level, the wave setup and wave action also determines the condition of our first-line sea defenses and the ability to maintain it. The level of protection is determined on the basis of extreme values statistics, whereby a sea level rise of one meter already implies a risk increase by a factor 100.

The possible consequences of extreme storm surges are correspondingly. Calculations indicate that at an expected water level of +7m TAW, the human toll and material damage as a result of a failing sea defense, possible dike breaches and flooding, is extremely great. So we'd all better be well prepared for this imminent threat, whatever climate scenario will unfold in reality.

The Agency for Maritime and Coastal Services is responsible for your coastal safety in Belgium and the implementation of adaptive measures now and in the near future. On June 10th 2011, the former Flemish Government approved the Master Plan Coastal Safety. The official start of the implementation took already place in the autumn of that same year with a medium beach nourishment in Koksijde. We are now ten years beyond that milestone, ten years of investing in a safe, attractive and natural coast.

The principle choice from start was convincingly made in favor of soft, flexible measures wherever possible, rather than rigid, hard measures. We therefore prefer to work with natural solutions (Nature Based Solutions) to strengthen this natural, sandy coast of beaches and dunes. Nourishments are still the basic solution. On a wider and higher beach, waves can break and lose their energy before they can damage the seawall or the buildings on top. The final findings of the 2019 CREST research project demonstrated that this flexible approach actually works. By adding extra sand to the beaches, to the foreshore (= the stretch of beach just below the low-water mark) or at the foot of the dunes, we do not only reinforce the sea defense but also strengthen the natural coastal dynamics and ecology. Finally, it is a flexible solution that allows the coast to grow with the rise in sea level. With the replenishment of Knokke-Heist (works partially carried out in Duinbergen during the spring of 2021), the ultimate goal of the Master Plan to raise our protection level against storm surges with a return period of 1 in 1000 years, is clear in sight.

Apart from the adaptation measures in the context of a future-oriented coastal vision, we fall back on a necessary maintenance regime. The sand that disappears from the dry beach or tidal zone during a storm is moved towards the low water mark and the foreshore and still contributes to the safety level. Research shows that after a storm, some beaches partially recover spontaneously within the following months. The wind and tide return some of the washed-away sand to the beach. At the same time, the maintenance nourishments strengthen the dunes and erosive zones and provide a protective buffer for the sea dikes against the force of nature.

Since 2011, 13.2 million cubic meters of sand has been deposited on our beaches in the interest of coastal safety. About 84% of this comes from the primary licensed extraction zones on the Belgian Continental Shelf. The remaining 16% falls under the term beneficial use. Sandy dredged material or sand from small to large (infrastructure) works on- and offshore, finds a useful application in sea defenses if all quality requirements can be met. The intention is at least to increase this share in the coming years and to actively look for new synergies around. Therefore, the sand demand for primary sea sand originating from the BCP can be significantly reduced, aiming to make a positive contribution to the circular use of raw materials and reducing the cost of the nourishment program.

Even better is when the sand can also be retained in those exact places where it is of maximum use. Successful projects involving the planting of marram grass and the fixation of sea defense dunes are in full development in Westende, Raversijde, Mariakerke and Oostende Oosteroever in collaboration with various scientific institutions.

At the beginning of October 2021, the construction of four new beach groynes in the critical and maintenance-intensive area around Wenduine has started. The purpose of this proven technique is also to retain the sand and to reduce longitudinal transport to the marina of Blankenberge.

Finally, special attention should also be paid to the final part of the Masterplan coastal safety, adjacent to the Dutch border. In the period 2016 to 2019, sand from deepening the main channel at the Zwin entrance was used for the construction of the core of a new 4km International Zwin Dike. Large-scale works that led to the rebirth of the Zwin nature reserve.

POSTERS

Coarse sand or fine sand? Illustrating the importance of gradients in seafloor characteristics when developing classifications of sand extraction zones based on MBES.

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Over the last 20 years, multibeam echosounder (MBES) bathymetry and backscatter data and sediment samples have been acquired at regular intervals to monitor the impact of marine aggregate extraction in the Belgian part of the North Sea (BPNS). Although very valuable to monitor changes in seabed characteristics, no systematic and repetitive classifications of the seafloor were produced with these data until now.

Anticipating on a next era in multibeam monitoring with the new RV Belgica, a specific approach is being developed to (1) map gradients in seafloor characteristics based on MBES data acquired at different frequencies and sediment samples and (2) identify gradual changes in seafloor characteristics over time. To achieve this, a detailed characterization of the acoustic, sedimentological, geotechnical and macrobenthic properties of archetypal morpho-sedimentological environments of the BPNS is required.

A preliminary version of the classification approach is developed and tested on former MBES data acquired at 300 kHz. The approach relies on the hyper-angular cube concept [Alevizos and Greinert, Geosciences, 8, 446 (2018)] and fuzzy classification approaches.

The poster illustrates:

1. why the concept of gradients in seafloor characteristics is critical when classifying environments such as the BPNS based on a MBES mapping and sediment sampling that was realized along a transect across the Kwinte – Kwintebank with the RV Simon Stevin (Figure 1);

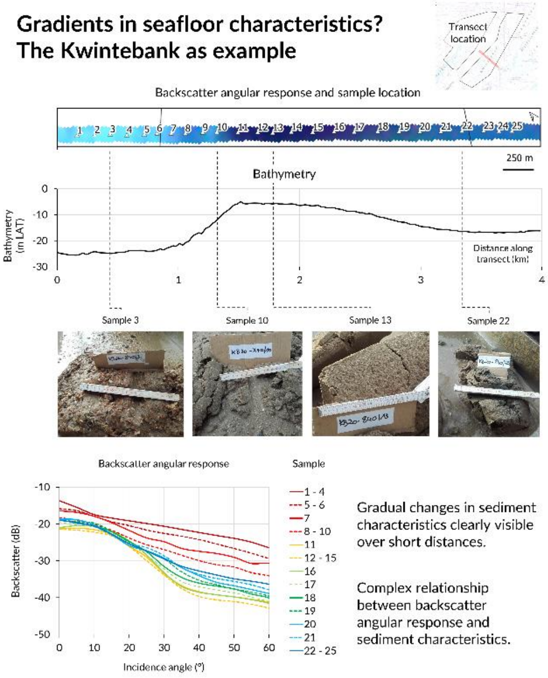
2. the added value of the hyper-angular cube concept to discriminate different seafloor types;

3. how the concept of gradients can be accounted for when classifying MBES data and;

4. some preliminary classification results based on historic MBES data acquired on the Buiten Ratel.

Keywords: classification, multibeam echosounder, backscatter angular response, sediment samples.

Figure 1. Illustration of gradients in seafloor characteristics on the Kwintebank.



Gradients in seafloor characteristics? The Kwintebank as example

Gradual changes in sediment characteristics clearly visible over short distances.

Complex relationship between backscatter angular response and sediment characteristics.

From paper to bits: Towards the digitalization of the register

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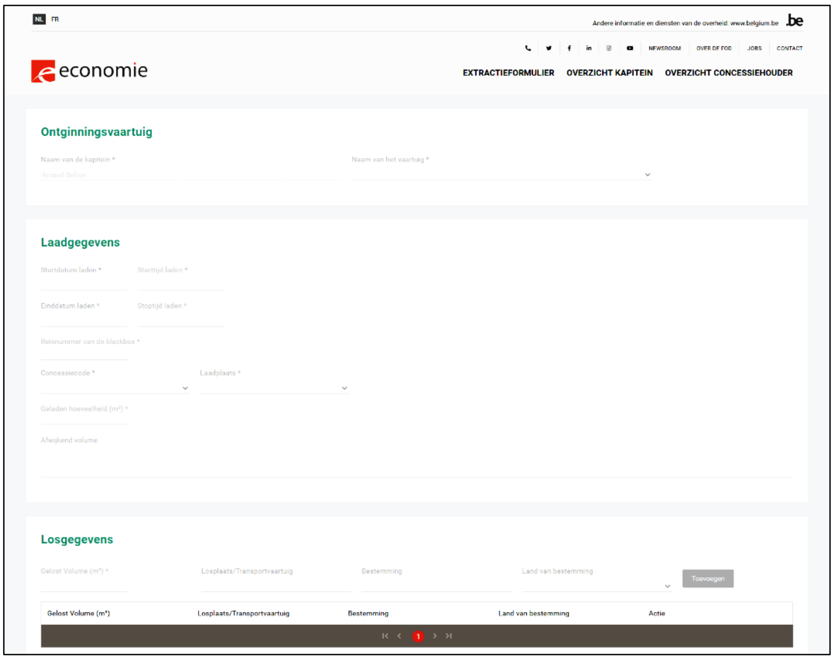
The corona pandemic highlighted the need to simplify the exchange of the register (i.e. sand extraction declaration form). The Continental Shelf Service therefore started a project in collaboration with the IT-department of the FPS Economy to digitize the register. The digitalization of the register will benefit to all the parties involved in the use of the register by among others (1) bringing an end to the exchange of the paper-based register and (2) simplifying and speeding up the management of the registers (e.g. visualization, validation and control of the register), as well as the exchange of information between the parties.

A dedicated online application is currently in development to digitize the register. The application will consist of three modules. The first module will allow the captain or second mate of an aggregate extraction vessel to fill, eventually adapt (for a limited period of time), query, visualize and export declarations. The declaration form is illustrated in Figure 1. The second module will allow the concession holder to visualize, eventually adapt, query, validate and export the declarations attributed to their concession. The application will allow the concession holders to monitor their extraction activities in near real time (i.e. once the declaration has been submitted and the period dedicated for eventual modifications elapsed). The third module will allow the Continental Shelf Service to manage the application, as well as to visualize, query and export declarations.

The testing of the application is expected in the fall of 2022. The effective use of the application is expected for the beginning of 2023.

Figure 1. Illustration of the sand extraction declaration form.



Ontginningsvaartuig

Naam van de kapitein *
Arnaud Dehon
Naam van het vaartuig *

Laadgegevens

Startdatum laden *
Starttijd laden *
Einddatum laden *
Stoptijd laden *
Reisnummer van de blackbox *
Concessiecode *
Laadplaats *
Geladen hoeveelheid (m³) *
Afwijkend volume

Losgegevens

Gelost Volume (m³) *
Losplaats/Transportvaartuig
Bestemming
Land van bestemming

Gelost Volume (m³)	Losplaats/Transportvaartuig	Bestemming	Land van bestemming	Actie

Keywords: digitalization, register, sand declaration form

Acoustic cartography of the Sierra Ventana extraction and dumping area

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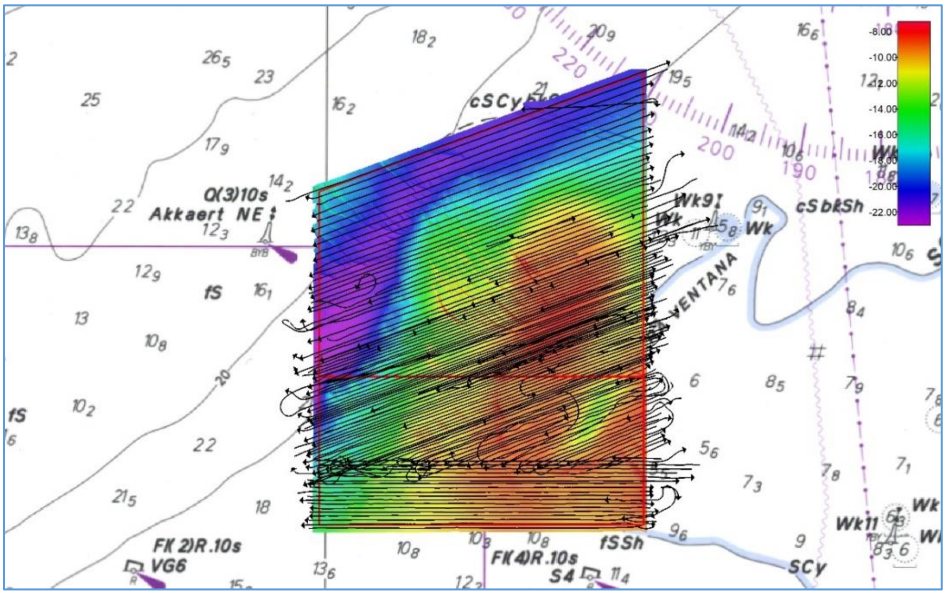
To evaluate the global impact of sand extraction, to establish the reference surface, and to accurately map the available resources, the Continental Shelf Service executes a continuous mapping program of the extraction areas. Due to the change in boundary of control zone 3 in the last Marine Spatial Plan, the Sierra Ventana area was re-mapped from November 2019 till September 2020.

The cartographic project was executed on board the RV Belgica, using the Kongsberg EM2040D at 300kHz. Spanning four campaigns and 173 survey lines this resulted in more than 900.10^6 available soundings (see figure 1). After thorough cleaning and processing of the bathymetry, detailed models of each survey were constructed and combined in one global terrain model of the entire control zone. Simultaneously the recorded backscatter values were processed to produce a reflectivity map.

Figure 1. Bathymetry (in meter LAT) and survey lines (in black) of the cartographic project on the control zone (in red) on the Sierra Ventana.

Background: hydrographic chart D11 – Flemish Hydrography



Building on this data the evolution between the former reference model for the area (constructed with EM1002S MBES data from 2005 and 2006) was mapped and the available Holocene sediment layer was re-evaluated. Both illustrate the diverging evolution in both sectors: accretion of material in the northern sector b, where dumping took place during the entire timespan, and decrease in the southern sector, witnessing increasing sand extraction. First and second derivative maps emphasize the main geomorphological features of the Sierra Ventana area: natural sand waves and ripples and the traces of the principal human activities in each sector: dump mounds in the north and dredge furrows in the south.

Keywords: Sierra Ventana, MBES, Bathymetry, Anthropogenic impact, Sand Reserve

The new RV Belgica shallow water multibeam echosounder

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A strong synergy links the Continental Shelf Service (COPCO) of the FPS Economy (FPSE), in charge of the control on the sand extraction, and the Operational Directorate Natural Environment (OD Nature) of the Royal Belgian Institute of Natural Sciences (RBINS), in charge of the old and the new Belgica. Between 1999 and 2020, COPCO financed and maintained two generations of multibeam echosounders (MBES) that were installed on the A962 Belgica. During this period, COPCO has carried out its legal mission of mapping and monitoring the sand extraction areas in the Belgian part of the North Sea with the required quality level. One of the essential factors in this success has been the optimal operation of the A962 Belgica, which has enabled COPCO to carry out practically without interruption, the measurement campaigns at sea required for its legal mission.

Building on the excellent cooperation, FPSE - COPCO supported the new research vessel Belgica by financing a high resolution shallow water MBES and its auxiliary sensors. The shallow water MBES installed on the new RV Belgica is a Kongsberg EM2040 model 04 MKII with two receivers (Dual Rx). It can operate at three frequencies of 200, 300 and 400 kHz with beam widths of 0.4° in transmit and 0.7° in receive at 400 kHz. This system allows the use of multi-frequency mode by alternating pinging at 200, 300 and 400 kHz. The control software includes many settings (emission, transmit sector and beam spacing modes, pulse length…), permitting trained users to select the optimal settings for their specific needs. This MBES is fully adequate to acquire seabed bathymetric and backscatter (BS) high resolution data required to fulfill the legal monitoring obligations (e.g. sand extraction, MSFD) in the Belgian part of the North Sea. Furthermore, this equipment is essential for the achievement of innovative research projects (e.g. high resolution habitat mapping, quantification of suspended particulate matters in the water column).

After the design by RBINS, Kongsberg and Freire shipyard (in charge of the construction of the new Belgica), the EM2040 Dual Rx was installed on the port side drop keel of the vessel together with a Kongsberg MGC R3 SB motion sensor and gyrocompass and a Valeport miniSVS Sound Velocity Sensor (figure 1 next page). The EM2040 Dual Rx and its auxiliary sensor installed on the port drop keel are connected to the processing unit, which receives the position data from the Kongsberg Seapath 380-R3 and the VERIPOS GNSS receivers, and the ship's motion data measured by the MGC-R3 located near the centre of the vessel. This system architecture allows a precise control of the location and motion of the MBES and a regular maintenance of the transducers from inside the vessel. The vertical position of the drop keel is adjustable up to 2.5 m below the flush position and is controlled by a cable extension position sensor ASM posiwire WS21.

The new RV Belgica shallow water multibeam echosounder performance was evaluated through a series of measurements carried out jointly by COPCO, RBINS, Kongsberg and Freire. The surveys took place on 6, 7 and 8 February 2020, off the coast of Vigo, and at depths ranging from 50 to 200m. The measurements, all carried out in CW emission mode, demonstrate that the EM2040 Dual Rx as installed on the new research vessel Belgica and connected to its auxiliary sensors meets the technical specifications stipulated by the manufacturer. In particular for COPCO, the final Sea Acceptance Test surveys on 50 m deep flat and rocky areas with an opening angle of 75° confirm that this new generation MBES has the qualities required to ensure our legal mission of monitoring the sand extraction in the Belgian part of the North Sea (figure 2). The SAT was signed by Kongsberg Spain, COPCO and RBINS on 8 February 2021 on board the Belgica.

The transit of the RV Belgica from Vigo to Zeebrugge is scheduled for December 2021. Measurements will be made around and in the Bay of Brest on several reference areas and targets to perform a fine patch test and to evaluate the hydrographic quality in XY and Z of the EM2040 Dual Rx. The French Naval Hydrographic and Oceanographic Service (SHOM, F) will perform a quality control of the bathymetric measurements and issue a hydrographic certification based on the results. On the reference area Carré Renard in the Bay of Brest, a series of controlled backscatter measurements at different frequencies using usual modes - settings will be carried out to calibrate the backscatter according to the method used by the French Research Institute for Exploitation of the Sea (IFREMER, F, Eleftherakis et al 2018, MGR https://doi.org/10.1007/s11001-018-9348-5). Backscatter measurements will also be carried out on the Kwinte reference area just before the long-awaited arrival of the RV Belgica in Zeebrugge. The analysis of the backscatter data and the creation of the BScorr file will be done jointly by COPCO and IFREMER and independently by Kongsberg, using its own methodology. In the future, the derived BScorr file will allow acquisition of online calibrated backscatter during surveying.

Figure 1. The new RV Belgica EM2040 dual Rx shallow water multibeam echosounder.

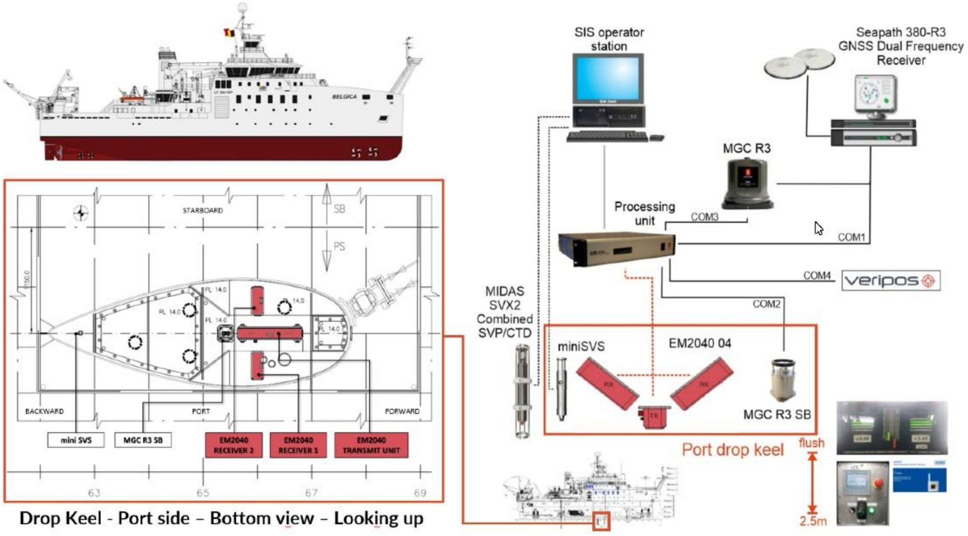
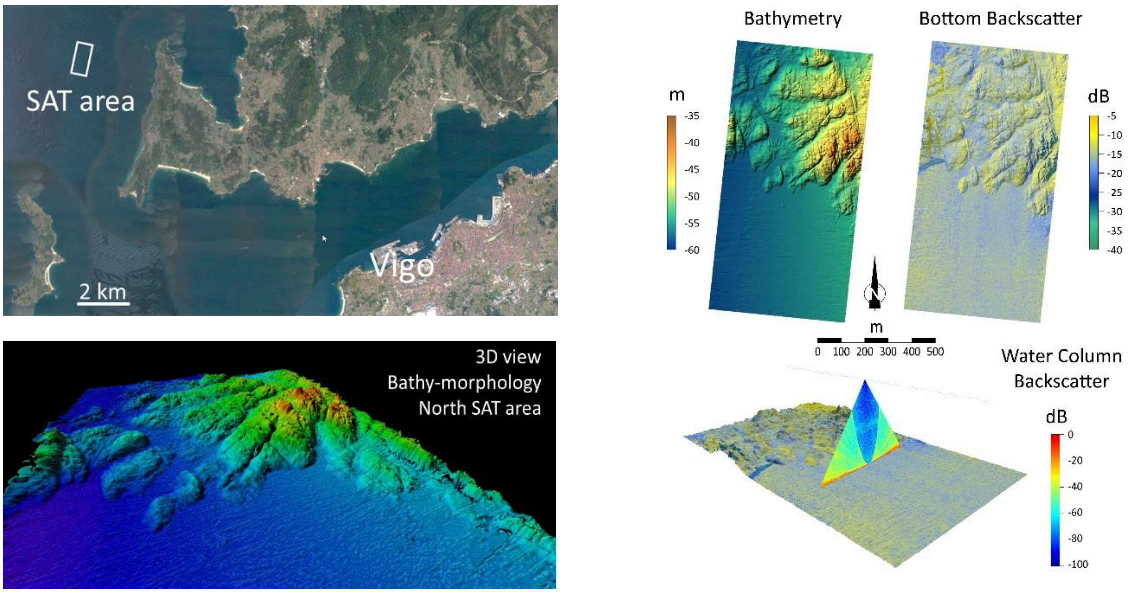


Figure 2. Location, bathymetry, backscatter and water column image of the 08/02/2020 SAT survey near Vigo.



Quantifying Suspended Particles Matter (SPM) Plumes to assess the far field impact of sand extraction: a new multidisciplinary challenge

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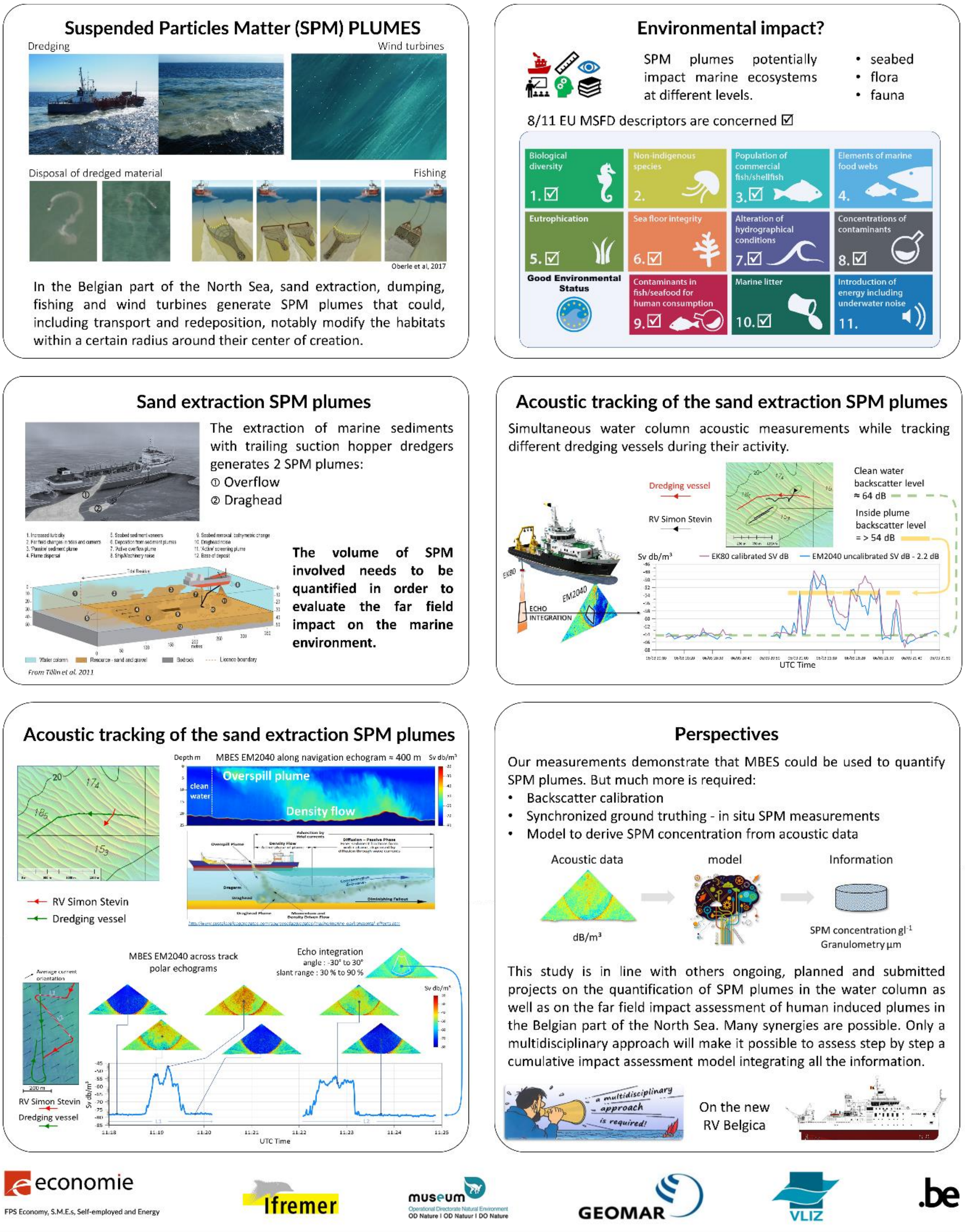
The Belgian part of the North Sea is an area of dense economic activities generating various impacts on the marine environment. Most of these activities are closely monitored, but important questions remain regarding the cumulative far field impact. This delayed impact is induced by the plumes of sediment particles generated by human activities which coexist close to each other. To the point, human-induced Suspended Particle Matter (SPM) plumes could, through transport and redeposition, notably modify the habitats within a certain radius around their center of creation. After 20 years of monitoring the impact of sand extraction on the seabed, on and near the extraction areas (direct near-field impact), it is now time to assess the impact that sand extraction may have on the marine environment at greater distance outside the extraction areas (far field impact). Far field impact assessment is a complex scientific issue that must be studied rigorously and comprehensively by integrating all the aspects involved (e.g., nature and source of the sediment plume, hydrodynamics, measurement tools). The combination of sediment transport predictive models with measurements at sea (e.g. calibration of the sensors involved, rigorous spatial and temporal synchronization of acoustic and in situ measurements, real-time integration of hydrodynamic models) is a serious challenge.

Several multibeam echosounder (MBES) water column measurements have been carried out in recent years to assess the potential of this technology for tracking sediment plumes generated by sand extraction. During one dedicated survey, series of simultaneous acoustic water column measurements were conducted with a Kongsberg EM2040 dual RX MBES and a Simrad EK80 calibrated single beam echosounder (SBES) onboard the RV Simon Stevin, while closely following sand dredging vessels during their activity. RBINS - OD Nature, IFREMER, GEOMAR and VLIZ participated in the measurements, the analysis of the data and in the development of specific algorithms to extract statistics from the measured amplitudes in the water column. The dynamic observation of polar and longitudinal echograms derived from the acoustic volume backscattering strength (Sv in dB/m^3, normalized for the volume of water involved), revealed vortices of highly variable Sv levels that could be attributed to SPM plumes generated during the dredging operations. The development of specific echo-integration algorithms makes it possible to quantify the Sv level within different slant ranges and angular intervals of the water column, as a function of time. Sv level time series acquired near the seabed made it possible to distinguish between stable Sv levels, characterizing water masses that are not affected by human activity, and intense and fluctuating Sv level phases, linked to the presence of sediment plumes. Fundamentally missing at this stage, is an inversion model to derive the concentration of SPMs from Sv values, assuming an average SPM grain size. Various projects are underway to establish such model on an empirical basis from highly controlled measurements with calibrated sensors. With its armada of calibrated acoustic instruments, the new RV Belgica will be an important tool to achieve this.

The sediment plumes generated by human activities at sea are difficult to grasp due to their diffuse nature, implying strong spatial and temporal variability. Their quantification with currently available scientific instruments is feasible but highly challenging, requiring suitable logistics, the implementation of dedicated calibrated acoustic devices synchronized with in situ SPM measurements and inversion models to derive SPM concentration from acoustic data. Real-time integration of hydrodynamic models combined with precise positioning of research vessel and sediment plume source, must be considered as well. Only this multidisciplinary quantitative approach to the entire dynamic life cycle of sediment plumes will lead to an assessment model of the far field impact of sand extraction.

Figure 1. Themes presented on the poster.



Suspended Particles Matter (SPM) PLUMES

In the Belgian part of the North Sea, sand extraction, dumping, fishing and wind turbines generate SPM plumes that could, including transport and redeposition, notably modify the habitats within a certain radius around their center of creation.

Environmental impact?

SPM plumes potentially impact marine ecosystems at different levels.

- seabed
- flora
- fauna

8/11 EU MSFD descriptors are concerned ☑

1. ☑ Biological diversity
2. Non-indigenous species
3. ☑ Population of commercial fish/shellfish
4. Elements of marine food webs
5. ☑ Eutrophication
6. ☑ Sea floor integrity
7. ☑ Alteration of hydrographical conditions
8. ☑ Concentrations of contaminants
9. ☑ Contaminants in fish/seafood for human consumption
10. ☑ Marine litter
11. Introduction of energy including underwater noise

Sand extraction SPM plumes

The extraction of marine sediments with trailing suction hopper dredgers generates 2 SPM plumes:

① Overflow
② Draghead

From Tillin et al. 2011

The volume of SPM involved needs to be quantified in order to evaluate the far field impact on the marine environment.

Acoustic tracking of the sand extraction SPM plumes

Simultaneous water column acoustic measurements while tracking different dredging vessels during their activity.

Acoustic tracking of the sand extraction SPM plumes

Perspectives

Our measurements demonstrate that MBES could be used to quantify SPM plumes. But much more is required:

- Backscatter calibration
- Synchronized ground truthing - in situ SPM measurements
- Model to derive SPM concentration from acoustic data

This study is in line with others ongoing, planned and submitted projects on the quantification of SPM plumes in the water column as well as on the far field impact assessment of human induced plumes in the Belgian part of the North Sea. Many synergies are possible. Only a multidisciplinary approach will make it possible to assess step by step a cumulative impact assessment model integrating all the information.

On the new RV Belgica

Keywords: Sand extraction, Suspended Particle Matter SPM, plumes, far field impact.

Effects of sand extraction on epibenthos and demersal fish assemblages

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Background

In Belgium, marine sand extraction has been growing since the 1970s, steadily gaining economic value over the years. In recent years, around 3 to 4 million m^3 of sand has been extracted yearly from sandbanks in the Belgian Part of the North Sea (BPNS) (FOD Economie site). Sand extraction activities have the potential to affect the marine ecosystem (Froján et al., 2011; Waye-Barker et al., 2015). Changes in the macrobenthic community due to sand extraction have been observed in a number of areas in (De Backer et al., 2010; Froján et al., 2011; Waye-Barker et al., 2015; De Backer et al., 2017) and around the North Sea (Desprez, 2000; Cooper et al., 2008; Krause et al., 2010). Because of the direct link between macrobenthos and the sea bottom, they are ideal candidates for quantifying sand extraction impact. Hence, most studies have focused on the effect of sand extraction on the macrobenthic ecosystem component. Nonetheless, it remains important to incorporate as much associated ecosystem components as possible to get a more holistic evaluation of induced changes on the marine ecosystem. Therefore, the focus of this study is on the effects of sand extraction on epibenthos and demersal fish assemblages in the BPNS.

We studied the most intensively extracted sandbanks Buiten Ratel (BR), Thorntonbank (TB) and Oosthinder (OH). Whereas the latter has been exposed to intense extraction for coastal protection during a short period in the year, BR and TB have been exploited intensively more continuously throughout the year to serve industrial purposes. The Buiten Ratel used to be an ‘extraction hot spot’ up to 2014. In total 11.6 million m^3 of sand has been removed from this area, mainly between 2007 and 2014 (Roche et al., 2017). After the closure of this extraction zone in January 2015, dredging activity shifted towards the Thorntonbank, that has been subjected to a steady increase in extraction pressure since 2010. By 2016, the cumulative volume of extracted sand reached 10 million m^3, making this area the epicentre of industrial sand extraction in more recent years (Roche et al., 2017). Extraction on the Oosthinder started in 2012 and has since then shown extraction peaks during a couple of months of the year followed by months without extraction. In 2014, for example, a substantial extraction peak of 2.6 million m^3 took place and more than half of this volume was extracted within 2 months (Roche et al., 2017).

This study aimed to investigate how these different extraction regimes affect the epibenthos and demersal fish assemblages within these three extraction areas. Several trawl samples were taken both inside and outside the extraction areas. Sampling was done in autumn with an 8 m beam trawl with a fine-meshed shrimp net (stretched mesh width 22 mm in the cod-end), mainly between 2009 – 2019. For TB, a baseline study was carried out in 2004, hence these data were also taken into account. Several statistical analyses were performed using Primer 7 with Permanova add-on. Our main findings are based on Permutational multivariate analysis of variance (PERMANOVA) and principal coordinate analysis (PCO). All required assumptions for the used techniques were taken into account.

Results and discussion

Effects of long term continuous, increasing (TB) and decreasing (BR) sand extraction

For Thorntonbank, a time series covering years with no extraction (baseline period, 2004), lower extraction activity (period moderate, 2010 - 2014; < $1x10^6 m^3$ sand/year) and more recent years with higher extraction impact (period heavy, 2016 - 2019; >$1.5x10^6 m^3$ sand/year) was available. For Buiten

Ratel, a distinction was made between high extraction years (period heavy, 2010 - 2013; >$1.2\text{x}10^6 \text{m}^3$ sand/year) and the following years with decreased or ceased extraction (period post-heavy, 2014 and 2019; <$0.6\text{x}10^6 \text{m}^3$ sand/year).

Temporal variation is clearly a structuring driver for both epibenthos and fish assemblages on the Thorntonbank. Both impact and reference samples can be seen following a similar pattern throughout the years, mainly along the X-axis for epibenthos and along the Y-axis for fish (Figure 1). Year-to-year variation is also observed in the Buiten Ratel, albeit less pronounced. This variation can probably be attributed to larger temporal patterns in the North Sea but environmental variables should be included in the analyses in order to be able to support this hypothesis. Within this temporal pattern, some years can be distinguished because of extreme densities of certain species e.g. *Asterias rubens* and *Ophiura albida* in 2018 and *Trisopterus luscus* in 2019 for TB (Figure 2). It remains unclear why this is the case. Nevertheless, despite the observed temporal variation, a clear effect of sand extraction pressure on the species assemblages of TB and BR is detected, with a similar response observed for both TB and BR.

On the Thorntonbank, the epibenthic assemblage significantly differed between impact and reference samples in the heavy ($p_{\text{perm TB}} = 0.0002$) and moderate ($p_{\text{perm TB}} = 0.0082$) period, with no difference found in the baseline period ($p_{\text{perm TB}} = 0.5014$). On the Buiten Ratel, we observed a significant difference in epibenthic assemblage between impact and reference samples in both the heavy and post-heavy period ($p_{\text{perm BR}} = 0.0167$). For both sandbanks BR and TB, years subjected to high sand extraction levels (heavy periods) showed a shift in the epibenthos assemblages discerned with impact samples clustering away from reference samples (Figure 1, Figure 3). This shift in epibenthic assemblage is not due to a difference in species composition, as species richness of the area mostly remained unaffected. The shift was mainly due to increased densities of the already present opportunistic predator and scavenger species, which resulted in significantly increased total densities. In particular brittle stars (*Ophiura ophiura*, *O. albida*) and the starfish *A. rubens* (common predator scavengers in BPNS) were responding very clearly with increased species densities together with increased levels of sand extraction (Figure 2). Likely, the continuous high disturbance caused by the drag head of the dredging ships may lead to the death, injury or exposure of the macrobenthic fauna, thus creating a potential food source for predators and scavengers (Ramsay, 1996). Additionally, scavenger and predator densities on the impacted samples of Buiten Ratel displayed a remarkable drop when dredging activity in this area reduced from 1.245 million m^3/year to 0.604 million m^3/year in the period 2013 – 2014. Probably food availability decreased in the area after the reduced sand extraction activities, as such unable to support similar scavenger densities as before. Similar behaviour as described for brittle stars and *A. rubens* is observed for other scavenging species *Liocarcinus holsatus*, *Pagurus bernhardus*, *Tritia reticulata* and *Psammechinus miliaris*, albeit less pronounced.

Figure 1. PCO plot based on Bray-Curtis resemblance matrix of fourth root transformed for epibenthic (left) and demersal fish (right) density data for Thorntonbank with indication of impact and reference period. Baseline = 2004, moderate impact = 2010 – 2014, heavy impact = 2015 – 2019.

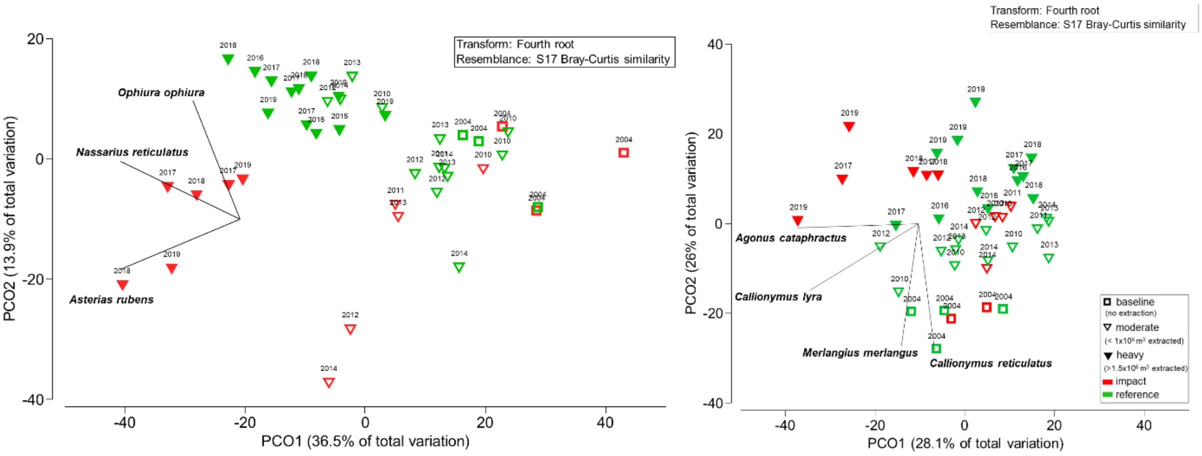
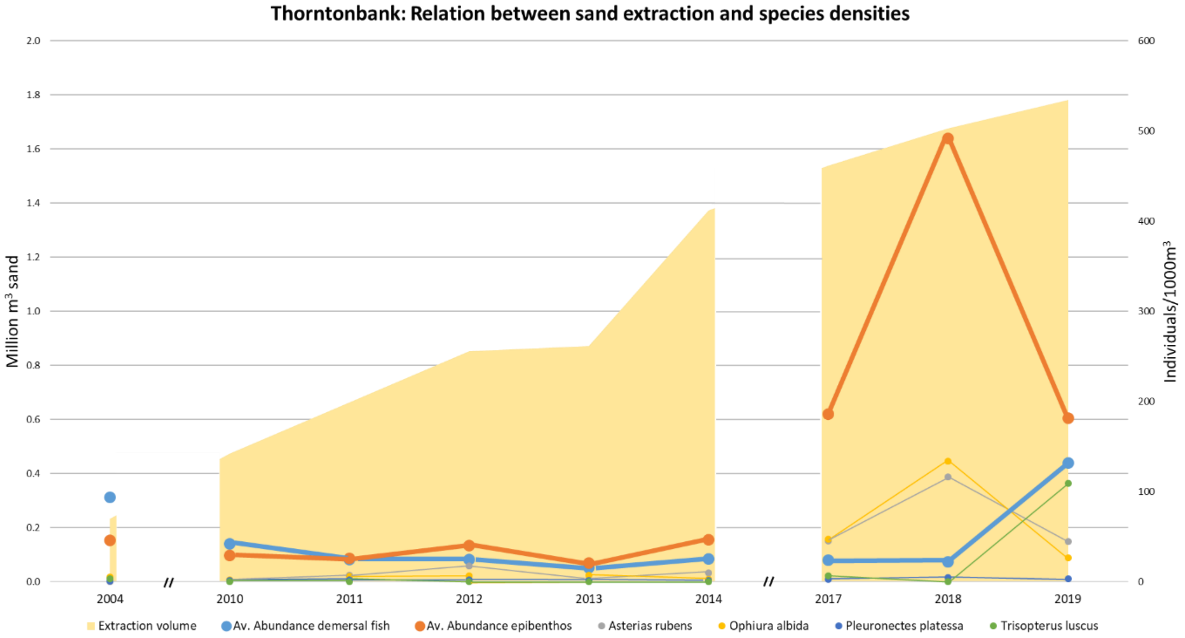


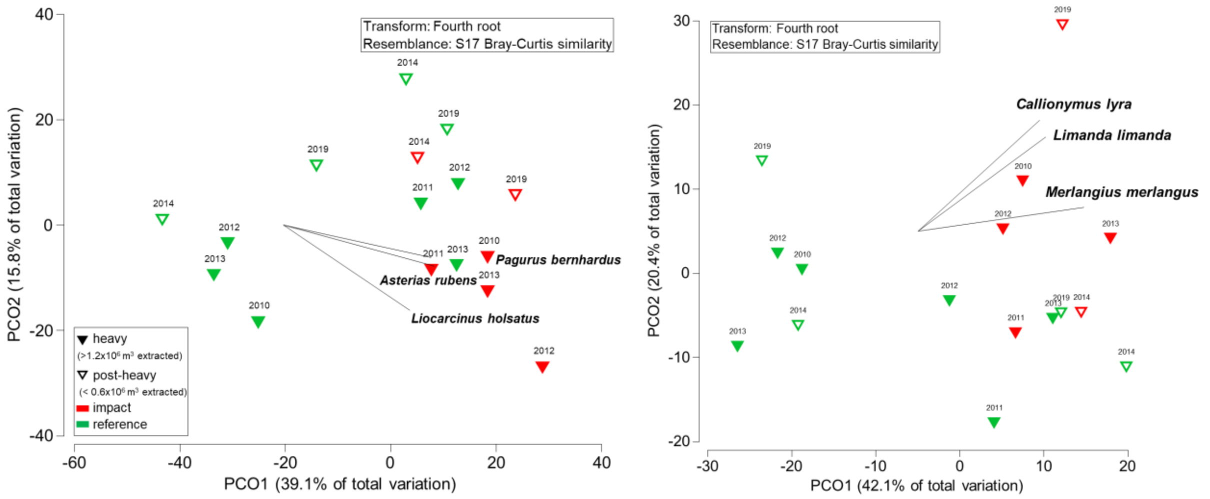
Figure 2. Relation between volume of sand extracted (m³) and species densities in impact sample(s) on the Thorntonbank. Epibenthos (thick orange line) and demersal fish (thick blue line) display the yearly total average density of the impact samples (TB1, TB2). Densities of the epibenthic scavengers A. rubens, O. albida and generalistic benthic fish Pleuronectes platessa and T. luscus are also shown, emphasizing the role of this type of consumers in the observed increase in species densities.



Demersal fish assemblages at TB and BR undergo a similar shift as seen for the epibenthos but less pronounced. On TB, the demersal fish assemblage significantly differed between impact and reference samples in the heavy period ($p_{\text{perm TB}}$ = 0.0005), while this was not the case in the moderate ($p_{\text{perm TB}}$ = 0.2187) and baseline period ($p_{\text{perm TB}}$ = 0.5259) (Figure 1). On BR, impact and reference samples differed significantly in both periods ($p_{\text{perm BR}}$ = 0.0059). Species composition did not change, but densities of benthic feeders as hooknose *Agonus cataphractus*, dab *Limanda limanda* and common dragonet

Callionymus lyra increased with increasing volumes of sand extracted. This response is likely caused by increases of their food sources, mainly amphipods and small crustaceans (Wyche & Shackley 1986, Klimpel et al. 2003, Griffin et al. 2012). Furthermore, these benthic omnivorous fish can benefit directly by foraging on the organic matter released by the drag head, or indirectly by preying on the increased amounts of epibenthic scavengers. Other species showing similar trends include *Solea solea*, *Merlangius merlangus* and *Pleuronectes platessa*.

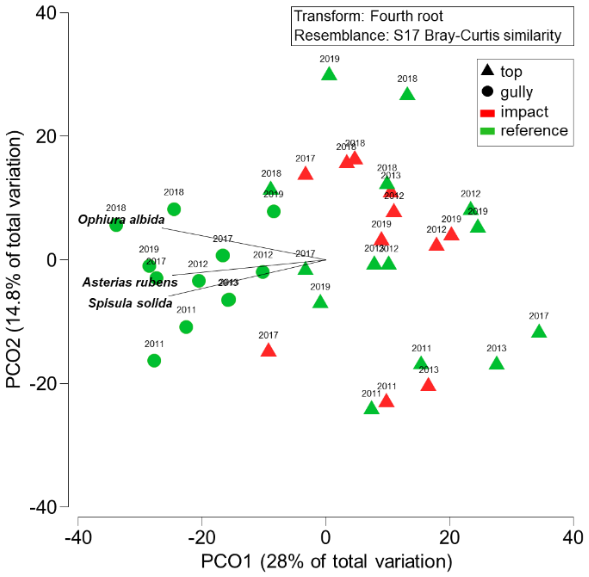
Figure 3. PCO plot based on Bray-Curtis resemblance matrix of fourth root transformed for epibenthic (left) and demersal fish (right) density data for Buiten ratel with indication of impact and reference period. Heavy impact = 2010 – 2013, Post-heavy impact = 2014 – 2019



Effects of periodically high sand extraction (OH)

For Oosthinder, extraction started in 2012. Samples for analysis were available for the years 2011– 2013 and 2017 – 2019. The periodic high extraction events (> 1 x 10^6 m^3 in 2 to 3 months in 2013, 2014, 2017 and 2018) did not affect epibenthic and demersal fish assemblages. Sand extraction in this area only takes place on the sandbank tops. For comparison we also took a number of reference samples in the adjacent gullies, resulting in a clear spatial structuring force, with significant differences in species assemblages depending on the location, be it on top of the sandbank versus the gully (p_{perm} = 0.0001 for both epi and fish) (Figure 4). The absence of a clear effect of sand extraction could have several reasons: (1) although extracted volumes are high, the frequency of extraction is low compared to the continuous extraction on BR and TB. Moreover, the extraction events for beach nourishment mainly took place in spring, while our beam trawl sampling took place in autumn. As the BPNS is a dynamic and naturally resilient system, it may be possible that mobile ecosystem components as epibenthos and demersal fish recover by this time; (2) Site specific differences such as distance to shore (the Oosthinder extraction site is located furthest offshore), depth, sediment type and hydrographic conditions could make a difference, when compared to the observed effects on TB and BR; (3) The Oosthinder is, together with the other banks in the Hinderbanken complex, characterized by a young (upper-Holocene), relatively homogenous upper layer of sand (Van Lancker et al., 2019). This geomorphological feature may serve as a buffer against disturbance, thus ensuring that high levels of extraction do not impact seafloor integrity.

Figure 4. PCO plot based on Bray-Curtis resemblance matrix of fourth root transformed epibenthic density data for Oosthinder with indication of impact/reference and sample position on the sandbank (top/gully). Gully samples cluster together clearly, this is also the case for the demersal fish dataset (not shown).



Conclusion

Epibenthic and demersal fish species assemblages changed due to continuous high (>1.2x10^{6}m^3 sand/year) sand extraction pressure in the Belgian North Sea. Moderate pressures (< 1x10^{6}m^3 sand/year) affected the epibenthic assemblages, but not demersal fish. No overall changes in species richness attributable to extraction pressure were observed (2009 – 2019), but increased densities of opportunistic epibenthic scavengers and generalist benthic feeding fish were recorded on Thorntonbank and Buiten Ratel, involving species as *A. rubens*, *Ophiura sp.*, *L. holsatus*, *P. bernhardus*, *L. limanda*, *C. lyra* and several other species. On the other hand, when sand extraction occurred at high levels for a short period of time (> 1x10^{6}m^3 sand in ±3 months; e.g. the more offshore Oosthinder), no effects on the epibenthic and demersal fish assemblages were noted. This indicates that the frequency of disturbance appears to be an important variable when analysing dredging impact. Preferably, future dredging activities should be optimized in terms of frequency of extraction and extracted amounts of sand in such way that marine environmental impact is minimized.

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The impact of sand extraction on benthic ecosystem functioning

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The ecological impact of sand extraction in the Belgian part of the North Sea (BPNS) has been closely monitored in the past decades. Focus of these monitoring activities has primarily been on investigating the effects on benthic community structure (e.g. density, species number, species composition). Observed changes in benthic community response due to sand extraction always matched changes in the seabed, and especially changes in sediment characteristics caused by extraction where extraction regime and local geological context were identified as important driving factors herein. Physical changes of the habitat due to sand extraction may not only change the biological community structure, but also the functional traits expressed by the community, thereby affecting ecosystem functioning and its services. Moreover, these structural changes will not always reflect their functional properties. It is therefore, from an ecosystem management perspective, necessary to improve our understanding of how the quality and quantity of ecosystem services provided by coastal marine ecosystems may change in relation to disturbances. Hence, gathering empirical information on the impact of sand extraction on the functional diversity and benthic ecosystem functioning is the way forward and is the main objective of a recently started PhD study.

During this PhD, we will unravel the impact of sand extraction on benthic ecosystem functioning by focussing on three different aspects of functioning: functional traits of benthic organisms, benthic food web functioning and sediment biogeochemistry. Within this contribution, we will put most attention on what our objectives are for the latter aspect.

Sand extraction takes mainly place in coarser grained, permeable sediments, characterised by fast mineralization rates of organic matter. As a consequence, permeable sediments harbor relative low carbon stocks year-round and play a crucial role in the mineralization of carbon and the regeneration of nitrogen, supplying the overlying water column with fresh nutrients, necessary to support phytoplankton blooms. We can thus expect that extraction-induced changes in e.g. granulometry and biological community structures will influence benthic functions such as organic matter mineralization, nutrient recycling to the overlying water column and/or carbon storage. To study how sand extraction affects these processes and more specifically the carbon and nitrogen cycles, three research questions are posed: 1) What is the impact of different extraction regimes (different frequency and intensity) on the sediment biogeochemistry, 2) what is the acute impact of an extraction event and 3) how does the seabed recover after such a disturbance event? To answer these questions, *in situ* box core sampling along an intensity gradient and after a one-off large scale dredging event, combined with sediment incubations to measure oxygen consumption, nutrient fluxes and faunal activity will be conducted.

Results from this study will contribute to a better understanding on how sand extraction activities affect ecosystem functions and what this means for vital ecosystem services benefitting human wellbeing, such as food provisioning and carbon storage.

Keywords: Ecosystem functioning, Sand Extraction, Seabed, Biogeochemistry, Carbon, Nitrogen

The new RV Belgica – The legacy continues

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The new RV Belgica is a multipurpose, silent, green, ice-strengthened and full ocean research vessel which is able to work in water depths up to 5000 m and is able to deploy a large variety of European marine infrastructure (incl. AUVs, ROVs, 3D seismic systems, sediment coring & rock drill devices, etc.). The ship has 13 labs & scientific rooms with a total space of more than 400 m^2. There is deck space for seven gear and lab containers. The ship is equipped with a full acoustic underwater instrumentation suite which allows the scientists to map and analyze the full water column (incl. fauna), the seafloor and the subsurface.

New capabilities are also available, such as dynamic positioning (DP-2), two integrated drop keels allowing ad hoc instalment of subsea sensors and a roll stabilization system. All these systems allow the 28 scientists and marine technicians to perform their work as comfortable and as safe as possible and this for the coming 30 years. The new ship will be at sea for 300 days per year and this with a 30-day autonomy.

Based on these capabilities the new RV Belgica will support the complete Belgian marine science community and will also strengthen the Belgian role in the Blue Economy via its researchers, training centers and maritime industry. Ship time exchange with European research institutes will allow us to enhance the research capacity and to enlarge the study areas based on shared costs. We also foresee a financial return by deploying the new RV Belgica as an exploration- & test platform, a research- & monitoring ship and an education- & training platform.

The delivery of the new Belgian research vessel is foreseen in December 2021.

Figure 1. A picture of the new RV Belgica during the sea trials in the Ria de Vigo.

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The Electronic Monitoring System (EMS) as a tool for long-term 4D monitoring of sand extraction on the Belgian part of the North Sea

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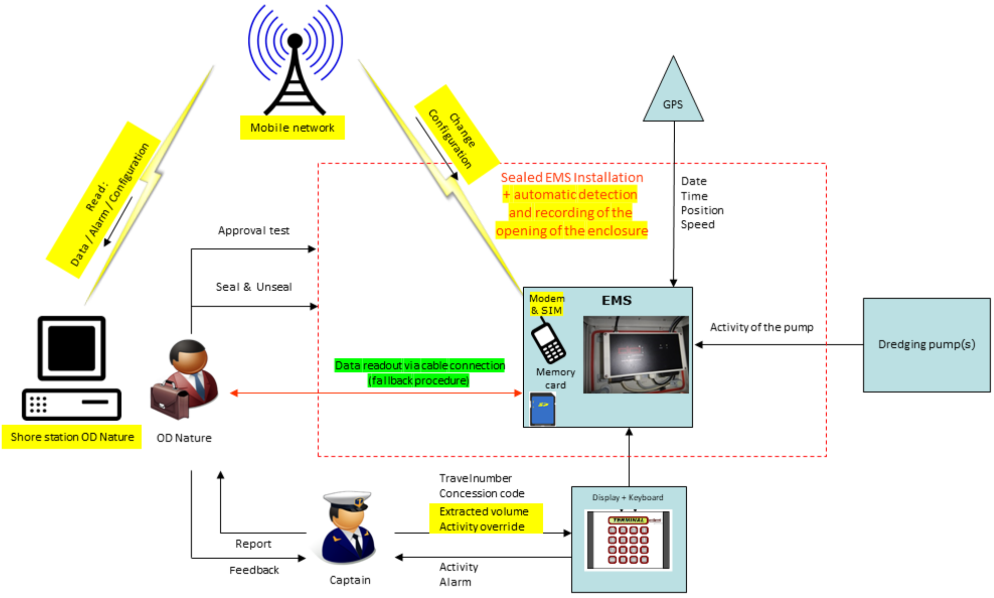
This contribution outlines the Electronic Monitoring System (EMS, black box or automatic registration system) since its introduction, its history, evolution and functioning, data processing methods, data results, the weaknesses of the system as well as possible future improvements to ensure the continuity in the follow-up of sand extraction on the Belgian part of the North Sea.

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. From 2006, extraction activities for the protection of the Belgian coast are also being monitored by this EMS. Since 2014, 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 this current EMS of the second generation are: remote data transfer, remote configuration changes, automatic alert messages and local keyboard input for the obliged parameter 'declared load' (see Fig. 1) and hardly missing data compared to the previous generation. The main weakness of the current EMS is the outdated communication protocol used for the data transfer. The latest supplier developments for a new generation EMS (IP-based solution) doesn't yet meet our requirements.

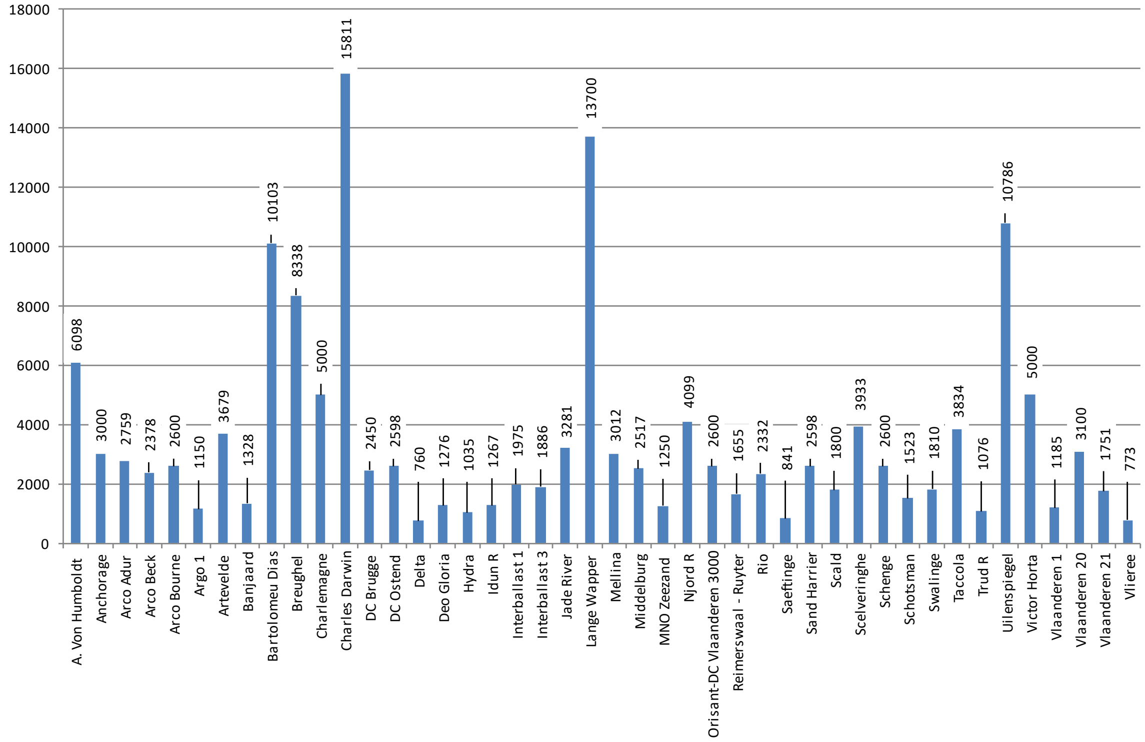
Figure 1. Schematic overview of the EMS and the interactions with the system with changes compared to the first systems in yellow (2014) and green (2021)



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. During periods of technical breakdowns of the EMS or its associated sensors, the necessary steps are taken (manual processing, for example based on the readings of the pressure gauges) to apply documented corrections to the data. The recorded and processed EMS data (43 085 833 records available so far in the database) provides one of the sources for the continuous monitoring of sand and gravel activities in the Belgian part of the North Sea. 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.

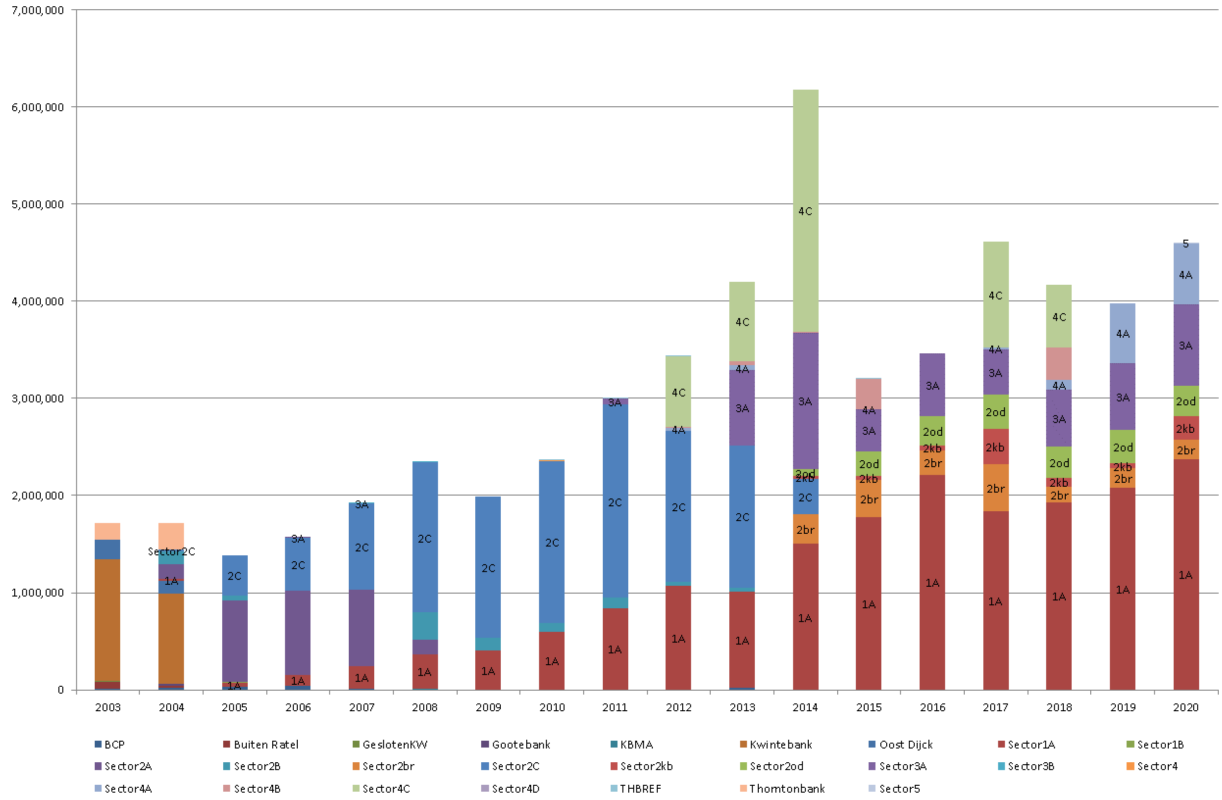
The EMS data records allow for an estimation of the sand extraction intensity, in particular the volume extracted by the dredging vessel per time frame by using either the declared load (available since 2014 based on the information entered by the crew) or the known fixed loading capacity (available since June 2002) (see Fig. 2). Since September 2019, extraction in 2 different sectors without unloading the cargo in the meantime is considered as 2 different trips meaning the declared load is in this case more correct than the fixed loading capacity. In addition, since 2020, all extractions with a missing declared volume in the EMS data are manually completed with the subsequently requested volumes making this parameter also representative. These 2 values 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). The first value (declared load) may be the most realistic but the second value (the use of the fixed loading capacity) ensures continuity in the representation as the first is only fully available since 2020.

Figure 2. Overview of the used fixed loading capacity (m^3) (specified by the concessionaire or calculated as average of the declared extracted volumes) of the vessels (ever) equipped with an EMS.

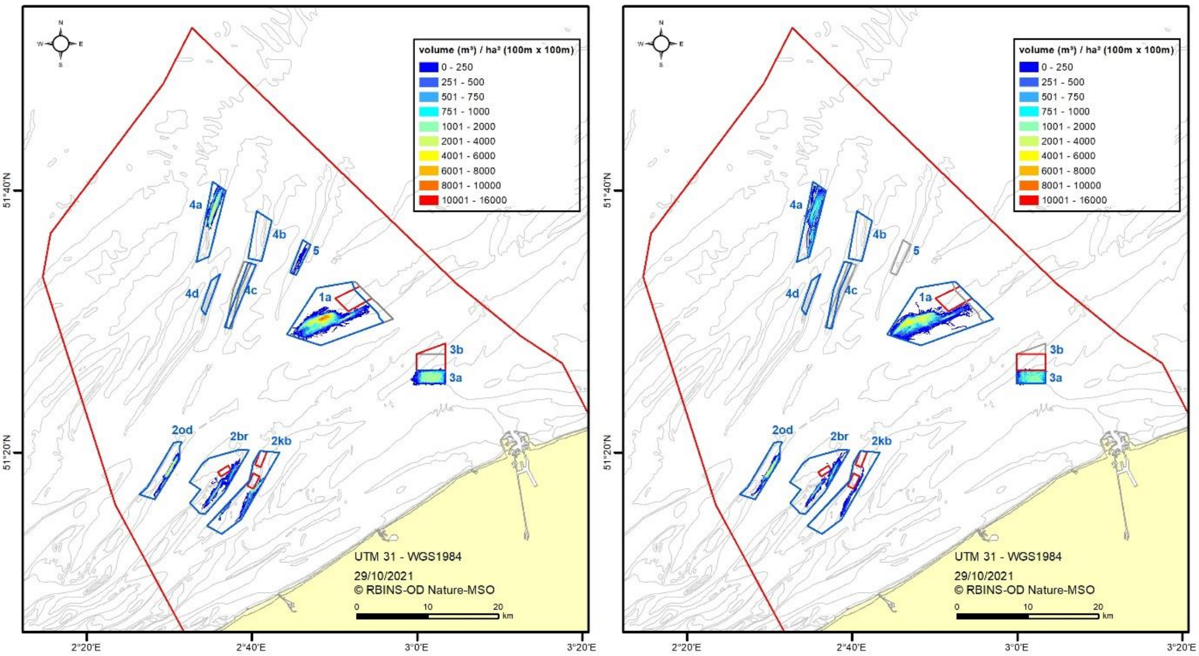


Based on all available EMS data and the above described method (making use of the vessels fixed loading capacity), the cumulative extracted volumes are presented as an annual overview in figure 3 (2003-2020) and as a geographical distribution (100 m x 100 m grids) in the figures 4 to 7 (2020-2017). For the geographical distribution of the EMS data for the period before 2017, reference is made to the conference proceedings of the previous study days of June 2017, October 2014 and October 2011.

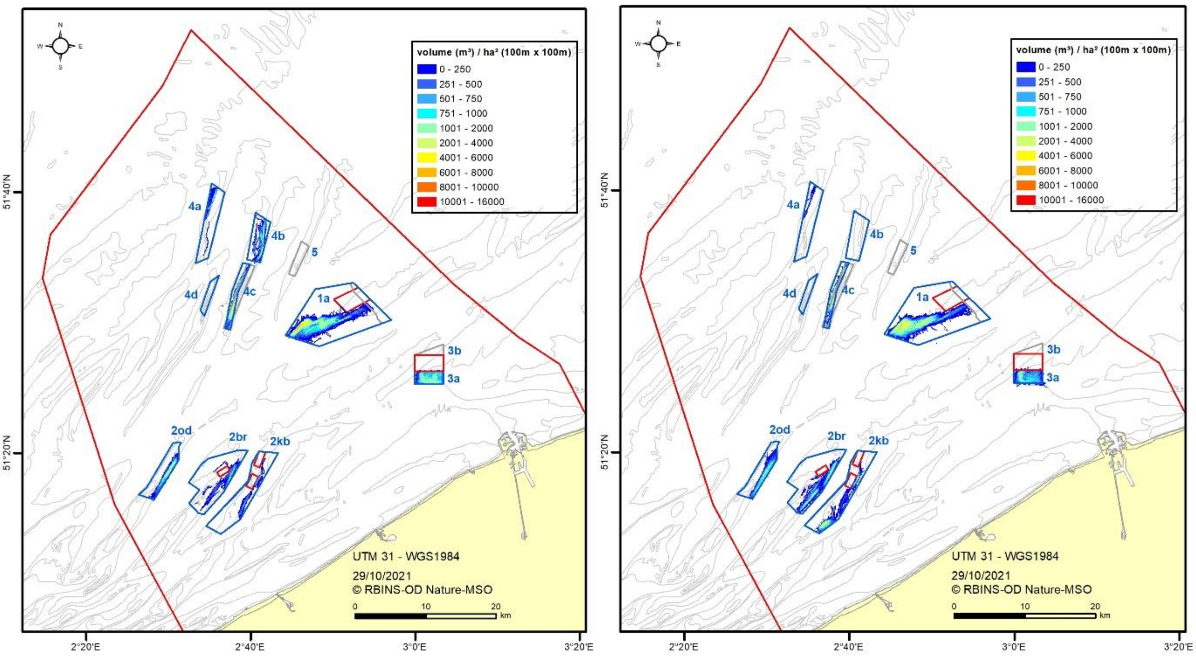
Figure 3. Yearly extracted volumes (m³) versus sector.



Figures 4 and 5. Geographical distribution of the cumulative volumes (m³/ha²) for 2020 (left) and 2019 (right).



Figures 6 and 7. Geographical distribution of the cumulative volumes (m³/ha²) for 2018 (left) and 2017 (right).



The regulations for the EMS obligation have made it possible over the last 19 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.

Acknowledgements

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Joint acoustic and sediment fingerprinting during a period of intensified sand extraction in sector 4a on the Noordhinder sandbank

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In the Hinder Bank area, sand extraction is permitted in four dedicated zones and is monitored closely using multibeam technology (COPCO). Most activities took place on the Oosthinder (sector 4c), where repetitive sediment sampling has been performed to validate the acoustic data series and to account for spatial variability across sandbanks. Recently, sand extraction on the Noordhinder (sector 4a) has been intensified as this sector has been designated as a future wind-farm area (Marine Spatial Plan of 2020-2026). In the first three months of 2021, more sand was extracted than in the past three years combined.

During the penultimate campaign of the RV Belgica A962, COPCO and OD Nature jointly collected acoustic and sediment information in sector 4a. Multibeam echosounder (MBES) and backscatter (BS) data with a spatial coverage of 15.85 km² were acquired, and 20 Reineck box cores were taken, subsampled and sliced every centimetre to validate the acoustic facies. Good spatial representation across the entire sandbank was achieved, both within, near and outside the intensively dredged areas.

Backscatter values were extracted within the incidence angles of ± 30° to 50°, that best distinguish between different sediment types. Sediment parameters such as mean grain size, sorting, clay-silt-sand-gravel percentages were calculated from the complete grain-size distribution for each sliced subsample. Organic matter and carbonate content are available as well.

Preliminary results of the processed acoustic and analysed sediment data are presented in this poster, both separately and combined. The datasets provide insight into sediment changes due to natural variability and sand extraction. Ultimate goal is the unravelling of sediment-acoustic data relationships to optimise remote monitoring of sediment changes in heavily extracted areas.

Keywords: Noordhinder, sector 4a, acoustic facies, sediment properties, intensified sand extraction

Seabed Community Initiative:

communicating sustainability challenges of marine sand use in a changing world <Seabed4U>

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The foundation of sustainability in a sand resource context is the availability of a knowledge base comprising the quality and quantity of the resource, in combination with reliable estimates of the environmental impact of extraction. For the Belgian and southern Netherlands part of the North Sea relevant data and models, building on years of research and exploration, are now available via standardized data bases on geological properties and subsurface models. The synthesis was done during a four-years multidisciplinary research project <TILES>, funded by Belgian Science Policy (Transnational and Integrated Long-term marine Exploitation Strategies) (see Van Lancker et al., this volume for an update). Furthermore, the continuous monitoring of seabed state and dynamics has reached a level of maturity to predict adverse effects to the benthic ecosystem accounting for extraction rates, intensity and geological context (Wyns et al., this volume).

Meanwhile, a wider international debate is ongoing on the long-term use of marine sands. With UNEP's 2019 report on "Sand and sustainability: Finding new solutions for environmental governance of global sand resources", a new impetus was given to initiatives, from diverse stakeholders, to discuss common challenges and solutions. The report led to a United Nations Environmental Assembly (UNEA-4) highlighting the need to identify principles guiding sustainable sand management. A principles report is now drafted for UNEA-5, and IUCN adopted a resolution "for the urgent global management of marine and coastal sand resources" (WCC-2020-Rec-029-EN).

Recognizing the needs set out by these global initiatives, a further digitization of the Belgian geological knowledge base is ongoing and is further embedded in European research actions (e.g. on the establishment of a Geological Service of Europe) and data portals (e.g., EMODnet-Geology and the European Geological Data Infrastructure) under the umbrella of the European Geological Surveys, and in cooperation with the Belgian Geological Survey in particular. Modelling frameworks are further investigated, seabed mapping products updated (e.g., on grain size, gravel distribution, (non-)depositional areas), as well as developing new decision support tools, and knowledge systems to function in a wider European context.

A newly developed Seabed4U platform synthesizes all on-going initiatives, bringing awareness on the challenges of using finite resources (also via #SeabedMatters), and stimulating a wider community to participate in resource mapping and innovate in solutions. We have further embedded an illustrated Code of Sand (<TILES>) with messages on a more sustainable management of marine sand.

Keywords: sustainable sand management, geological knowledge base, resource mapping, community platform

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