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/).

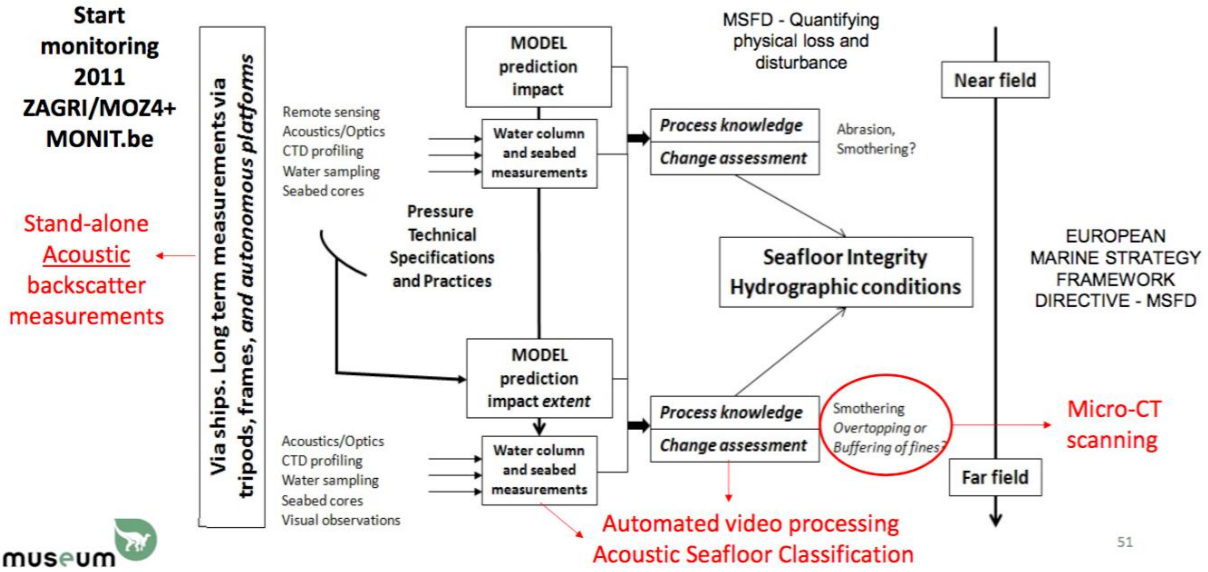
3.2. Methodology

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.

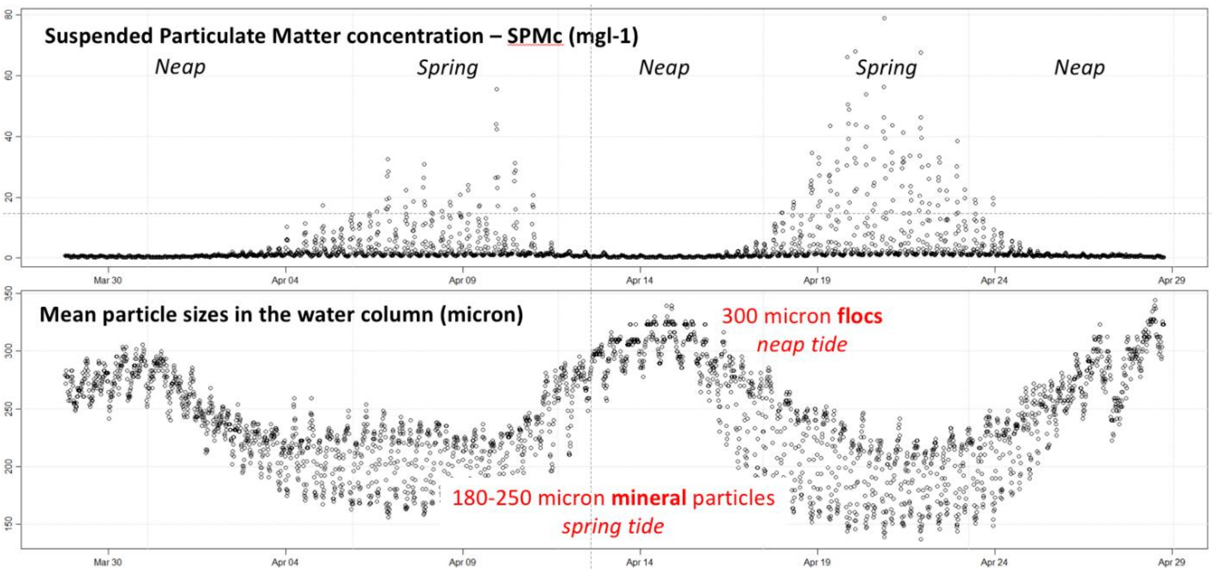
3.3.1. Quantifying natural and human-induced changes in sediment characteristics and processes

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.

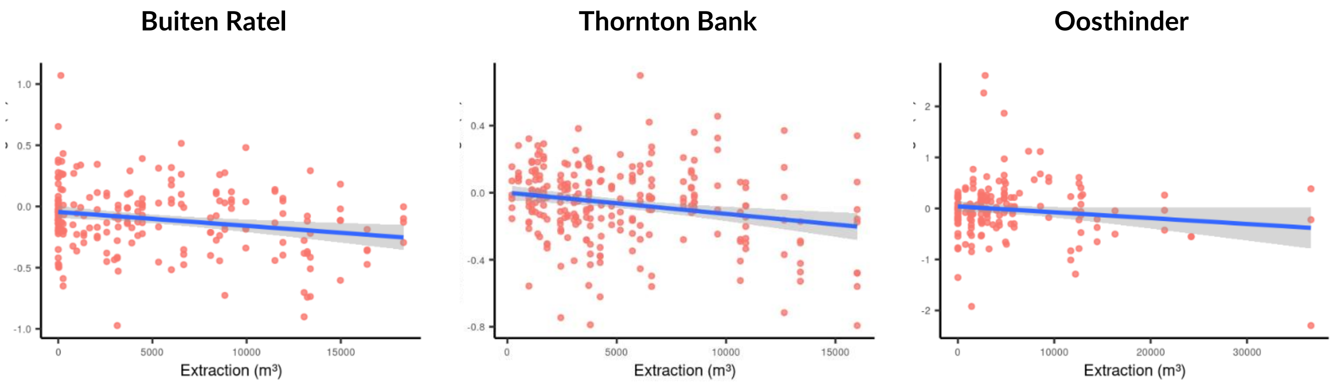
3.3.3. Towards a more sustainable use of marine resources

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

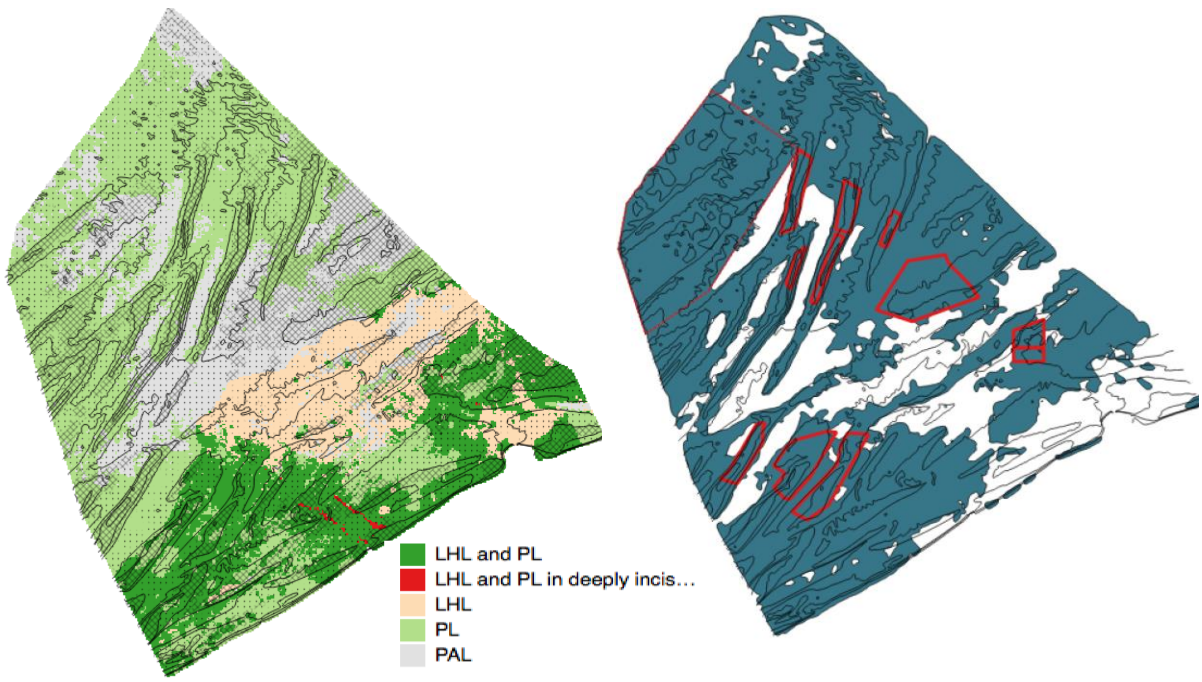
Significant progress was made in the methodological procedures for detecting and assessing changes in major sediment types using multibeam depth and backscatter values (see Montereale Gavazzi, 2019 for in-depth analyses and discussions). The study also demonstrated the continued importance of good site 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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