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

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Abstract

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

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

Introduction

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

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

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

Study area

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

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

(1) Based upon calculated bottom shear stresses over a 14-days spring-neap tidal cycle, using validated mathematical models, an impact should be evaluated when one of the following conditions is met:
    (i) There is an increase of more than 10% of the mean bottom shear stress;
    (ii) Variation of the ratio between duration of sedimentation and duration of erosion is beyond the "-5%, +5%" range.
(2) The impact under consideration should remain within a distance equal to the square root of the area occupied by this activity and calculated from the inherent outermost border.
(3) All developments need compliance with existing regulations (e.g., EIA, SEA, and Habitat Directive Guidelines) and legislative evaluations are necessary in such a way that an eventual potential impact of permanent changes in hydrographic conditions is accounted for, including cumulative effects. This should be evaluated with relevance to the most suitable spatial scale (ref. OSPAR common language).

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

(1) The areal extent and distribution of EUNIS level 3 Habitats (sandy mud to mud; muddy sand to sand and coarse sediments), as well as of the gravel beds, remain within the margin of uncertainty of the sediment distribution, with reference to the Initial Assessment.
(2) Within the gravel beds (test zones to be defined), the ratio of the surface of hard substrate (i.e., surface colonized by hard substrata epifauna) against the ratio of soft sediment (i.e., surface on top of the hard substrate that prevents the development of hard substrata fauna), does not show a negative trend.

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

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

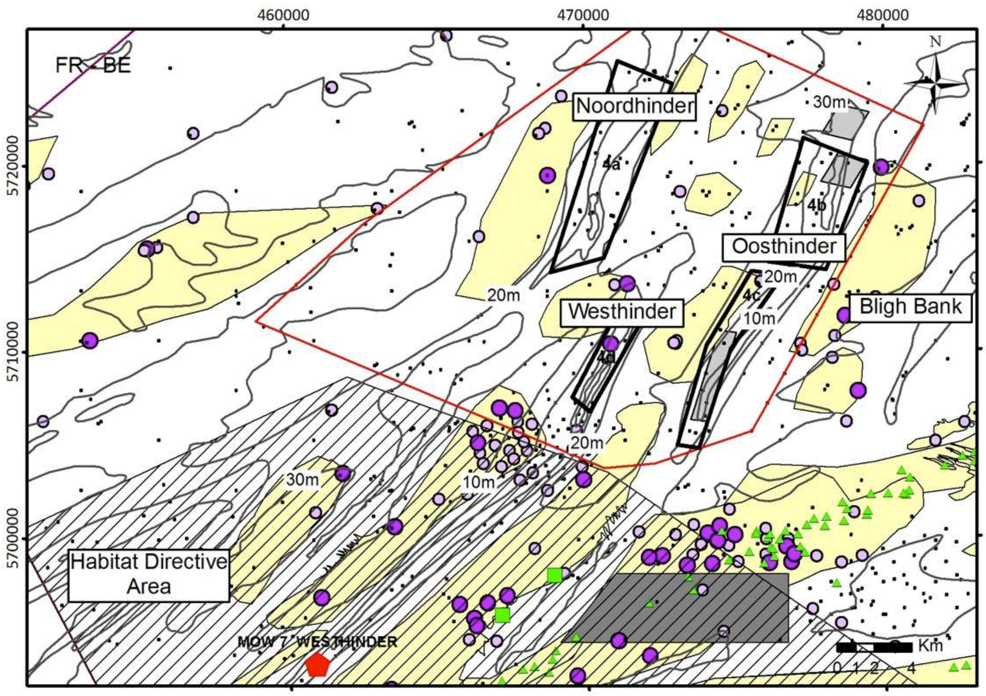

Figure 1: Area of the Hinder Banks, where intensive marine aggregate extraction is allowed in zone 4 (red line) along 4 sectors (black polygons). Within these sectors geomorphological monitoring is carried out by FPS Economy (light grey polygons). A Habitat Directive Area (hatched) is present at a minimum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

Material and methods

Measurements and spatial observations

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

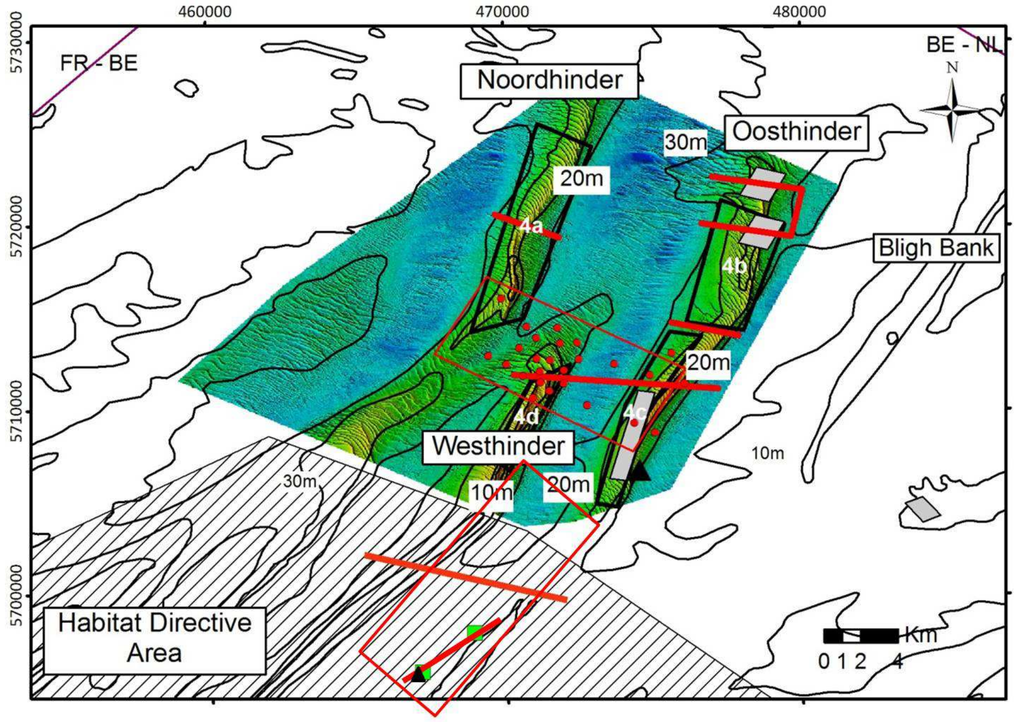

Figure 2: Areas of investigation in the Hinder Bank region. Cross-sectional lines show the locations of ADCP profiling, along which also water sampling and vertical profiling were performed. Bathymetric surveys were performed in the red delineated zones in the central and southern part of the Hinder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

The following measurements were executed:

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

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

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

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

Modelling

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

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

External data

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

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

Results and discussion

Natural variation

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

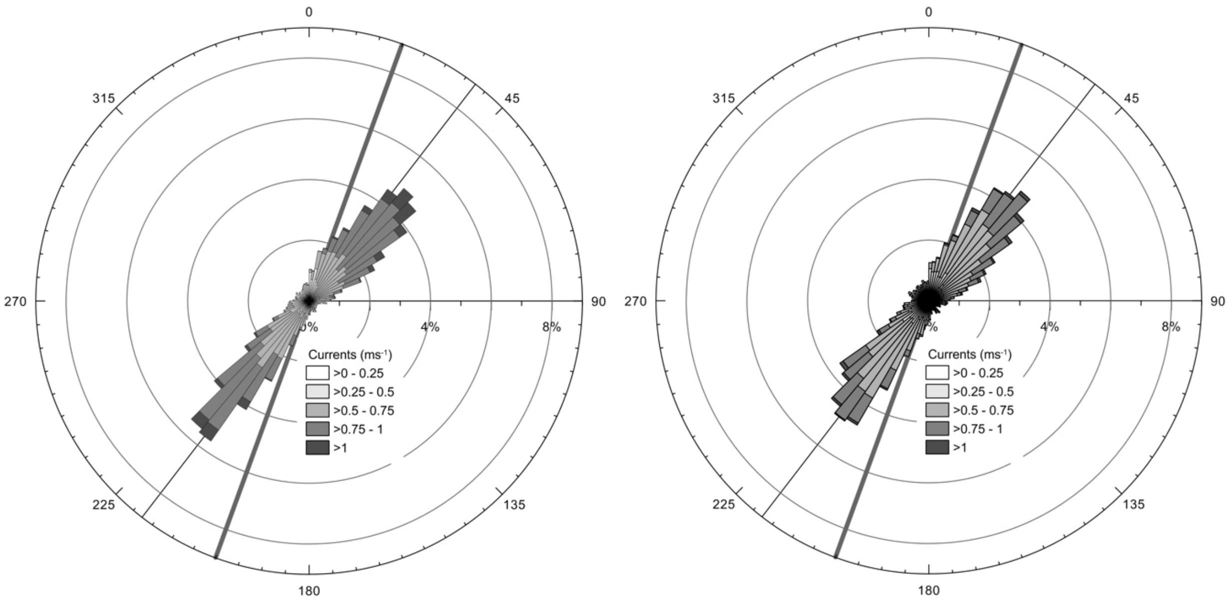

Figure 3: Frequency of occurrence of currents from all hull-mounted ADCP data series (RV Belgica) with 1 m bin size. Troughs and sandbanks are covered. Left: Measured currents for the upper water layers (angle of maximum current (-)). Right: for the lower water layers (angle of maximum current (-). Note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

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

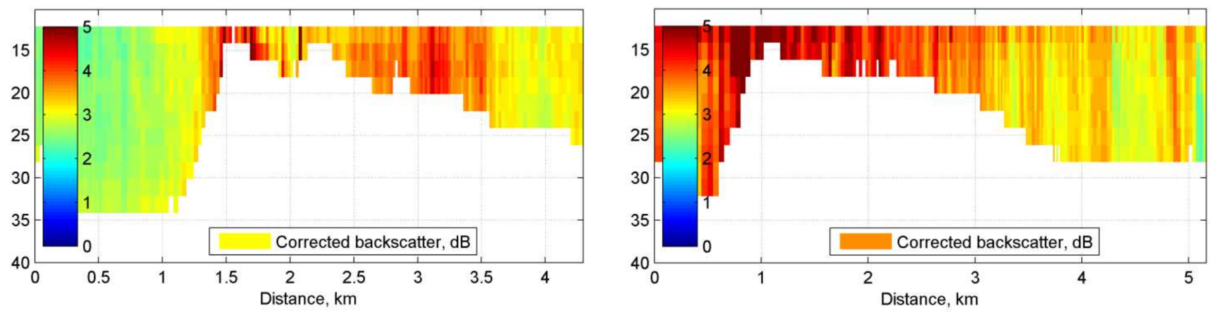

Figure 4: Resuspension events along the Oosthinder sandbank, north part Sector 4c. Left: Example of topography-induced resuspension (Hs < 1 m). Right: Example of topography-induced resuspension under higher wave conditions (Hs: 1-2 m). Wave Glider dataset (Van Lancker & Baeye, subm.).

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

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

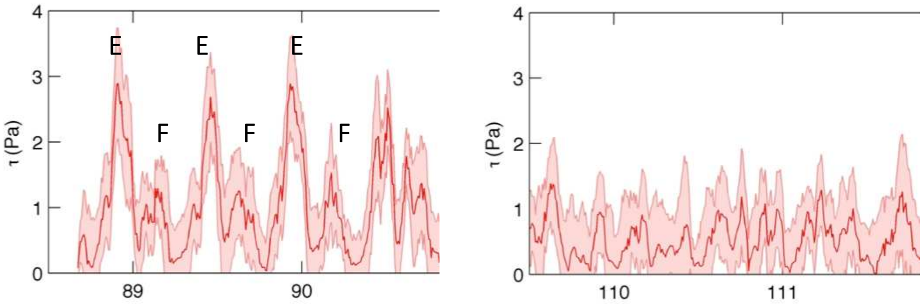

Figure 5: Extract of a 27-days time series on bottom shear stress (with error envelope, based on uncertainties in the calculations), calculated from in-situ BM-ADCP data, acquired along the east flank of the Oosthinder sandbank. Left: Spring tide; Right: Neap. Note the variation in bottom shear stress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

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

Human-induced variation

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

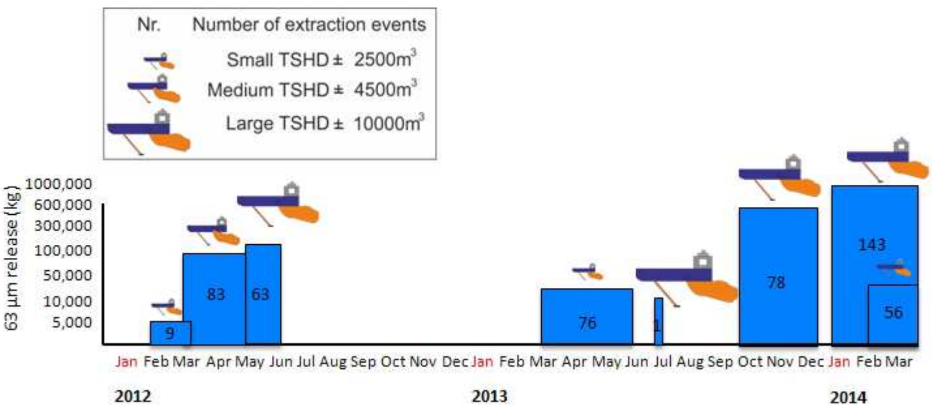

Figure 6: Extraction practices in sector 4C, Oosthinder sandbank, from January until March 2014. Periods of extraction are indicated with number of extraction events of small, medium and large TSHDs. Y-axis is an indicative estimate of the amount of release of fines (63 µm in kg) during those periods.

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

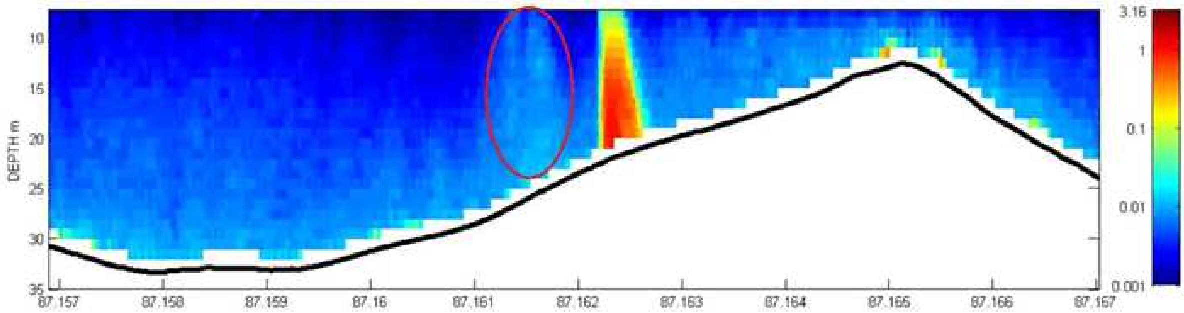

Figure 7: ADCP profile over the Oosthinder sandbank showing deposition of a 50-m wide dynamic plume of a small TSHD. ADCP-derived SPM concentrations were up to 1 gl^{-1} (right scale). Note a secondary plume with derived SPM concentrations around 0.01 gl^{-1}. RV Belgica March 2014 (Evangelinos, 2014).

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

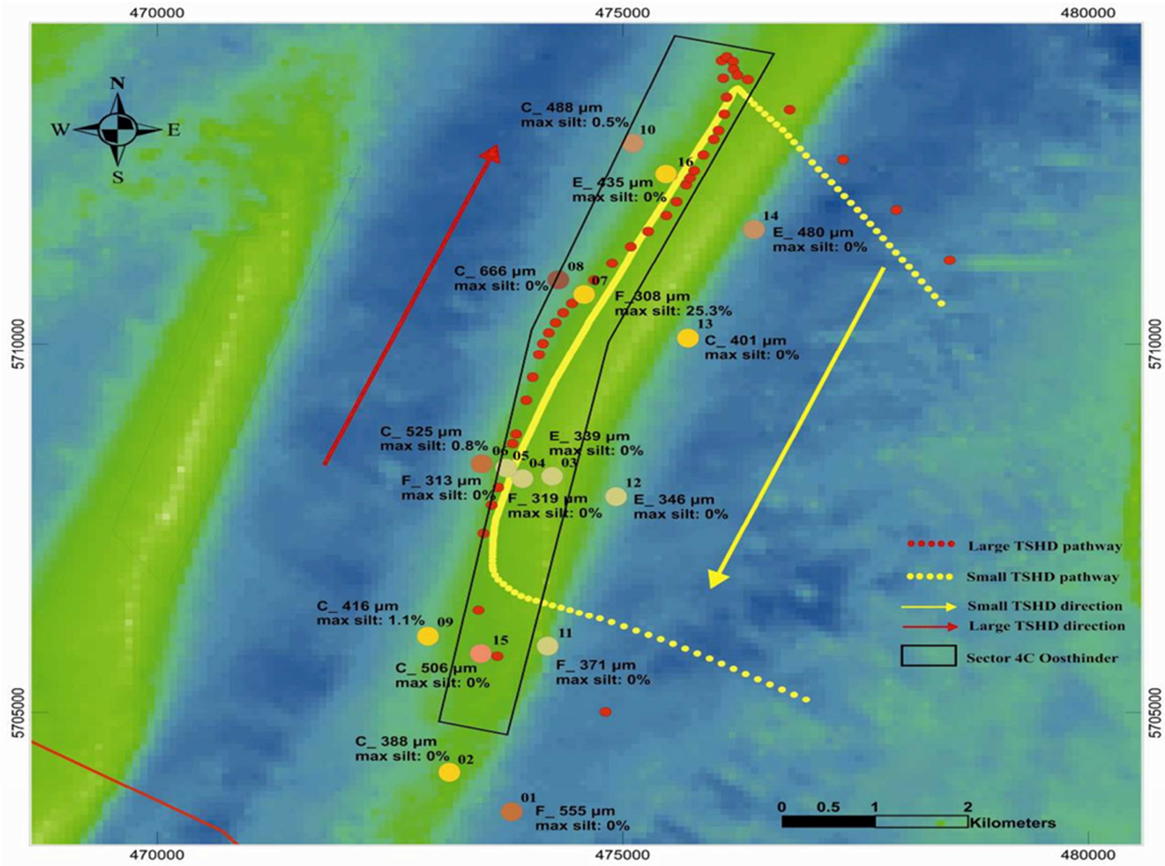

Figure 8: Sediment characteristics along Sector 4c, Oosthinder sandbank, based on shallow cores (up to ± 15 cm). Particle sizes refer to the top cm of the core; darker colours are coarser. F: indicates sediment fining in the top layers; C: indicates coarsening; and E indicates no difference. The maximum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

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

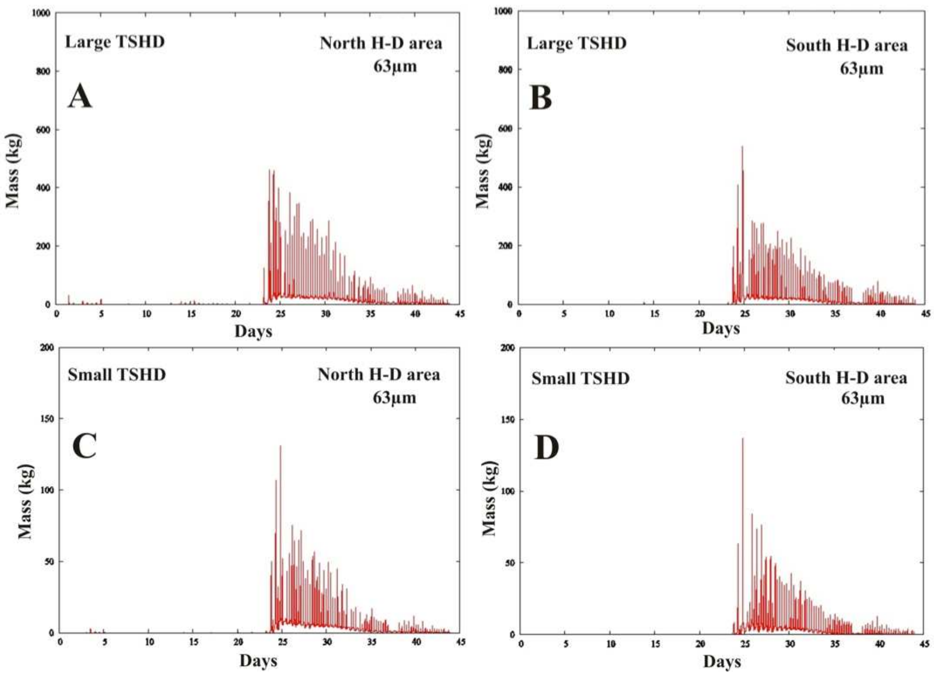

Figure 9: Simulation of the deposition of very fine sands (63 µm) in Mass (kg). Period: 15/02/2014 - 22/03/2014 (45 days). (A) Deposition of 63 µm particles along a northern location in the Habitat Directive Area (H-D Area), arising from a large TSHD. (B) Similar, but along a southern location. (C) Deposition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

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

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

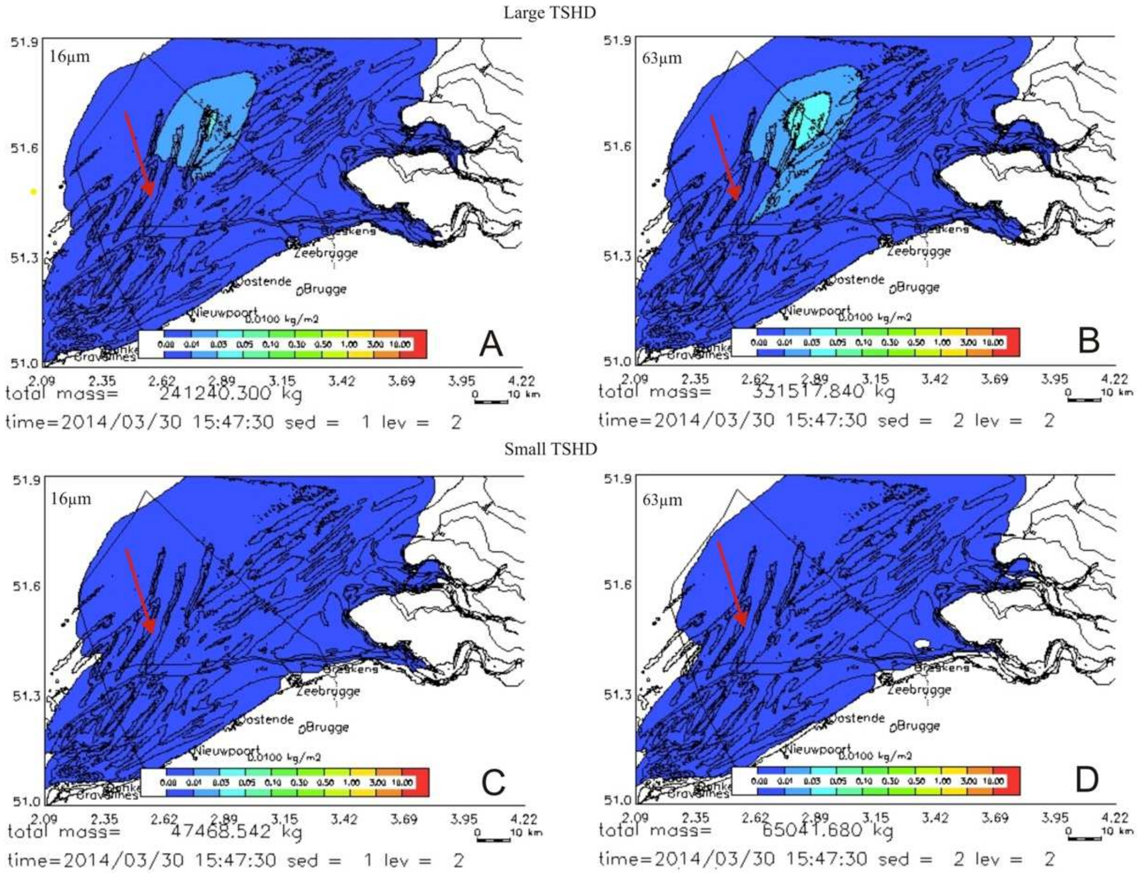

Figure 10: Results of plume modelling (MU-STM) illustrating the dispersion of fine sediment fractions from a large and small TSHD, as well as the total mass dispersed (kgm^{-2}). Period: 15/02/2014 - 30/03/2014; end result presented. (A) and (B) represent the fine silt particles released from a large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

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

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

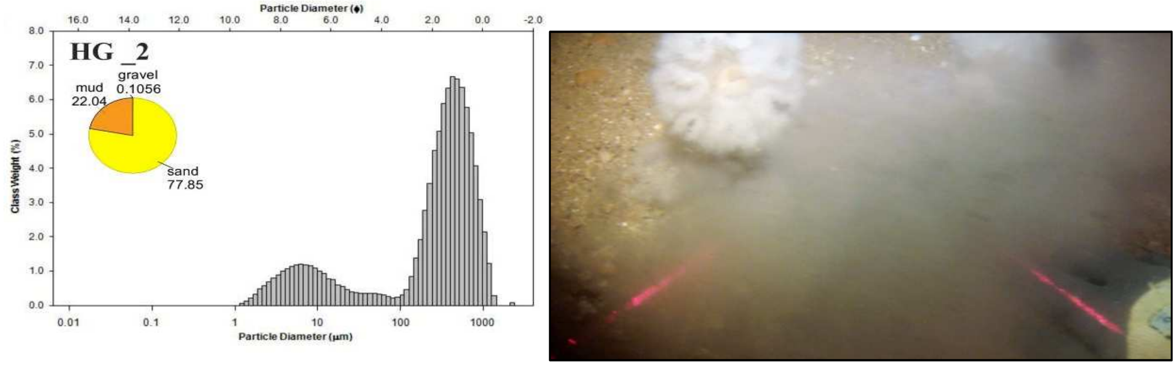

Figure 11: Seabed characteristics of the gravel-rich area. Left: Grain-size analyse of the soft sediment in-between the gravel. Sands are coarse-grained (median grain-size around 400-500 µm), however with an admixture of fines, up to 22 % (March 2014). Right: Video observation showing a coarse top surface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

Conclusions

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

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

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

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

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