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

*Van Lancker Vera[1], Baeye Matthias[1], Evagelinos Dimitris[1,2°], Francken Frederic[1], Montereale Gavazzi Giacomo[1,2], and Van den Eynde Dries[*1]*

[*]*Presenting author: dries.vandeneynde@naturalsciences.be*

[1]*Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Suspended Matter and Seabed Monitoring and Modelling Group, Gulledelle 100, 1200 Brussels, Belgium*

[2]*Ghent University, Dep. Geology, Renard Centre of Marine Geology, Krijgslaan 281, s-8, 9000 Gent, Belgium °Msc Oceans and Lakes*

Introduction

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

Study area

The Hinder Banks form part of a sandbank complex, located 40 km offshore in the Belgian part of the North Sea (BPNS). On these sandbanks, depths range from -6 m to -40 m Lowest Astronomical tide (LAT) (Figure 15); they are superimposed with a hierarchy of dune forms, often more than 6 m in height. The channels in-between the sandbanks reach 40 m of water depth. Extraction of aggregates is allowed in 4 sectors (a to d; Figure 1), though most of the activity takes place on the Oosthinder sandbank (Sector 4b and 4c). Sediments are medium to coarse sands, including shell hash, with less than 1 % of silt-clay enrichment (Van Lancker, 2009). Tidal currents reach more than 1 ms^{-1}; the significant wave height of the waves is easily more than 1 m. These offshore sandbanks are the first wave energy dissipaters in the BPNS.

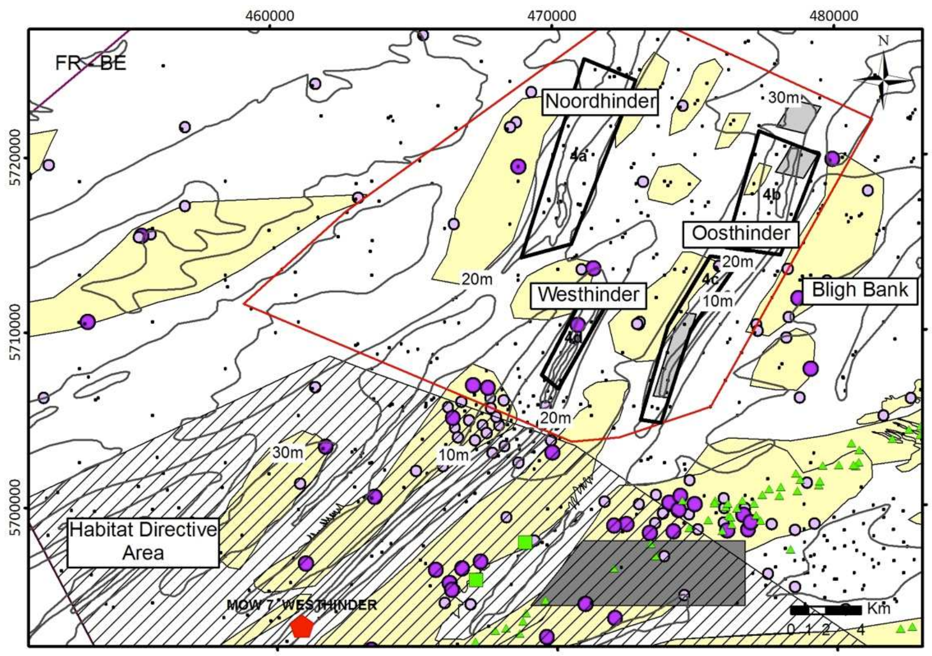

Figure 15: Area of the Hinder Banks, where intensive marine aggregate extraction is allowed in zone 4 (red line) along 4 sectors (black polygons). Within these sectors geomorphological monitoring is carried out by FPS Economy (light grey polygons). A Habitat Directive Area (hatched) is present at a minimum of 2.5 km from the southernmost sectors. Presence of gravel (purple circles) and stones (green triangles) is indicated (size/colour of the dots represents relative amounts of gravel with a minimum of 20 %). In the light yellow areas the probability of finding gravel is high (based on samples, in combination with acoustic imagery). In the gravel refugia (green rectangles), west of the southern part of the Oosthinder, ecologically valuable gravel beds are present. Black dots are positions where no gravel was sampled. Indicated also is the position of the Westhinder measuring pole (Flanders Hydrography) (red pentagon) where most of the hydro-meteorological data were derived from. Grey polygon in the Habitat Directive Area is an anchorage zone.

Over a 10 years period intensive extraction of marine aggregates (up to 2.9 million m³ over 3 months) is allowed in this area, with a maximum of 35 million m³ over a period of 10 years. Large trailing suction hopper dredgers (TSHD) can be used, extracting up to 12,500 m³ per run. Such intensive extraction is new practice in the BPNS and the environmental impact is yet to be determined. See also Roche et al. (this volume) and De Backer et al. (this volume).

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

Habitat Directive

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

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

Material and methods

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

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

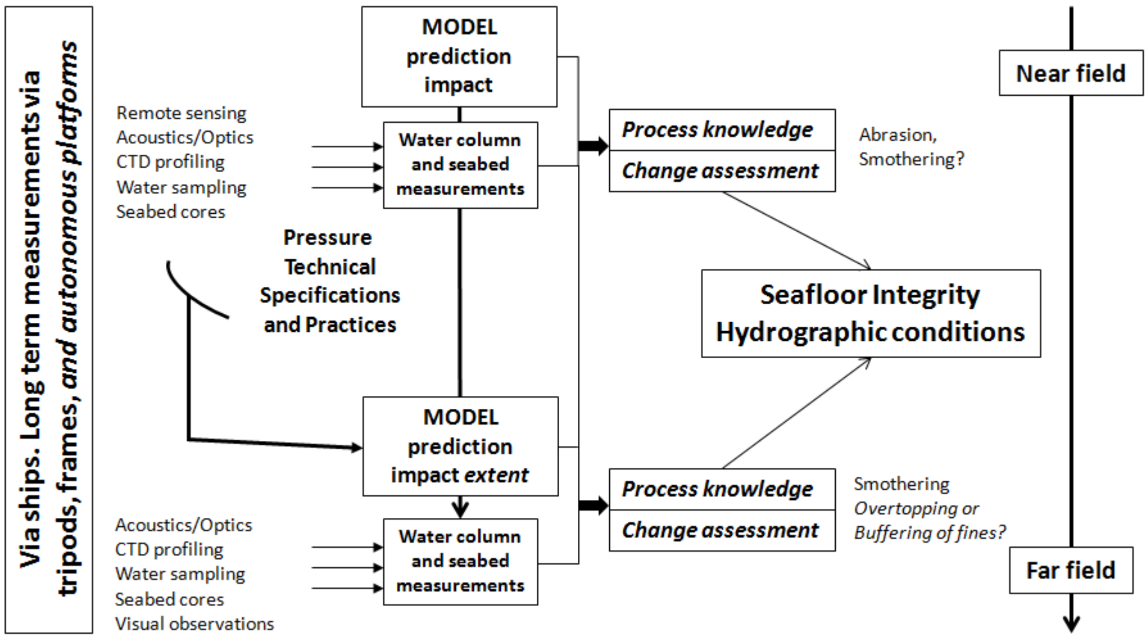

Figure 16: Overview of the RBINS OD Nature research strategy aiming at quantifying both near- and far-field impacts of marine aggregate extraction.

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

1. A new workflow for sediment plume modelling was developed coupling technical specifications of a series of trailing suction hopper dredgers (TSHD) and data on extraction activities to an advection-diffusion model that predicts the extent and total mass / concentration of sediment fractions released from the TSHDs. Effects of differences in extraction practices, particularly related to the use of small (2,500 m^3), medium (4,500 m^3) and large (> 10,000 m^3) TSHDs were modelled.

2. The suite of hydrodynamics and sediment transport models were validated with the newly acquired measurements to optimize modelling in the Hinder Banks.

3. Regarding bottom shear stress, a variety of calculations from measurements and modelling approaches were revisited. Recommendations were formulated when using bottom shear stress models in impact predictions under various scenarios of extraction.

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

Results

Physical impact assessment

Monitoring results

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

TSHD characteristics and their operations

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

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

Hydrodynamics and sediment transport

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

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

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

Seabed substrate

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

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

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

Seabed morphology

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

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

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

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

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

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

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

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

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

Near-field

Settling of dynamic plume

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

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

Far-field

Habitat Directive area

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

Belgian part of the North Sea

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

Hypothetical cause-effect relationships

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

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

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

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

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

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

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

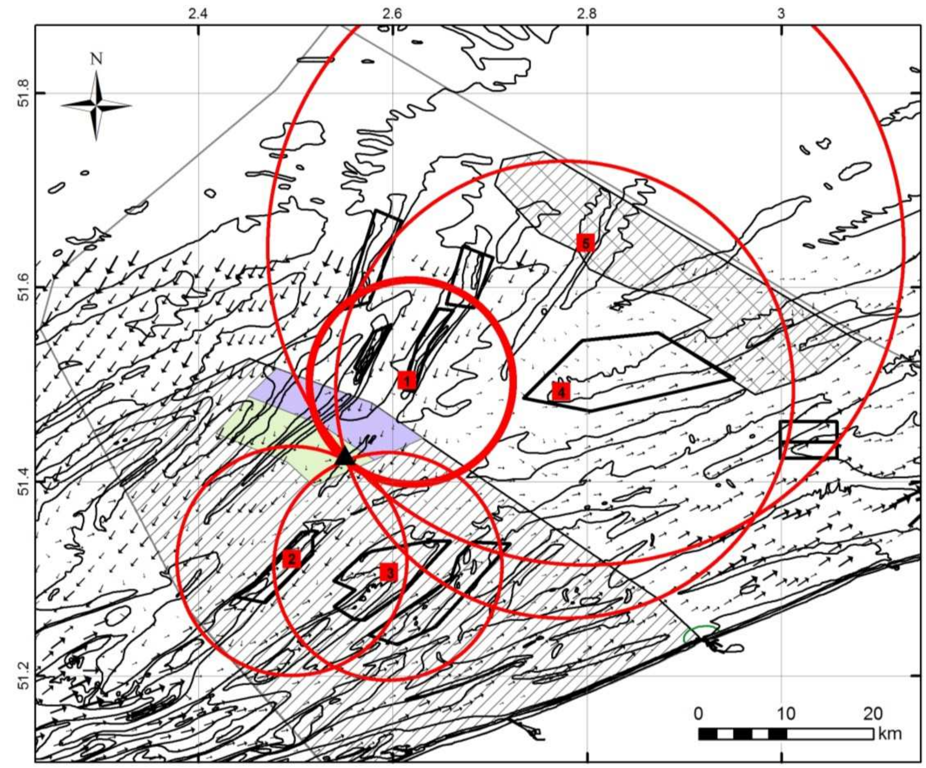

Figure 17: Ecologically valuable gravel beds in the Habitat Directive Area (centroid triangle) with the distances to the different pressures (red squares). (1) Extraction in Sector 4c, Hinder Banks; (2) and (3) Extraction in zone 2: Oostdijck and Buiten Ratel; (4) Extraction in zone 1 Thornton Bank.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

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

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

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

1. ET 7: *The areal extent and distribution of EUNIS level 3 Habitats (sandy mud to mud; muddy sand to sand and coarse sediments), as well as of the gravel beds, remain within the margin of uncertainty of the sediment distribution, with reference to the Initial Assessment.*

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

2. ET 17: *Within the gravel beds*[1] *(in test zones), the ratio of the surface of hard substrate (i.e., surface colonized by hard substrata epifauna) against the ratio of soft sediment (i.e., surface on top of the hard substrate that prevents the development of hard substrata fauna), does not show a negative trend.*

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

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

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

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

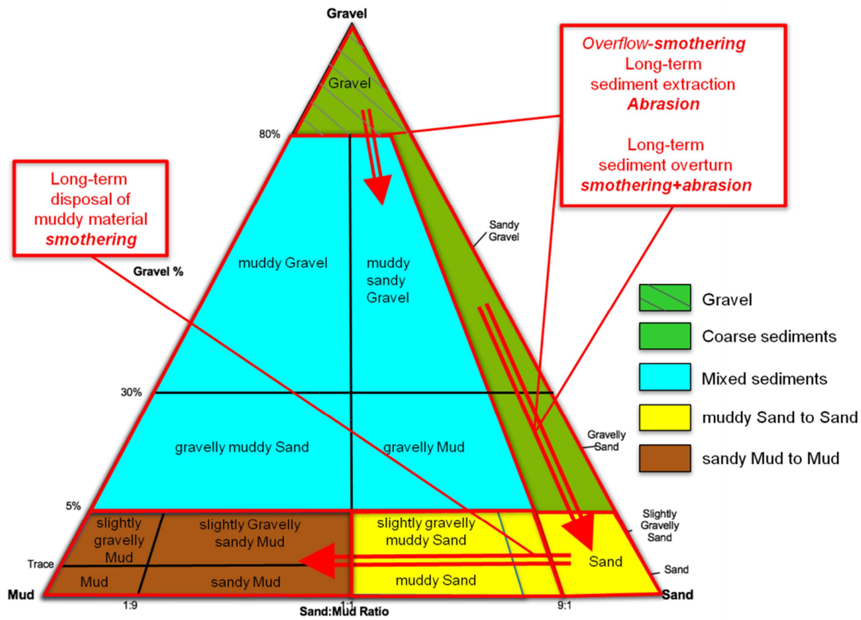

Figure 18: Relationships between EUNIS Level 3 Habitats (sandy mud to mud; muddy sand to sand; mixed sediments and coarse sediments) as derived from a grouping of the 14 Folk substrate classes (Folk, 1954). For the Belgian MSFD implementation, gravel is also considered individually. Regarding changes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

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

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

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

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

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

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

Hydrographic conditions (GES descriptor 7)

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

1. ET 29: *A human impact demands consideration if one of the following conditions – related to the bottom shear stress on a 14 days spring tide/neap tide cycle as computed by validated mathematical models – is met: i) there is a difference of more than 10 % in the mean bottom shear stress; ii) the variation of the ratio between the duration of the bottom shear stress and the duration of the erosion is outside the "-5%, +5%" range*.
2. ET 30: *The impact, that needs consideration, should remain within a distance equal to the root square of the surface occupied by this activity and taken from its external limit*.
3. ET 31: *All developments must comply with the existing regulatory regime (e.g., EIA, SEA, and Habitats Directives) and regulatory assessments must be undertaken in such a way that it takes into consideration any potential impacts arising from permanent changes in hydrographical conditions, including cumulative effects, at the most appropriate spatial scales following the guidance prepared to this end*.

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

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

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

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

Discussion

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

Baseline – natural variability

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

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

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

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

Cause-effect relationships

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

Significance of the effects on larger scales

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

Recommendations for the continuation of extraction

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

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

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

Conclusions

Integrated monitoring of the effects of aggregate extraction is needed to reach Good Environmental Status of the marine environment by 2020 (European Marine Strategy Framework Directive (MSFD); 2008/56/EC). To improve the management of the activity, understanding of the causes of the impact is crucial, as well as insight into natural variability, and therefore increased process and system knowledge is required. Additionally, when exploitation is within or near Habitat Directive areas, appropriate assessments are needed of all stressors (92/43/EEC). In 2012, new extraction activities started in far offshore sandbanks of the Hinder Banks, just north of the 'Flemish Banks' Habitat Directive area. Here, ecologically valuable gravel beds occur adapted to a clear water regime. Therefore, a dedicated monitoring programme was set-up, with focus on assessing changes in seafloor integrity and hydrographic conditions, two descriptors that define Good Environmental Status. Seafloor integrity relates to the functions that the seabed provides to the ecosystem (e.g., structure; oxygen and nutrient supply), whilst hydrographic conditions refer to currents, turbidity and/or other oceanographic parameters of which changes could adversely impact on benthic ecosystems.

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

It needs emphasis that during this first phase of the monitoring, development of monitoring strategies and methodologies was critical, as well as setting-up baselines. Important new results were obtained; for the period 2011-2016 these relate to: (1) quantification of natural variability; (2) sediment plume formation and deposition, differentiating between small and large trailing suction hopper dredgers; (3) far–field impacts, with focus on the gravel beds within the Habitat Directive area, and (4) bottom shear stress modelling in view of predicting long-term changes in hydrographical conditions.

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

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

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

Acknowledgements

The ZAGRI monitoring programme, paid from the revenues of extraction activities, and the Flemish Authorities, Agency Maritime Services and Coast, Coast (MOZ4: Contract 211.177), are acknowledged for financially contributing to the monitoring activities. The BELSPO Brain-be projects TILES (contract BR/121/A2/TILES) and INDI67 (contract BR/143/A2/INDI67) contribute respectively to quantifying natural variability incorporating the geological substratum, and the modelling of bottom shear stresses and the quantification of benthic habitat changes from multibeam data.

RV Belgica shiptime was provided by RBINS OD Nature and Belgian Science Policy (BELSPO). The commander and crew are acknowledged for their support during the measuring campaigns. Lieven Naudts, and other team members of the Measuring Service Ostend (MSO) (OD Nature) are thanked for their logistical support, especially during the deployment of the bottom-mounted ADCPs. A special thanks goes to Reinhilde Van den Branden for her continuous support throughout all measurements, and for providing, together with Gregory De Schepper, processed data on the dredging activities. Flanders Marine Institute, VLIZ, is thanked for the use of its LISST instrument and the Hamon grab for gravel sampling. Additionally, a video frame was provided for visual observations, and their Remote Operated Vehicle, GENESIS operated from RV Simon Stevin. Ghent University, Renard Centre of Marine Geology, is acknowledged for providing laboratory facilities and sediment analyses. Furthermore, several OD Nature teams are acknowledged for their contributions: ECOCHEM for the analyses of the filtrations of the water samples; MFC, Sébastien Legrand, for modelled hydro-meteorological data. Measurements of hydro-meteorological data were acquired from the Flemish Government, IVA MDK;,-afdeling Kust, 'Meetnet Vlaamse Banken'. FPS Economy, Continental Shelf Service (COPCO) is thanked for assistance with multibeam data processing, and active cooperation in general. COPCO and ILVO are thanked for sharing data and ideas.

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