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SUSPENDED MATTER AND SEABED MONITORING AND MODELLING GROUP

Monitoring of the impact of the extraction of marine aggregates, in casu sand, in the zone of the Hinder Banks

Scientific Report 6 – January - December 2019 and Synthesis for the period 2016-2019

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MOZ4-ZAGRI/I/VVL/2020/EN/SR01

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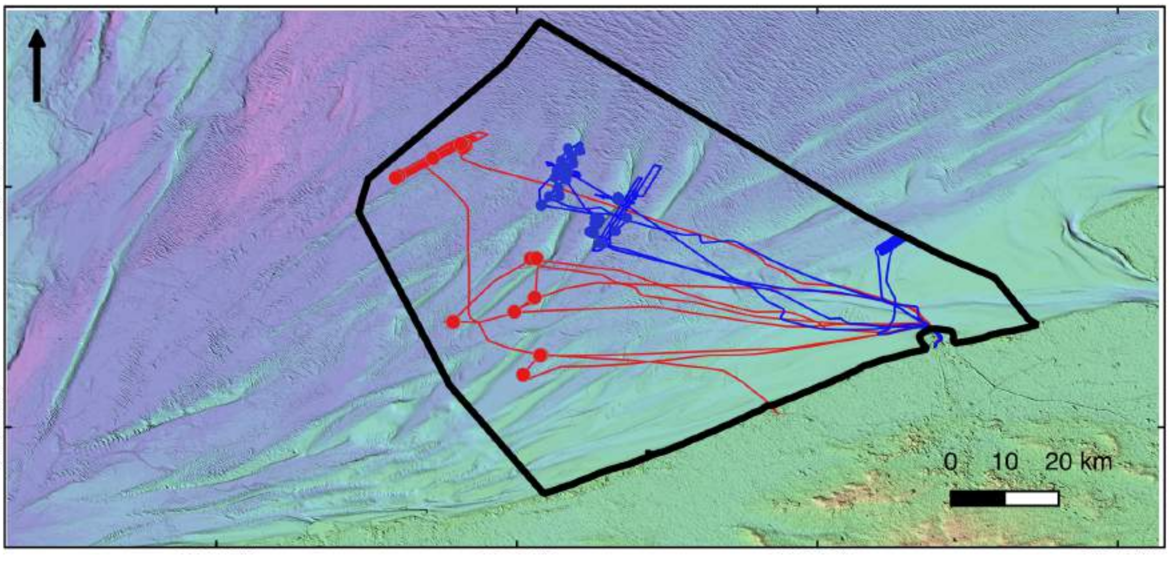

Background: EMODnet bathymetry

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Abbreviations

ADCP	Acoustic Doppler Current Profiler
AUMS	Autonomous Underway Measurement System
BM-ADCP	Bottom-mounted Acoustic Doppler Current Profiler
BPNS	Belgian Part of the North Sea
COPCO	Continental Shelf Service of FPS Economy
CTD	Conductivity-Depth-Temperature
DGPS	Differential Global Positioning System
EMS	Electronic Monitoring System
FPS Economy	Federal Public Service Economy, SMEs, Self-Employed & Energy
GES	Good Environmental Status
HM-ADCP	Hull-mounted Acoustic Doppler Current Profiler
Hs	Significant wave height
ILVO	Institute for Agricultural and Fisheries Research
LISST	Laser In-Situ Scattering and Transmissometry
Mab:	Depth in Meter above bottom
MFB, MP7	Measuring Network Flemish Banks; measuring pile 7 (Westhinder; Flanders Hydrography)
MSFD	European Marine Strategy Framework Directive
NE	Northeast-directed (flood)
OBS	Optical Back Scatter
ODAS	Oceanographic Data and Acquisition System
OPTOS-BCZ	Hydrodynamic model applied to the Belgian coastal zone
POC	Particulate Organic Carbon
PON	Particulate Organic Nitrogen
PSD	Particle-size distribution
RV	Research Vessel
SPM(c)	Suspended Particulate Matter (concentration)
SW	Southwest-directed (ebb)
TKE	Turbulent kinetic energy
TSHD	trailing suction hopper dredgers
UGent-RCMG	Ghent University, Renard Centre of Marine Geology
UGCT	UGent Centre for X-ray tomography
UTC	Universal Time Coordinates
VLIZ	Flanders Marine Institute

Executive summary

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 a far offshore sandbank area in the Belgian part of the North Sea (BPNS), just north of a 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 2016-2019 phase focused on methodological progress to better quantify changes in the descriptors of good environmental status. It should be stressed that change detection remains a complex endeavour and is sensitive to many factors that require research and wider cooperation. Changes are often minor, but can still prove detrimental to the seabed environment. It is therefore important that measurements, in combination with models, lead to a better understanding of the processes, the scale on which they operate, and the systematics. Margins of error must be known from the instruments used in monitoring, which is an investigation in itself. This is all the more important when assessing changes in the water properties of areas with low sediment concentration with concentrations 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, sedimentation processes in sand bank environments are spatially and over time highly variable, requiring flexibility of the monitoring programme. Since 2011, therefore, measurements have been carried out at various locations, comparative datasets have been compiled, and basic information and system knowledge have been increased in order 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 settles in the near field while the finer particles continue to spread. Organic matter has been measured in areas with extraction activities which can also influence 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 with gravel beds with richer biodiversity. In the gravel biodiversity hotspots 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 present in the area. However, the pores of the sand layer contained fine-grained material,

which was now clearly demonstrated, for the first time, by means of micro-CT scans. Whether this leads to pore clogging that can reduce the functions that the seabed provides to the ecosystem needs further investigation. Compared to historical data, seabed mapping and visual observations tend to indicate an increasing presence of sand ripple fields. From depth measurements, however, this is difficult to deduce, the more such changes fall within the margin of error of the depth measurements (+/- 30 cm in 30 m water depth). A sand expansion, overtopping gravel, leads to a homogenisation of the seabed, resulting in less structure for benthic and epibenthic species. However, sand thickness is hardly known and, if it is and remains small, gravel fauna may not suffer adverse effects. In the next phase of monitoring, historical multibeam data sets will be re-analysed, focusing on pattern changes. Different source-to-sink scenarios will also be investigated, taking into account 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 various extraction areas, there are indications that despite the restoration of dune structures after extraction, the development of dune height remains slightly negative. Overall, dune heights are lower than would be expected on the basis of their wavelength. The significance of this should be studied in a broader context, with the detailed and renewed multibeam-EMS analyses by FPS Economy leading the way.

Samenvatting

Geïntegreerde monitoring van de effecten van aggregaatextractie is nodig om een goede milieutoestand van het mariene milieu te bereiken (Europese Kaderrichtlijn Mariene Strategie (KRMS); 2008/56/EG). Om het beheer van de activiteit te optimaliseren, alsook om de oorzaak-gevolg relaties te begrijpen en inzicht te hebben in natuurlijke variabiliteit, is een grotere proces- en systeemkennis nodig. Bovendien, wanneer de exploitatie in, of in de buurt van een Habitatrichtlijnengebied valt, is een passende beoordeling nodig van de effecten van alle stressoren (92/43/EEG). In 2012 startten nieuwe extracties op ver zeewaarts gelegen zandbanken in het Belgische deel van de Noordzee, net ten noorden van een Habitatrichtlijnengebied. Hier komen ecologisch waardevolle grindbedden voor, aangepast aan helder water. Een gericht monitoringsprogramma werd opgezet, met focus op het beoordelen van veranderingen in de zeebodemintegriteit en hydrografische condities, twee KRMS descriptoren om de mariene milieutoestand te evalueren. Zeebodemintegriteit betreft de functies die de bodem biedt aan het ecosysteem (bv. structuur, zuurstof en toevoer van voedingsstoffen), terwijl hydrografische condities verwijzen naar stromingen, turbiditeit en/of andere oceanografische parameters waarvan veranderingen een negatieve invloed kunnen hebben op benthische ecosystemen.

In de fase 2016-2019 werd vooral ingezet op methodologische vooruitgang om veranderingen in de descriptoren van goede milieutoestand beter te kwantificeren. Het dient beklemtoond dat veranderingsdetectie een complexe aangelegenheid blijft en gevoelig is aan vele factoren die onderzoek en ruimere samenwerking vereisen. Veranderingen zijn vaak gering, maar kunnen toch nefast blijken voor het zeebodemmilieu. Daarom is het van belang dat metingen, in combinatie met modellen, leiden tot een beter begrip van de processen, de schaalgrootte waarop ze werken, en de systematiek. Foutmarges dienen gekend te zijn van de instrumenten die bij het toezicht worden gebruikt, wat een onderzoek op zich is. Des te meer is dit van belang bij het beoordelen van veranderingen in de watereigenschappen van gebieden met een lage sedimentconcentratie. De concentraties zijn vaak te laag voor herhaalbare, goede metingen. Het ontwikkelen van robuuste meetprotocollen en kwaliteitsstandaarden stond dan ook voorop, evenals instrumentkalibratie. Bijkomend zijn sedimentprocessen in zandbankomgevingen ruimtelijk en in de tijd zeer variabel wat noopt tot flexibiliteit van het monitoringprogramma. Sinds 2011 worden dan ook op verschillende locaties metingen uitgevoerd, worden er vergelijkende datasets samengesteld, en wordt de basisinformatie en systeemkennis vergroot om beter inzicht te krijgen in de oorzaak-gevolgrelaties.

Tot nu toe waren veranderingen in watereigenschappen alleen zichtbaar in het nabije veld van de winningsactiviteiten. Deeltjesgroottespectra tonen zowel een waterkolom- als een zeebodem-gerelateerde component. Het zand dat bij extractie vrijkomt zet zich af in het nabije veld terwijl de fijnere deeltjes zich verder verspreiden. Organische aanrijking werd aangetoond in gebieden met winningsactiviteiten wat ook het verspreidingsgedrag van de fijnere deeltjes kan beïnvloeden. Kritisch blijft het voorspellen waar de fijnkorrelige deeltjes zich vestigen en hoe dit het zeebodemmilieu beïnvloedt, vooral in gebieden met grindbedden met een rijkere biodiversiteit. In de hotspots van grindbiodiversiteit waar in

2006-2007 door duikers geen zanddikte werd gemeten, werd in 2019 een zandbedekking van 8-10 cm gemeten. Het zand bestond vooral uit permeabel middelgrof tot grof materiaal dat in de omgeving aanwezig is. De poriën van de zandlaag bevatten echter fijnkorrelig materiaal wat nu voor het eerst duidelijk werd aangetoond door middel van micro-CT scans. Of dit leidt tot poriënverstopping die de functies die de zeebodem aan het ecosysteem levert kan verminderen, moet verder worden onderzocht. In vergelijking met historische data, wijzen zeebodemkartering en visuele waarnemingen eerder op een toenemende aanwezigheid van zand. Vanuit dieptemetingen is dit echter moeilijk af te leiden temeer dergelijke veranderingen binnen de foutenmarge van de dieptemetingen vallen (+/- 30 cm in 30 m waterdiepte). Een zandverbreiding over grindgebieden leidt tot een homogenisering van de zeebodem, waardoor er minder structuur is voor benthische en epibenthische soorten. De zanddikte is echter nauwelijks gekend, en, indien dit gering is en blijft, bestaat de mogelijkheid dat grindfauna hier geen adverse effecten van ondervindt. In de volgende fase van de monitoring zullen historische multibeamdatasets opnieuw worden geanalyseerd, met vooral aandacht voor patroonveranderingen. Ook zullen verschillende bron-tot-afzettingsscenario's worden onderzocht, rekening houdende met verschillende menselijke activiteiten, in een poging om typische sedimentbronsignaturen te vinden. Op basis hiervan worden nieuwe inzichten verwacht in cumulatieve, en in-combinatie-effecten.

Tot slot zijn er, voor verschillende ontginningsgebieden, aanwijzingen dat ondanks het herstel van duinstructuren na extractie, de ontwikkeling van de duinhoogte licht negatief blijft. Over het geheel genomen zijn de duinhoogtes lager dan op basis van de golflengte zou verwacht worden. De significantie hiervan dient in een ruimer kader te worden bestudeerd waarbij de gedetailleerde en vernieuwde multibeam-EMS analyses van FOD Economie leidend zullen zijn.

Preface

Results presented in this report relate to the monitoring of aggregate extraction in zone 4, Hinder Banks (MOZ4), for the year 2019. It is a follow-up of the reporting *w.r.t.* the yearly monitoring since 2013 (synthesis in Van Lancker et al., 2016), and provides a synthesis for the period 2016-2019.

Since 2013, the monitoring activities were financially supported by the Flemish Authorities, Agency Maritime Services and Coast, Coast. The monitoring programme ZAGRI, funded by the revenues of the private sector, and covering all concession zones in the Belgian part of the North Sea, provides a continuous support to MOZ4, as well as for the measurements that commenced in 2011, as for the model development. In the period 2015-2018, monitoring was also supported by the Belspo INDI67 research project. In that project, the Marine Strategy Framework Directive indicators on the physical properties of the water-column and seabed interface and related to the descriptors of Good Environmental Status (GES) 'Seafloor Integrity' and 'Hydrographic Conditions', were investigated in more detail. Particularly, the research on quantifying changes in bottom shear stress and benthic habitats (from multibeam backscatter) benefitted from this additional funding.

The synthesis on the second phase of the monitoring integrates the results obtained and puts them in perspective of the results of the morphological and biological monitoring, respectively carried out by the Continental Shelf Service of FPS Economy (COPCO) and the Institute for Agricultural and Fisheries Research (ILVO).

Backbone of the MOZ4 monitoring:

ZAGRI ('Sand and Gravel') monitoring programme focusing on:

1. **Quantification of natural and human-induced variability of sediment characteristics and processes, focus sand**: *Studied at different spatial and temporal scales, based on measurements and modelling. In-situ data for the offshore areas are mostly gathered under the MOZ4 monitoring programme, Hinder Banks region.*
2. **Process- and system modelling and understanding of the activity-pressure-effect chain; near and far field**: *Numerical modelling of hydrodynamics/sediment transport, including bottom shear stress, as well as dune dynamics.*
3. **Recommendations on a more sustainable use of marine raw materials:** *Results are valorized against the European Marine Strategy Framework Directive striving towards Good Environmental Status of marine waters. This comprises improvement of the environmental baseline by (i) seabed mapping and ground-truth validation; (ii) compiling and valorising databases on seabed sediments, the latter including the geological subsurface. Aggregate resource assessments are targeted, supporting long-term marine exploitation strategies.*

MONIT.be: the Belgian monitoring programme assessing Good Environmental Status of its marine waters, European Marine Strategy Framework Directive.

MSFD website: https://odnature.naturalsciences.be/msfd/
Monitoring programmes: https://odnature.naturalsciences.be/msfd/nl/monitoring/2020/
Assessment seafloor integrity 2018: https://odnature.naturalsciences.be/msfd/nl/assessments/2018/page-d6
Assessment hydrographic conditions 2018: https://odnature.naturalsciences.be/msfd/nl/assessments/2018/page-d7

RBINS-**MUMM Scientific service**: https://odnature.naturalsciences.be/mumm/

1. Introduction

Over a 10-yrs period extraction of marine aggregates (up to 2.9 million m^3 over 3 months) is allowed in the region of the offshore Hinder Banks (concession zone 4), with a maximum of 35 million m^3 over a period of 10 years. Concessions were granted in four sectors of extraction: 4a-b-c-d, respectively on the sandbanks Noordhinder, Oosthinder north, Oosthinder middle, and Westhinder. Large trailing suction hopper dredgers (TSHD) can be used, extracting up to 12,500 m^3 per run. These practices contrast strongly with previous extraction activities: up to 3 million m^3 per year, in 2011, and mostly using vessels with a capacity of 1500 m^3 only. Since 2012, extraction is allowed in concession zone 4, reaching a peak extraction of nearly 2.5 10^6 m^3 in 2014 (Sector 4c) (Van den Branden et al., 2020) (Figure 1). In 2015 extraction shifted to Sector 4b, northern part of the Oosthinder. No extraction took place in 2016, but activities retook in 2017 and 2018 (Sector 4c). In 2019, extraction took place only on Sector 4a, Noordhinder sandbank as a response to the delineation of a new offshore windfarm foreseen in the Marine Spatial Plan of 2020-2026. The volumes are mostly needed in response to the needs of the Coastal Safety Plan bringing the level of protection against extreme storm events at a 1:1000 years return period, including a +30 cm sea level rise by 2050 (www.kustveiligheid.be).

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 Lowest Astronomical Tide (LAT) (Figure 2); 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 LAT of water depth. Sediments are medium- to coarse sands, including shell hash. Tidal currents reach more than 1 ms^{-1}; waves are easily more than 1 m in height (44 % of the time). These offshore sandbanks are the first wave energy dissipaters in the BPNS.

The extraction sectors on the Hinder Banks are near an area protected under the Habitat Directive (92/43/EEC; see box below), called the "Vlaamse Banken". The northern limit of this area was drawn to include ecologically valuable gravel beds (Houziaux et al., 2008) (Figure 2). These beds have the status of "reefs" (Habitat type code 1170). At present, and in contrast to 100 yrs 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. 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), and as such considered more protected from trawling activities.

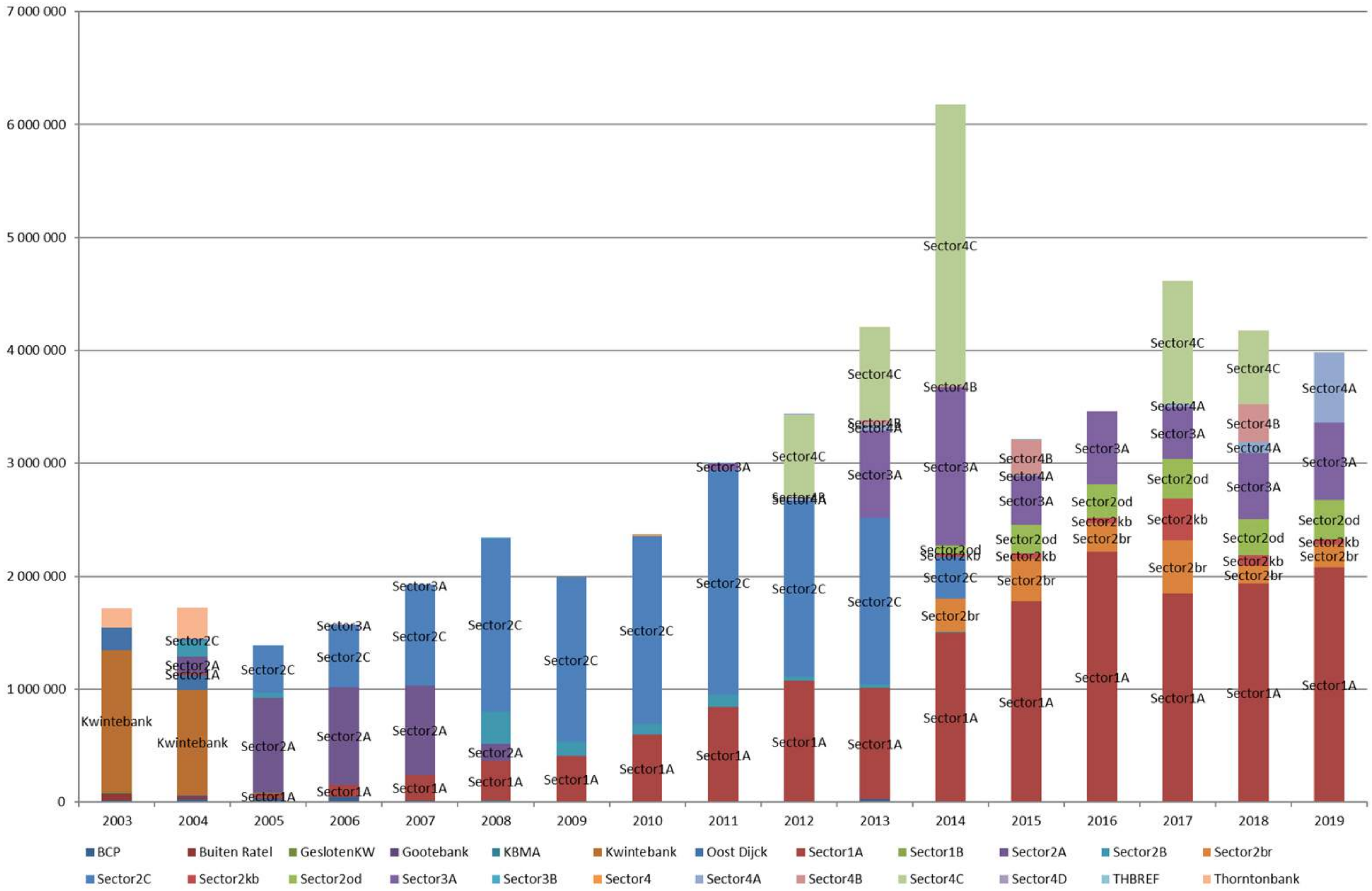

Figure 1. Extracted volumes of marine aggregates (m^3) in the period 2003-2019 (Van den Branden et al., 2020). Labels 4, 4a-b-c-d relate to the extraction on the Hinder Banks. Note a peak extraction of nearly 2.5 10^6 m^3 on Sector 4c in 2014, whilst in 2019 extraction only took place in Sector 4a, Noordhinder.

Habitat Directive

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

In implementation of the Habitats Directive (92/43/EEC), the Belgian State designated a Habitat Directive Area "Vlaamse Banken" (Royal Decree of October 16, 2012). The area is 1099.39 km^2 and 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 “Vlaamse Banken” 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).

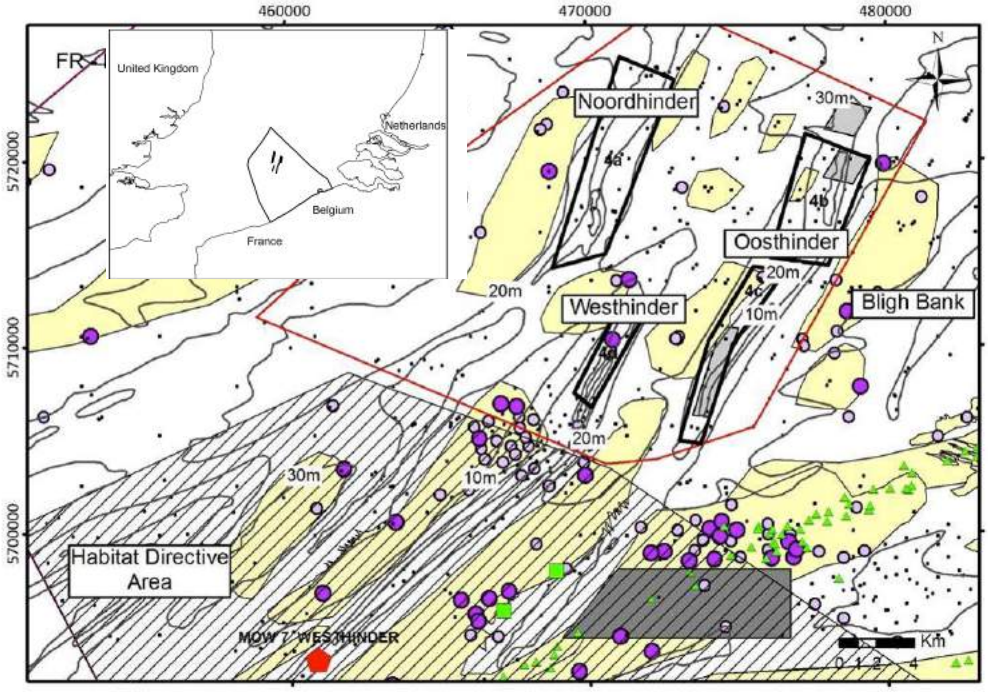

Figure 2. Area of the Hinder Banks, where intensive marine aggregate extraction is allowed in zone 4 (red line) along 4 sectors (black polygons). Within and outside these sectors geomorphological monitoring is carried out by COPCO (light grey polygons). A Habitat Directive area (hatched) is present at a minimum of 2.5 km from the southernmost sectors. Presence of gravel (purple dots) and stones (green triangles) is indicated (size 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) (Van Lancker et al., 2007). In the gravel refugia (green squares), west of the Oosthinder, ecologically valuable epifauna is present. Indicated also is the position of the Westhinder measuring pole MOW7 (Flanders Hydrography) (red pentagon) where most of the hydro-meteorological data are derived from. Dark grey polygon in the Habitat Directive area is an anchorage zone.

2. Monitoring design

A monitoring programme, with focus on hydrodynamics and sediment transport, has been designed allowing testing hypotheses on the impact of marine aggregate extraction in the far offshore Hinder Banks. Impact 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) (Belgische Staat, 2012, 2018). In the context of the present monitoring, main targets are assessing changes in seafloor integrity (descriptor 6) and hydrographic conditions (descriptor 7), two key descriptors of good environmental status, in six-yearly cycles.

Summarized, main hypotheses to be tested 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 (MSFD descriptor 6); (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); (5) Marine aggregate extraction has no significant impact on seafloor integrity, nor it will significantly lead to permanent alterations of the hydrographical conditions (MSFD descriptor 7); (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 coastwards occurring habitats.

The monitoring follows a tiered approach, consisting of in-situ measurements and modelling (Figure 3). Critical is to assess potential changes in hydrographic conditions (MSFD, descriptor 7), as a consequence of multiple seabed perturbations (e.g., depressions in the seabed) and their interactions. This could lead to changes in bottom shear stresses, a MSFD indicator that should remain within defined boundaries[1]. Therefore, considerable effort went to current velocity and turbidity measurements along transects crossing the sandbanks, as also on point locations for longer periods. These data serve as a reference and are compared to datasets recorded under the events of intensive aggregate extraction. The extraction gives rise to sediment plumes and subsequent release of fine material in the water column. As such, dispersion of the fine-grained material and the probability of siltation in

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[1] For descriptor 7 on hydrographic conditions, the monitoring programme should allow evaluating the following specifications (Belgische Staat, 2018):

D7.1: The infrastructure works are significant when at least one of the following criteria is met:

- There is a physical loss (as defined by criterium D6C1)
- There is a variation of more than 10% of the mean bottom shear stress;
- There variation of more than 10% of the time of the duration of sedimentation or the duration of erosion.

The bottom stress should be calculated taking in to account the effects of both currents and waves on the sea bottom. For infrastructure works that cause changes on small scale, the bottom stress could be calculated with a hydrodynamic model for on a spring-neap tidal cycle (14 days)

D7.2: The spatial scale of each benthic habitat type that is affected negatively by permanent changes of the hydrological conditions the nearby Habitat Directive area are studied, since this may cause deterioration of the integrity of gravel beds present in this area. This relates directly to Belgium's commitments within the MSFD stating that the ratio of the hard substrata surface area versus the soft sediment surface area should increase in time (Belgische Staat, 2012, 2018). Furthermore, abrasion of the sandbank and/or enrichment of finer material, could lead to habitat changes[2], another indicator within MSFD (descriptor 6 Seafloor Integrity).

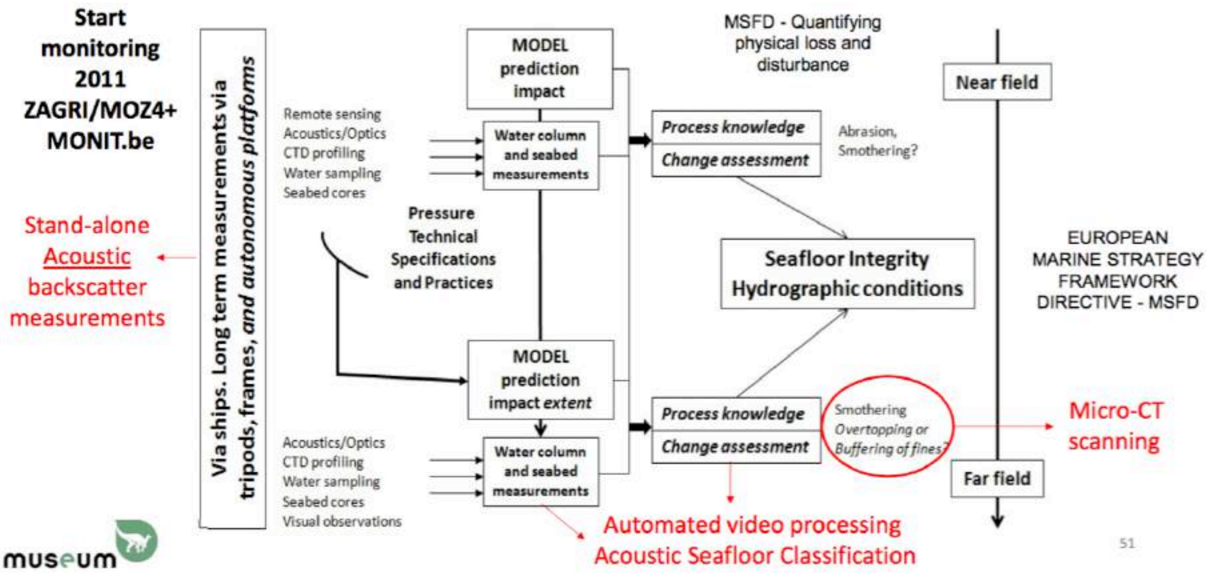

Figure 3. Overview of the research strategy aiming at quantifying both near- and far-field impacts of marine aggregate extraction.

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[2] For descriptor 6 this monitoring programme contributes to the evaluation of the following environmental targets and associated indicators (Belgische Staat, 2018):

(1) The areal extent and distribution of EUNIS (marine level 2) 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 (selected 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.

3. Materials and methods

3.1. *Measurements and spatial observations*

In 2019, three 1-week campaigns, were organized, all with RV Belgica (ST1909, ST1919, ST1930). One longer term bottom-mounted ADCP (BM-ADCP) deployment was also conducted. See Table 1, for an overview of the data periods and research areas.

Table 1. Overview of RV Belgica campaigns in 2019. HD area: Habitat Directive area. OH: Oosthinder sandbank; NH: Noordhinder sandbank; BB: Bligh Bank. See Figure 4 and Figure 5 for locations and RV Belgica cruise reports for more details on the data acquisition (Annex).

Campaign	Area	Start	End	Tidal phase
ST1909	OH-BB; OH, NH	2019-03-25	2019-03-29	Spring tide
ST1919	HD Area; northern exploration zone	2019-07-08	2019-07-12	Neap tide
ST1930	Calibration of HM-ADCP*	2019-11-25	2019-11-29	Spring tide

**Adverse weather conditions did not allow to conduct dedicated measurements.*

3.1.1. Longer-term measurements at a fixed location

Near-bottom processes (currents and turbidity) were further studied using an upward looking bottom-mounted Acoustic Doppler Current Profiler (BM-ADCP; Teledyne/RD Instruments, 1200 kHz Workhorse Sentinel) near Sector 4a Noordhinder sandbank to study natural variability of sediment processes and the effects of marine aggregate extraction (Table 2).

Table 2. Longer term deployments with a BM-ADCP. Settings of the deployments are given, as also the position. Data were recorded with reference to the bottom; depth in meters above bottom is abbreviated as mab.

Type	Start	End	Bin Size (m)	Remarks
Noordhinder NH Sector 4a RDI-BB 1228.8 kHz	2019-03-28 18:31	2019-06-14 13:47* ± 78 days (43 days were considered good data)	0.25	Fast pinging mode Bins [0.81-15] mab; average ensemble interval 15 min Location: 51°34.338N; 002°32.682'E (± 23 m LAT)

**The BM-ADCP could not be recovered as planned originally due to failure of the acoustic response of the instrument. A Navy ship was able to recover it after 78 days. Due to algae bloom only 43 days of the dataset were considered of good quality.*

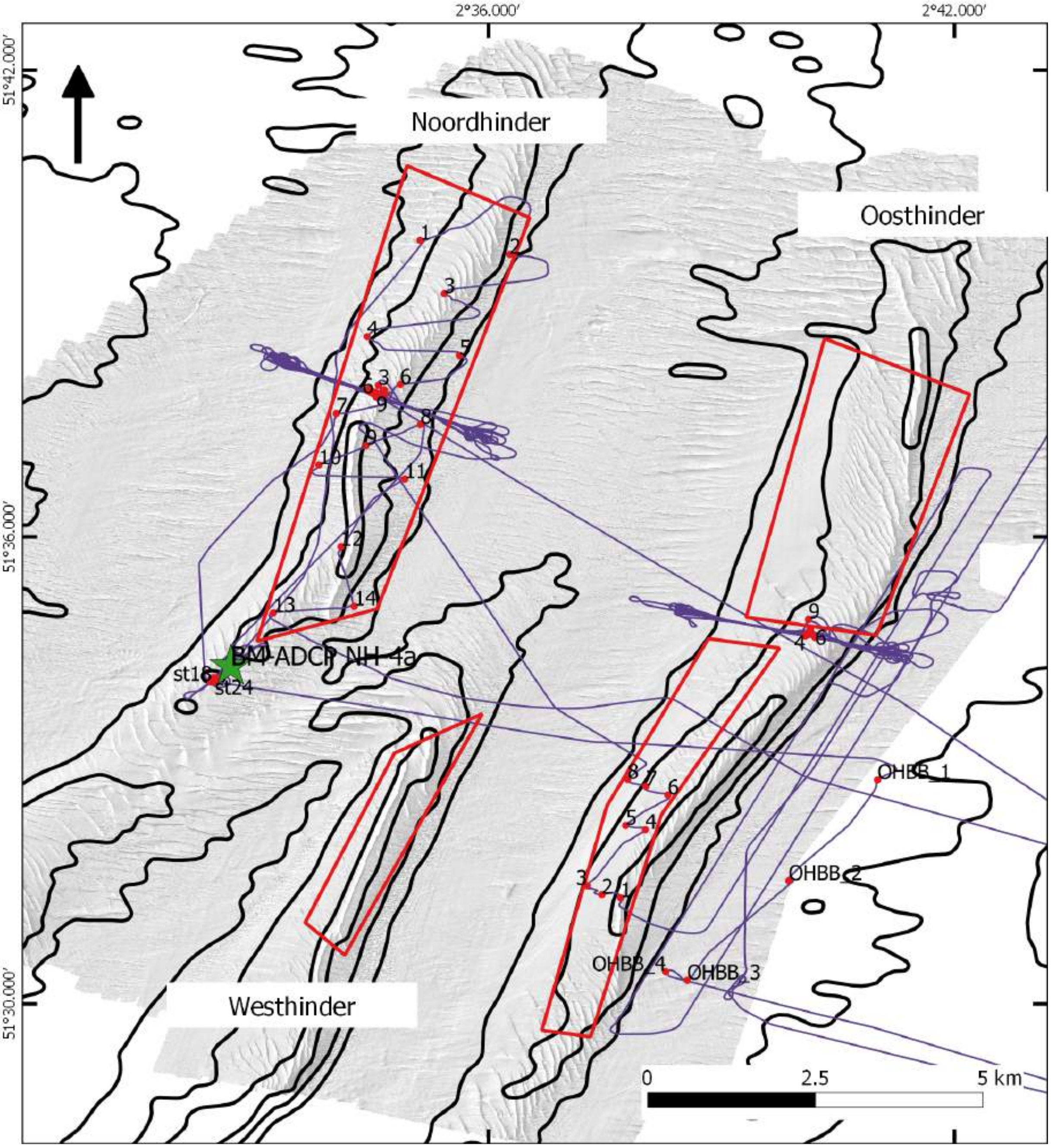


Figure 4. Overview of the measurements during RV Belgica ST1909. Focus was on near-field measurements in relation to the aggregate sector 4a, Noordhinder, and sector 4c, Oosthinder sandbank. Reineck boxcores were taken in both sectors and sliced at 1-cm for detailed analyses of sediment characteristics of the upper seabed. Cross-bank transects (HM-ADCP) were sailed to investigate sediment properties in the water column. Water samples were taken intermittently at the top of the sandbanks. At the southern edge of sector 4a, through-tide, stationary, 13-hrs measurements in the water column were taken at the position where a multi-sensor bottom frame was deployed for 78 days. Hamon grab samples were taken in the gully east of the Oosthinder sandbank to investigate gravel occurrences (lower right: OH-BB samples).

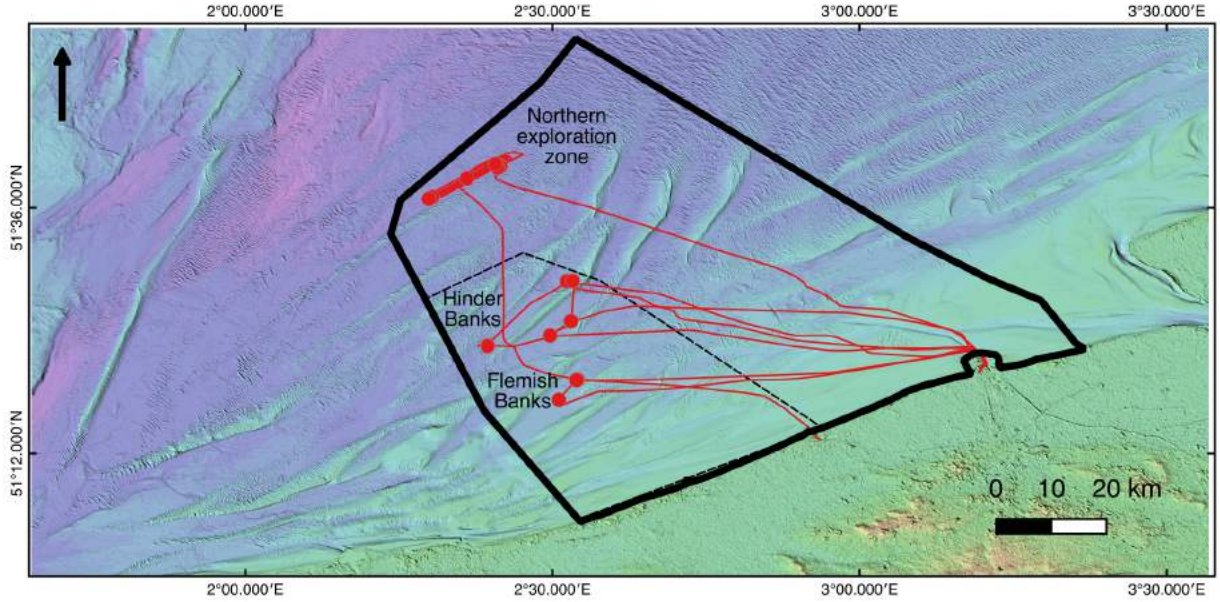


Figure 5. Overview of the measurements during RV Belgica ST1919. Focus was on far-field measurements focussing on gravel beds in the Habitat Directive area, and was a combined effort with RBINS OD Nature Marine Ecology team. Per location, multibeam depth and back-scatter data were gathered and validated with seabed samples, as well as visual observations (video frame, and scientific diving). Similar data were acquired in the northern exploration zone. Background: EMODnet-Bathymetry.

3.1.2. Short-term spatial observations (*RV Belgica*)

In 2019, the following observations were made:

(1) Very-high resolution acoustic measurements were performed with RV Belgica's multibeam system (Kongsberg-Simrad EM3002, 300 kHz):. Depth and backscatter data were obtained.

(2) Through-tide (13-hrs cycle) transect measurements of hull-mounted ADCP (HM-ADCP) over Noordhinder and Oosthinder: in-between Sector 4c and Sector 4b, and cross Sector 4a. Currents and turbidity were measured. Water samples and oceanographic profiling was conducted to calibrate the HM-ADCP measurements (ST1909, ST1930).

3.1.3. In-situ measurements and sampling

Water properties

For calibration of the continuous registrations (HM-ADCP; BM-ADCP) water samples were taken using a Niskin bottle of 10 l, mounted on a Seacat profiler (SBE09 CTD system) (ST1909). The latter allowed vertical profiling of oceanographic parameters using CTD for salinity, temperature and depth; and optical backscatter sensor (OBS) for turbidity. Particle-size distribution (PSD) and volume concentration in the water column was measured using a Sequoia type 200 X Laser In-Situ Scattering and Transmissometry (LISST). Using an annular ring detector, the instrument derives in-situ particle sizes, in the range 1.0 to 500 µm, from the scattering of particles on 36 rings. PSD are presented as concentration ($\mu l l^{-1}$) in each of the 36 log-spaced size bins. Date and time, optical transmission, water depth and temperature are recorded as supporting measurements (http://www.sequoiasci.com). Water samples were filtered on board for suspended particulate matter (SPM) every 30′ for a 13-hrs cycle; sometimes ad hoc if alternating with other measurements. Mostly, 1.5 l of water was filtered. Within a 13-hrs cycle, extra filtrations were done, once per hour, for particulate organic carbon (POC/PON) (0.250 l), and a bottle of water (0.33 l) was kept for calibration of the conductivity sensor for salinity.

During RV Belgica campaign ST1930 dedicated datasets were acquired for the calibration of the HM-ADCP.

Seabed properties

On selected locations seabed sediment samples were taken:

(1) To characterize, in detail, sediment composition along Sector 4a and Sector 4c to enable evaluation of sediment changes due to deposition of the overflow deposits in the near and far field. During ST1909, in Sector 4a and 4c, Reineck boxcore sediment samples were taken and were on-board sliced at a 1-cm interval.

(2) Hamon grabs were taken along gravel beds (RV Belgica ST1909; ST1919). During ST1919, a combined physical-biological sampling was conducted joining up with RBINS OD Nature biological team. Locations were defined on the basis of previous sampling efforts. Areas of interest: gully between Oosthinder and Bligh Bank (ST1909); Habitat Directive Area (ST1919); Northern exploration zone (ST1919).

(3) Shallow sediment cores were taken by divers during ST1919. Aim was to collect undisturbed samples in the gravel bed areas to evaluate the sediment matrix in detail.

3.1.4. Visual observations

In 2019, video observations with a drop-camera took place during the three campaigns on RV Belgica (Table 3). The frame was provided by VLIZ (http://www.vliz.be/en/videoframe-en; footprint 1 m²). Standard it is equipped with a Bowtech Inspector colour zoom camera (Sony ¼″ SuperHAD CCD; 18:1 automatic zoom range) and LED lightning elements. One to two GoPro5/6 cameras (GoPro Inc, http://gopro.com) and extra lightning by one to two HUGYFOT Arius 1500 elements (http://www.hugyfot.com) (RBINS OD Nature) were mounted to increase the resolution and quality of the imagery. With installing the GoPros at ~75 cm above the bottom, the footprint reduced to ~0.4 m² (about half the footprint size of the gridded multibeam datasets). Two green laser pointers (VLIZ) were also installed to provide a reference scale (10 cm apart).

Table 3. Visual observations carried out in 2019

Period	Equipment	Platform	Modus
2019-03-26 and 2019-03-27	Larger video frame	RV Belgica cruise ST1909	Drift/transect
2019-07-08 to 2019-07-12	Larger video frame	RV Belgica cruise ST1919	On location/ Drift
2019-07-09; 2019-07-10	Scientific Diving RBINS OD Nature	RV Belgica cruise ST1919	Stills and transects. Core sampling

Visual observations were made along regions of interest. The refugia, as defined by Houziaux et al. (2008), were revisited. Extensive research took place also in the northern exploration zone, as to have reference material in areas with less seabed disturbance.

3.1.5. Water column properties derived from water samples

During ST1909, on board, water samples were filtered, in three replicates, using preweighted Whatmann GFC filters. These were analysed at the Marine Chemistry Lab (OD Nature, ECOCHEM). Suspended particulate matter concentration (SPMc) (Unit gl^{-1}) was obtained after drying of the filters for 48 hours, after which weight differences were calculated. A deviation of 12 % between the replicates is acceptable (ECOCHEM Standards). Measuring uncertainty of deriving SPM from filtrations is 17 %. Since 2011, 1911 water filtrations have been made in the Hinder Banks area (some in Kwinte Bank area, for comparison). POC/PON analyses (Unit gl^{-1}) were carried out in the laboratory using an Interscience FlashEA 1112 Series Element Analyser. Measuring uncertainty is 12 % for POC; 18 % for PON (ECOCHEM AK 7.0). For salinity (Unit PSU), a Laboratorium salinometer – Portasal 8410 (Guildline) van Ocean Scientific Int. was used; the measuring uncertainty is 0.15 % (ECOCHEM). It needs emphasis that water samples were taken at different levels in the water column. Normal procedure is to take a sample 2-4 mab, depending on wave action, hence platform motion. The depth of the water sample is derived from the CTD profiles (see below). Still, there are important uncertainties on the exact sampling depth, as the Seacat frame is easily carried away by the currents. This complicates the match-ups with ADCP data, a necessary step for calibration towards mass concentrations of SPM.

3.1.6. Water column properties derived from optical measurements

Conductivity-depth-temperature (CTD) and optical backscatter (OBS)

See Van den Eynde et al. (2020), in annex, for a detailed description of the calibration procedures and derivation of suspended particulate matter concentration.

In-situ particle size variation from LISST

After correction for the background (i.e., instrument and ambient water related) binary data from the rings were converted into volume concentrations ($\mu l l^{-1}$) per ring. The data were further processed using R-routines and analysed in terms of temporal variability (e.g., throughout a 13-hrs tidal cycle) and over the vertical (i.e., from the surface to 2-3 mab).

During ST1930, a dedicated dataset was recorded using the seawater pump, LISST200x and HACH turbidity measurements in view of a better calibration of the HM-ADCP measurements.

Water column properties derived from ADCPs

ADCPs detect the echoes returned from suspended material (i.e. "sound scatterers") from discrete depths of the water column. Echo intensities, per transmitted pulse, are recorded in counts (also termed the Received Signal Strength Indicator (RSSI), providing indirect information on the currents and density of suspended matter ('backscatter') within each ensonified bin. For the backscatter, the values remain relative as the instrument cannot differentiate the echo intensity from various sources (i.e. suspended sediments, debris, plankton, or air bubbles and high levels of turbulence, e.g. due to waves). This bias complicated interpretation of the datasets, as well as quantitative analyses to find correlation with hydro-meteorological datasets.

Turbidity

For recalculation of bin depth of the HM-ADCP to actual depth values below the water surface, a fixed draught of 4 m was added for RV Belgica. With the blanking distance associated to the type of instrument and the bin size, the first depth was around 7 m below the water surface for the hull-mounted profiles with RV Belgica (for 0.25 m bins). Pulses were averaged into ensembles at a time interval of 60 seconds per sample. Algorithms were used to convert the measured RSSI counts to acoustic backscatter in decibels (dB) using the echo intensity scale (dB per RSSI count). The echo intensity was multiplied by 0.43 in order to obtain dB values (instead of counts, and accounting for sound absorption, beam spreading and battery decline). These dB values were then converted to mass concentrations of suspended particulate matter (SPM in $g l^{-1}$), by calibration against SPMc values derived from water filtrations during several field campaigns.

3.1.7. Seabed properties derived from acoustical measurements

Very-high resolution multibeam (MBES) mapping was conducted recording depth and backscatter. For the calibration of MBES backscatter data, datasets are acquired along a reference area with known backscatter values (Kwinte gully, KWGS area; https://www.afdelingkust.be/en/acoustic-reference-area-kwinte).

In the framework of PhD research (funded by Belspo INDI67 project) on the use and repeatability of MBES data in a monitoring context, a standardized workflow was developed allowing classifying depth and backscatter data in view of seabed classification and change detection. See Montereale Gavazzi (2019) for an extensive description of the state-of-the-art, methodology and results.

3.1.8. Seabed properties derived from sampling

Sediment samples were analysed for grain size using a Malvern laser sizer at Ghent University, Department of Geology. In this report emphasis is on the sediment variation (particle size, organic matter and $CaCO_3$ content) of the sliced samples on the sandbanks Noordhinder and Oosthinder. A Reineck boxcorer was used allowing taking subcores that were sliced every 1 cm. In the gravelly area, samples were taken a Hamon grab (VLIZ). Compared to a Van Veen grab, a Hamon grab retrieves a rectangular volume of sediment from the seafloor, hence capturing all the sediment fractions available. *See Kint and Van Lancker (2020), in annex, for sediment analyses procedures.*

For the classification procedure of the MBES depth and backscatter data into sediment type maps, reference is made to Montereale Gavazzi (2019).

3.1.9. Dune dynamics derived from depth measurements

Initiated in the Belspo TILES project (Van Lancker et al., 2019) and further investigated as part of the ZAGRI monitoring programme, all multibeam depth datasets contributing to the monitoring carried out by FPS Economy COPCO were analysed. In order to facilitate and objectify the analysis of these repeated measurements, an automated approach was developed to estimate morphodynamic parameters such as dune migration, wavelengths and heights. The automated procedure, applied on regularly spaced bathymetric profiles extracted from multibeam bathymetry data in the monitored areas, is summarized in Figure 6.

To start, two components are separated in every bathymetric profile: the sandbank body, assumed to be stable over time, and the overlaying seabed, composed of different bedforms and considered to be the mobile part of the seabed (Figure 6a). Only the latter is conserved for further analysis. The approach is similar to Debese et al. (2018), who introduced the geomorphometric concept of osculatory surface matching the sandbank tangentially to the dune feet. Here, the sandbank body is obtained by joining all the troughs (i.e., the deepest points) between the largest successive bedforms (typically, very large dunes with wavelengths ~150-300 m), based on a wavelet analysis (Figure 6b-c). Once the dynamic upper part of two consecutive profiles are obtained (Figure 6d, red and black lines), a cross-correlation analysis is carried out (as if they were considered as two univariate time series, similarly to McElroy & Mohrig, 2009; Figure 6e). The migration distance is then provided by the spatial lag between the two profiles obtained from the cross-correlation (as would be the case for the time lag between two time series; ~10m in Figure 6e). The migration rate is obtained from the migration distance and the time separating the two successive campaigns, and is expressed per spring-neap cycle (SN) of 15 days. Using the identified troughs and crests (cyan and blue points respectively in Figure 6d) on the basis of the wavelet analysis, each bedform can be described by its height, wavelength, and migration rate, and tracked over time by applying this approach to all successive surveys in the monitored areas. To investigate the variability of the seabed beyond the direct alterations caused by human extraction, the extracted quantities between successive campaigns (estimated from the Electronic Monitoring System) are restored to the profile. Detected evolution hence corresponds to residual variations beyond human extraction (and is of course affected by measurement errors and imprecision originating from the automated procedure itself).

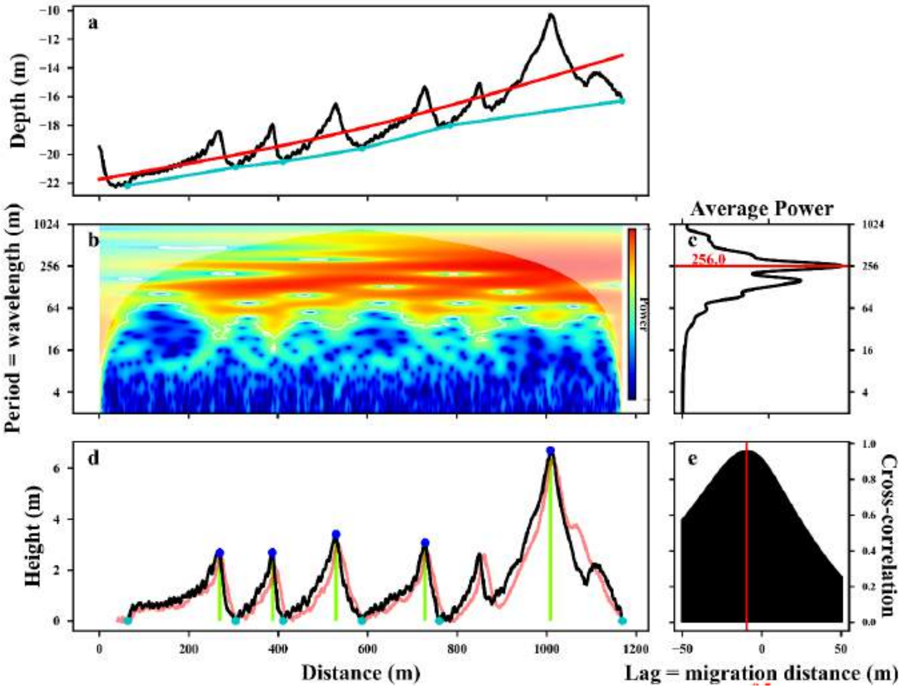


Figure 6. Automatic treatment of a bathymetric profile. (a) The original bathymetric profile (black line) is considered to be composed of one stable part corresponding to the sandbank (under the cyan line) and one mobile part on top of it (between the cyan and black lines) which is used for later analysis. The red line is a cubic regression spline used to detrend the bathymetric profile for the wavelet analysis. (b) Wavelet analysis of the detrended bathymetric profile: at each location on the profile (x axis), it indicates the preponderance (power, colour scale) of each wavelength (y axis) in the bathymetric profile. (c) Average power (x axis) of each wavelength (y axis) over the bathymetric profile. The maximum (red line) identifies the dominant wavelength (here, ~105 m). (d) Profile of the upper, mobile part of the seabed (black) with automatic detection of crests (blue) and trough (cyan) points, allowing the estimation of dune heights (vertical green lines). The bathymetric profile of the next survey is shown in red. (e) Cross-correlation between the red (recent) and black (old) profiles of (d). The maximum correlation (red line) identifies the spatial gap (i.e., migration distance) between the two profiles (here, ~10 m).

3.1.10. External data

Wave information (significant wave height in m, direction of low and high frequency waves in degrees, low frequency (0.03 Hz to 0.1 Hz) wave energy in cm^2) were obtained, at 30 min interval, from a Wavec buoy (Westhinder location, Flanders Hydrography) at 18 km southwest of the study area (Figure 2). Sea surface elevation and 3D currents (10 min interval) were extracted from the operational 3D hydrodynamical model OPTOS-

BCZ (Luyten, 2016). Wind velocity and direction (10 min interval) originated from the fixed Westhinder measuring pole (Flanders Hydrography) (for location, Figure 2).

3.2. Modelling

3.2.1. Model validations

Focus of the modelling is to assess changes in hydrographic conditions, as for the MSFD, Belgium stipulated that variations in bottom shear stresses should remain restricted in the advent of human activities (see footnote 1) (Belgische Staat, 2012, 2018). New results were reported earlier. In 2019, further developments were made on sediment plume modelling to assess deposition of fine material in the Habitat Directive area. These new model developments will be reported later.

4. Results 2019

4.1. *Introduction*

Results relate to assessing the physical impacts of marine aggregate extraction, caused by trailing suction hopper dredgers (TSHD). Two major alterations occur during an extraction process: (1) abrasion of the seabed; and (2) dispersion and deposition of sediment plumes, justifying measurements of both water column and seabed properties. The dispersion of plumes can easily extend several km from the vessel as such the far-field impact on a nearby Habitat directive Area where ecologically valuable gravel beds needs monitoring. To collect reference material, comparative measurements were conducted also in other gravel rich areas.

4.2. *Naturally- and human-induced variability in sediment processes*

4.2.1. Near field

In 2019, complementary measurements were made on water-column and seabed sediment properties using multiple sensors (Figure 7).

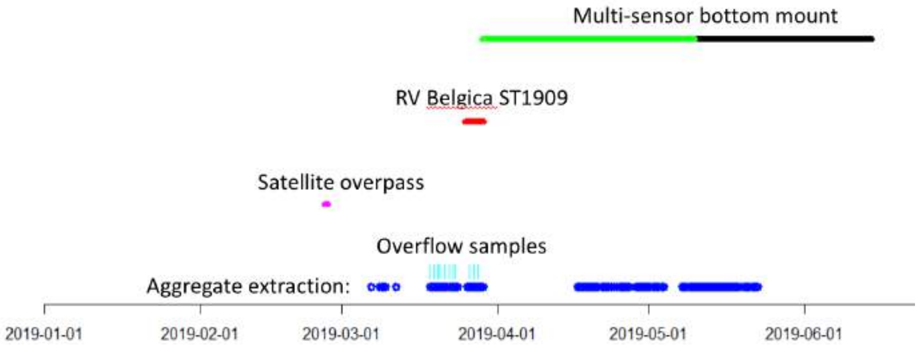


Figure 7. Overview of complementary measurements on water and sediment properties in the near field of dredging activities in 2019. The multi-sensor bottom mount was deployed for a long time but suffered from bio-fouling (see green line 'no fouling' and black line 'fouling'). Main instrumentation was a 1200 kHz acoustic doppler current profiler (ADCP), and a AQUAscat acoustic backscatter sensor (ABS). RV Belgica campaign ST1909 is presented in red. Through cooperation with a dredger for sediment-laden overflow samples was collected as well (see cyan vertical marks). The blue dots show the timings of sand extraction by trailing suction hopper dredgers.

Sediment plumes as observed from satellite overpasses

Space-borne imagery by Sentinel 2 shows an overflow plume signature in sector 4a, Noordhinder sandbank. Plume SPMc was around 0.01 gl^{-1}, diminishing downstream as a function of time (Figure 8).

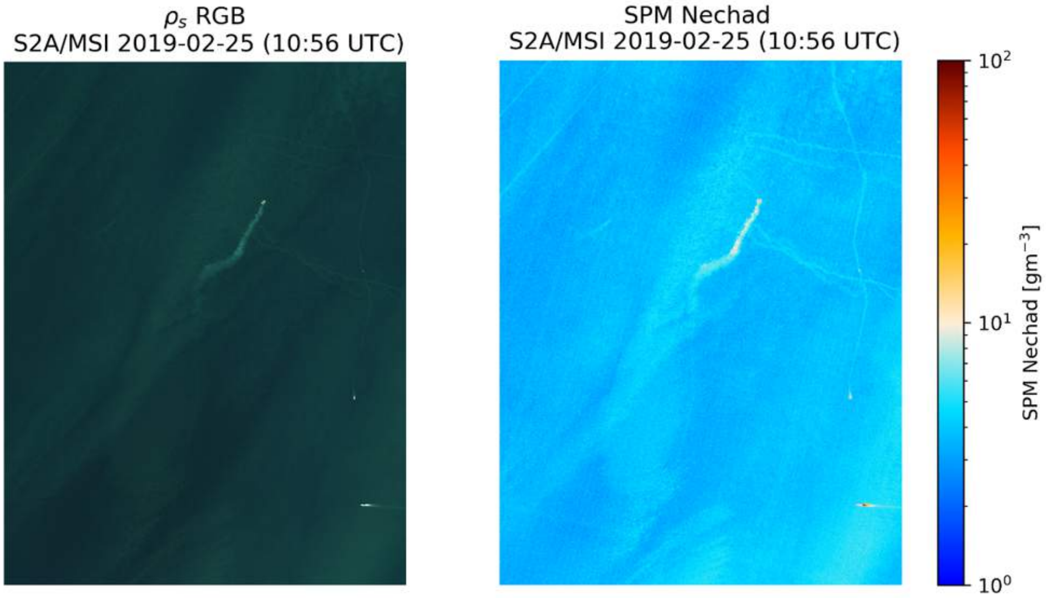


Figure 8. Space-borne imagery (Sentinel 2) showing an overflow plume signature of TSHD in sector 4a, Noordhinder sandbank. Left: synoptic satellite product; and Right: derived SPMc product of dredger activity. Plume SPMc are around 0.01 gl-1, diminishing downstream as a function of time.

Sediment properties of extraction-induced overflow deposits

The two following figures illustrate the dredging activity in sector 4a, with the intensity in hours per day (Figure 9) and per dredger the days in 2019 (Figure 10).

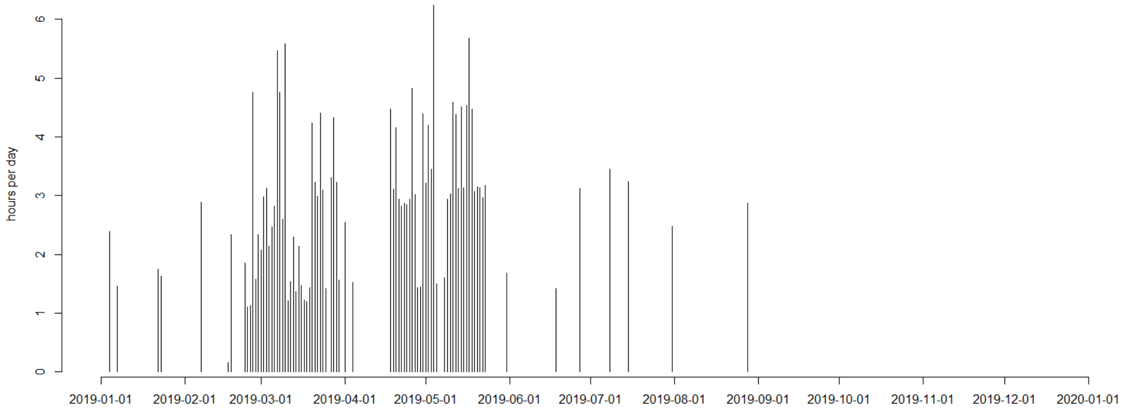


Figure 9. Hours of sand extraction (sector 4a) per day. Data source: EMS (Data by RBINS-MSO).

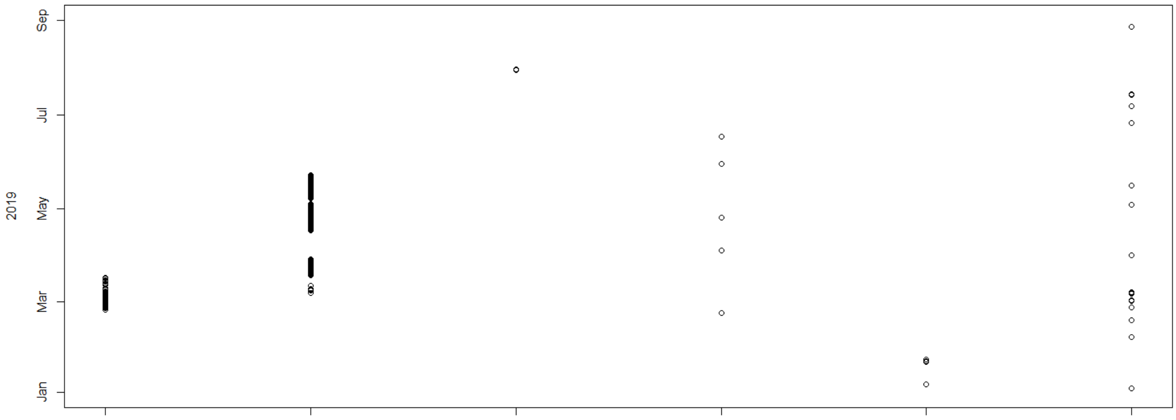


Figure 10. The timing of dredging activity in sector 4a in 2019 for each TSHD (6) separately. Data source: EMS (delivered by MSO). Note the concurrent dredging activity, mostly during the March extraction period.

Contrary to the consistent extraction around low water in Sector 4c in 2017, causing a predominant SW transport of fine-grained material towards the Habitat Directive area, the timing of sand extraction (by all TSHDs) with regards to low water at Zeebrugge for 2019, indicates an equal spread of extraction in the tidal window (Figure 11).

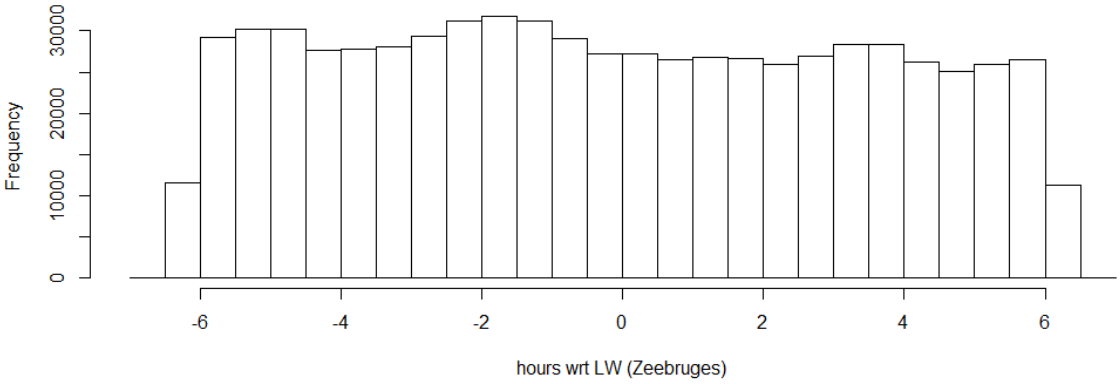


Figure 11. Timing of aggregate extraction with respect to low water Zeebrugge.

Particle-size distributions of overflow samples showed a particle mode around 25 µm, and one around 300 µm (Figure 12). The latter aligns clearly with the *in-situ* seabed sediments (see further).

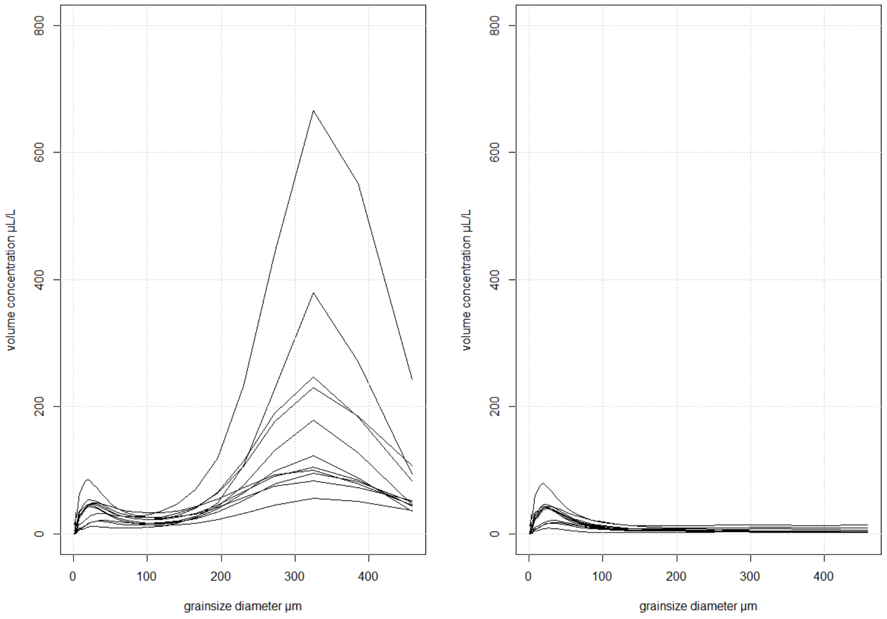


Figure 12. Particle-size distribution (PSD) of the overflow samples (bulk, left) and slow settling part (right). The bimodal character is present during the bulk PSD (25 and 320 µm). When turning off the mixing (magnetic stirring in beaker), only the 25 µm fraction remains.

Water-column and seabed sediment properties Sector 4a, Noordhinder, and Sector 4c, Oosthinder

Water-column sediment properties derived from a long-term deployment of a multi-sensor bottom frame, Noordhinder

From a total deployment length of 77.8 days, 42.7 days resulted in good quality data (i.e., no biofouling). The following figures show the main results of the measurements (Figure 13 to Figure 17), first focusing on results from an acoustic doppler current profiler (ADCP), then on results from an acoustic backscatter sensor (ABS).

Important to note is that the ADCP's first bin is located 0.8 m above the transducer head, and thus 1.5 meter above the seafloor (mab). Acoustic profiling reached up to 15.95 mab in the water column, hence the upper 7.2 to 11.5 m of the water column are missed. This is a result of the choice of the 1200 kHz ADCP that is superior for backscatter analysis, but the signal is not strong enough to capture the entire water column in 30m water depth.

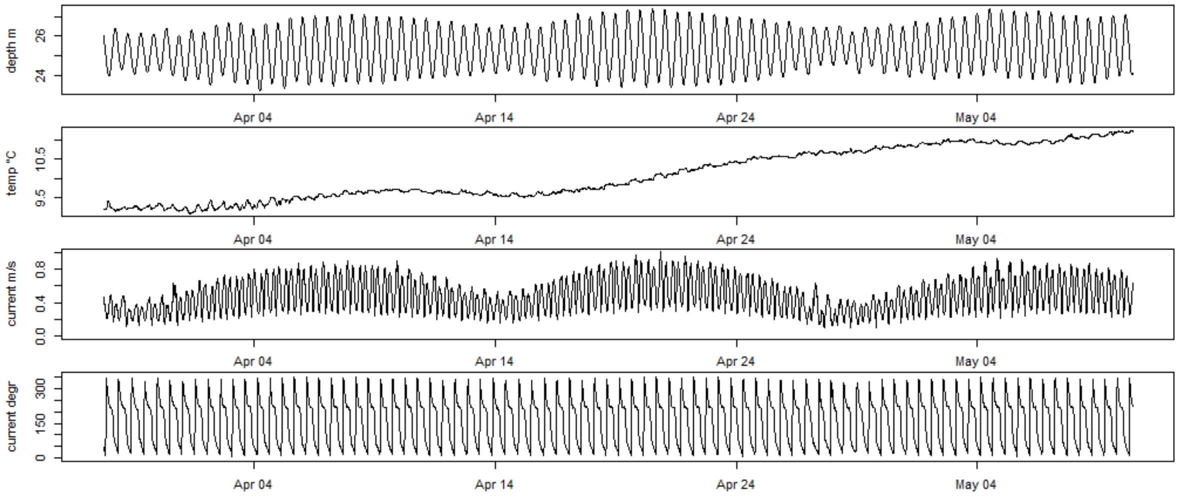


Figure 13. BM-ADCP long-term deployment near Sector 4a, Noordhinder. **Current speeds**. From top to bottom: water depth (m); temperature (°C); the depth-averaged current speed (ms^{-1}); and depth-averaged current direction (°).

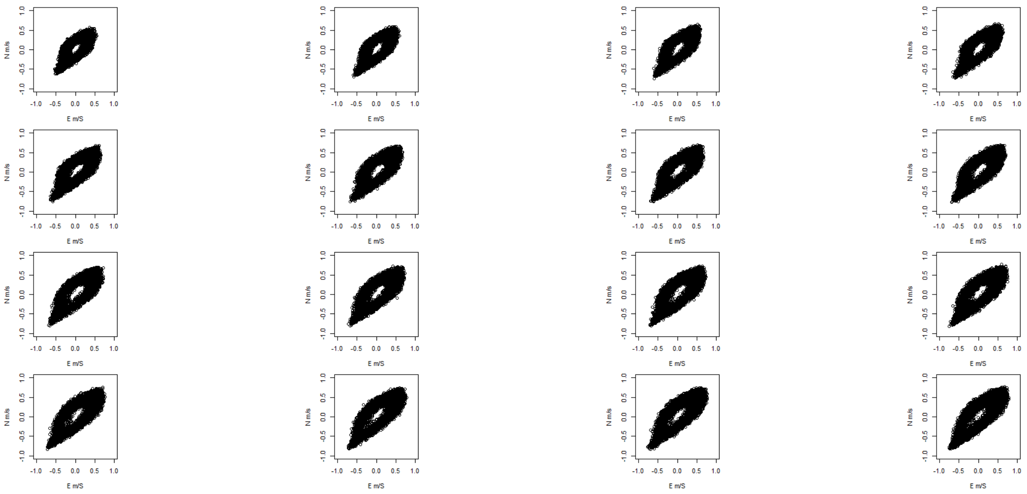


Figure 14. BM-ADCP long-term deployment near Sector 4a, Noordhinder. **Tidal ellipses** are plotted with in the top left to the top right, different bins (of height above the seafloor) bin 1, bin 5, bin 9 and bin 13; next row: bin 17, bin 21, bin 25, bin 29, etc., showing increasing current speeds from the bottom to higher up in the water column (less bed friction). Note flood and ebb peak tidal currents being quasi-equal in strength, but with longer lasting higher flood velocities and more peaked ebb-oriented flows.

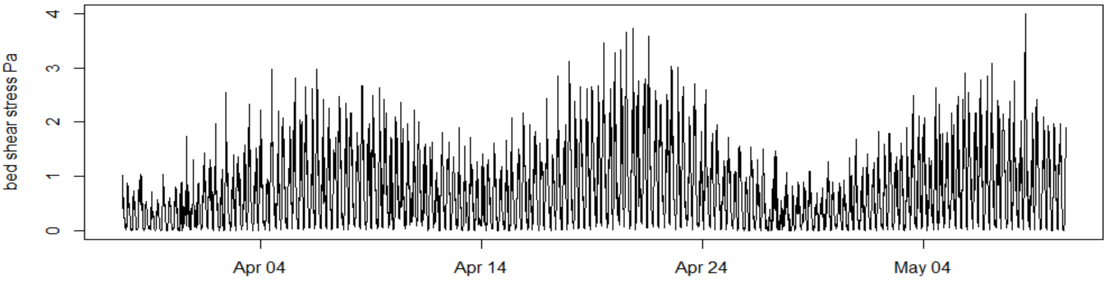


Figure 15. BM-ADCP long-term deployment near Sector 4a, Noordhinder. **Bed shear stress** derived through the "power law profile" method (Nowell and Jumars, 1987) analysing the linear regression between the current velocities and corresponding log form of the heights above the seafloor.

Next, results on mean grain size and SPMc are shown as calculated from the multi-frequency AQUAscat 1000S acoustic backscatter sensor (500 kHz, 1 MHz, 2 MHz and 4 MHz). A time-series of SPM concentration and mean grain size at the 1.5 mab level is shown in Figure 16.

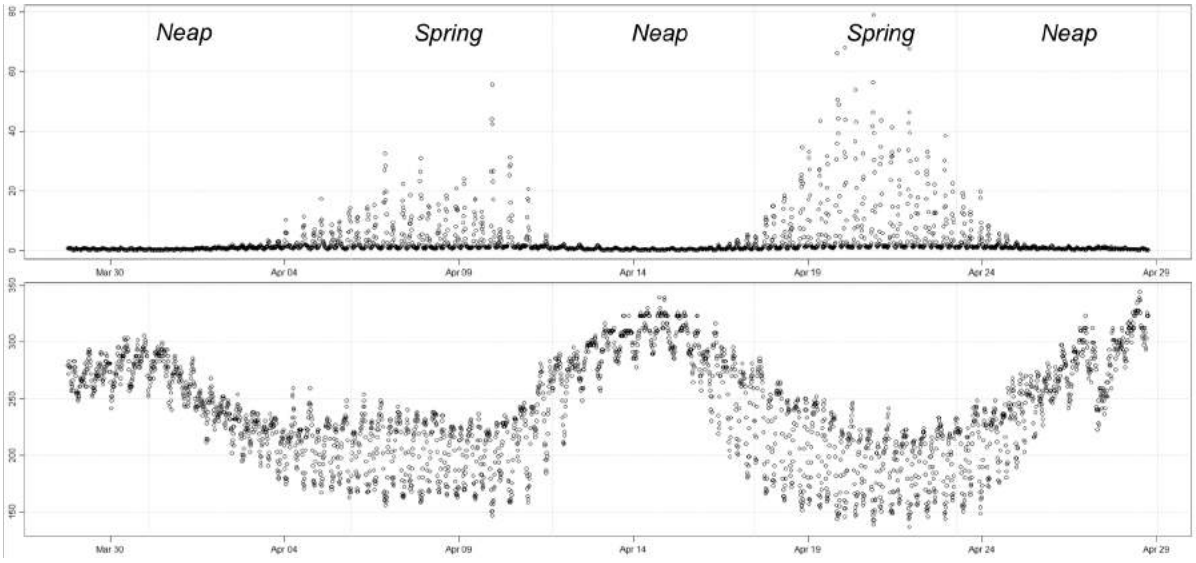


Figure 16. BM-AQUAscat long-term deployment near Sector 4a, Noordhinder. **SPMc times series** (upper panel) and **mean particle size** (lower panel) at 1.5 mab during a neap-spring-neap-spring-neap period. Striking are the highest near bottom mean particle sizes during slack tide, due to flocculation, whilst smaller sizes are found at high current speed (breaking up of flocs under high current speeds; aggregation into flocs under low current speeds).

The data indicate well the variation throughout spring and neap cycles, both in SPMc and mean grain size. During neap tides, the concentrations are low (around 0 and 0.001 gl^{-1} and no SPMc peaks occur during maximum current speeds); the mean grain size is around 300 µm (with subtle tidal fluctuations). During spring tides, the concentrations are higher (especially during maximum current speeds, easily up to 0.020 gl^{-1}). The mean grain size fluctuates strongly (again at semi-diurnal tidal frequency) between 150 and 230 µm. The latter is likely explained by the aggregation behaviour of particles in suspension (cycles of aggregation and break-up). During slack and neap tides the aggregating fraction of the SPM is much reduced, and the organic (or low-density) fraction remains in suspension and 'grows' in size.

Following, the AQUAscat data were used to calibrate the ADCP backscatter signal and convert it to SPMc (Figure 17).

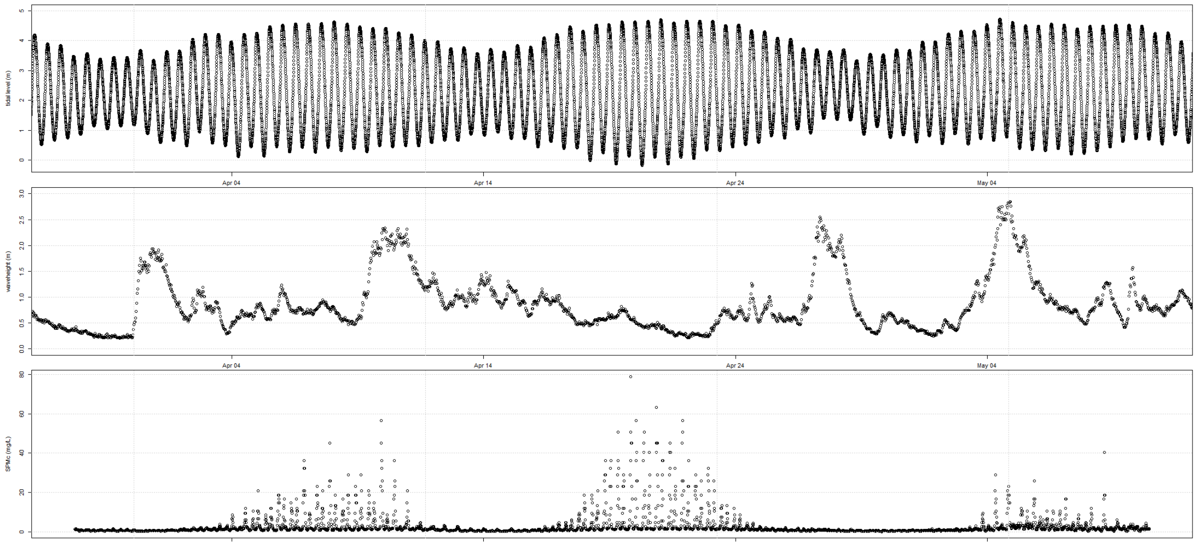


Figure 17. BM-ADCP long-term deployment near Sector 4a, Noordhinder. **SPMc times series** (lower panel) from the BM-ADCP (1.5 mab) plotted together with the water level (m) (upper panel) and wave height (m) during a neap-spring-neap-spring-neap period. Note the several hydro-meteo events with higher wave heights (up to 2.5-3 m), but resulting in no SPMc increases near the bottom (no instantaneous re-suspension of seafloor sediments) during the measurement period.

Water-column sediment properties derived during RV Belgica campaign ST1909, Sector 4a and 4c

During ST1909, a 13-hrs water sampling and vertical profiling of oceanographic parameters, including SPMc measurements were conducted at the southern edge of Sector 4a (in the trough of a very large dune). Cross-bank transects were also sailed to derive SPMc and current speed variability over the Noordhinder and Oosthinder sandbank. With co-occurrence of dredging activities, the Noordhinder transect could also allow depicting possible overflow plumes associated with dredging activities in Sector 4a. Figure 18 shows the location of the measurements.

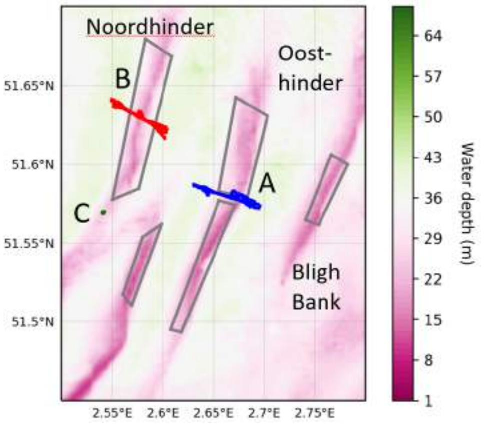


Figure 18. Location of the cross-bank transects. A. in-between Sector 4b and 4c, Oosthinder sandbank, B. Sector 4a, Noordhinder sandbank, and the 13-hr cycle at the southern edge of Sector 4a.

Figure 19 shows a synthesis of all water samples that were filtered and analysed for SPMc content each 1h during the Oosthinder and Noordhinder cros-bank transect; every 0.5h during 13-hr cycle at Noordhinder. During the 13-hr cycle at Noordhinder, also PON and POC samples were taken.

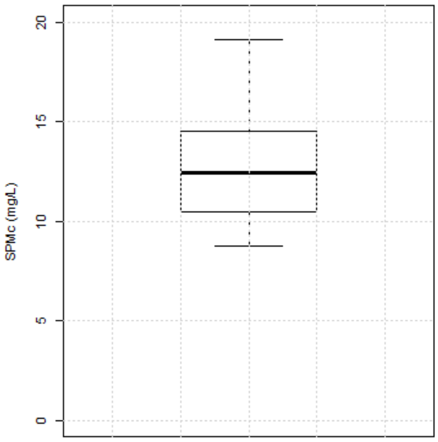


Figure 19. Range of SPMc as derived from filtrations of water samples taken with a Niskin bottle (10l). RV Belgica ST1909. The values are representative of a sandbank environment. Mean values are between 0.010 and 0.015 gl^{-1} here at 2-3 mab.

The depths and timing of the filtrations were related to the corresponding ADCP (starboard beam 2) backscatter values. This method of acoustic inversion, based on Hinder Banks water samples, is somewhat difficult due to small range of SPMc (from filtrations) (R-sq is 0.19). Therefore, the range was extended by including SPMc (filtration) data and associated ADCP-BS from another station (W05) acquired during the RV Belgica ST1901 (24/01/2019) (R-sq is 0.76) (Figure 20).

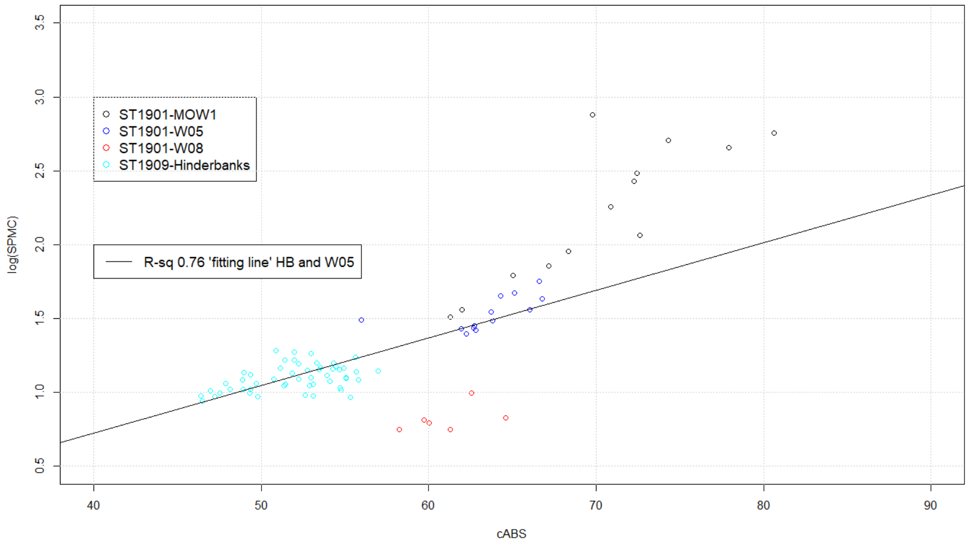


Figure 20. Combination of filtration datasets and acoustic backscatter to improve the calibration of acoustic measurements into SPMc.

The ADCP cross-bank transects (4b-4c, and 4a) and the stationary (anchored at southern edge of sector 4a) 1- hours cycle are presented below (Figure 21 to 22).

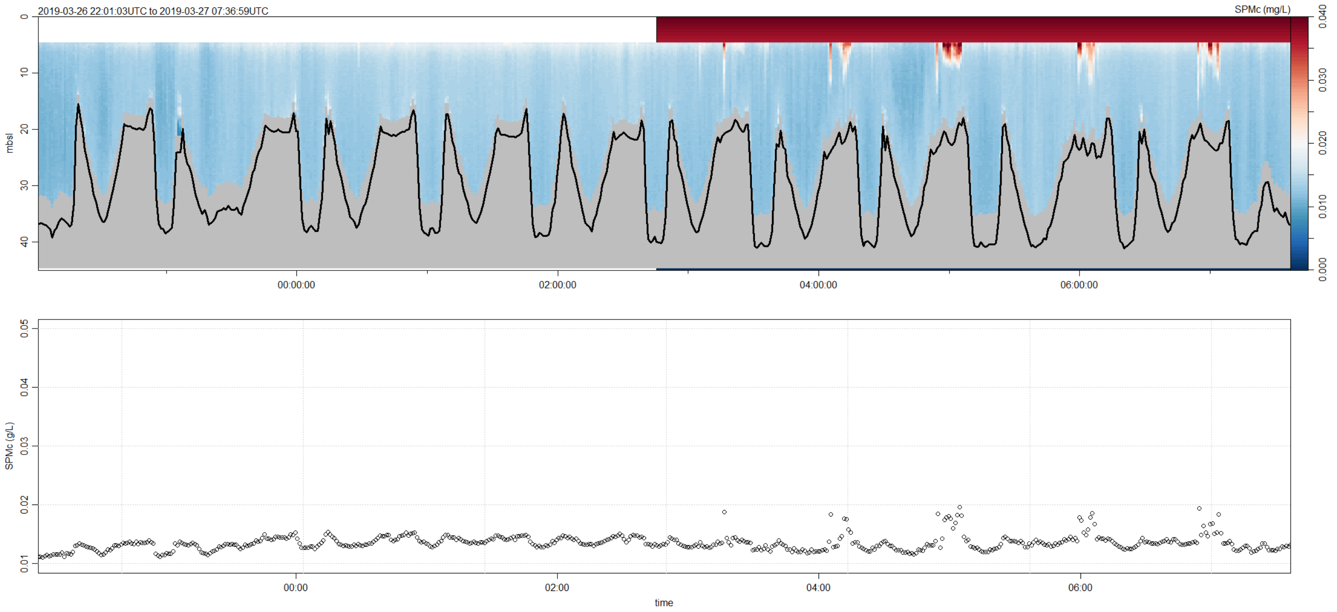


Figure 21. Cross-bank transect over the Oosthinder sandbank (in-between Sector 4b and 4c). Upper panel SPMc (gl^{-1}) over the water-column (+/- 7h time series) (mbsl: meter below sea level); lower panel represents the depth-average SPMc (gl^{-1}). Note that the increases in SPMc, as seen in both panels, are related to the times of the sampling (probably related to the ship's propeller) and not to hydro-meteo nor extraction events.

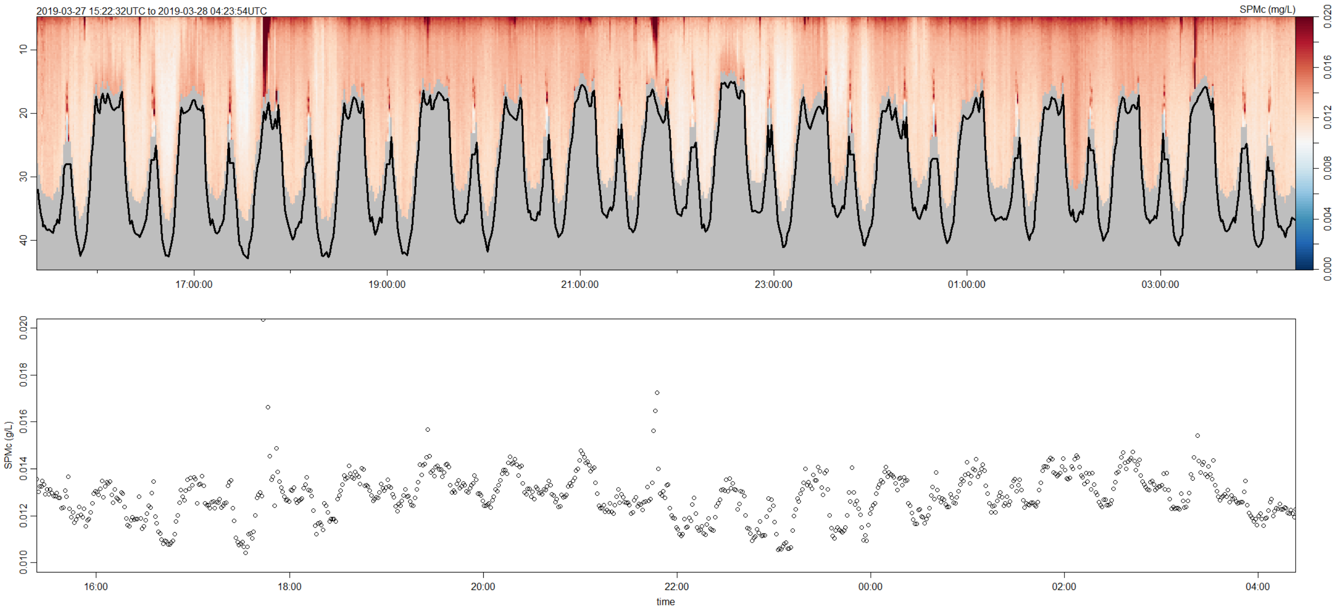


Figure 22. Cross-bank transect over the Noordhinder sandbank (Sector 4a). Upper panel SPMc (gl^{-1}) over the water-column (+/- 12h time series) (Y-axis: meter below sea level); lower panel represents the depth-average SPMc (gl^{-1}). The variation in depth-averaged SPMc is mostly related to the sandbank-gully transition, with higher SPMc clearly visible over the sandbank.

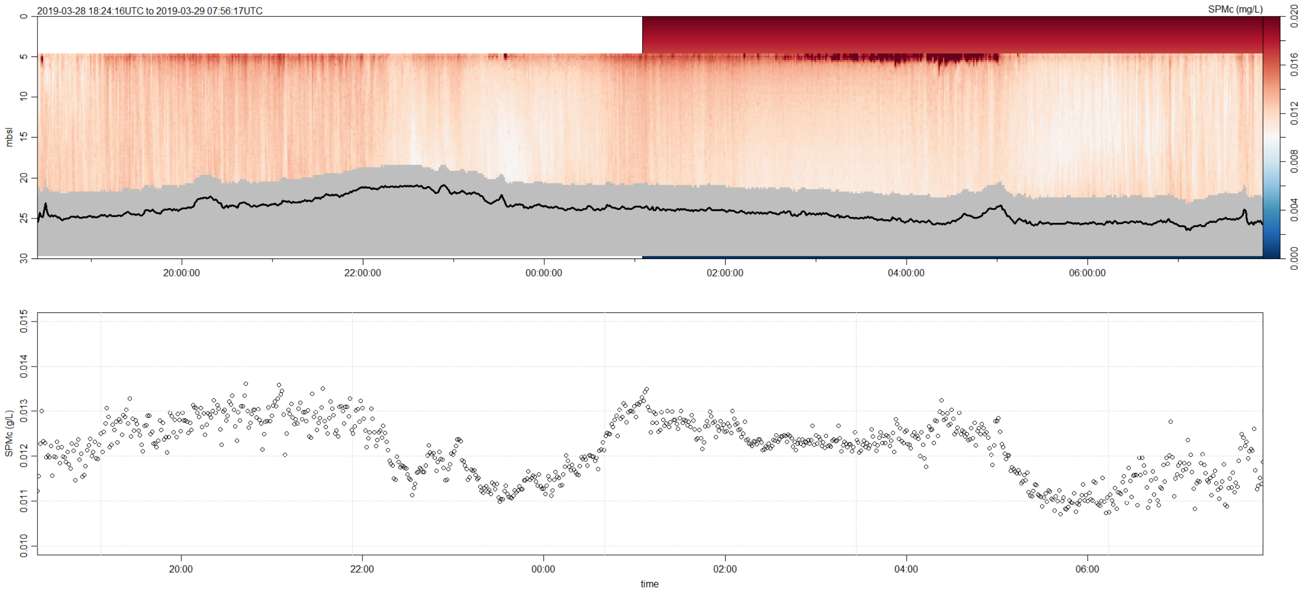


Figure 23. SPMc during the 13-hrs cycle at the southern edge of the Noordhinder sandbank (Sector 4a). Upper panel SPMc (gl^{-1}) over the water-column (mbsl: meter below sea level); lower panel represents the depth-average SPMc (gl^{-1}).

SPMc was also analysed per profile taken, during the sampling intermittent to the cross-bank transecting (OH, NH), as well as during the stationary 13-hr cycle (N1). Figure 24 shows the overall mean SPMc for each of the three locations. Figure 25 shows the spatial and vertical variability throughout the measurement period, extrapolated to the bottom using Van Rijn profiles. For an extensive representation of the results and discussion, reference is made to Van den Eynde et al. (2020) (Annex to this report).

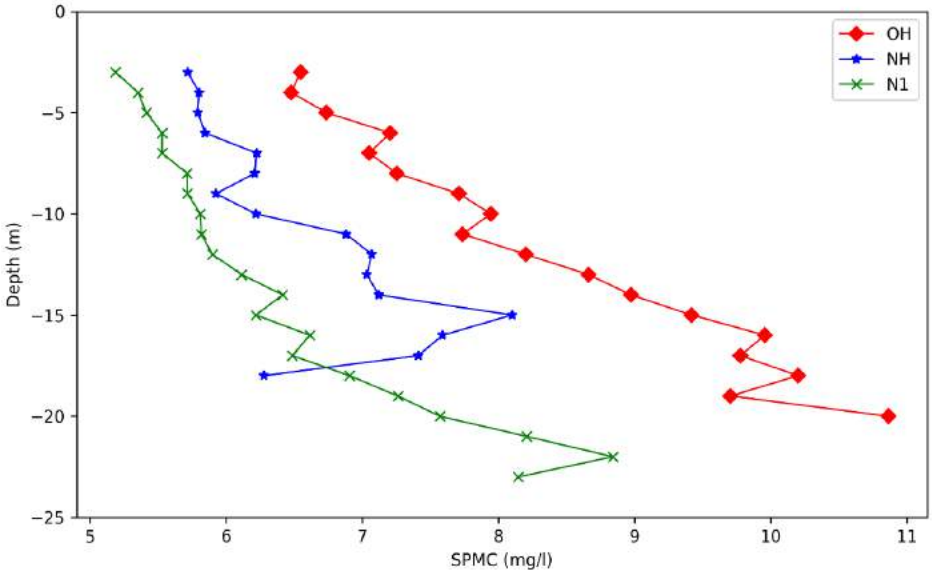


Figure 24. Overall mean SPM concentration profiles. Red: measurements at Oosthinder (OH); blue: measurements at Noordhinder (NH); green: measurements during 13h cycle (N1).

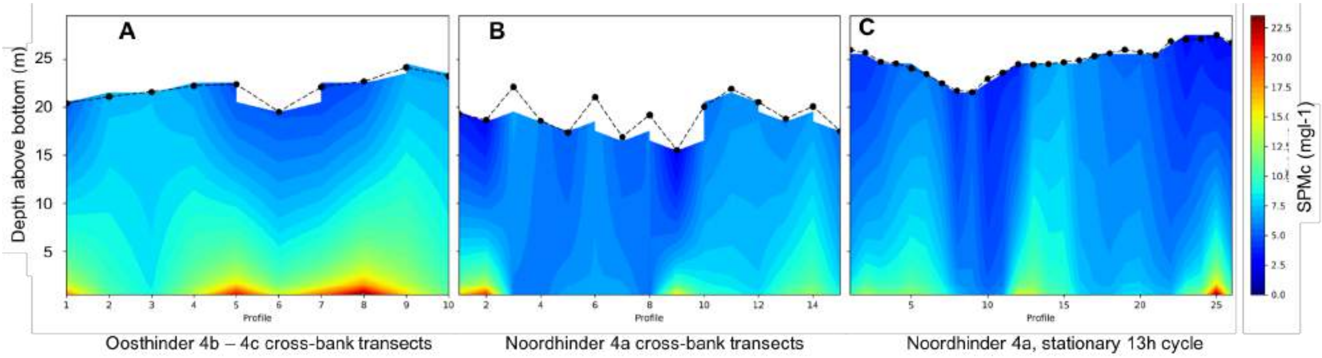


Figure 25. SPMc variation for the three locations, spatially and vertically, extrapolated using the Van Rijn profile. Note the overall higher SPMc values for the Oosthinder sandbank, though this may be due to the Oosthinder transect being sailed closest to Spring tide conditions. SPMc is highest near the bottom (up to 0.040 gl^{-1}). For the cross transects, the time between the different profiles is approximately 1 hour; for the 13-hr cycle 0.5h. The dotted black line represents the water depth. Oosthinder 4b-4c cross-bank transects: 26/3/2019 22h01 UTC- 27/3/2019 07h36 UTC); the Noordhinder 4a cross-bank transects: 27/3/2019 22h32 UTC – 8/3/2019 04h23 UTC); and the stationary 13-hrs cycle south of Sector 4a: 28/3/2019 18h24 UTC – 29/3/2019 07h56 UTC. Location A, B, C see Figure 18.

In Figure 26, the results from the LISST200 instrument, measuring *in-situ* particle sizes, are shown during the same periods as above. Only the data close to the bottom are shown. Clearly, the ~320 µm particles are most abundant, which complies with the size of the seabed sediments (see further).

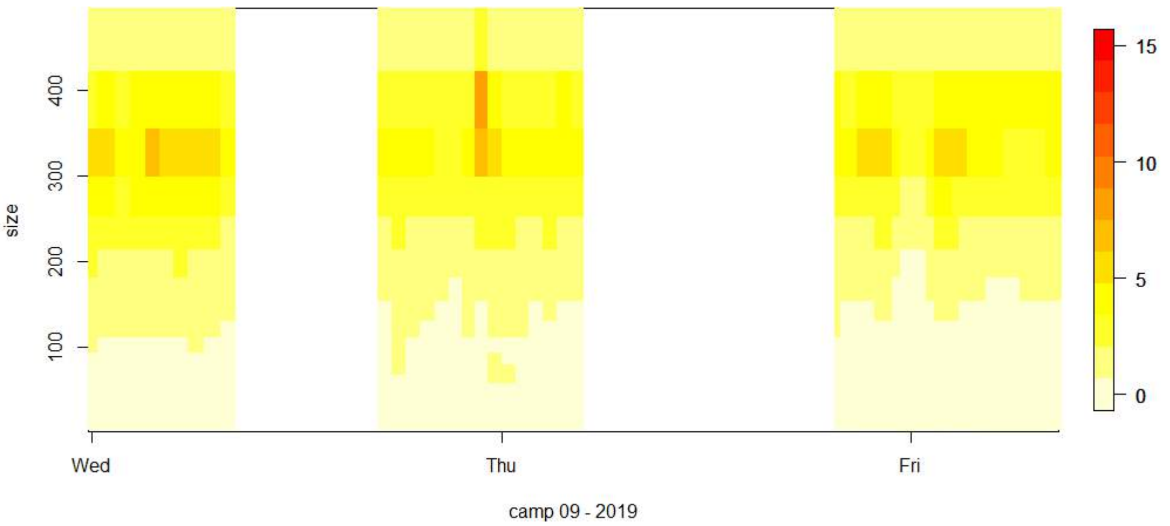


Figure 26. Averaged *in-situ* particle size near the bottom. From left to right, the measurements periods relate to the cross-bank transects over the Oosthinder sandbank 4b-4C (26/3/2019 22h01 UTC- 27/3/2019 07h36 UTC); the cross-bank Noordhinder sandbank, 4a (27/3/2019 22h32 UTC – 8/3/2019 04h23 UTC); and the stationary 13-hrs cycle south of Sector 4a (28/3/2019 18h24 UTC – 29/3/2019 07h56 UTC). Colour bar is the volume concentration (µll^{-1}). Size is particle diameter in µm.

An average of all LISST-derived particle-size distribution (PSD) in the deeper part of the water column is shown in Figure 27.

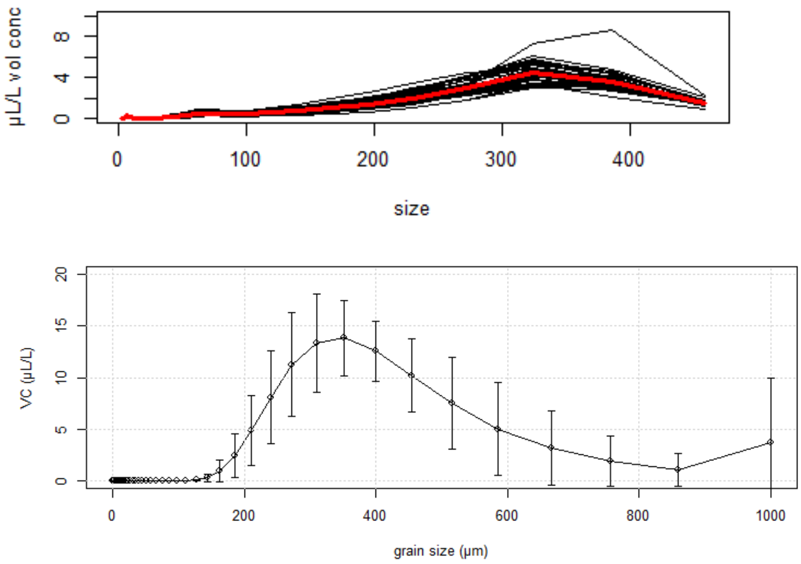


Figure 27. LISST200-derived particle-size distribution (PSD), Sector 4a Noordhinder. Upper panel: PSDs measured in the water column (average PSD in red); Lower panel: PSDs of all seabed sediment samples (with error bars representing standard deviations). Note the bimodality of the water-column PSDs, that is not visible in the seabed sediment PSDs; for the latter the main mode is around 350 µm; 180 µm particles form the lower limit.

Substrate characteristics – seabed sediments from Sector 4a and 4c

During ST1909, for both Sectors 4a and 4c, Reineck boxcores were taken and were sliced onboard at a 1-cm interval to characterize in detail variability in sediment properties in view of change detection. The 4c dataset forms part of a sampling time series. All of the sampling was done complementary to the multibeam backscatter time series as acquired by FPS Economy, Continental Shelf Service. Kint & Van Lancker (2020, Annex to this report) present and discuss results in detail; here only the main findings are presented. Figure 28 shows the grain-size characteristics in Sector 4a. Medium to coarse sands prevail; no silt-clay content was measured.

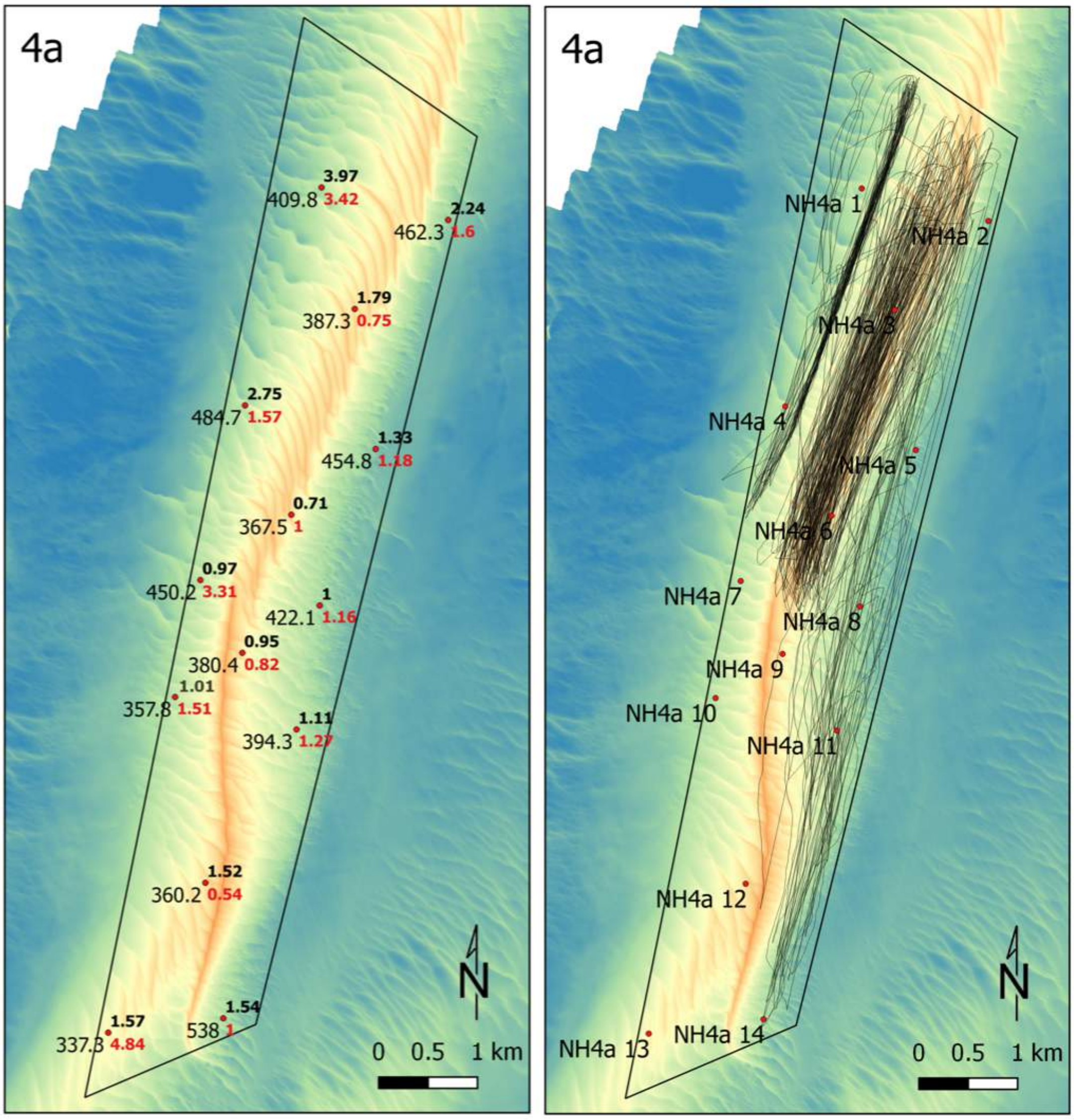


Figure 28. Left: Seabed sediment characteristics along Sector 4a, Noordhinder. Per location the median grain size (left), organic matter (right, black), and CaCO3 (right, red) content is shown. Right: Marine aggregate extraction tracklines complementary to the 2019 sampling. Bathymetry: FPS Economy.

For the vertical distribution of sediment properties at all locations reference is made to the Annex. Most homogenous sediment profiles correlate with those locations where no extraction took place. These have an organic matter (OM) content of 1-2% maximum.

Samples NH4a 1 to 4 have OM percentages of up to 5%; they correspond with the most heavily disturbed areas.

The 2019 seabed sediment sampling in Sector 4c correspond to a year when no extraction took place. Figure 29 shows the main characteristics for the eight sampled locations. Here medium sands prevail. In 2019, no silt-clay content was measured. Kint & Van Lancker (2020) also present a detailed comparison of the seabed sediment samples at 4c, obtained during RV Belgica campaigns: ST1407, ST1807, and ST1909. A detailed analysis of the samples of ST1407 was already presented in Van Lancker et al. (2014). Figures 30 and 31 show the percentage in lithological fractions for the three campaigns. No consistent trends can be derived in these percentages and both fining and coarsening trends occur. No silt-clay enrichment is seen in the near field.

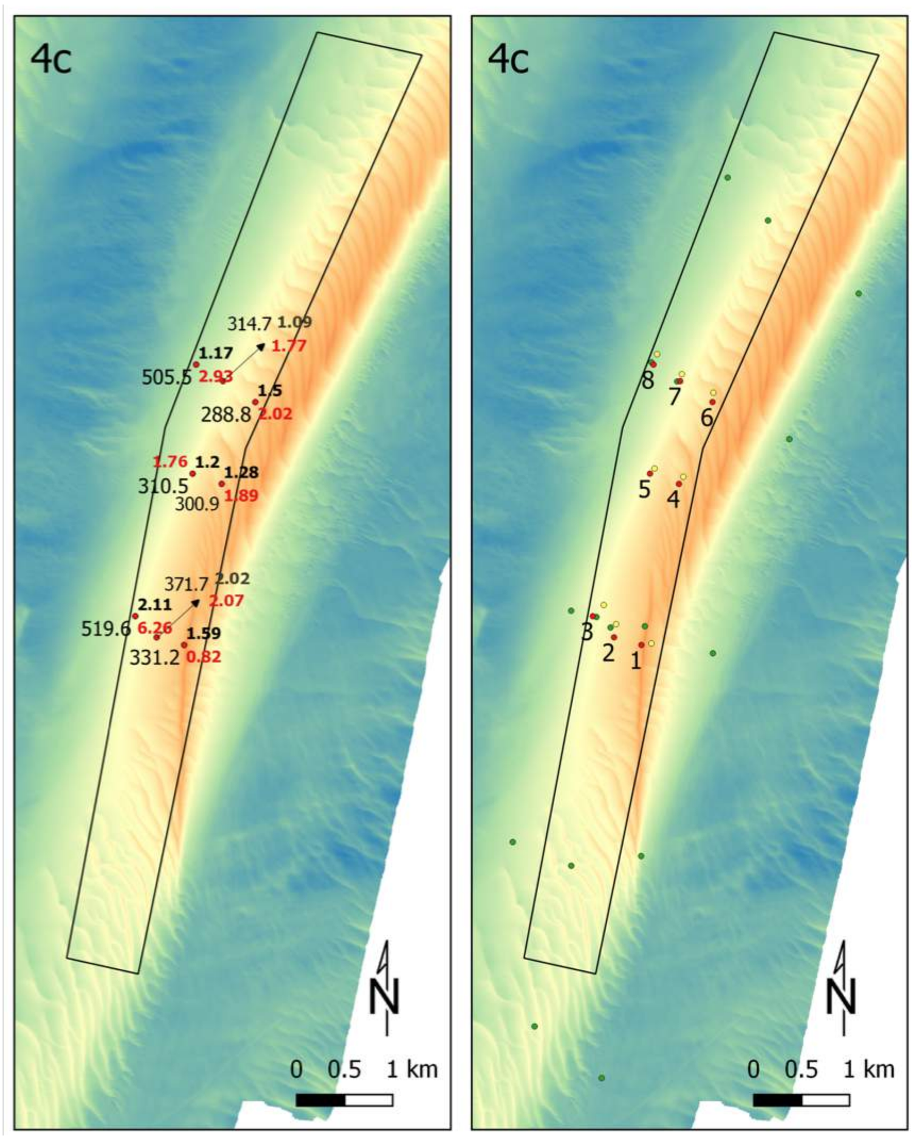


Figure 29. Seabed sediment characteristics along Sector 4c, Oosthinder. Per location the median grain size (left),organic matter (right, black), and CaCO3 (right, red) content is shown. Right: Marine aggregate extraction: no activity in 2019.

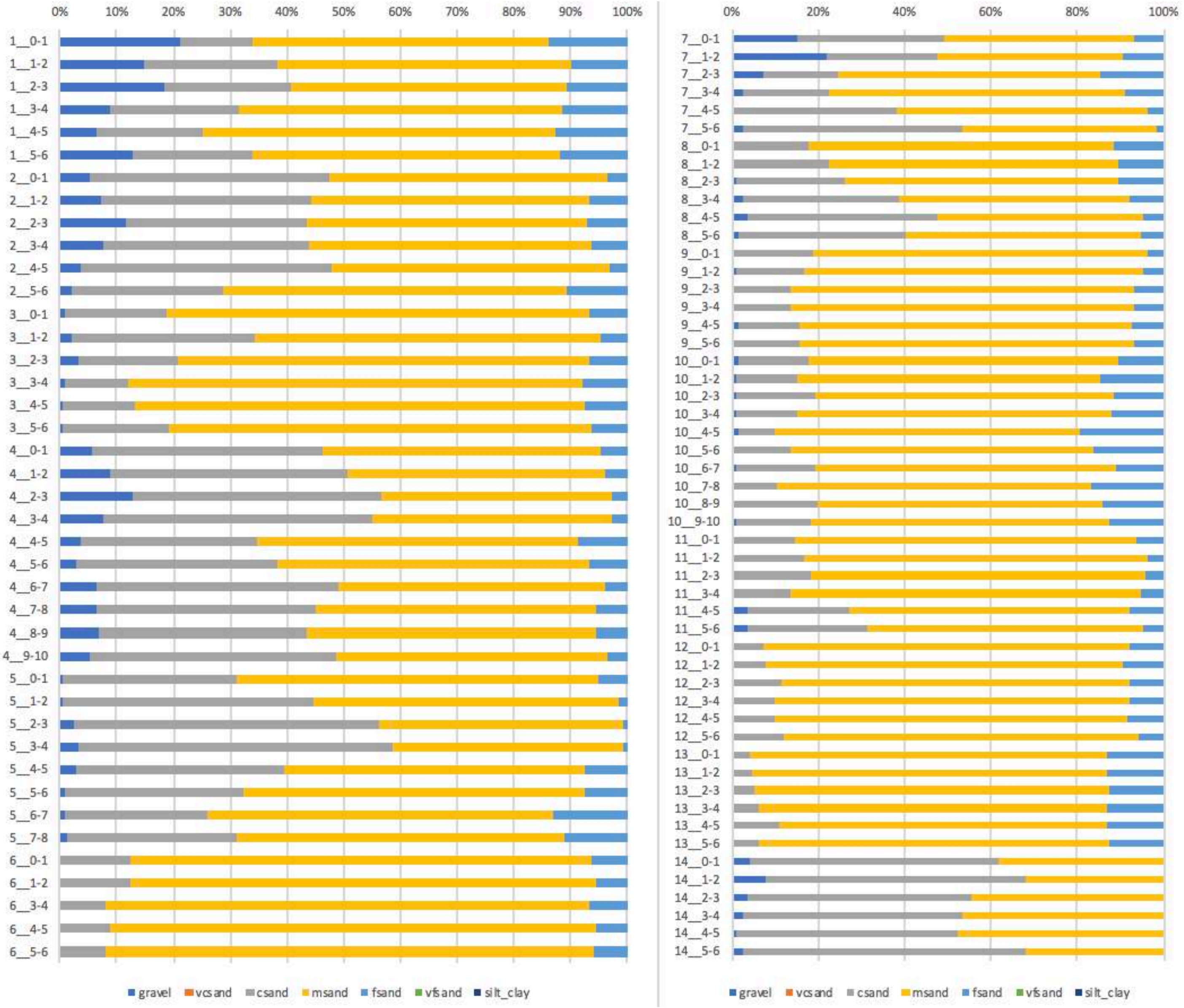
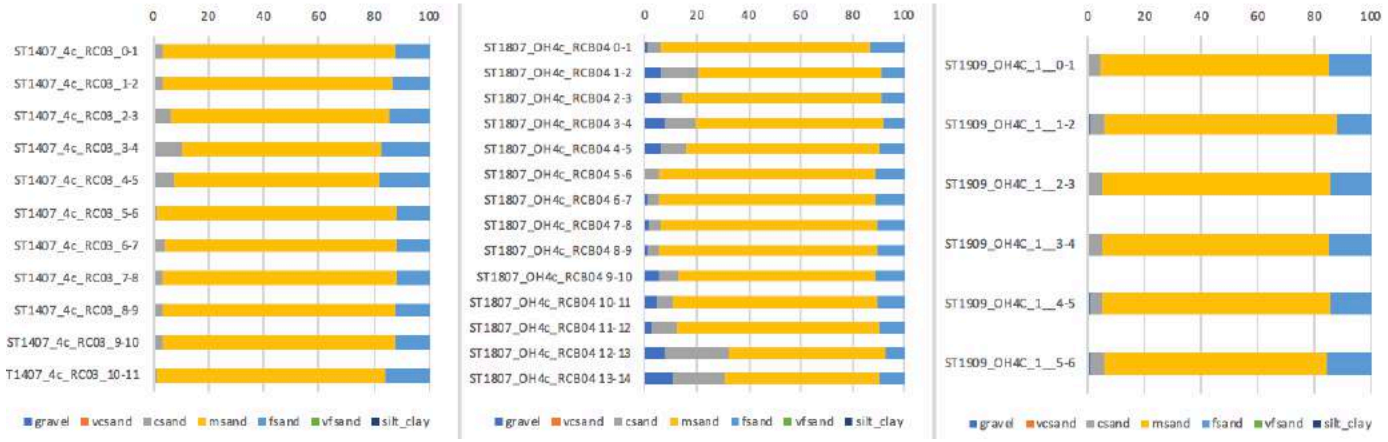
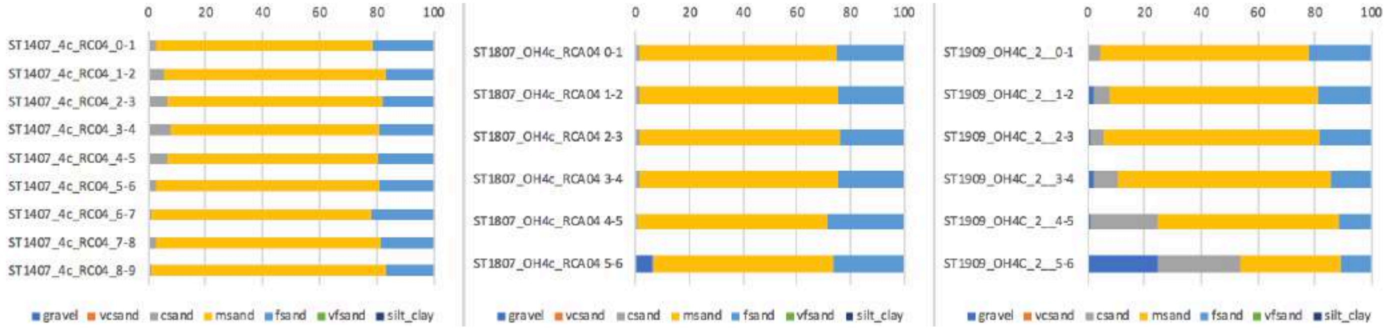


Figure 30. Noordhinder Sector4a - Lithological fraction percentages RV Belgica ST1909. Results from 1-cm slices at 14 locations, numbered from north to south.

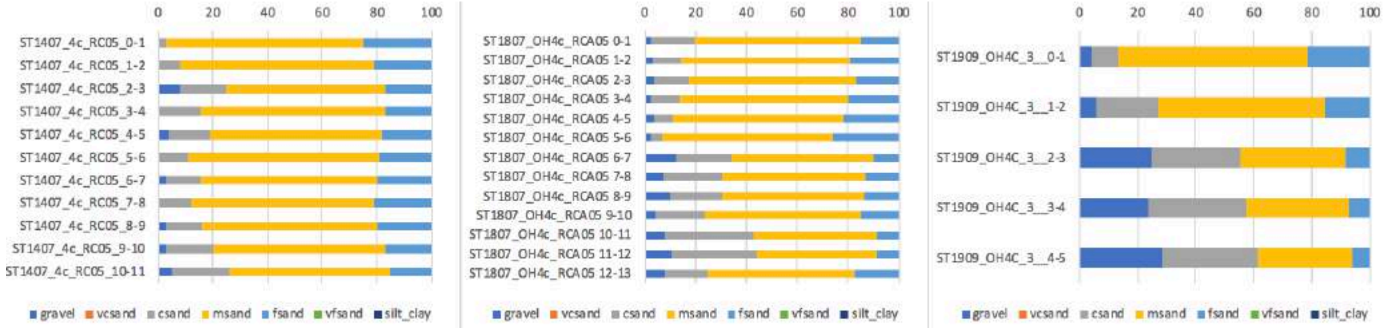
Important trends do exist *w.r.t.*: (1) Increased organic matter percentage where extraction is intensive; (2) With increasing extraction, decrease in calcium carbonate content; (3) Mixing of organic matter into the seabed matrix. The decrease in calcium carbonate content likely contributes to the decrease in backscatter strength over time, as shown by the multibeam time series from FPS Economy, Continental Shelf Service. Strongest changes are observed near the western edge of Sector 4c (location 3 and 8). Here, the seabed matrix is coarser with a high admixture of shell fragments. Correlation with geological data (TILES Consortium, 2018a,b) showed the shallowness of the Top Pleistocene deposits downslope of the sandbank. Note that the high mud percentage as measured at location 7 in 2014, did not appear in 2018 and 2019. This may indicate its anthropogenic origin during the intensive extraction activities of 2014, contrary to the hypothesis that it was due to outcropping of another geological layer.



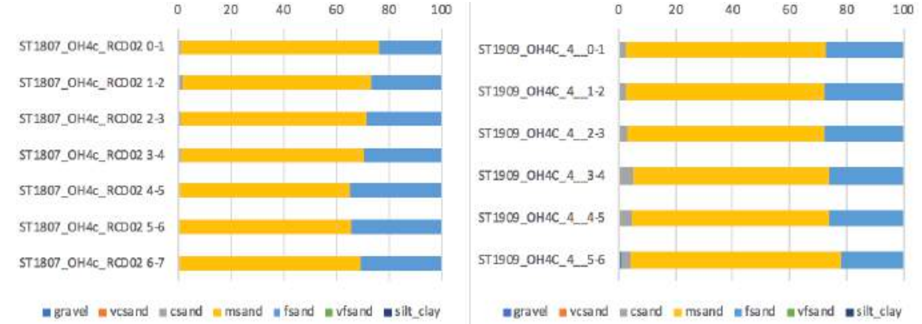
Location 1. From 2012 to 2019: Relative extraction: High > Moderate > High > / > / > Moderate > Moderate > None



Location 2. From 2012 to 2019: Relative extraction: Moderate > Moderate > High > / > / > Moderate > Low > None



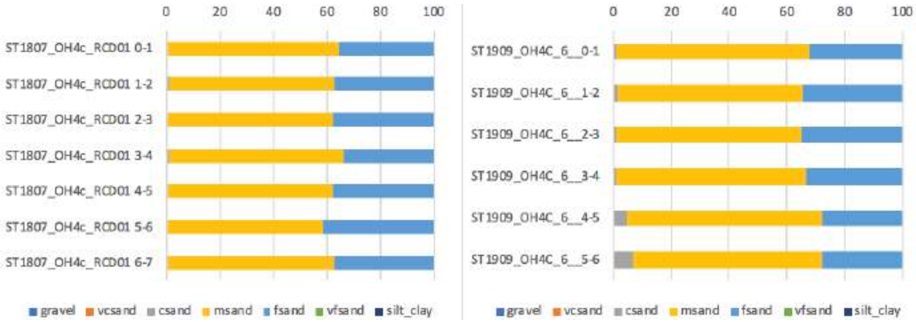
Location 3. From 2012 to 2019: Relative extraction: Low > Low > Moderate > / > / > Low > Low > None



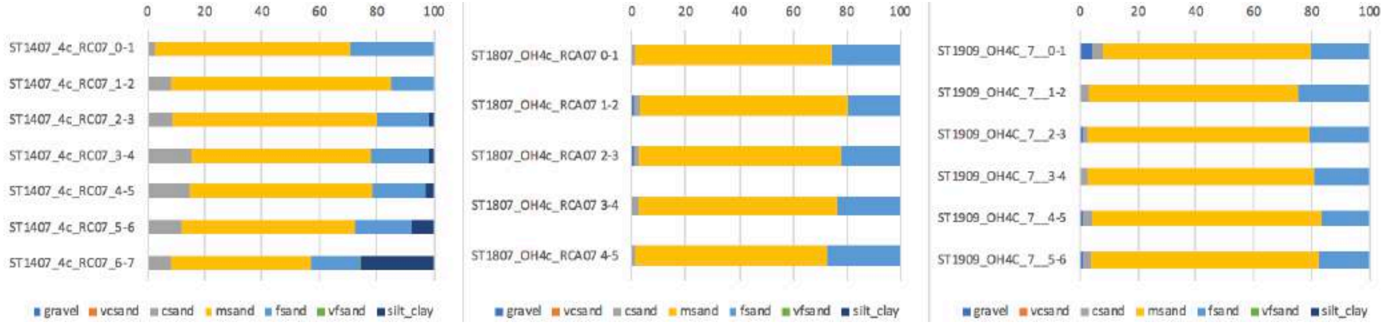
Location 4. From 2012 to 2019: Relative extraction: High > Moderate > High > / > / > Moderate > Moderate > None

Figure 31. Changes in lithological fraction percentages for the time series ST1407-1807-1909. Location 1-4 (1/2).

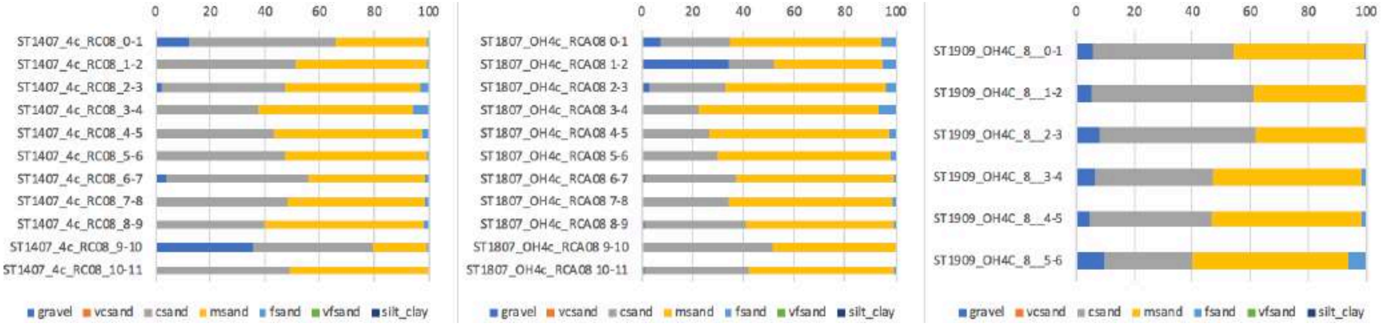
Location 5. From 2012 to 2019: Relative extraction: Moderate > Moderate > High > / > / > Low > Low > None



Location 6. From 2012 to 2019: Relative extraction: High > Moderate > High > / > / > Moderate > Moderate > None



Location 7. From 2012 to 2019: Relative extraction: Moderate > Moderate > High > / > / > Low > Low > None



Location 8. From 2012 to 2019: Relative extraction: Low > Low > Low > / > / > Low > Low > None

Figure 32. Changes in lithological fraction percentages for the time series ST1407-1807-1909. Location 5-8 (2/2).

4.2.2. Far field

Habitat Directive area, Oosthinder sandbank south and adjacent gullies

Seabed characteristics were further investigated in the Habitat Directive area, particularly in the troughs in-between the sandbanks, where ecologically valuable gravel beds occur (Figure 33). This relates to the investigation of a potential smothering process resulting from the dispersion of dredging-induced sediment plumes (see Van Lancker et al., 2016 for the rationale). In 2019, several gravel beds at different locations were sampled to investigate spatial differences using the same sampling technique.

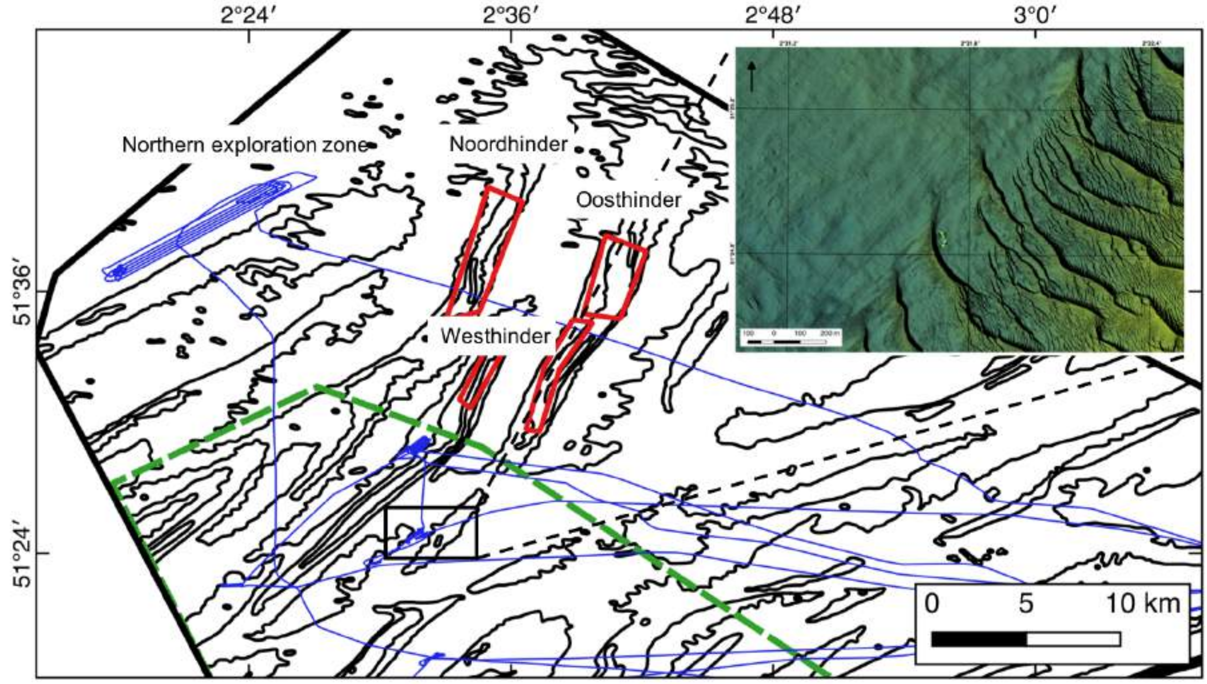


Figure 33. Overview of the main locations of seabed observations and sampling RV Belgica ST1919 (blue line). Marine aggregate extraction sectors (red polygons) and Habitat Directive area are indicated (dashed green line). The rectangular box gives the position of the barchan dune area, west of the Oosthinder sandbank (zoom in the upper right corner).

During RV Belgica campaign ST1909 multibeam data, in combination with Hamon grab samples and video imagery, were acquired in the gully between the Oosthinder sandbank and Blighbank. Data are not yet analysed. Below some sample pictures and images to demonstrate the main lithological content of the samples, and the silt-clay enrichment as evidenced by the brown colour of the water (Figure 34).

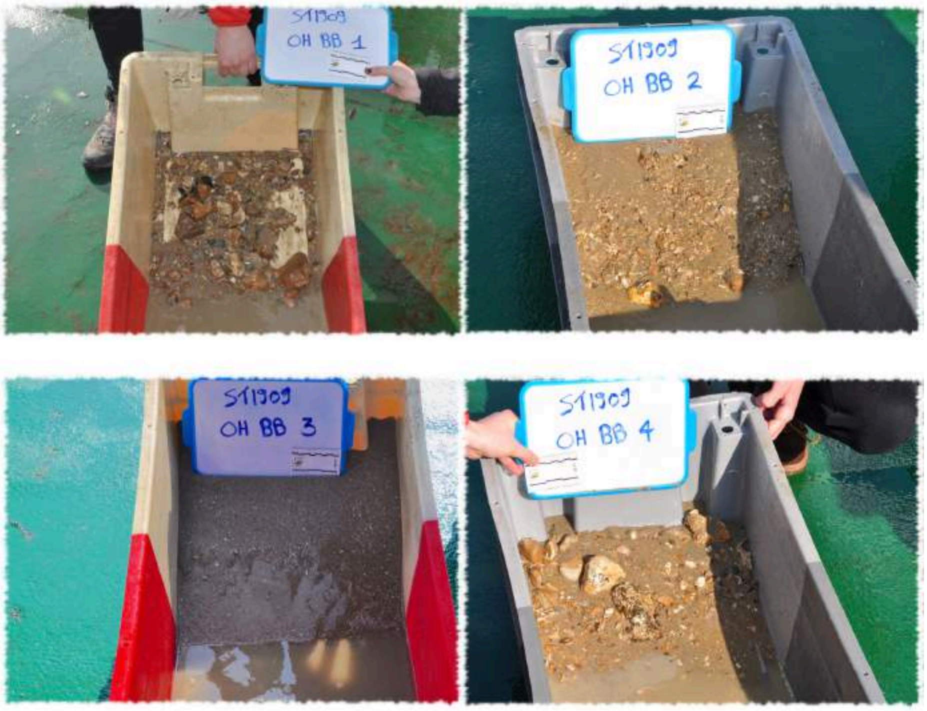


Figure 34. Seabed samples taken in the trough in-between the Oosthinder sandbank and Bligh Bank. The brown waters are indicative of silt-clay enrichment. For location, see Figure 4.

RV Belgica campaign ST1919 was conducted in cooperation with RBINS Marine Ecology team. Several gravel bed areas were sampled with a Hamon grab, and video recordings were made, both in conjunction with multibeam data acquisition. Figure 35 gives an overview of some gravel samples. For the MOZ4 programme particularly, scientific diving (RBINS lead Alain Norro) was conducted as well. Two diving teams were involved, one team was responsible for still photography; the other team for sand thickness measurements and retrieving shallow cores in-between gravel occurrences. As shown in Figure 36 the seabed is clearly composed of coarse sands and gravel.

Figure 35. Example of the gravel sampling during RV Belgica campaign ST1919.

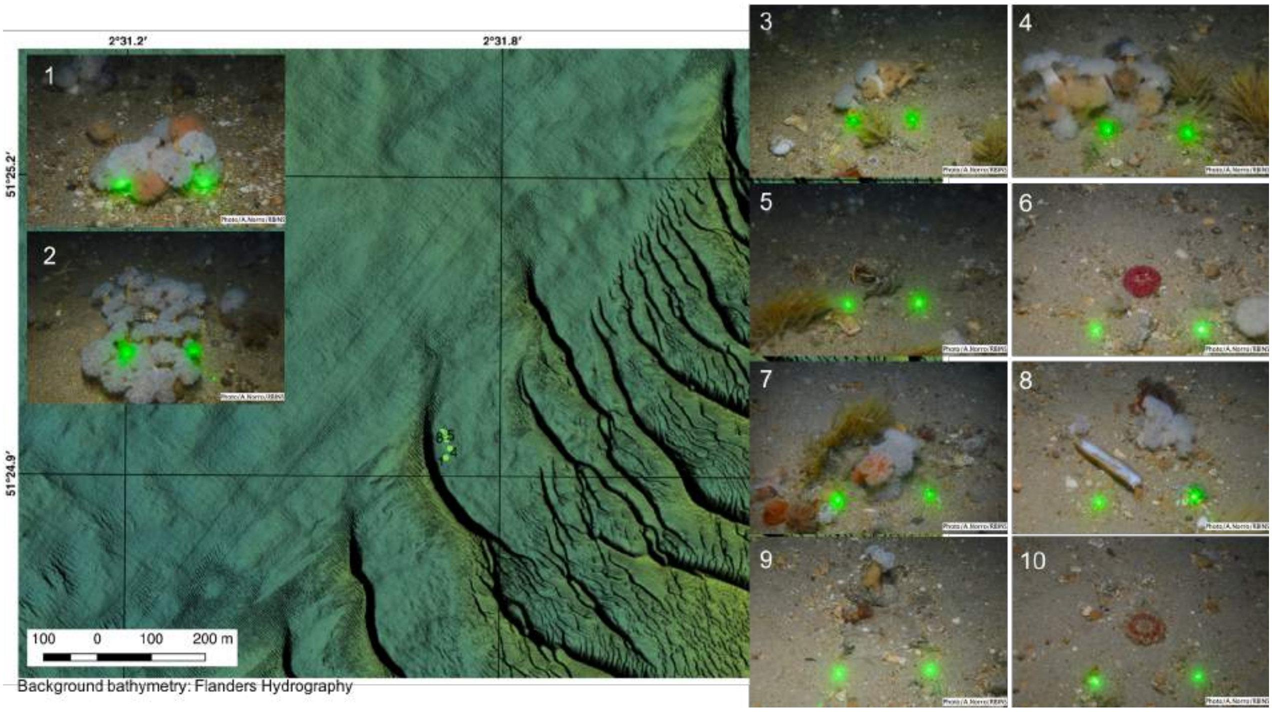
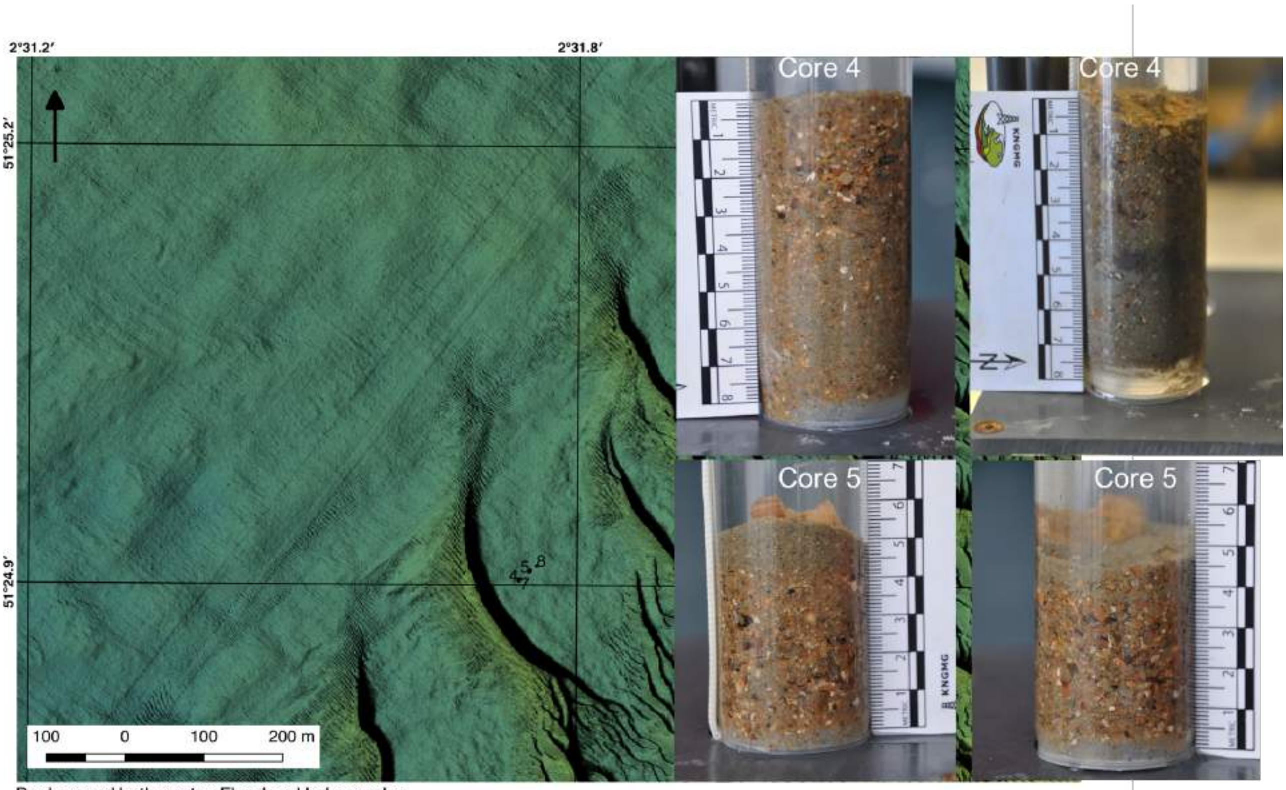


Figure 36. Still photography by divers in the barchan dune refugium area. RV Belgica campaign ST1919. Picture order from south to north along the transect. Laser pointers are 14 cm apart.

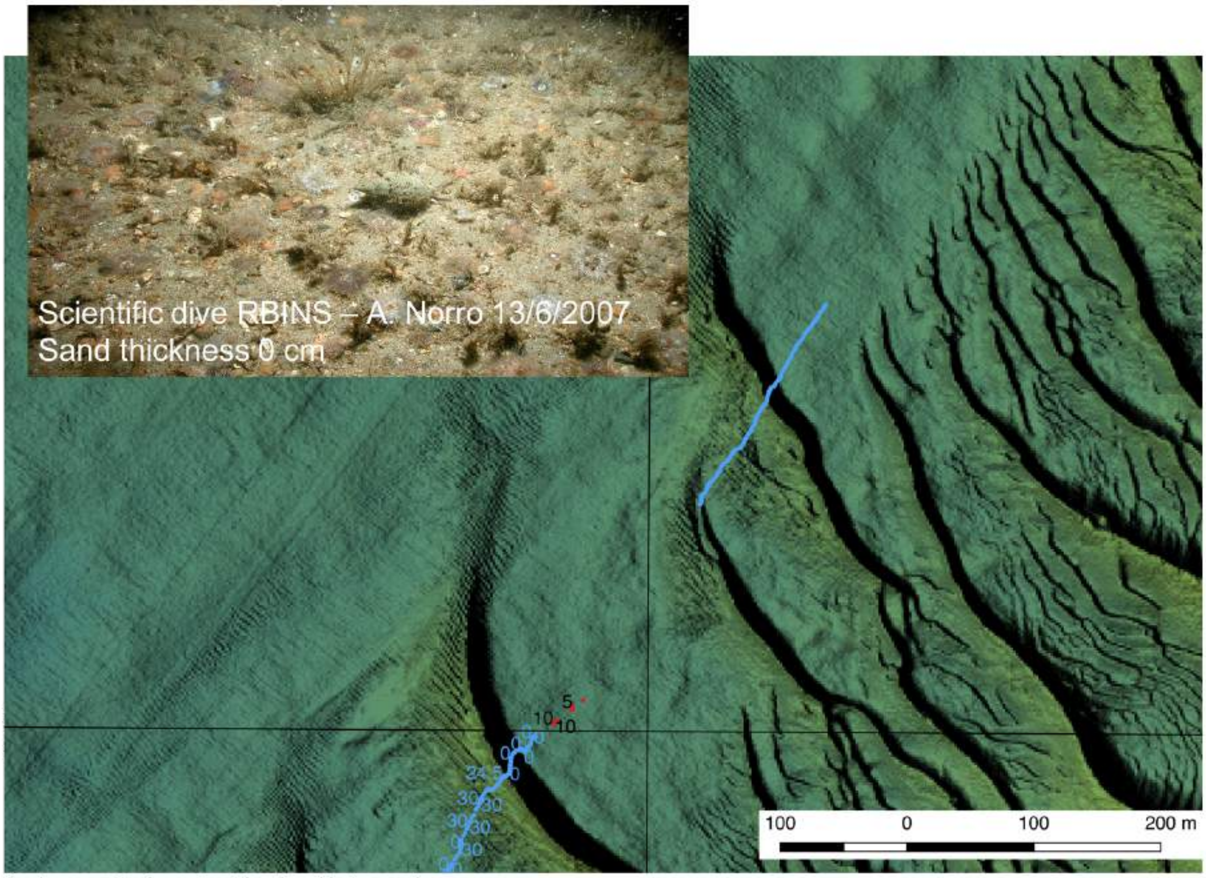
The shallow cores taken by divers witnessed clearly deposition of finer grained material on top of the coarser seabed matrix, as well as within the parent bed (Figure 37). To quantify this smothering process, it was decided to analyse the cores using micro computed tomography (micro-CT). This was done for two cores at Ghent University, Department of Geology, Pore-scale Processes in Geomaterials Research group (Prof. dr. V. Cnudde). Providing a core diameter of 4 cm, the best resolution of the scanning was 30 µm, which is the lowest resolution that material can be differentiated. See Van Lancker et al. (2020) (Annex A to this report) for more context and images of the micro-CT scans.



Background bathymetry: Flanders Hydrography

Figure 37. Shallow cores (4 and 5) and seabed samples (7 and 8) taken by divers in the barchan dune refugium area. RV Belgica campaign ST1919. Core 4 predominantly had shell hash in the top 2.5 cm. Finer-grained material is mixed in, as well as silt-clay layers and organic material (right). Core 5 has a coarse seabed matrix as well, though clearly shows deposition of fine-grained material at the top.

The divers measured also the thickness of the sand cover in an area where previously sand thickness was zero (13/6/2007) (Figure 38). In the July 2019 campaign a 10 cm sand cover was measured by divers.



Background bathymetry: Flanders Hydrography

Figure 38. Sand thickness measurements by divers. In blue is a dive of 13/6/2007 (picture upper left); 0 cm sand was measured away from the lee side of the barchan dune. In red are the measurements from 10/7/2019. Values ranged between 5 and 10 cm. RV Belgica campaign ST1919.

Northern exploration area

To have comparative samples in gravel areas in less disturbed regions, Hamon grabs, video imagery and multibeam were collected also in the northern exploration zone, as delineated in the Marine Spatial Plan 2020-2026. These data are currently worked up in a publication (Montereale Gavazzi et al., in prep.).

5. Synthesis measurements 2019

Measurements and observations in 2019 contributed further to testing hypotheses on the effects of marine aggregate extraction on the environment. Some new insights were obtained as well.

In the near field of extraction activities (Sector 4a, 4c Hinder Banks), they relate to:

- Increased organic material in the overflow of TSHDs. Grain-size spectra of the overflow showed modes of around 25 µm and 300 µm, respectively corresponding to a water column and a seabed-related fraction.
- At locations subdued to extraction, seabed sediments showed an increased organic material percentage, and a decrease in calcium carbon content.
- Longer term (43 days) water-column measurements showed an active transport of particles around 180 µm. Particle sizes up to 300 µm were measured during neap tide, indicative of a flocculation process whereby smaller particles are aggregated together. The fate of these particles is not yet clear, nor the extent to which the increase of organic matter contributes to the flocculation process.
- Water samples in combination with oceanographic profiling were used to derive suspended particulate matter concentrations. On the sandbanks measured concentrations (at 2-3 meter above the bottom) were in the range of 0.010-0.015 gl^{-1}, whilst in the gullies values were around 0.005 gl^{-1}. Extrapolation towards the seabed resulted in predictions of up to 0.040 gl^{-1} near the bottom. These values were much higher in Sector 4c, Oosthinder, then in Sector 4a, Noordhinder.

Noteworthy is the timing of the extraction activities in relation to tidal elevation. Extraction took place throughout the tidal cycle, resulting in a wide spread of fine-grained material, and not solely in the direction of the Habitat Directive area (towards the SW) as was the case in 2014. In 2019, up to three TSHDs operated in conjunction.

Measurements and observations continued in the far field, particularly in the Habitat Directive area where ecologically valuable gravel beds occur. These areas occur near the lee side of barchan dunes in water depths around 35m LAT. The dunes themselves consist of medium to coarse sand and may migrate under storm events. Near the lee side, Van Lancker et al. (2016) showed locally reversing currents due to current deflection over such steep dunes. Here, fine-grained sediments may be trapped, when available.

- Hamon grabs consistently show silt-clay enrichment, but this is also the case in the geographically wide variety of gravel beds sampled. Silt-clay enrichment is to be expected in the deeper lying throughs, though in the Hinder Banks region this has been rarely sampled prior to 2011.
- Shallow cores taken by divers near the lee side of the barchan dunes, evidenced deposition of fine-grained material in those gravel beds. Admixture of fine sands and mud was also shown in the parent bed. This was particularly demonstrated by micro computed tomography (micro-CT) scans of the cores.
- In those hotspots of biodiversity, sand thickness measurements by divers showed values of 5-10 cm in areas where in 2007 zero sand thicknesses occurred.

6. Integrated assessment of the monitoring 2016-2019

6.1. *Introduction*

The MOZ4 monitoring programme started in 2013, though since 2011 integrated monitoring of sediment processes is in place allowing assessing impacts of marine aggregate extraction in the Hinder Banks region for a period of nine years 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 seafloor integrity (e.g., sediment changes), and hydrographic conditions (e.g., changes in current regime). The assessment here presented focuses primarily on hydrodynamics and sediment transport (RBINS OD Nature), albeit with relevance to the geomorphological (FPS Economy, COPCO), and biological (ILVO) monitoring.

6.2. *Integrated monitoring approach*

Measurements were continued, in view of (1) characterizing the spatial and temporal variability in seabed nature; (2) building up knowledge on sediment processes in zone 4; and (3) testing of impact hypotheses, in which the investigation of cause-effect relationships was important. For the detailed rationale of the monitoring, and instrumentation deployed, reference is made to Van Lancker et al. (2016, synthesis report). It needs emphasis that impact assessment is complicated largely by the spatially-varying sandbank environment where sediment resuspension and advection may vary strongly with morphological position. Important lag effects exist between observed SPMc increases and the causal factors.

Development of numerical modelling tools and setting up automated analyses procedures is mostly done in the framework of the ZAGRI monitoring programme. Main goal is to support the assessment of changes in seafloor integrity and hydrographic conditions, two key descriptors in the definition of GES (MSFD). In the boxes, hereafter presented, some key projects are listed that contributed to the GES assessment.

Status numerical modelling

See synthesis report, and references therein, for results up to 2015 (Van Lancker et al., 2016). Van den Eynde (2016b) applied the bottom stress model to investigate the extraction of marine aggregates. Based on the new developments, Van den Eynde (2017) and Van den Eynde et al. (2017) applied the improved bottom shear stress modelling to support the definition of new reference surfaces for aggregate extraction (FPS Economy). To provide wider context to the variability of sediment transport parameters under different conditions, Francken et al. (2017a, 2017b) analysed long-term databases on sediment transport in the Hinder Banks region. Van den Eynde (2016a) invested further in the validation of bottom shear stress calculations and models. Finally, Van den Eynde et al. (2019b) assessed the impact of sand extraction on the wave height near the Belgian coast.

Developments of Indicators to improve monitoring of MSFD descriptors 6 and 7 on seafloor integrity and hydrographic conditions

Belspo INDI67 (2015-2019, Fettweis et al., 2020)

To support the Belgian MONIT.be monitoring programme, turbidity, bottom shear stress and seabed/habitat type, all related to sea floor dynamics, were investigated as key indicators for assessing changes in seafloor integrity and hydrographic conditions. Changes in the indicators result from the combined force that waves and currents exert on the sea floor, but also from human activities (e.g., dredging/disposal, aggregate extraction, constructions, fishery).

Under the umbrella of INDI67 PhD research was conducted on seabed classification using data collected in the MOZ4 Hinder Banks region:

- Montereale Gavazzi, G. (2019). *Development of seafloor mapping strategies supporting integrated marine management: application of seafloor backscatter by multibeam echosounders*. PhD Thesis. Ghent University, Faculty of Sciences: Gent. xxiii, 366 pp.
- Montereale Gavazzi, G., Roche, M., Lurton, X., Degrendele, K., Terseleer, N., Van Lancker, V. (2018). Seafloor change detection using multibeam echosounder backscatter: case study on the Belgian part of the North Sea. *Mar. Geophys. Res*. 39(1-2): 229-247. https://hdl.handle.net/10.1007/s11001-017-9323-6

Contributions of a geological knowledge base in impact assessments

Belspo TILES project (2014-2018; Van Lancker et al., 2019)

Seabed information, including geology, is critical baseline information to frame and understand impact analysis. Via the TILES aggregate resource decision support system, the subsurface geology can be queried. Borehole data contributing to the DSS can be consulted via the data portal. Standardization and data uncertainty is described in Kint et al. (2020).

- Kint, L., Hademenos, V., De Mol, R., Stafleu, J., van Heteren, S., & Van Lancker, V. (2020). Uncertainty assessment applied to marine subsurface datasets. Quarterly Journal of Engineering Geology and Hydrogeology.
- TILES Consortium 2018a. Aggregate Resource Decision-support Tool: http://www.bmdc.be/tiles-dss/#. Brain-be project TILES (Transnational and Integrated Long-term Marine Exploitation Strategies, BR/121/A2/TILES), Belgian Science Policy, Brussels.
- TILES Consortium 2018b. Geological data portal: http://www.bmdc.be/tiles-dataportal/#. Brain-be project TILES (Transnational and Integrated Long-term Marine Exploitation Strategies, BR/121/A2/TILES), Belgian Science Policy, Brussels.

Relevant results of the modelling and long-term data analyses, as well as geological knowledge bases, and the listed other projects, *w.r.t.* the assessment of physical impacts and the evaluation of MSFD indicators are taken up in the next sections.

6.3. *Physical impact assessment*

6.3.1. Assessing impacts from long-term dune dynamics

As part of the ZAGRI monitoring programme, an automated estimation of morphodynamic parameters (bedform height, wavelength, migration rate) was developed and is here reported because of its relevance to the MOZ4 monitoring programme. In total, 187 multibeam echosounding campaigns (FPS Economy COPCO, see Figure 39 for an overview of the locations) were treated distributed over 10 different areas over a monitoring period of 20 years, leading to 1000+ observations of 100+ individual dunes.

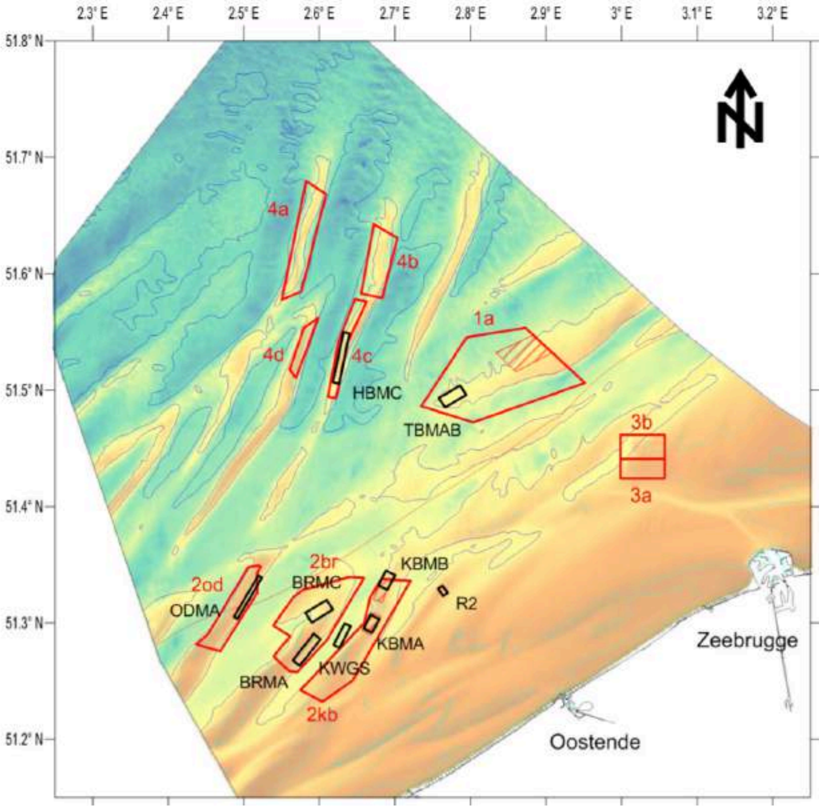


Figure 39. Marine aggregate extractions (red) and the monitoring areas (black) where FPS Economy conducts a regular follow-up of depth and backscatter. Investigated sandbanks include for the Flemish Banks BR: Buiten Ratel, KB: Kwinte Bank, OD: Oostdijck, and the Middelkerke Bank serving a reference area (R2); for the Zeeland Banks TB: Thornton Bank; and for the Hinder Banks: Westhinder, Oosthinder and Noordhinder (HB). "M": monitoring area; A-B-C the different monitoring areas per sandbank. Figure from FPS Economy.

Obtained bedform wavelengths and heights are shown in Figure 40. Most wavelengths range from 100 to 300 m, and heights from 1 to 5 m (except for HBMA and HBMB, where the sandbank itself is caught by the procedure for some investigated profiles across it), mostly corresponding to very-large dunes.

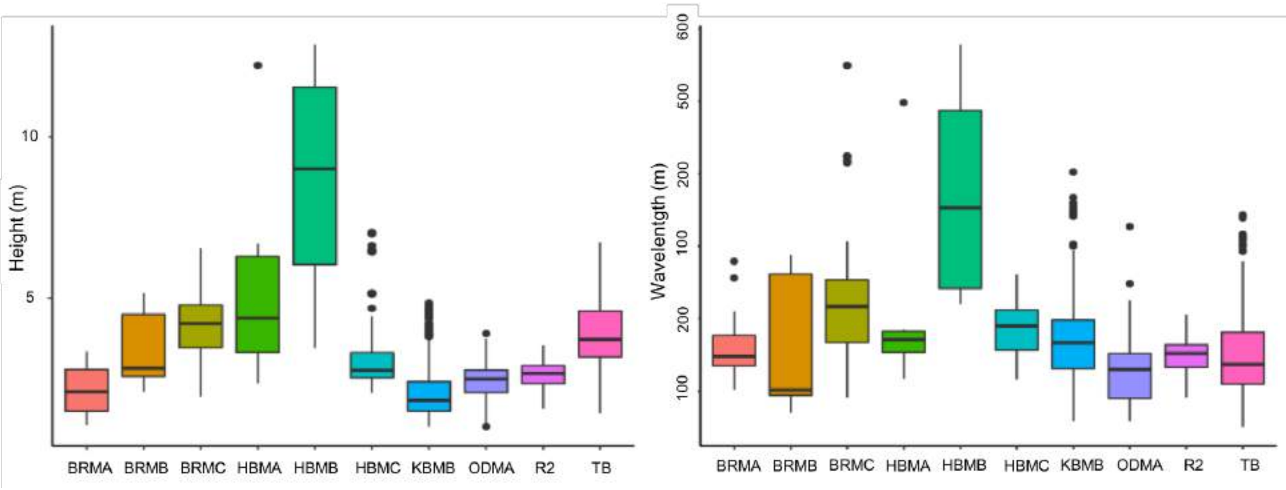


Figure 40. Morphological parameters: boxplots of (a) dune heights and (b) wavelengths per monitoring area. For location, see Figure 39.

Figure 41 shows the relationship between bedform height and wavelength comprising smaller bedforms (megaripples; wavelength ~10 m), very-large dunes, and megaripples on top of very-large dunes on sandbanks (wavelength close to 1000 m). Results are plotted together with the relationship observed by Flemming (1978; black line) based on a huge observation database of subaqueous sand dunes. The automatically extracted bedforms are located close to this Flemming (1978) relationship, though with some dispersion and a tendency to show smaller dune heights for a given wavelength (especially for the smaller bedforms occurring on top of the very-large dunes; left cloud of points in Figure 41). Observations in the Hinder Banks follow the trend.

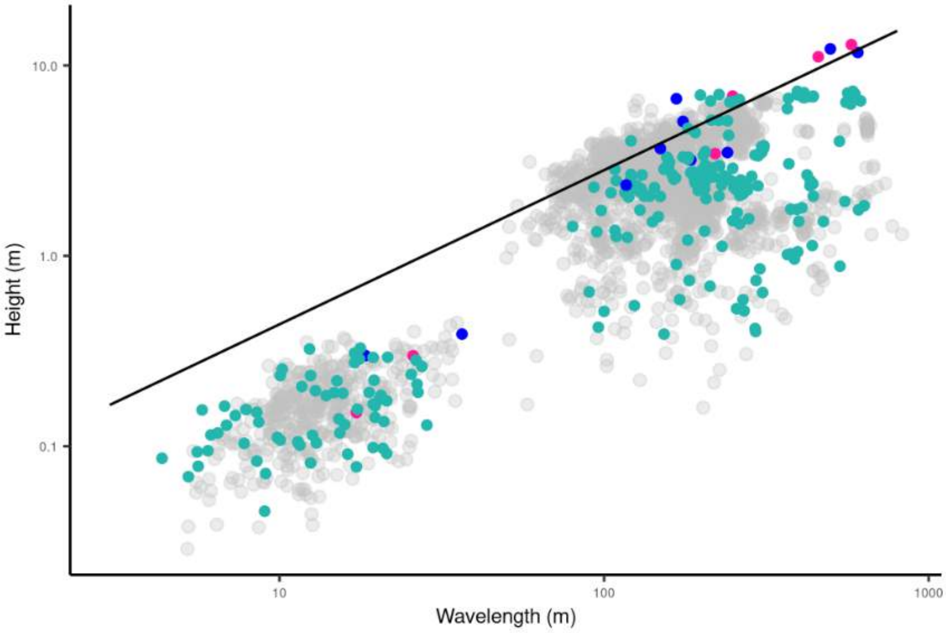


Figure 41. Dune Height *vs* Wavelength for the automatically generated dataset, here focussing on the Hinder Banks region (HBMA: blue; HBMB: red; HBMC: green; Other monitoring areas in grey), compared to the Flemming (1978) curve (for mean height values with Height = 0.0677 x Wavelength$^{0.8098}$).

Estimated migration rates range from 0 to 2 or exceptionally 4 m per Spring-Neap (SN) cycle, with median values ranging from 0 to 0.7 mSN^{-1} cycle (Figure 42). HBMC appears as a dynamic area, with bedforms having median migration rates between 0.2 and 0.6 mSN^{-1} cycle; only the bedforms in the ODMA are moving faster. Contrary to the monitoring area ODMA, situated on the South part of the sandbank, with migration mostly occurring towards the ebb direction, dune migration over HBMC is mostly flood-directed (not shown).

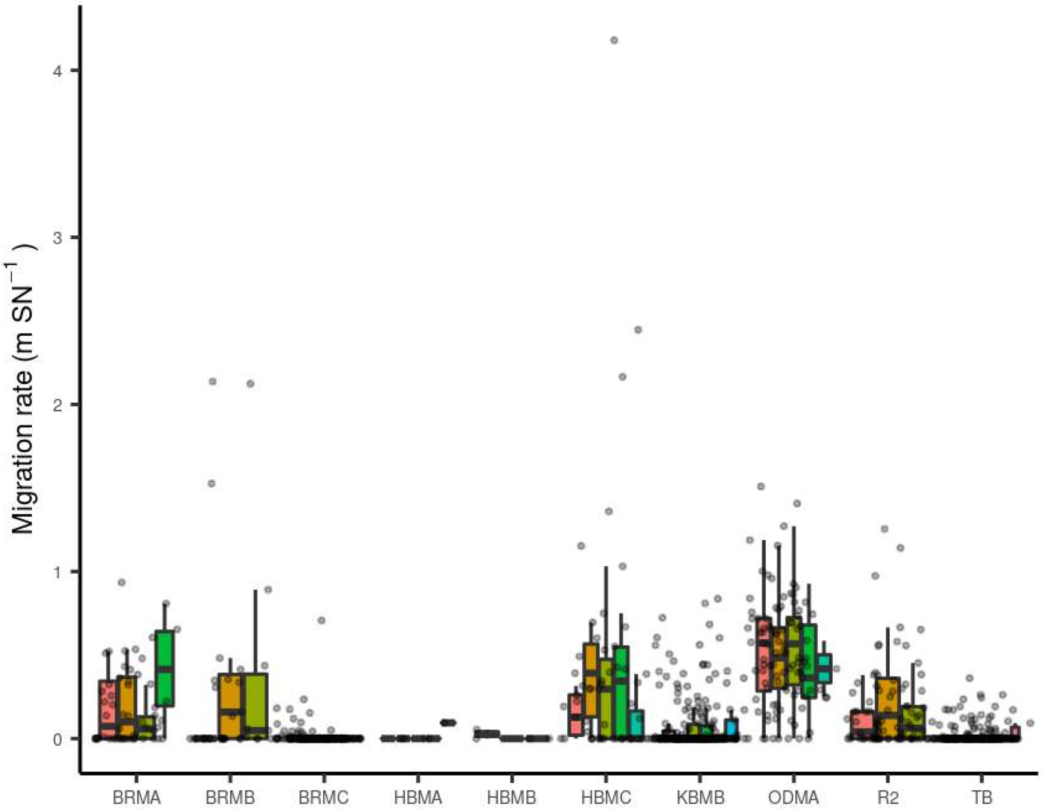


Figure 42. Estimated migration rates of the different dunes detected in each area. Each dune is associated to a coloured boxplot, illustrating the variability over the full time series of bathymetric data.

Based on this automated approach, it is possible to track the time evolution of the very-large dunes in the monitored areas. Figure 43 shows the time evolution of the height of the different dunes identified in each area. Dune height appears fairly stable in some areas such as BRMB and R2, with no extraction taking place on the latter. A long-term decrease in dune height is visible especially for BRMC, HBMC and TB, or the areas experiencing the most intense marine aggregate extraction over the period of observations. Noteworthy is that BRMC shows a steady decrease in dune height up to ~2014-2015, when extraction was halted. Since then, a stabilization of the dune height seems to occur. This provides insight into the effect of marine aggregate extraction on the seabed morphology, and on its recovery potential: five years later, original dune heights are not restored, but the height decrease stopped.

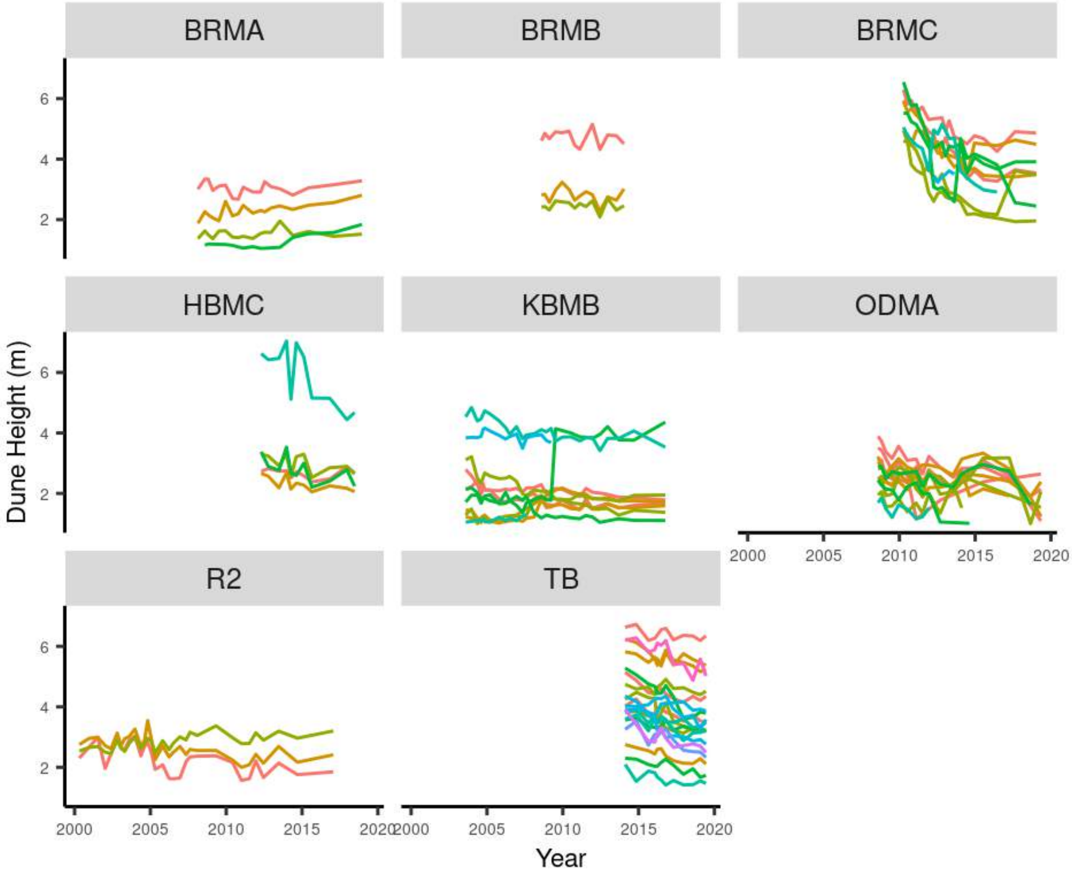


Figure 43. Time evolution of the dune heights in each area. Note the strongest decrease in dune height for the monitoring areas TB, BRMC and HBMC. After halting the extraction at BRMC, the dune decrease stabilized.

Figure 44 shows the difference in dune height between successive monitoring surveys compared to the extraction occurring between them. Despite the high variability in the observations and the uncertainty attached to the measurements and the methodology, an overall trend seems to confirm that marine aggregate extraction can induce a decrease in bedform heights beyond the removed material. This is not visible for HBMC alone, and further investigation will be needed to draw conclusions, as the trend is mostly induced by the observations on the two most extracted areas, BRMC and TB.

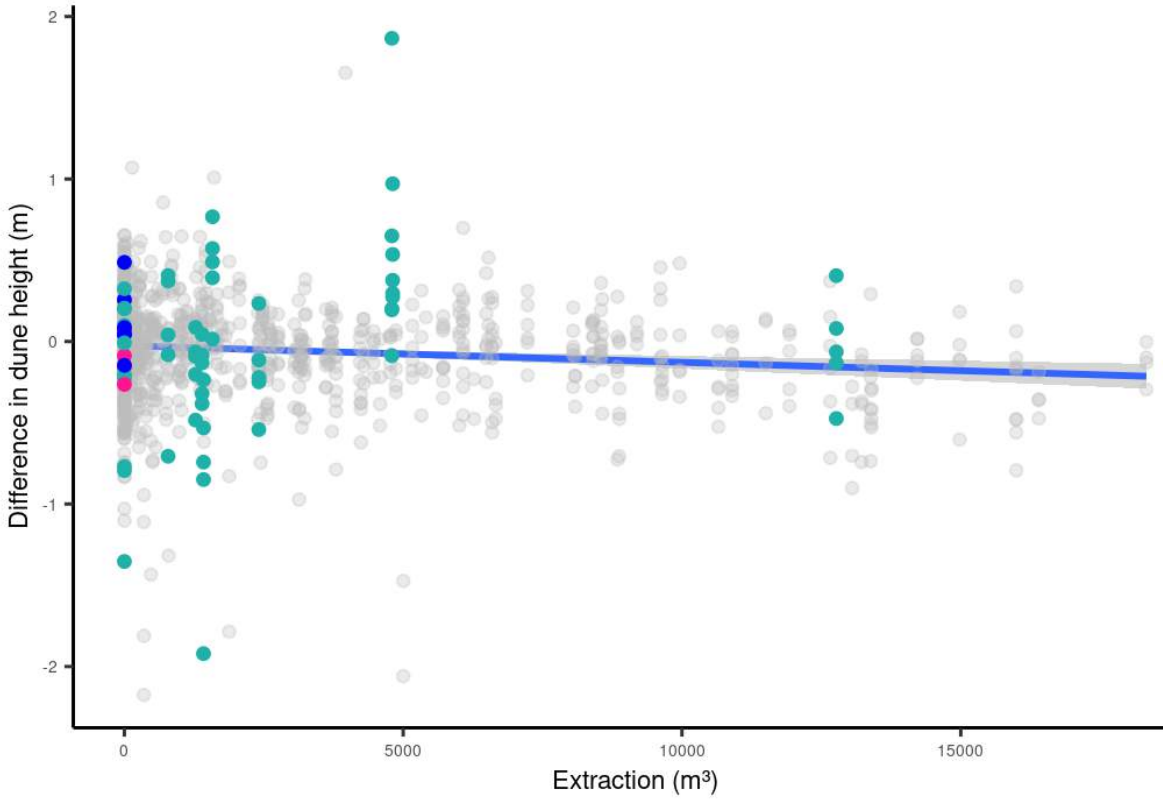


Figure 44. Difference in dune height between successive dune observations *vs* sand extraction in the direct neighbourhood of the bathymetric profile (with a 25 m buffer). Focus is here on the Hinder Banks region (HBMA: blue; HBMB: red; HBMC: green; Other monitoring areas in grey), Despite the very large variability in the data, a slightly negative significant linear relationship is suggested. It points to a residual dune height decrease beyond the extraction. This would imply that long-term predictions on the decrease of sediment volumes on extracted sandbanks should account for more erosion than solely based on the extraction rate.

The automated procedure is under its final developments, and the resulting dataset will be further investigated to assess the potential sources of variability affecting the morphodynamic parameters of the seabed (e.g., meteorological data, hydrodynamics) to complete the preliminary analysis as shown here.

6.3.2. Monitoring results, synthesis 2011-2015 and 2016-2019

The following results were obtained when assessing near- (in and around the sectors of extraction) and far-field impacts towards the south, where ecologically sensitive gravel habitats occur in a Habitat Directive Area. First some characteristics of TSHD are provided, typical for the operations in the Hinder Banks region. Subsequently, some factual observations are listed. Finally, some hypothetical impact relationships are put forward that were further tested. See Van Lancker et al. (2016), synthesis report, for more details on the period 2011-2015.

TSHD characteristics and their operations

2011-2015	**2016-2019**
W.r.t Sector 4c, 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).	*In 2017, extraction in Sector 4c occurred during ebbing phase of the tide.* *In 2019, extraction in Sector 4a was executed under all phases of the tidal cycle.*
Water samples taken near TSHDs are multimodal, including a 10 µm mode.	*Overflow samples from a TSHD (hopper volume 12000 m*^{3}*) operating on Sector 4c (April, 2017) showed that around 85% of the overflow was silt or fine-grained, with a d50 of around 25 µm ; concentrations were up to 1 gl*$^{-1}$*. Calculations estimated a water-column release of 16-17 tonnes sediment per single extraction event. Typically, two large TSHDs operated twice daily, resulting in an amount of overflow particles equivalent to four heavy trucks per day. In this period TSHD vessels were commissioned to combine both sand mining and harbour (access) maintenance operations. Hoppers still had a residual coastal silt-clay load whilst dredging in the offshore (Baeye et al., 2019).* *Increased organic material in the overflow of TSHDs. Grain-size spectra of the overflow show modes of around 25 µm and 300 µm, respectively corresponding to a water column and a seabed-related fraction (this report). In 2019, up to three TSHDs operated in conjunction.*
TSHD-related dynamic sediment plumes were observed using acoustics (multibeam, ADCP).	*Joint campaigns with FPS Economy, ILVO and external partners focussed on plume detection using acoustics (Roche et al., 2020). Results are underway.*
Deposition of a passive plume was observed acoustically also, 3 hrs after an extraction event.	*Only episodic observations of increased SPMc beyond natural levels.*
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).	*Renewed sediment plume modelling is underway.*
Since the start of extraction in 2012, and especially in 2014 on sector 4c. 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.	*Similar findings in the period 2016-2019.*

Hydrodynamics and sediment transport

2011-2015	**2016-2019**
From 30-days current measurements around Sector 4c using a Wave Glider, and conform to the other measurements, peak flood and ebb tidal currents were overall quasi equally strong. Still, at the sandbank level, the western slopes are flood dominated; the eastern slopes ebb dominated. However, hydro-meteo conditions are able to reverse the residual current direction.	*Similar findings in 2016-2019. In duration, currents remain high for a longer time in the flood direction.* *Longer term (43 days) water-column measurements show an active transport of particles around 180 μm. Particle sizes up to 300 μm were measured during neap tide, indicative of a flocculation process whereby smaller particles are aggregated together.*
Peaks in 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. Under wave conditions, SPMc on sandbanks is high throughout the water column.	
Tidally-induced SPMc was similar under NE- and SW-directed currents, though higher concentrations were generally measured under flood (NE) conditions. In the upper water layers, at -10 m, median values of SPMc reached about 0.010 gl^{-1}. 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 was 0.011 to 0.015 gl^{-1} in the deepest areas and up to 0.019 gl^{-1} over the sandbank crests.	*On the sandbanks measured concentrations (at 2-3 meter above the bottom) were in the range of 0.010-0.015* gl^{-1}*, whilst in the gullies values were around 0.005* gl^{-1}*. Extrapolation towards the seabed resulted in predictions of up to 0.040* gl^{-1} *near the bottom. These values were much higher in Sector 4c, Oosthinder, then in Sector 4a, Noordhinder.*
The gravel fields in the barchan dunes of the Habitat Directive area are subdued to a dominance of the flood current, though the flood current was decelerated near the bed, potentially pointing to a vortex structure along the steep side of the barchans.	
Natural variability of sediment processes in the Hinder Banks region was much more variable than previously expected. This applied to bedform migration, 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	*Compared to all aggregate extraction monitoring areas, HBMC appears as one of the more dynamic areas, with bedforms having median migration rates between 0.2 and 0.6* mSN^{-1} *cycle.*

Seabed substrate

2011-2015	2016-2019
Predominance of medium sands in the aggregate sectors. The topzone 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 outcropping of Pleistocene deposits was shown downslope of the sandbank. Some downslope cores also contained muddy layers. These constrain the extent of the extractable resource potential to the main body of the sandbank. 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 mode around 10 µm. Regular observation of organic matter in video imagery.	*At locations subdued to extraction, seabed sediments showed an increased organic material percentage, and a decrease in calcium carbonate content.*

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

2011-2015	2016-2019
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 modelling showed that deposition of fine-grained material from Sector 4c is possible.	
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°. The 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	*Bathymetric time series showed progressive bedform migration, from ca. 20 m from 2004 to 2010, ca. 10 m from 2010 to 2013 and less than 5 m up until late 2015. Within the relatively flat and gravel-populated areas, devoid of dunes, the seabed showed an overall stability. Deposition was observed, but the change remained within the bathymetric confidence envelopes. Nonetheless, a loss of seabed complexity was observed (Montereale Gavazzi et al., 2017).*

settle. This was partially demonstrated from new measurements and modelling in the study area.	
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.	*Shallow cores demonstrated deposition of fine-grained material at the seabed, but also mixed within the sediment matrix.*
In the gravel bed refugia, much more sand was observed visually than expected from previous visual observations (diving observations of 2006/2007, OD Nature, Norro). 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 2006/2007, sand thickness measured by divers was zero.	*Scientific divers in 2019 measured sand thicknesses of 8-10 cm where in 2007 zero thicknesses were measured.*

The drivers of the observations and processes described are under investigation and are a combination of both naturally and anthropogenically-induced events. In the following phase of the monitoring, multiple sources of fine-grained material will be investigated in more detail. This remains complicated research given that most sediments are being reworked over time. Still, because of some renewed human activities, such as cable laying, and the extraction activities in the Hinder Banks region, some sediment signatures/spectra may become more pronounced. In the next years, research will be intensified on the impacts of windfarms as well, with an important focus on water-column measurements. As such, more comparative material will become available.

6.3.3. Relevance of results *w.r.t.* to other monitoring

This section relates to the monitoring results of FPS Economy and ILVO, focussing respectively on the geomorphological and biological evolution of the extraction sectors in the Hinder Banks region. Only first reflections are presented since all of the new monitoring results will be discussed, in depth, during the coming months.

Since 2012, FPS Economy is monitoring changes in depth and backscatter using multibeam technology in the Hinder Banks region. Monitoring areas are defined per sector, and a transect approach is followed covering the sandbanks (Noordhinder, Westhinder, Oosthinder) (see Barette et al. 2020 for a detailed overview). New results confirm the significant change in seabed backscatter in Sector 4c, i.e. a decrease in backscatter strength (more negative dB values), that was most striking after the peak extraction in 2014.

Subsequently, the measurements merely showed a stabilization of the seabed state, although 2018 and 2019 again point to a decrease in backscatter strength. This complies with an increase in absorption of the acoustic energy that could be indicative of a fining trend in grain size. ILVO's sediment samples taken from Van Veen grabs align with this trend, as well as their observed shift in benthic community composition (Wyns et al., 2020). They observe an enrichment of fine sands comparing extraction zones against a reference area without extraction. However, from the data shown in this report (Figures 28, 29) and shown in greater detail in Kint & Van Lancker (2020) such a fine sand enrichment is not easy to evidence. This may be due to spatial variability and/or the availability of datasets only in 2014, 2018 and 2019. Still, the samples discussed in this report were derived from Reineck boxcores from which cores were taken and cm-sliced. It is however remarkable that the dunes of Sector 4c seem to migrate faster compared to other dune areas over the BPNS (see section 6.3.1) with dune heights being smaller than would be expected from their wavelength (Figure 40). Increased seabed sediment reworking may play, or increased seabed mobility because of an increase of fine sand. Increased mobility could lead to increasing erosion rates and needs further investigation. The same holds true for the source and process of the fine sands: redistribution from top to flanks; deposition from overflow; or deeper lying sediment layers that are finer-grained? W.r.t. the results of the transect-based approach covering multiple sandbanks, extracted, and non-extracted, Barette et al. (2020) confirm the previous trend (2017) of a slight overall decrease in bathymetry in the parts of the zones where no extraction took place.

Biological monitoring of the hard substrates is carried out by RBINS OD Nature in the context of the Belgian MSFD implementation. This monitoring is aligned with the monitoring presented in this report. As such, from many of the gravel samples taken in this monitoring also biological analyses are performed. De Mesel et al. (2018) reports on the status of gravel beds as sampled in 2015 and reports that the state of the gravel beds is assessed as severely disturbed and not complying with good environmental status. Many of the target species included in the various environmental targets are either missing or have only been observed as juveniles or in an impoverished state. Fisheries is regarded the main cause of disturbance, though additional disturbance should be avoided.

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

In this section, the compliancy of the marine aggregate extraction activities versus the environmental targets, defined by Belgium in its implementation of the Marine Strategy Framework Directive, is further discussed. For a full rationale see Van Lancker et al. (2016) and see Belgische Staat (2018) for a first assessment cycle of MSFD 'Good Environmental Status' (GES) compliancy (https://odnature.naturalsciences.be/msfd/nl/assessments/2018/). In relation to the monitoring reported in this document, focus is on the assessment of the physical part of the descriptors seafloor integrity and hydrographic conditions.

6.4.1. Evaluation

Seafloor integrity (GES descriptor 6, D6)

Following the Commission Decision 2010/477/EU on this descriptor, *"Seafloor integrity should be at a level that ensures that the structure and functions of the ecosystems are safeguarded and benthic ecosystems, in particular, are not adversely affected. The objective is that human pressures on the seabed do not hinder the ecosystem components to retain their natural diversity, productivity and dynamic ecological processes, having regard to ecosystem resilience"*.

For the pressure part of seafloor integrity, the Commission put forward three primary criteria that need assessing: 1) Physical loss (D6C1, D6C4); 2) Physical disturbance (D6C2) and 3) Spatial extent of adverse effects from physical disturbance on benthic broad habitats (D6C3, D6C5). For (1) and (2) the spatial extent and distribution of human activities needs quantification. Following ICES newest advice to the European Commission, physical loss is defined as a permanent change to the seabed for which recovery, without human intervention, is not possible (ICES, 2019). Physical disturbance is a change to the seabed which can be restored if the activity, causing the disturbance pressure, ceases.

Related to the seafloor integrity criteria physical loss and disturbance, Belgian State (2012, 2018) defined two targets/indicators for which new monitoring programmes were set up.

1. The areal extent and distribution of EUNIS level 2 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 2 habitats has a high confidence; (ii) transect seabed mapping crossing the EUNIS Level 2 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 yrs) is envisaged.

In 2016-2019, datasets were acquired compliant with the newly proposed MSFD monitoring programme (see Van Lancker et al., 2017 and Van den Eynde, et al., 2019, for a full description). Since the methodological approach was new, there were no comparative datasets available that allowed for proper change detection. Importantly, significant progress was made in the acoustic mapping of seabed habitats (silt, sand and coarse-grained sediment) based on dedicated PhD research on acoustic seafloor classification and change detection (Montereale Gavazzi, 2019). Comparing those acoustic results to sampling point observations proved prone to changes being mostly attributed to differences in methodological approach. Similar datasets will be acquired in 2021.

In this report, several observations have been described that could point to sediment changes. Issues to consider are described in detail in Van Lancker et al. (2016). Since cause-effect relationships are in investigation, they can yet not be linked to physical disturbance. In any case, the assessment of EUNIS level 2 changes that is here targeted applies to gross sediment changes, i.e., transitions between mud, sand, gravel. Transition from gravel to sand is particularly investigated.

2. Within the gravel beds[3] (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 (June/July) was proposed to enable linking observed changes to human activities. Also multibeam bathymetry and backscatter were proposed as methodology, in combination with visual observations and seabed sampling; the latter following a stratified random sampling approach.

An approach was developed newly and tested on the two testzones as described in the Belgian MSFD monitoring programme. For both areas (Oosthinder, barchan dune gravel area, as described in this report (section 4.2.2); Kwinte gully 'KWGS', Roche et al., 2018) repetitive multibeam data were available. Time series of seabed acoustic measurements (dB value ranges) mainly showed fluctuations within the margin of error (Van Lancker et al., 2018). However, more detailed seabed classifications within the barchan dune gravel areas allowed identifying variations in the gravel/sand ratio that could be related to changing sedimentation (see Montereale Gavazzi et al., 2018 for results). Most pertinent change was observed after the peak aggregate extraction period on Sector 4c in 2014, though Francken et al. (2017a, b) also showed that 2014 was an exceptional year in terms of predominant SW conditions leading to higher sediment fluxes. Meanwhile, quantification of the gravel/sand ratio is being further based on video imagery. Automated procedures have been developed and are further tested.

Hydrographic conditions (GES descriptor 7, D7)

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 (D7.1); and (2) Spatial extent of adverse effects on benthic habitats from permanent alteration of hydrographical conditions (D7.2). They are meant to prevent human-induced permanent changes to hydrographic conditions. In Belgische Staat (2018) indicators were defined as:

1. Infrastructure works are considered significant when at least one of the following criteria is met (D7.1):
   a. There is a physical loss (as defined by criterium D6C1, see above)

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[3] For the monitoring of this indicator, the Belgian State defined two testzones 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).

   b. There is a variation of more than 10% of the mean bottom shear stress;
   c. There is a variation of more than 10% of the time of the duration of sedimentation or the duration of erosion.

   The bottom shear stress should be calculated taking into account the effects of both currents and waves on the sea bottom. For infrastructure works causing changes on the small scale, the bottom shear stress could be calculated with a hydrodynamic model for on a spring-neap tidal cycle (14 days).

2. The spatial scale of each benthic habitat type that is affected negatively by permanent changes of the hydrological conditions (D7.2).
3. 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.

Applied to the MOZ4 study area, in-situ data on bathymetry, currents and bottom shear stresses are being collected and used for the validation of 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. In this second phase of the monitoring this was used in simulations for the refinement of the new reference surface for aggregate extraction (Van den Eynde, 2017).

6.4.2. Recommendations on the MSFD indicators, monitoring and evaluation

See Fettweis et al. (2020) for a discussion of the Belgian MSFD indicators on seafloor integrity (seabed/habitat) and hydrographic conditions (bottom shear stress, SPMc/turbidity). No scientific ground is yet available to add SPMc as GES indicator. Meanwhile, guidelines on how to address seafloor integrity and hydrographic conditions are still being adapted at the European level. Next assessment cycles may require adaptation and/or extension of current approaches.

6.5. *Lessons learned and recommendations for the continuation of extraction practices*

6.5.1. Lessons learned

Knowledge and data gaps have been extensively discussed in Van Lancker et al. (2016). These relate to: (1) Poor knowledge of the baseline, and natural variability; (2) Complex cause-effect relationships; and (3) Significance of the effects on larger scales.

Since the start of the monitoring considerable new data have being acquired on water and seabed sediment properties both in the near and far field. A large effort in seabed and sediment mapping took place, supplementary to FPS Economy, largely increasing the insight into nature and dynamics of the Hinder Banks region. Meanwhile, a geological knowledge base is available as well (TILES Consortium, 2018a, b), allowing to frame better the observations. Modelling outcome has also improved significantly. Process understanding and system knowledge is gradually being built up. This is important for the understanding of recovery and resilience of ecosystems.

Main lessons learned:

- Importance of the local geology when predicting sediment changes or evaluating their permanent character.
- High spatial variability in water and seabed sediment properties; depth and morphological position of the samples being important to consider when comparing samples.
- Natural variability and changes in SPMc still difficult to quantify, because of difficulties in the calibration of optical and acoustical sensors in areas with low concentrations. Measurements remain having a high uncertainty.
- Organic matter correlating with extraction activity.
- Important flocculation processes in the offshore area, now made visible in longer term time series. The influence of flocculation on the fate of fine-grained sediments is not yet clear.
- Relatively high seabed mobility (dune dynamics) and resuspension potential (water-column SPMc) of Sector 4c, Oosthinder, compared to other nearby sandbanks. Hydro-meteo forcing needs further quantification.
- Silt-clay enrichment in gravel-rich throughs is probably omnipresent, though is missing in historic samples, probably because of inappropriate sampling gear, and thin sand sheets buffering the material.
- Unbiased quantitative sampling of gravel beds remains utmost difficult. Scientific diving with visual descriptions and local shallow coring is still the best approach.
- Micro-computed tomography provides insights into the percolation of fine-grained material into coarse permeable sands, and may shed new light on smothering.
- The acoustic mapping of gravel beds remains challenging with the relief, and the gravel geometry also influencing the backscatter signal.
- Sand overtopping gravel is unlikely to be derived from multibeam backscatter, though very-high resolution digital terrain models do show whenever the sand cover is thick enough to form small-scale bedforms.
- The permanent character of such sand veneers is yet to be determined.
- Most of the erosion/sedimentation changes observed occur within the error margin of the instrumentation used (e.g., in 30 m water depth, the bathymetric vertical uncertainty with ± 95 % confidence levels of the depth measurements is 0.33 m for the EM3002D echosounder). If ripples develop in the sand cover, detection will depend on their size *w.r.t.* the footprint of the echosounder used.
- No information on long-term variability introduced by climate change or long-term cycles in sediment dynamics (e.g., 18.6 yr lunar cycle). This might also be a factor in explaining the varying sand layer observations overtopping the gravel lags in the gullies.
- The study of cause-effect relationships can only be executed once renewed

sediment transport and advection-dispersion models are validated accounting for the three-dimensional nature of the phenomena. Meanwhile, new input data are being generated.

- Significance of seabed smothering (both surficial and within the sediment matrix) needs further clarification. Implications for biogeochemistry and food webs (elements of functional biodiversity) are investigated in the Belspo project, FaCE-It[4] of which a compilation of final results will become available in 2021-2022.
- Effects of different combinations of stressors (aggregate-extraction at multiple sites; fishing; dredging and disposal of dredged material; windmill farms), hence cumulative and in-combination effect as well as climate change are hitherto unknown.

6.5.2. Recommendations for the continuation of extraction

Recommendations 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.

(1) and (2) indicate the importance to restrict extraction to areas where sufficient sand of similar characteristics is present, especially avoiding areas containing clayey, muddy or gravelly layers. This can best be accomplished by restricting extraction to the Upper Holocene cover. This can now be queried using the freely accessible voxel-based aggregate resource model (TILES Consortium, 2018a; http://www.bmdc.be/tiles-dss/#). In areas with a thin Upper Holocene cover, changes to sediment types are more likely to occur. This is often the case at the lower slopes of the sandbanks (e.g., Sector 4c, Thornton Bank). The change may become permanent, and lead to physical loss of a habitat. Fast recovery is at best when the grain-size characteristics of the extracted sediment aligns closely with the characteristics of the natural supply. Clearly, when extracting bedforms composed of older lag deposits, often coarser in size, new bedform development will be hampered.

To avoid sediment changes in the far field of extraction activities, it is advised to spread the activity over different sectors, and to spread the timing of extraction over the tidal cycle, whenever possible. Persistent extraction in one sector, and consistently during the ebbing phase of the tide results in preferential deposition of extraction-induced fine-grained material towards the Habitat Directive Area, at least in the case of the Hinder Banks.

When combining extraction activities with harbour maintenance works in the mud-dominated coastal zone, the hopper should be cleaned properly after the maintenance works in order not to bring coastal muddy sediments into the offshore zone.

Planning of large-scale extraction activities should include modelling of changes in

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

bottom shear stresses. Although calculation and modelling of this parameter is still prone to many uncertainties, it does provide insight into where most changes in sediment distributions are likely to occur and how this can be better anticipated. Also, wave modelling under different scenarios of extraction is a guidance to what level reduction of the height of sandbanks should be restricted to avoid cascading effects towards the coast.

7. Outreach

An important valorisation of the research related to the assessment of Good Environmental Status as required for the Belgian implementation of the Marine Strategy Framework Directive (Belgische Staat, 2018; Van Lancker et al., 2018).

A1 publications related to the gravel beds in the Habitat Directive area (Van Lancker, 2017; Montereale Gavazzi et al., 2018), and insights into the short-term tidal variability of multibeam backscatter (Montereale Gavazzi et al., 2019). The data contributed largely to PhD research on developing innovative methodologies on the use of multibeam technology for the mapping and monitoring of seabed habitats (Montereale Gavazzi, 2019).

Papers are in preparation, e.g., on the natural variability of water column properties, the dynamics of bedforms, sediment changes in marine aggregate extraction zones, and new monitoring techniques unravelling smothering processes.

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MDK - afdeling Kust – 'Meetnet Vlaamse Banken', Flemish Hydrography. Some of the depth data used were retrieved via the bathymetry data portal. Continental Shelf Department (COPCO), FPS Economy, Self-Employed, SMEs and Energy are thanked for assistance with multibeam data processing, and active cooperation in general. Last, but not least, Msc Oceans & Lakes students are thanked for assisting in the measurements at sea.

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10. Annexes

Annex A. Monitoring sediment changes in the seabed matrix using micro computed tomography. Context and first results

Annex B. Analysis of oceanographic profiles taken during RV Belgica campaign ST2019/09

Annex C. Sediment analyses of ST1407, ST1807 and ST1909

Annex D. RV Belgica Campaign Reports

Annex E. Publications

COLOPHON

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Annex A.

Monitoring sediment changes in the seabed matrix using micro computed tomography. Context and first results[1]

Vera Van Lancker[1], Lars Kint [1], Giacomo Montereale Gavazzi[1], Maxim Deprez[2], Veerle Cnudde[2]

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Context

During RV Belgica campaign ST1919, 8-11/7/2019, the status of the gravel beds in the Habitat Directive Area "Flemish Banks" was further investigated. Aim is to assess seafloor integrity, one of the descriptors of Good Environmental status within Europe's Marine Strategy Framework Directive (MSFD). Assessing the status of gravel beds remains very challenging and is hitherto oriented mostly towards biological studies and the follow-up of indicator species (e.g., MONIT.be, https://odnature.naturalsciences.be/msfd/nl/assessments/2018/page-d1-d6). Potential threats relate to smothering due to excessive fine-grained material that could originate from human activities and this has been one of the main concerns within the ZAGRI/MOZ4 monitoring programme, focussing on the effects of marine aggregate extraction in concession zone 4, Hinder Banks (see Van Lancker et al., 2016 for an overview). Several techniques were used to assess changes, hitherto mostly by a combination of multibeam depth and backscatter (e.g., Montereale Gavazzi et al., 2018), Hamon grab sampling and video imagery. From a synthesis of information provided by Van Lancker et al. (2016), it became clear that two processes may cause smothering of gravel beds: (1) a sandification process with expanding sand veneers that may overtop the gravel beds, potentially enhanced by an excessive release of sand in the near field and subsequent reworking by beam-trawling fisheries; (2) deposition of fine-grained material (e.g., mud) from passive plumes originating from the overflow of trailing suction hopper dredgers (e.g., Van Lancker & Baeye, 2015). Extensive video imaging and diving observations could hitherto not evidence any surficial accumulation of mud, though Hamon grab analyses clearly showed a mud enrichment (Van Lancker et al., 2016). To have a better understanding of the smothering process two dives were planned in 2019 during which it was envisaged to take shallow cores (4 cm in diameter) by hand in the sandy matrix of the gravel beds, combined with visual observations and measurements of sand thickness. The latter was important given historic measurements of quasi zero thicknesses in those biodiversity hotspots. Upon retrieval the cores showed clearly accumulation of fine sand and mud, on top of a coarse-grained sandy matrix, but also levels of mud enrichment within the parent bed. To quantify the smothering process, it was decided to analyze the cores using micro computed tomography, micro-CT.

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[1] Van Lancker, V., Kint, L., Montereale Gavazzi, G., Deprez, M., and Cnudde, V. (2020). Annex A. Monitoring sediment changes in the seabed matrix using micro computed tomography. Short introduction and first results, pp. 1-3. In: Van Lancker et al. *Monitoring of the impact of the extraction of marine aggregates, in casu sand, in the zone of the Hinder Banks Scientific Report 6 – January - December 2019 and Synthesis for the period 2016-2019.* Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Brussels, 72 p. (+5 Annexes).

Data acquisition

Shallow cores (4 cm diameter) were taken by divers at a location previously recognized as a biodiversity hotspot (Houziaux et al., 2008) and where diving took place in 2007. Two cores were retrieved, numbers 4 and 5, having a sediment column of 7 and 5 cm high, respectively. See Van Lancker et al. (2020, this report) for details on the locations.

Data processing

The micro-CT system HECTOR (High Energy CT Optimized for Research) was used, available at Ghent University Centre for X-ray Tomography (UGCT). It consists of a mechanical setup with nine motorized axes, a microfocus directional target X-ray source up to 240 kV and a large flat-panel detector. The system can accommodate large samples up to 80 kg, 1 m long and 80 cm diameter. For small sample sizes, high resolution scans up to maximal 3-4 µm resolution are possible (Masschaele et al., 2013[2]). Given a core diameter of 4 cm, resolution for the seabed cores were less, but 'stacked' scans were made whereby 2 to 3 scans allowed obtaining a voxel size of 30 µm over the entire height of the core. Data were made available at the 30 µm resolution and await further qualitative and quantitative analyses (e.g. grain size). To determine grain size three voxels are needed minimally, hence only grain sizes from 90 µm onwards can be quantified. Below that size, the image is blurred. Also, boundaries between mineral grains, mud and organic material are blurred extensively when the resolution is not high enough.

First results

(1) Core photographs

Core 4 - front

Core 4 - back

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[2] Masschaele, B., Dierick, M., Van Loo, D., Boone, M.N., Brabant, L., Pauwels, E., Cnudde, V., Van Hoorebeke, L., 2013. HECTOR: A 240kV micro-CT setup optimized for research. J. Phys. Conf. Ser. 463, 12012.

Core 5 - front

Core 5 - back

Figure A-1. Core 4: Photographs show an infiltration of fine sand into the parent bed with local accumulation of muddy sediments. Core 5: Photographs show clearly brownish sands with broken shells as the parent bed. At the top fine sands are observed.

(2) Micro-CT scans

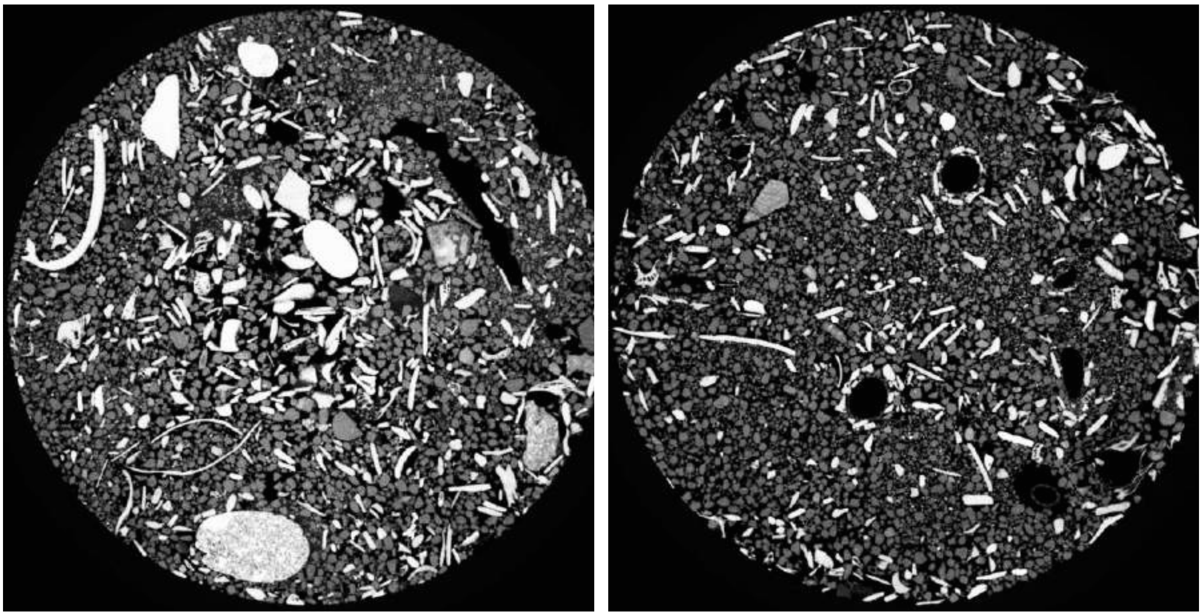

Figure A-2. Cuts of a micro-CT scan (diameter 4 cm). Left: upper part of the core showing abundance of shell material (white fragments) and relatively coarser grains. Right: slice mid-way the height of the core, showing a mixture of small and coarser grains, as well as shell fragments. Micro-CT HECTOR, Ghent University, Centre for X-ray Tomography (UGCT).

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RBINS Scientific team is acknowledged for their participation to the cruise. In particular the divers Alain Norro (lead), Valerie Woit, Marie Vigoni and Marc Van Espen are warmly thanked for their time and enthusiasm. RV Belgica shiptime was granted by Belspo and RBINS OD Nature.

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Management Unit of the North Sea Mathematical Models (MUMM)

Analysis of oceanographic profiles taken during RV Belgica campaign ST2019/09

Dries Van den Eynde, Matthias Baeye and Vera Van Lancker

ZAGRI-MOZ4/X/DVDE/2020/EN/SR07

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1. Introduction

In the framework of the ZAGRI-MOZ4 projects, measurement campaigns were carried out in the year 2019, amongst other to investigate the effect of extraction of sand on possible sediment plumes, and to get more insight in the background suspended particulate matter (SPM) concentration in the Hinder Banks region.

In this report, an analysis is presented of the SPM concentrations that were measured during the campaign 2019/09, where profile measurements from the RV Belgica were taken. At three locations profiles were taken over a 10h to 13h cycle, to get more insight into the background SPM concentration. Water samples were taken to calibrate the data that were taken with a Seapoint optical back sensor (OBS).

First, the calibration of the data is presented. Next, the profiles are combined to get some more insight in the variation of the SPM concentration over the water column and during a tidal cycle. Finally, a Van Rijn-Rouse profile is fitted to extrapolate the data to the bottom. A discussion of the data is put forward in the final section.

2. Materials and methods

2.1. *Overview of measurements*

During RV Belgica campaign 2019/09 (see https://odnature.naturalsciences.be/belgica/nl/campaign/1673 for planning and report), that was executed from March 25 to March 29, 2019, measurements were performed at three locations to get more insight into the background SPM concentration. Two cross-banks tracks were sailed and one 13h through-tide measurements was executed. The position of the tracks between sector 4b and 4c, Oosthinder sandbank and over the sector 4a, Noordhinder sandbank are indicated, as well as the position of the 13-h measurements just south of the sector 4a, Noordhinder, in Figure 1 and Figure 2 (detail). During the cross-bank tracks, every hour, a profile with CTD and Seapoint were taken and water samples were taken at the top of the bank, to calibrate the Seapoint. A total of 10 and 15 water samples were taken for the tracks between 4b and 4c and over 4a respectively. Measurements with a Hach Turbidimeter were taken onboard as an additional proxy for the SPM concentration. During the 13h cycle, a profile and water samples were taken every half hour, at position 51°34.160′N 2°32.42′ E, at the edge of the sector 4a, together with measurements with the LISST-200 to measure the particle size distribution. A total of 27 water samples were taken in this case.

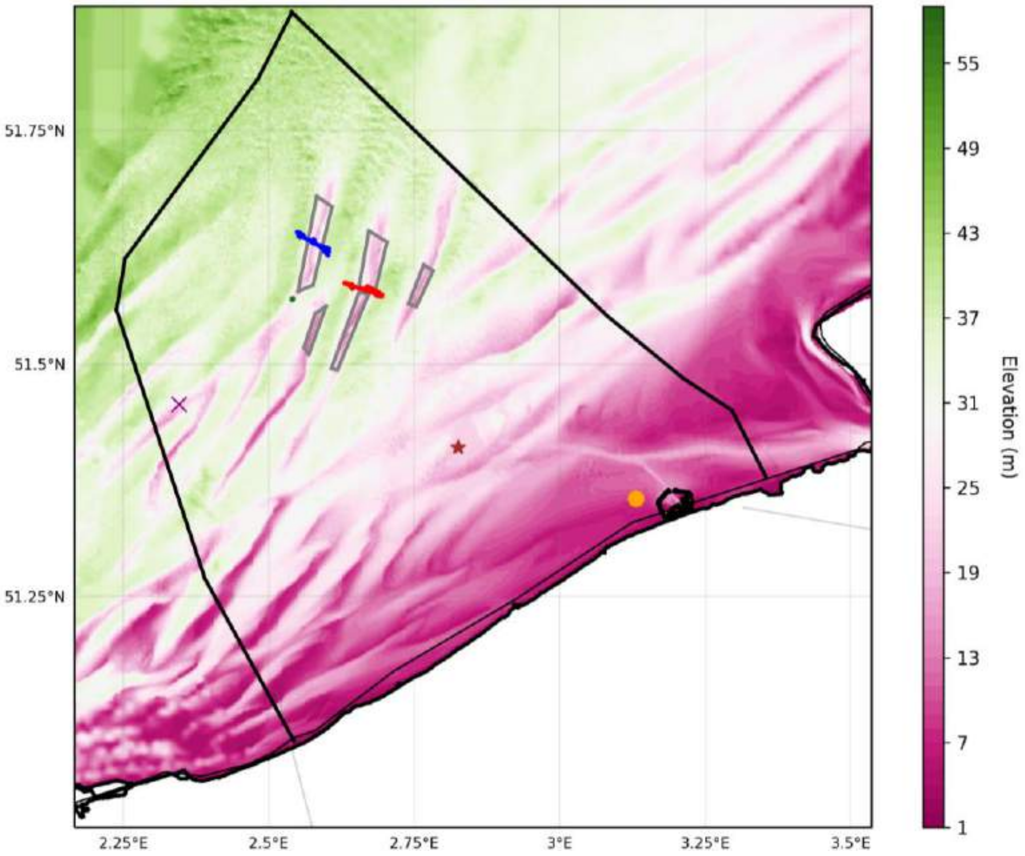

Figure 1: Position of the cross-bank tracks over the Noordhinder sandbank, sector 4a (blue), between sector 4b and 4c, Oosthinder sandbank (red); position of the 13 h cycle measurements south of sector 4a, Noordhinder (green); position of measuring stations MOW1 (orange dot), W05 (brown star), W08 (purple cross).

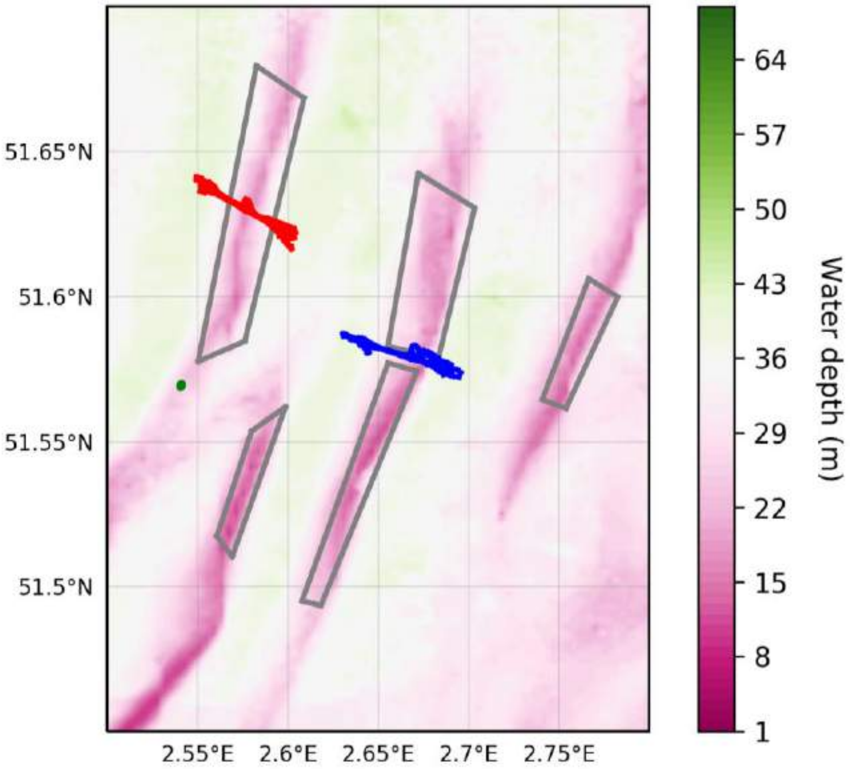

Figure 2: Position of the cross-bank tracks over sector 4a (red), between sector 4b and 4c (blue); position of the 13 h cycle measurements south of sector 4a (green).

2.2. *Water samples*

Water samples were taken for calibration of the continuous registrations (Seapoint OBS, hull-mounted ADCP; bottom-mounted ADCP) using a Niskin bottle of 10 l, mounted on a Seacat profiler (SBE19 CTD system). The latter allowed vertical profiling of oceanographic parameters using CTD for salinity, temperature and depth, and optical backscatter sensor (OBS) for turbidity.

Particle-size distribution (PSD) and volume concentration in the water column was measured using a Sequoia type C 200 X Laser In-Situ Scattering and Transmissometry (LISST). Using an annular ring detector, the instrument derives in-situ particle sizes, in the range 1.2 to 460 µm, from the scattering of particles on 36 rings. PSD are presented as concentration ($\mu l\ l^{-1}$) in each of the 36 log-spaced size bins. Date and time, optical transmission, water depth and temperature are recorded as supporting measurements (http://www.sequoiasci.com).

Water samples were filtered on board for suspended particulate matter (SPM). Mostly, 1.5 to 2.0 l of water was filtered. During the cross-bank transects, almost every hour a profile was taken and filtrations were executed. During the 13-hrs cycle, filtrations were done every half hour. In addition, once per hour, filtrations were taken for determination of particulate organic carbon and nitrogen (POC/PON) (0.250 l), and a bottle of water (0.33 l) was kept for calibration of the conductivity sensor for salinity.

On board, water samples were filtered, in three replicates, using pre-weighted Whatmann GFC filters. These were analysed at the Marine Chemistry Lab (OD Nature, ECOCHEM). Suspended particulate matter concentration (SPMC) (Unit mg l^{-1}) was obtained after drying of the filters for 48 hours, after which weight differences were calculated. A deviation of 12 % between the replicates is acceptable (ECOCHEM Standards). Measuring uncertainty of deriving SPM from filtrations is 17 %. Furthermore, three replicas of the turbidity were also taken on board with a TL 23 Hach Laboratory Turbidimeter. These measurements are used for calibration of the Seapoint OBS or of the filtrations.

POC/PON analyses (Unit g l^{-1}) were carried out in the laboratory using an Interscience Flash EA 1112 Series Element Analyser. Measuring uncertainty is 12 % for POC; 18 % for PON (ECOCHEM AK 7.0). For salinity (Unit PSU), a Laboratory salinometer – Portasal 8410 (Guildline) van Ocean Scientific Int. was used; the measuring uncertainty is 0.15 % (ECOCHEM).

It needs emphasis that water samples were taken at different levels in the water column. Normal procedure is to take a sample at 2m to 4 m above the sea bottom (mab), depending on wave action, hence platform motion. The depth of the water sample is derived from the CTD profiles (see below). Still, there are important uncertainties on the exact sampling depth, as the Seacat frame is easily carried away by the currents.

2.3. *OBS Seapoint measurements*

Since 2017, the OBS3 and OBS3+ turbidity sensors were replaced by the Seapoint OBS sensor, that measure more accurately low SPM concentrations in offshore areas. The Seapoint OBS has a working range from 0 to 125 NTU, which was obtained through the use of a jumper cable that amplified the signal by a factor of 20. As such, the sensitivity was 40 mV/NTU compared to 2 mV/NTU without cable and for the standard range of 0-750 NTU (Sea-Bird Electronics Inc., 2013). Following technical specifications (Sea-bird Electronics Inc., 2013), the following formula was used to convert the voltages into NTU (see Van Lancker et al., 2016):

$$NTU = 25 * Voltage \qquad (1)$$

3. Results

3.1. *Introduction*

In the current section the results of these measurements are discussed. First, the calibration of the Seapoint optical back sensor is discussed, to convert these data into suspended particulate matter concentration. Also, the measurements with the Hach turbidimeter are considered for the calibration.

In a second section the profiles are discussed. The data are extrapolated using a Van Rijn-Rouse profile to get more information on the total SPM concentration (SPMC) and to get more insight in the behaviour of the material near the sea bottom.

3.2. *Calibration of the Seapoint sensor*

3.2.1. Calibration between Seapoint sensor and SPM concentration

Water samples were used to calibrate the turbidity Seapoint sensor and to convert the NTU of the Seapoint, calculated from the output in voltage with the previously mentioned formula, to mg l^{-1}. The SPMC of the water samples was determined in the laboratory and a linear relationship was established between SPMC and the Seapoint output (in NTU) at the same moment. Unfortunately, something went wrong with the time registration of the instrumentation so that the exact moment when the Niskin bottles were closed were not well recorded. This will introduce some uncertainties in the linear regression.

During the cross-bank measurements between sector 4b-4c and over sector 4a, profiles were taken at the top of the sand bank. When taking the profiles during the cross-bank measurements, the CTD and Seapoint were lowered in the water column, to take a profile, was held shortly at depth, and before the CTD and Seapoint were brought on board again, taking another profile, the bottles were closed. The mean time for taking the profile was around 41 seconds for both measurements (to reach 98% of the maximum depth that was obtained with the CTD), while the CTD and Seapoint were held near the bottom for a mean period of 47 or 31 seconds during the cross-bank measurements between sector 4b-4c and over sector 4a respectively. During the 13h measurements, the time to take the profile was a little bit longer, around 71 seconds, and the CTD was left near the bottom for a much longer period, around 22 minutes.

To get a representative Seapoint value that can be compared with the results of the filtrations, the mean Seapoint reading during 11 seconds was considered first, just before the CTD was hauled on board again. Since the exact time of the closure was not known, this time of closure was estimated manually (see Figure 3 to Figure 5).

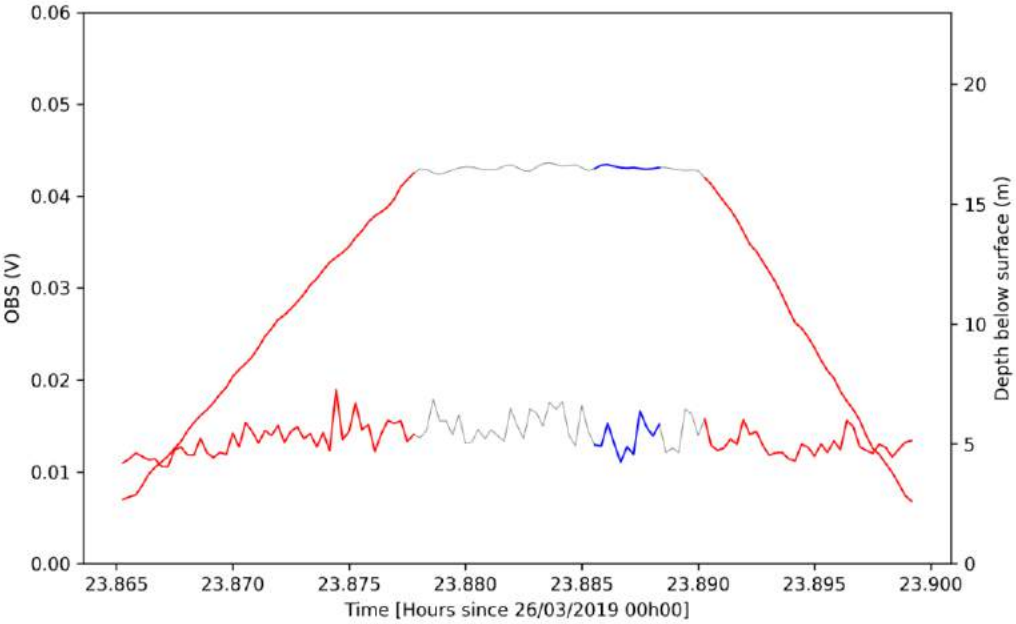

Figure 3: OBS voltage output and depth below surface as a function of time for the second profile taken during the cross-bank measurements between sector 4b-4c (Oosthinder). Blue: 11 seconds during 'closure of the bottle'; red: the profile downwards and upward (until 98% of maximum depth is reached).

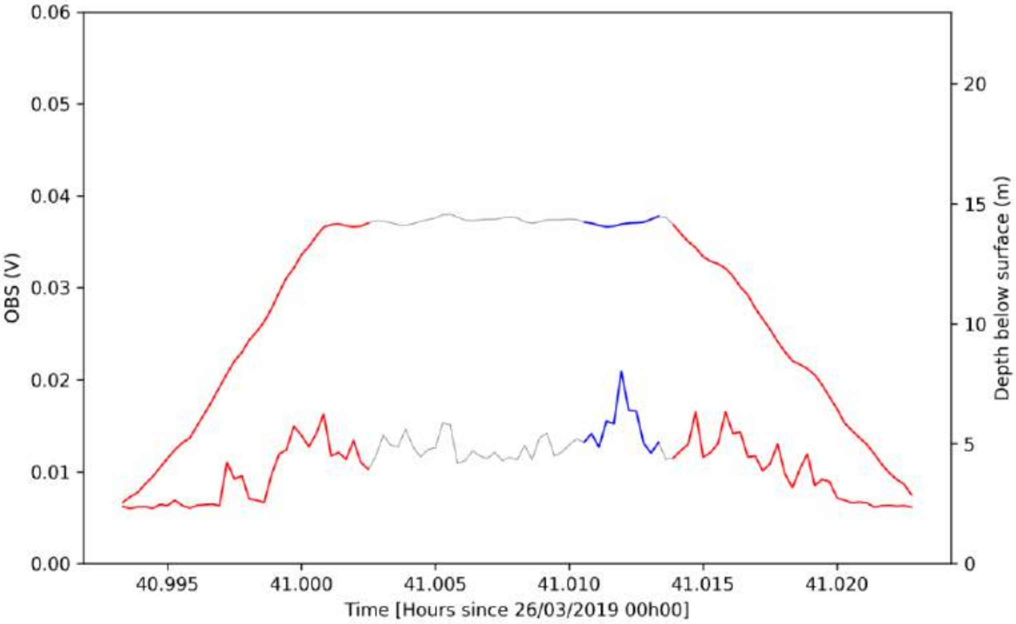

Figure 4: OBS voltage output and depth below surface as a function of time for the second profile taken during the cross-bank measurements between sector 4a (Noordhinder). Blue: 11 seconds during 'closure of the bottle'; red: the profile downwards and upward (until 98% of maximum depth is reached).

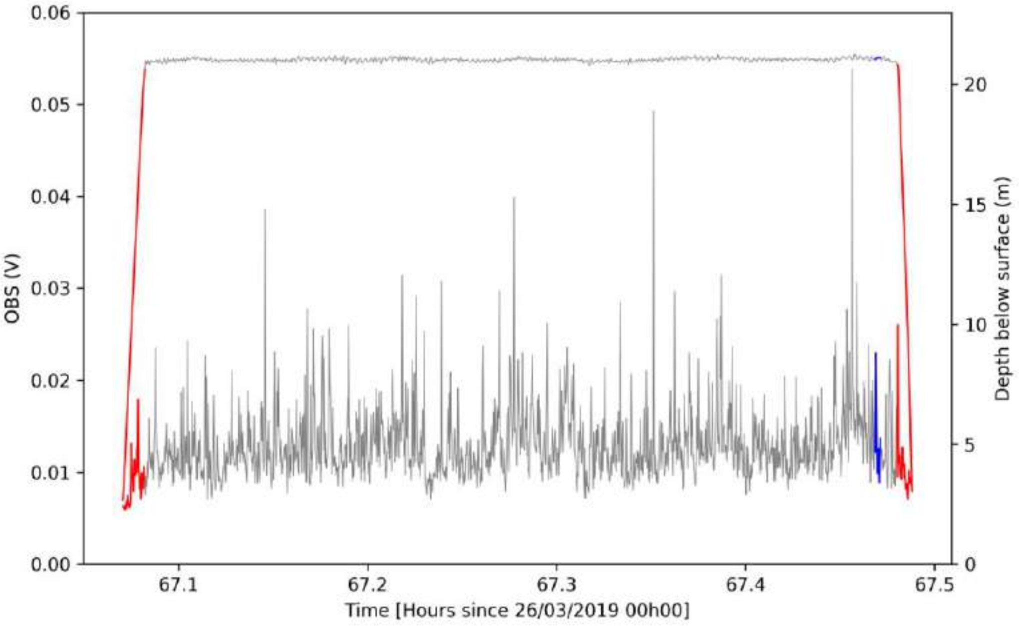

Figure 5: OBS voltage output and depth below surface as a function of time for the second profile taken during the 13-h tidal cycle measurements south of sector 4a (Noordhinder). Blue: 11 seconds during 'closure of the bottle'; red: the profile downwards and upward (until 98% of maximum depth is reached).

One can see that during the 11 seconds that the bottle is closed the OBS voltage can still vary over some range. The exact moment of the closure of the bottles is however not known. Taking the mean over 11 seconds just before the upwards profile is taken seems to be a reasonable solution. Remark that other methods were tested to get an estimate of the OBS reading during the closure of the bottoms, but these tests did not change the results significantly.

A total of 52 profiles and water samples were taken during the entire campaign: 10 over the sector 4b-4c, 15 over the section 4a, and 27 south of sector 4a. For each of the water samples, three water filtrations were taken that were weighted in the laboratory. When the relative standard deviation (RSD) is smaller than 12 % between the three results, the results are reported without error code. When the RSD is higher than 12 %, the outlier is reported suspected when the RSD is without the outlier below 12 %. If with removing an outlier, the RSD is never below 12 %, all data are reported suspected. During this campaign, only 16 of the 52 SPM concentration measurements were reported without error code, while 25 measurements had one outlier and 11 of the data had all suspected values. This rather low quality of the measurements is probably mainly a result of the low values in the water, which make accurate measuring more difficult. Additionally, it needs emphasis that on sandbank environments sand grains are found in the water samples, weighing disproportionally on the result of the filtration. Human errors are not excluded as well.

In Fettweis et al. (2019) a thorough discussion is found on the uncertainties related to gravimetrical measurements of the SPM concentration, by filtering and weighing. The removal of salt in the filters, if not well done, could lead to an overestimation of the SPM concentration (Neukermans et al., 2012). In high turbid waters, the difficult homogenization of a sample prior to subsampling and filtering (Fettweis, 2008) could lead to errors, but this is not the case here. Fettweis et al. (2019) mention an uncertainty of 8.5 % for sample values lower than 5 mg l^{-1}.

An overview of the gravimetrical measurement of the SPM concentration of the water samples is presented in Figure 6. It can be seen that four high values (higher than 15 mg l^{-1}) are taken during the cross-bank measurements over sector 4a and five high values are taken during the 13h cycle, south of sector 4a. All the measurements are taken relatively short after each other, which give some consistency in these results. Moreover, most of the high values measured were not categorized as suspicious values.

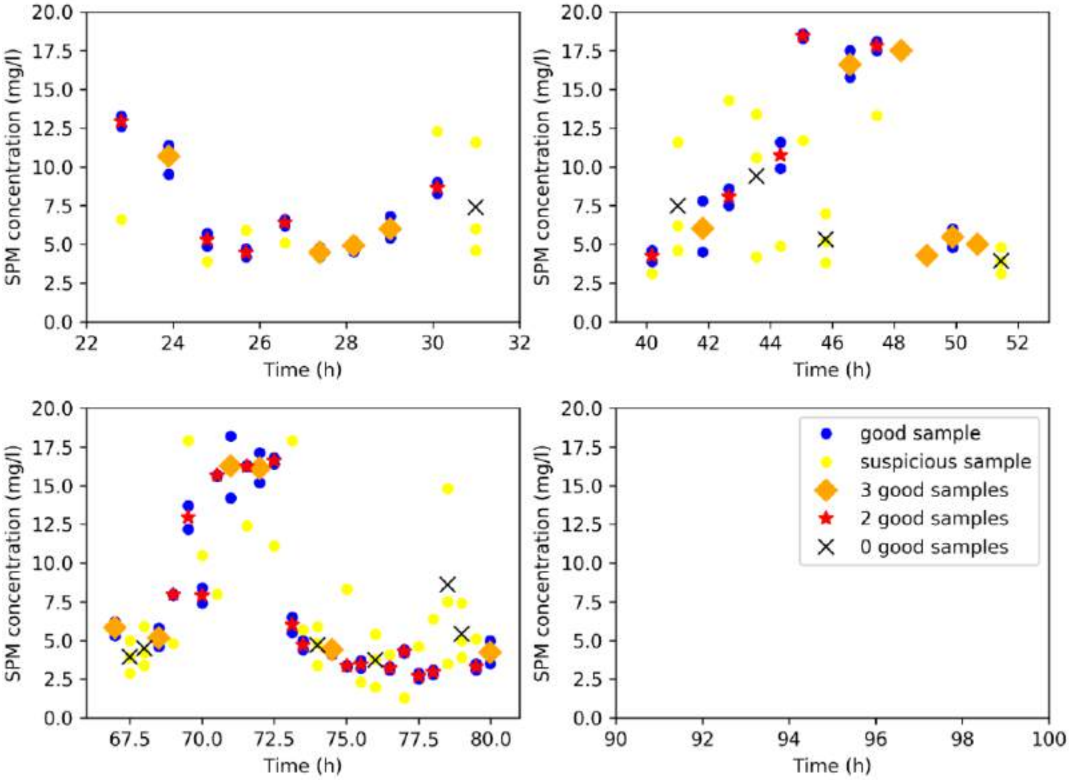

Figure 6: Overview of the results of the three gravimetrical measurements for the water samples taken during the campaign. Blue dots: good samples, yellow dots: suspicious samples (see above). Orange diamonds: red stars: mean of the two good samples, black cross: mean of three suspicious samples, these data are not used.

The difference between taking the mean over all samples and taking the mean over two samples only, removing the outlier, is shown in Figure 7. The overall differences remain acceptable. It seems therefore reasonable to take the mean of the good samples into account for the calibration of the OBS sensor. The samples with three suspicious values are not considered in the further analysis. Therefore, 11 samples were removed from the analysis. Only for 16 samples, no suspicious values were found.

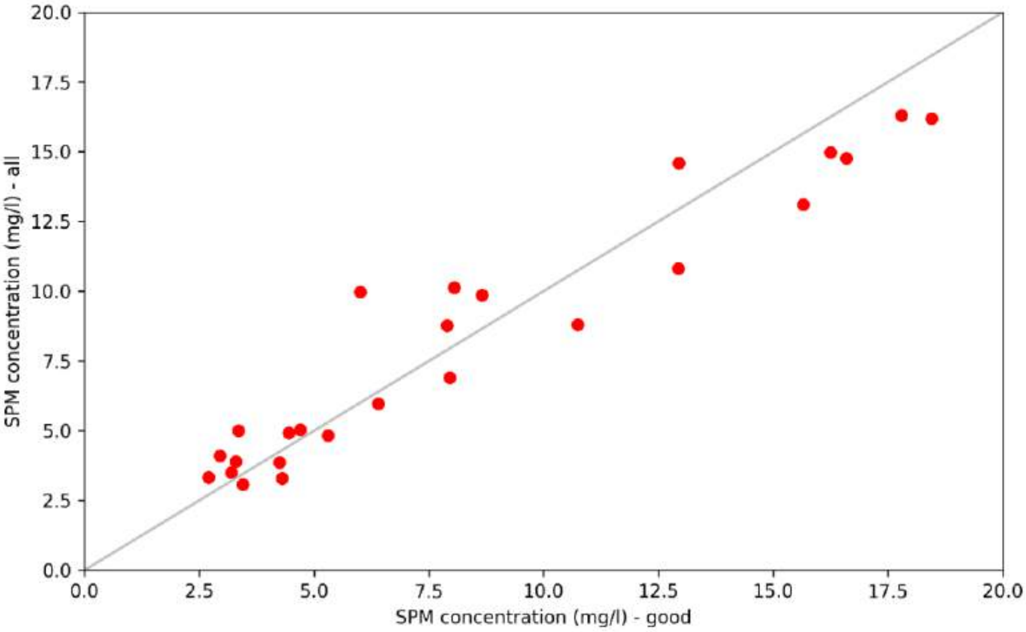

Figure 7: Mean SPM concentration when taking only the two samples into account without error code, compared to the mean SPM concentration when taking all three samples into account, including the outlier.

In Figure 10, the time series of the SPM concentration, as determined by the water samples are presented. The differences between taking only the good samples into account, or taking all water samples into account are not very big. Only during the track over the Noordhinder one data point gives a much lower value, when all data points are considered, around hour 46. During the 13h-cycle, a second small peak in SPM concentration is visible when all data are considered between hour 77 and 80, which is not apparent, when only the good filtrations are accounted for.

A linear regression is calculated between the Seapoint OBS voltage readings, converted to FTU, via the formulae above, and the SPM concentrations, obtained via filtrations. Only the 41 non-suspicious results were used. These were compared with the OBS readings at the closure of the bottles. The results are shown in Figure 9. The correlation coefficient R is even negative, with a coefficient of determination R^2 of 0.001.

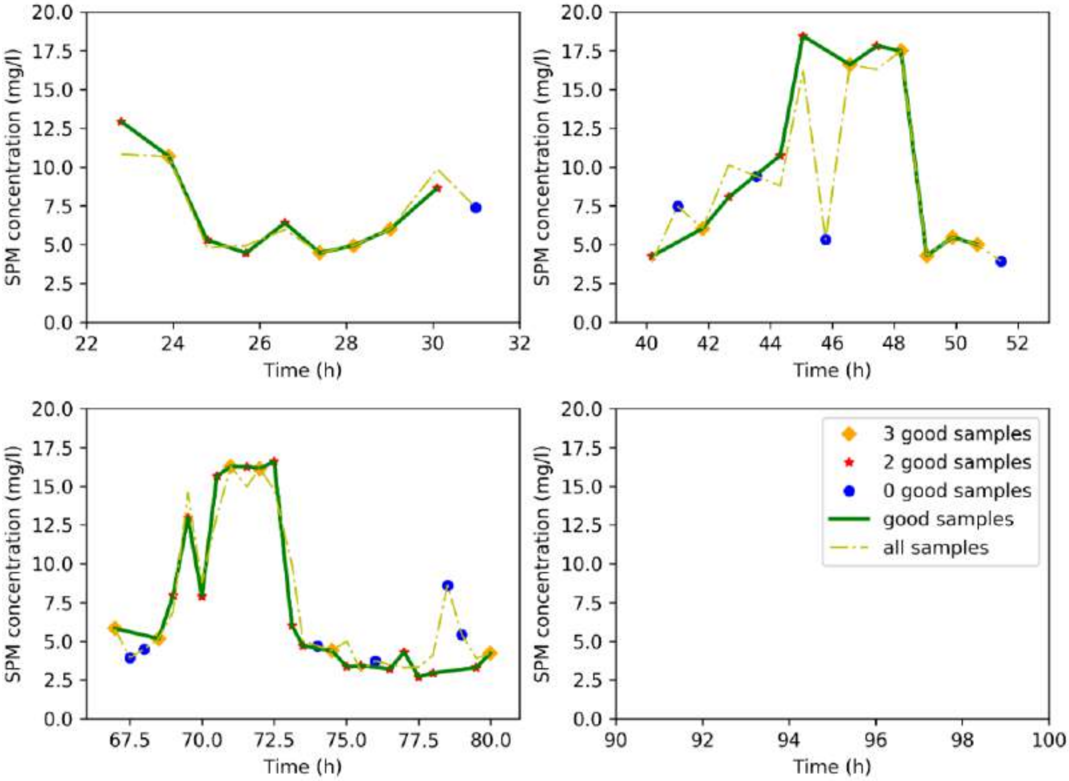

Figure 8: Overview of the results of the three gravimetrical measurements for the water samples taken during the campaign.

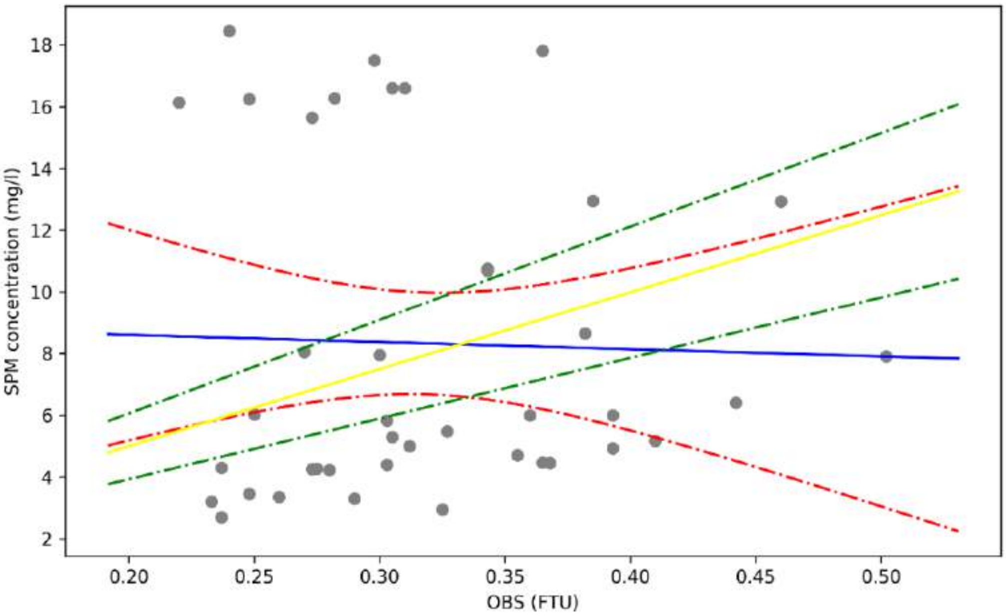

Figure 9: SPM concentration as a function of the OBS reading during (11 seconds of) closure of the bottle. Only 41 water samples, with only good values, are considered. Blue line: linear regression, red lines: 95 % confidence interval; yellow line: linear regression through the origin, black lines: 95 % confidence interval.

This could be due to the nine water samples having SPM concentrations that are higher than 15 mg/l, for rather low OBS readings. If the linear regression is calculated for the three tracks separately (Figure 10), the results are quite different. Mainly the measurements during the 13h cycle give unreliable results with a negative slope and a coefficient of determination of 0.002. The bad results are again mainly due to the four water samples with high SPM concentrations for low OBS voltages. The coefficient of determination R^2 for the tracks at sector 4b-4c (OH) and sector 4a (NH) are 0.18 and 0.04 respectively. When removing the nine samples that have SPM concentrations higher than 15 mg l^{-1} improves the correlation, resulting in a coefficient of determination of 0.28. This is however still low. Furthermore, there is no obvious reason to remove those results.

Other tests have been executed by using the tracks over the sector 4b-4c and 4a the mean OBS reading, when the sensor is near the bottom, and by using all the SPM concentration measurements, without removing the measurements with more than one outlier. That however did not improve the results.

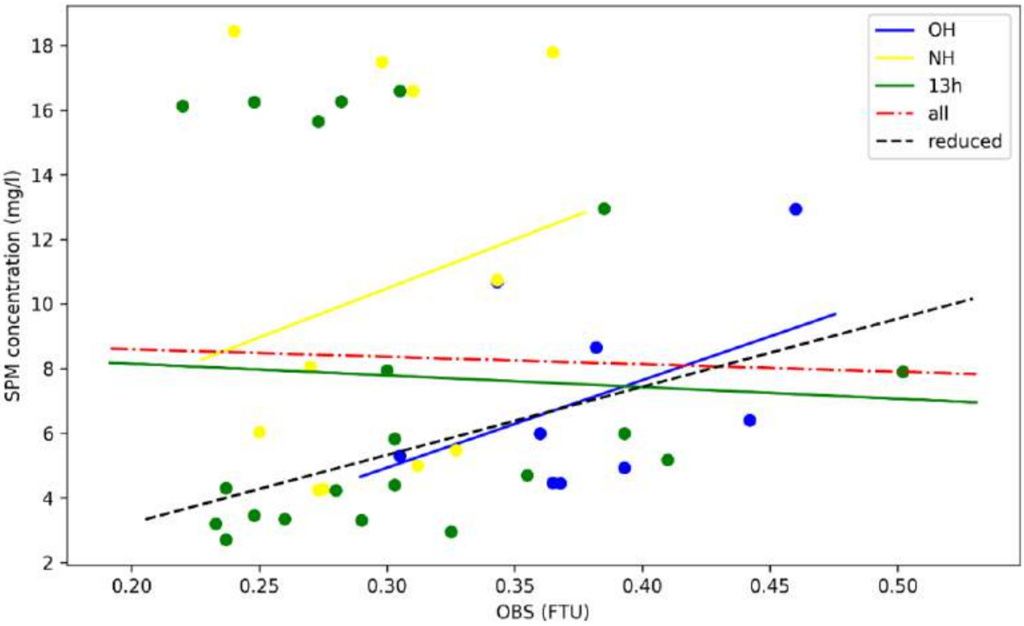

Figure 10: SPM concentration as a function of the OBS reading during (11 seconds of) closure of the bottle. Only 41 water samples with good filtrations are considered. Blue: data from measurements between 4b-4c (OH); yellow: data from measurements at 4c (NH), green: data from 13h tidal cycle (13h); red: linear regression for all data; black: linear regression for the reduced data set.

A negative slope for the relation or a slope of zero is not useful. For a slope of zero, the SPM concentration is constant during the entire time. Therefore, also the regression is calculated, forced through the origin. The results are shown in Figure 11.

Following relation, when all data are considered, is found:

$$SPMC\ (mg\ l^{-1}) = 24.96 * OBS\ (FTU) \tag{2}$$

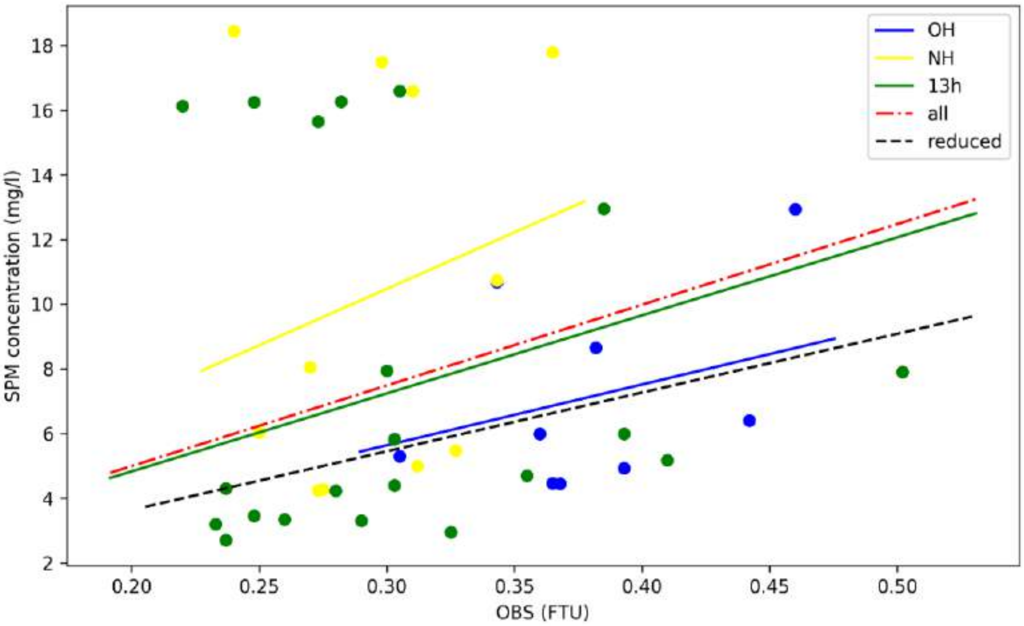

Figure 11: SPM concentration as a function of the OBS reading during (11 seconds of) closure of the bottle, but forced through the origin. Only 41 water samples are considered. Blue: data from measurements between 4b-4c (OH); yellow: data from measurements at 4c (NH), green: data from 13h tidal cycle (13h); red: linear regression for all data; black: linear regression for reduced data set.

3.2.2. Calibration between Seapoint sensor and Hach

Instead of correlating the readings of the Seapoint sensor to the SPM concentrations that were derived from the water samples, a second possibility exists in relating the reading of the Seapoint sensor to the measurements with the Hach turbidimeter, which was used using water samples on board of the ship. This eliminates possible human errors during the filtrations of the water samples on board or in the laboratory. It however assumes a good correlation between the SPM concentration and the Hach turbidimeter. Since, Fettweis et al. (2019) found a stable relationship between Hach water sample turbidity and sample SPM concentration for different locations, this relationship was considered in further analyses.

3.2.2.1. *Relation OBS-Hach*

In Figure 12, the linear regression between the Seapoint OBS readings (converted to FTU) and the Hach readings are shown for the different tracks and the 13h-cycle measurements.

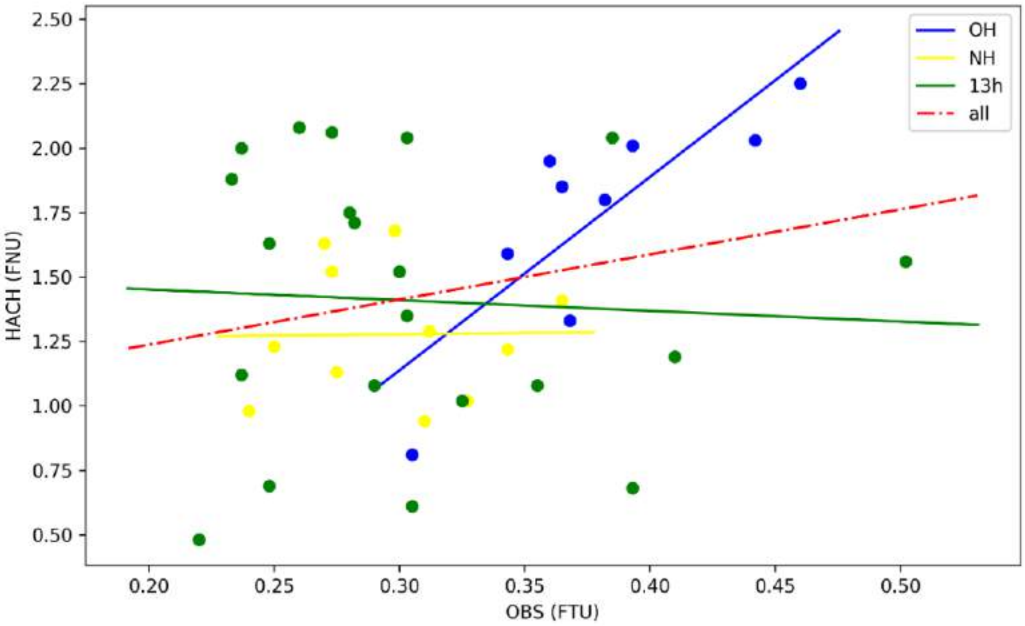

Figure 12: Linear regression between the Seapoint OBS readings and the Hach measurements for the different tracks and the 13h-cycle measurements.

Only for the measurements at the Oosthinder (track between section 4b and 4c), the coefficient of determination R^2 is relatively high, at 0.66. For the other tracks or for all data, the correlation coefficients are low. Also, for the relation through the origin, the correlation coefficients, as defined by Kozak and Kozak (1995), are very low (not shown here).

Since the relation between the OBS Seapoint and the Hach is not a clear relationship with a high correlation, this method of conversion was not taken forward for deriving SPM concentrations.

3.2.2.1.1. Relation Hach-SPM concentration

Also, the relation between the SPM concentration and the Hach has been looked at. In Figure 13, the linear regression between the Hach turbidimeter and the SPM concentrations, obtained in this campaign were shown. Again, the best results were found for the measurements at the Oosthinder, but overall the correlation is not good. For all measurements, the correlation is even negative, with higher Hach readings indicating lower SPM concentrations. The stable relation between Hach and SPM concentration clearly is not reproduced in this case.

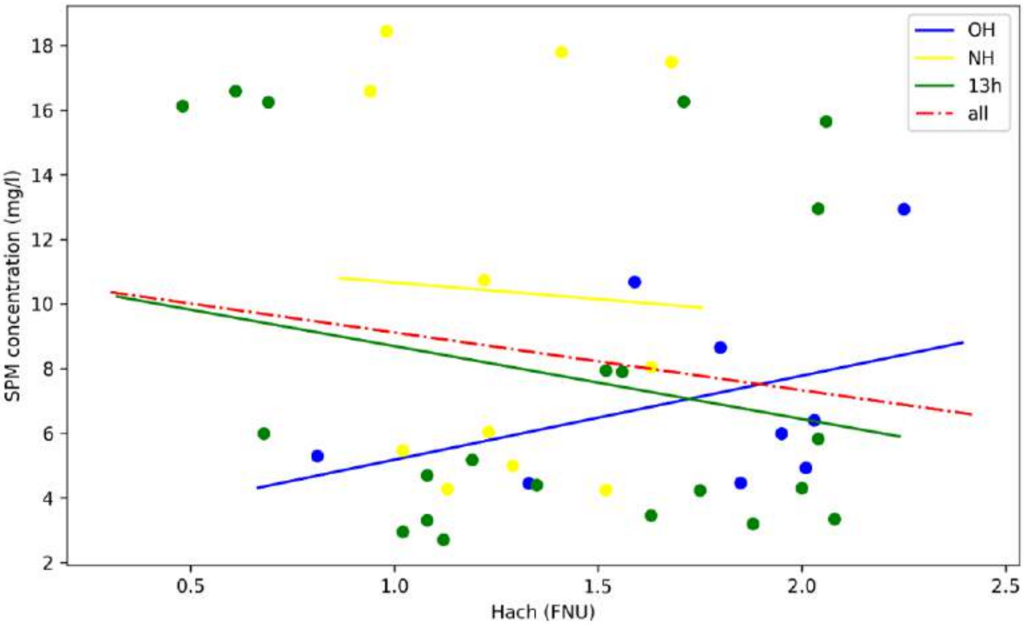

Figure 13: Linear regression between the Hach measurements and the SPM concentration measurements for the different tracks and the 13h-cycle measurements.

When the linear regression is forced through the origin (Figure 14) it seems that the found relation indicate a higher SPM concentration that was indicated by the stable relationship, that was derived from all measurements, using the Hach, on the Belgian Part of the North Sea (Figure 13). This relationship, which is forced through the origin, reads:

$$SPMC = 1.29 * Hach \quad (3)$$

It is clear that this stable relationship is very useful for large OBS values, as has been shown by Fettweis et al. (2019). However, this relationship is likely less useful for lower values of SPM concentrations.

To test this stable relationship for lower OBS values, all data that were obtained during the measuring campaigns in 2019 and 2020 so far were looked at. During these campaigns, a total of 1013 matching measurements have been executed where the Hach measurements could be compared with SPM concentrations. The measurements were taken at three stations, i.e., MOW1, W05 and W08. The position of these three stations are indicated in Figure 1. While the MOW1 is near the coast, near the harbour of Zeebrugge, the W05 is more offshore, while the W08 station is furthest offshore, to the west of the marine aggregate concession zone 4. The relationship for the results in the different stations is shown in Figure 15. Remark that the subplots in this figure have different scales.

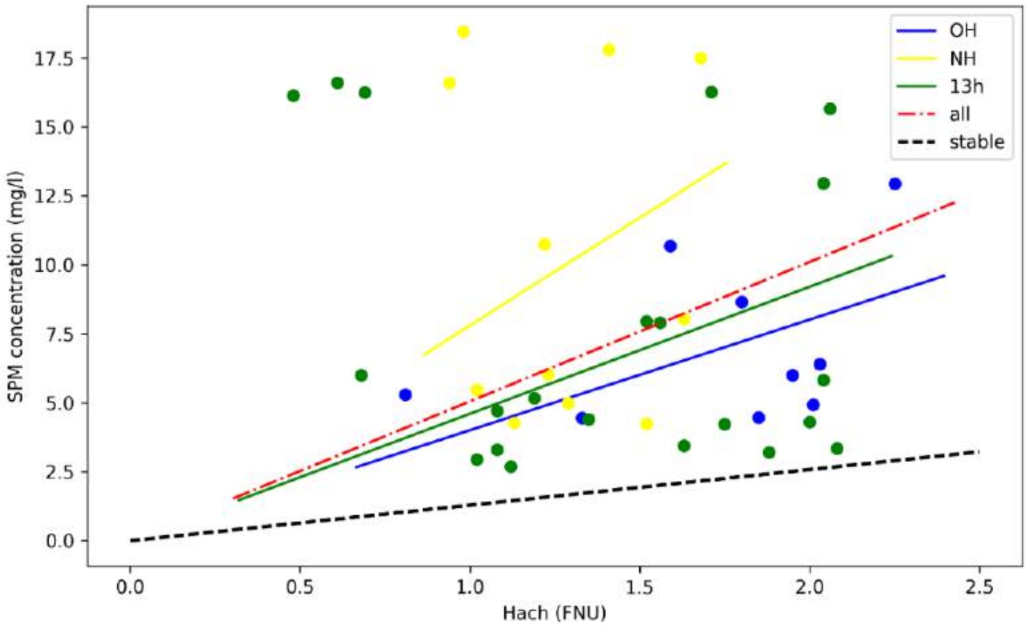

Figure 14: Linear regression through the origin between the Hach measurements the SPM concentration measurements for the different tracks and the 13h-cycle measurements.

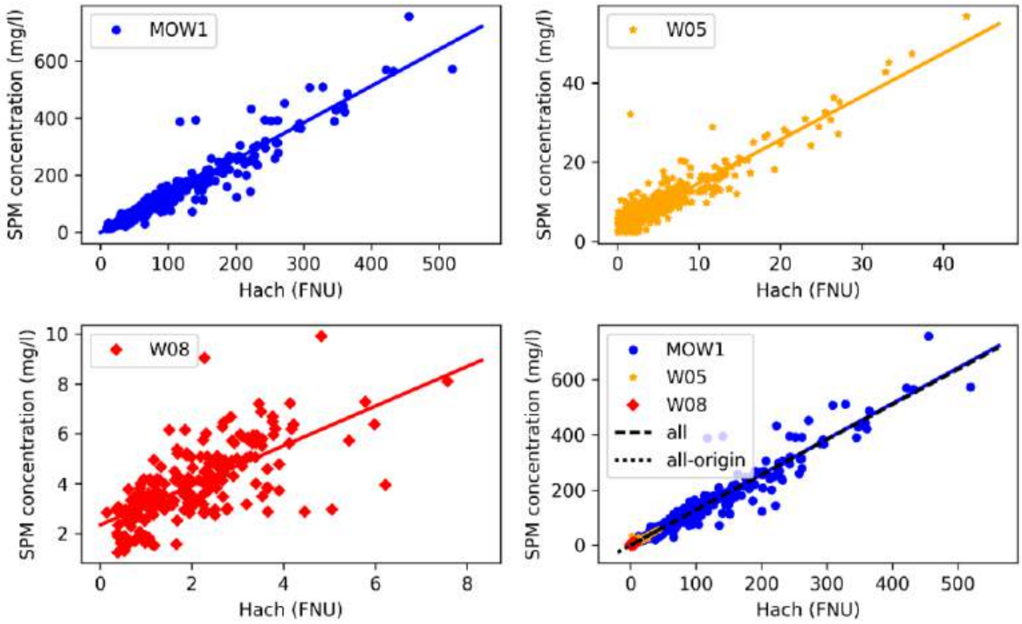

Figure 15: Relationship Hach – SPM concentration for different stations MOW1, W05 and W08. Different scales for the different figures.

Whilst for the data at MOW1, the coefficient of determination R^2 between the Hach and the SPM concentration is 0.92, this correlation coefficient decreases for the W05 to 0.85 and for the W08 to 0.46. The slope of the regression line is respectively 1.29, 1.09 and 0.79, see Table 1. The slope between the Hach and the SPM concentration for MOW1 and for all the data is close to the relation that Fettweis et al. (2019), which are of course, partly based on these data. The relation for the W05 and the W08 stations however has lower slopes, indicating lower SPM concentration values for the same Hach reading than would be obtained using the overall relationship. Remark however that the intercept is relatively high at 3 mg/l for the data from W08. When a relation through the origin is forced, the slope is higher for the W05 and W08 stations and even higher than the results for the MOW1 station.

Table 1: Slope and intercept for linear regression and correlation coefficient for the relation between Hach and SPM concentration for stations MOW1, W05 and W08. Also *slope_0*: slope of the linear regression through the origin.

	Data	Slope (mg/l/FNU)	Intercept (mg/l)	Correlation	Slope_0 (mg/l/FNU)
MOW1	464	1.29	-1.29	0.92	1.28
W05	347	1.09	3.80	0.85	1.40
W08	199	0.79	2.34	0.46	1.62
Winter	303	1.29	-0.76	0.95	1.29
Spring	223	1.31	2.94	0.97	1.34
Summer	224	1.38	0.24	0.90	1.37
Autumn	260	1.11	2.98	0.97	1.12
All	1010	1.28	1.21	0.95	1.28

A possible reason for these deviations is the uncertainty in the results when filtering the water for SPM concentrations for lower concentrations. An effect of the seasons could be important as well. These linear regressions for the different seasons are therefore shown in Figure 16. The parameters for the linear regression are shown in Table 1.

Although there are differences shown for the different seasons, the differences are less important than the differences for the stations, where the slope is much lower and the intercept higher for the stations W05 and W08 than for the stations MOW1. All results are summarized in Figure 17 and Figure 18, where the different linear regressions are shown on a log-log scale and for the range 0-20 FNU and 0-20 mg/l respectively. While the intercept is below zero for the winter and the MOW1 data, the intercept is above zero for all the data and for the other seasons and stations. On a log-log scale the difference in slope for the different linear regressions is not very apparent. Also, from Figure 18, it is clear that the intercept seems to have a more important influence than the difference in slope between the different regressions, at least for the lower ranges.

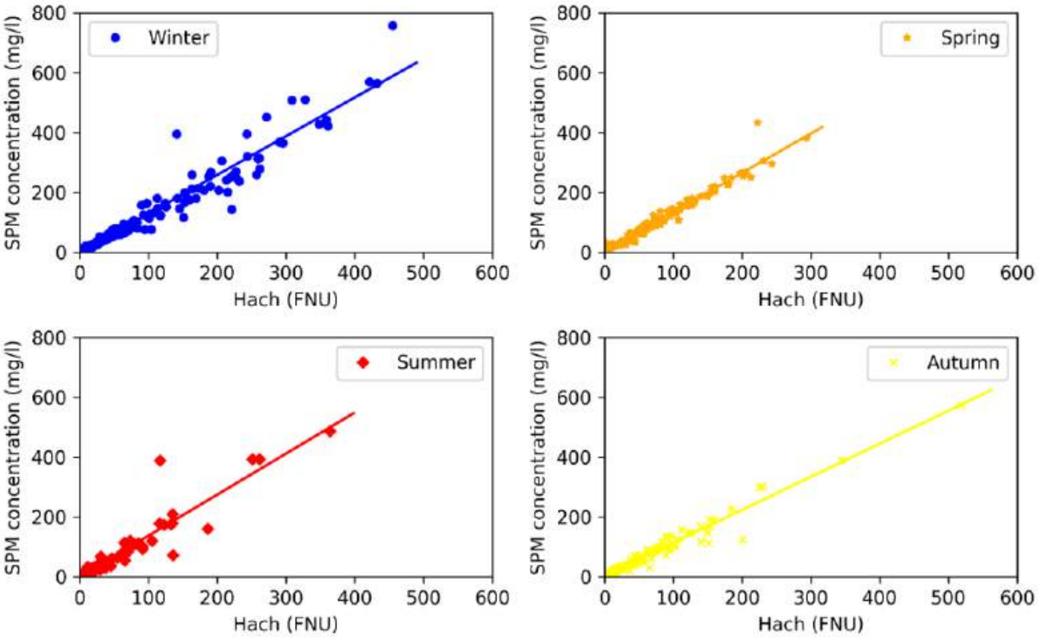

Figure 16: Relationship Hach – SPM concentration for different seasons

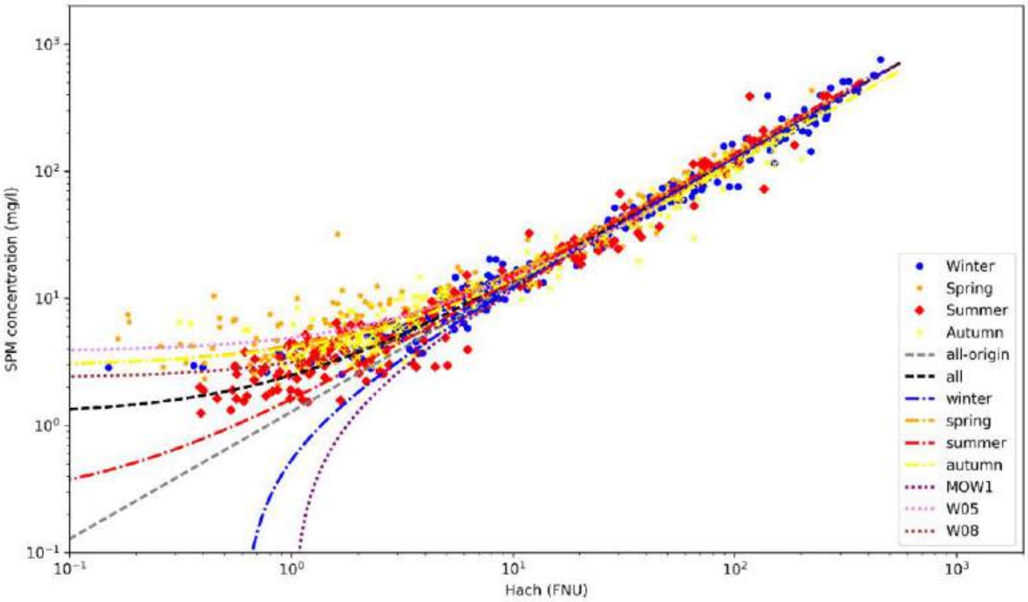

Figure 17: Relationship Hach – SPM concentration for different seasons and for different MOW1, W05 and W08 on a log-log scale

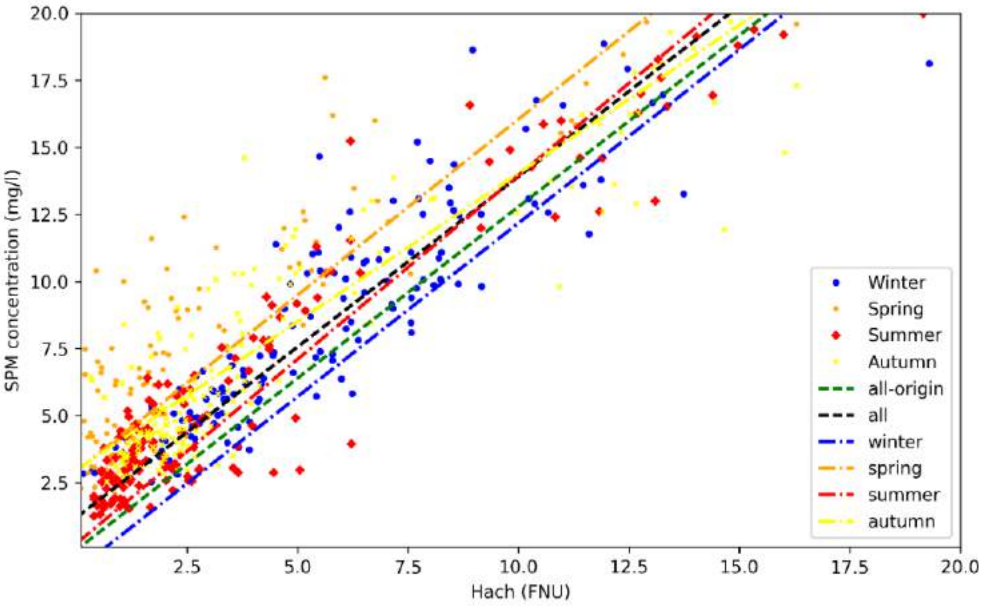

Figure 18: Relationship Hach – SPM concentration for different seasons and for the different locations MOW1, W05 and W08 for the range 0-20 FNU and 0-20 mg/l.

3.2.2.2. *Discussion*

Also, the use of the Hach-SPM concentration relation does not give good results for the calibration of the Seapoint OBS measurements. First of all, there does not seem to be a good correlation between the OBS Seapoint FTU and the Hach FNU. Furthermore, the stable relationship between Hach and SPM concentrations, as put forward by Fettweis et al. (2019) is not very accurate for very low SPM concentrations, as found at the Hinder Banks.

3.2.3. Conclusions

Since no good correlation was found between the Seapoint and the SPM concentrations, or between the Seapoint and the Hach values, no easy calibration of the Seapoint was found. Therefore, one solution could be using the calibration curve (Figure 19), that has been set up previously, using data from the RV Belgica ST1502 and ST1507 campaigns (Van Lancker et al., 2016), during which measurements took place in sector 4b (Hinder Banken), Westhinder and an area near the Kwinte Bank. Good results were obtained during these campaigns and the correlation coefficient is in this case 0.92. The results of the regression were:

$$SPMC = 4.731 * \mathrm{NTU} + 3.556 \tag{4}$$

The correlation and the 95% confidence limits are presented in Figure 19. This relationship is not forced through the origin and therefore indicates a minimum SPM concentration value of 3.6 mg l^{-1}.

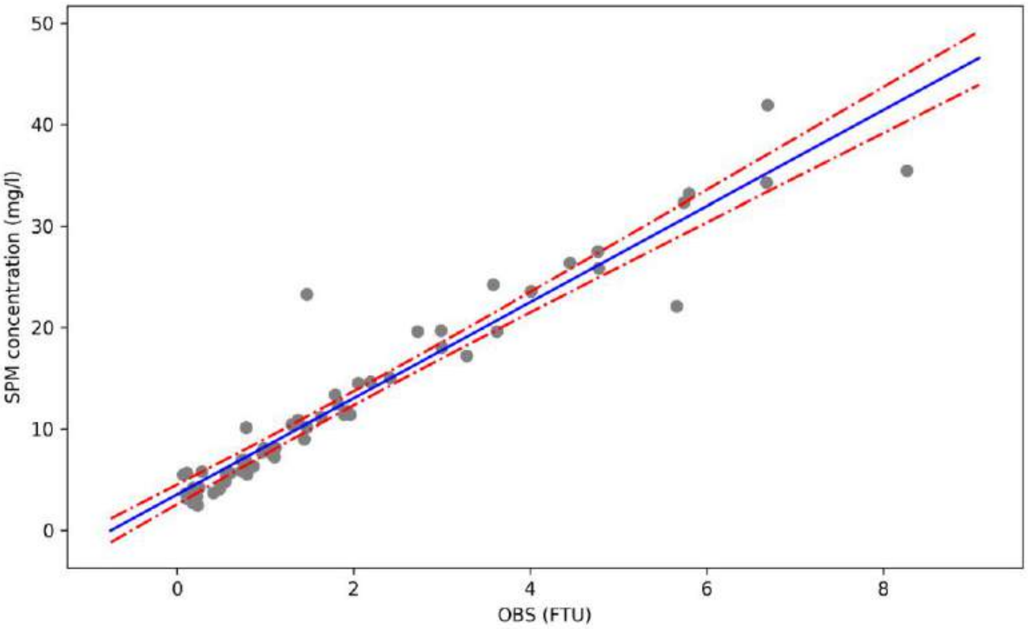

Figure 19. Calibration curve of the Seapoint OBS, using data from RV Belgica campaigns ST1502 and ST1507. A regression was fitted (black line) with the top (blue) and bottom (red) 95 % confidence intervals. Results regression: SPM = 4.7314 * NTU + 3.5599; R2 = 0.9218; 61 data points used.

Another solution could be to use regression through the origin using the actual data (Eq. 1). In Figure 20. Three profiles in OBS voltage (brown) and in SPM concentration after conversion using Equation 1 (red) or conversion using Equation 4 (blue). Left up: downward profile 1 at Oosthinder; Right up: downward profile 1 at Noordhinder; left down: downward profile 1 during the 13h cycle. Black diamond: SPM value after conversion at closure of bottle, using Equation 1: green star: SPM value after conversion at closure of bottle, using Equation 4; purple circle: SPM value of filtration on board.

Figure 20 some OBS voltage profiles and SPM profiles, after conversion, are shown for the first downward profiles during the three measurements. Also, the SPM concentration (after conversion) during the closure of the bottles is shown, together with the SPM concentration from the filtrations. The conversion using Equation 4 gives much less variation and overall lower values, although with lower OBS voltages, this conversion can give higher SPM concentrations. The error between the OBS voltages, at the moment of the closure of the bottles, converted to SPM concentration following the two equations, and the SPM concentration, as found by the filtrations is presented in Figure 21. Both the differences and the squared differences are smaller, using the Eq. 1 for converting the OBS voltages to SPM concentrations, than using the more general Eq. 4, although the differences can be quite high. Therefore, this conversion is used in the remainder of the study.

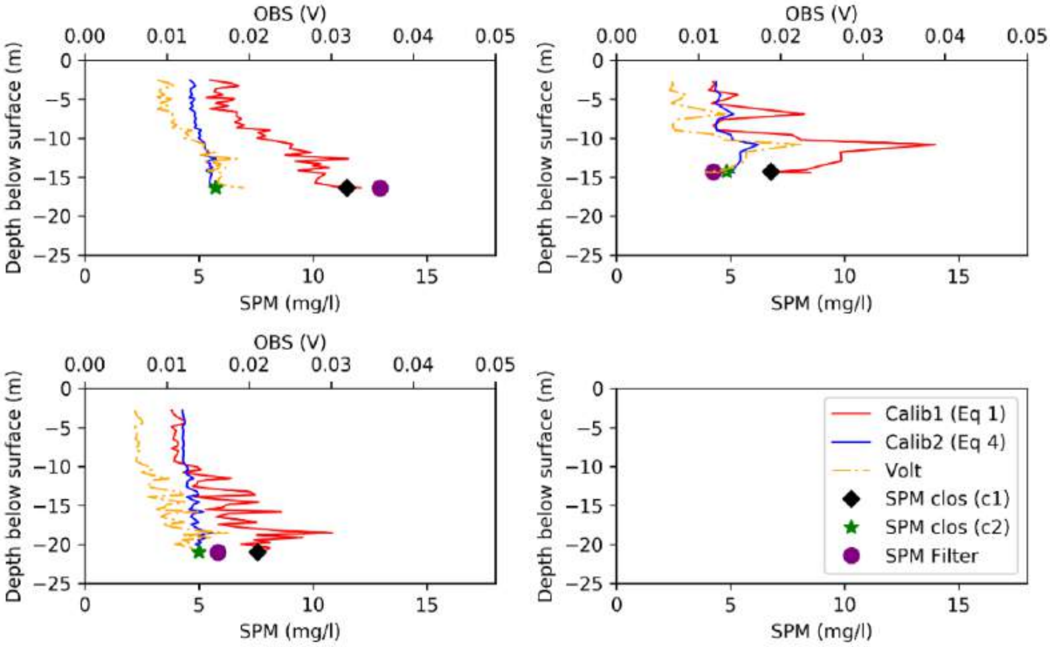

Figure 20. Three profiles in OBS voltage (brown) and in SPM concentration after conversion using Equation 1 (red) or conversion using Equation 4 (blue). Left up: downward profile 1 at Oosthinder; Right up: downward profile 1 at Noordhinder; left down: downward profile 1 during the 13h cycle. Black diamond: SPM value after conversion at closure of bottle, using Equation 1: green star: SPM value after conversion at closure of bottle, using Equation 4; purple circle: SPM value of filtration on board.

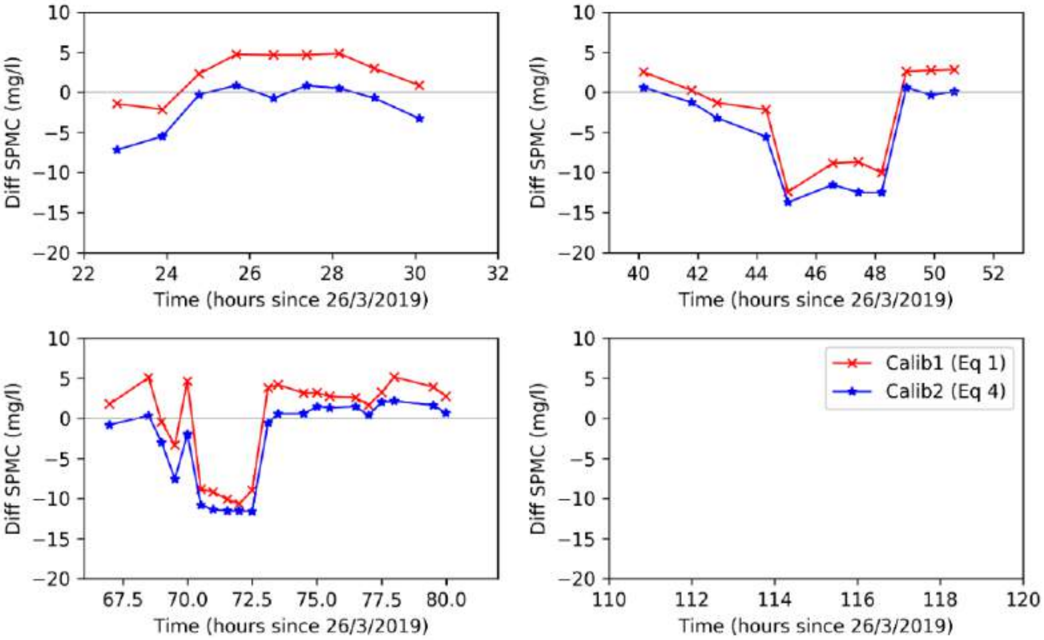

Figure 21. Difference between SPM filtrations and SPM concentration from OBS readings at the time of closure of the bottom. Positive is overestimation of the SPM from OBS sensor, compared to the filtration.

3.3. *Variation of the SPM concentration*

3.3.1. Combination of profiles

To get insight in the variation of the SPM concentration, the time series of the profiles that were taken are combined. First of all, the downward and the upward profiles are combined together to get one profile for each hour in the case of the tracks, or to get one profile for each half hour, in the case of the 13h cycle. In the first case, the two profiles at the beginning and the end of the measurement are taken. The time difference between these profiles is around 90" or around 74" for the tracks over Oosthinder and Noordhinder respectively. For the 13h cycle, the time difference between the downward track and the next upward track is much longer, because the CTD is held near the bottom during around 23 minutes. In this case the time difference between the upward profile and the next downward profile is much less, only around 386", thus round 6 to 7 minutes. In this case, these two profiles are combined. Some examples of these combined profiles are shown in Figure 22.

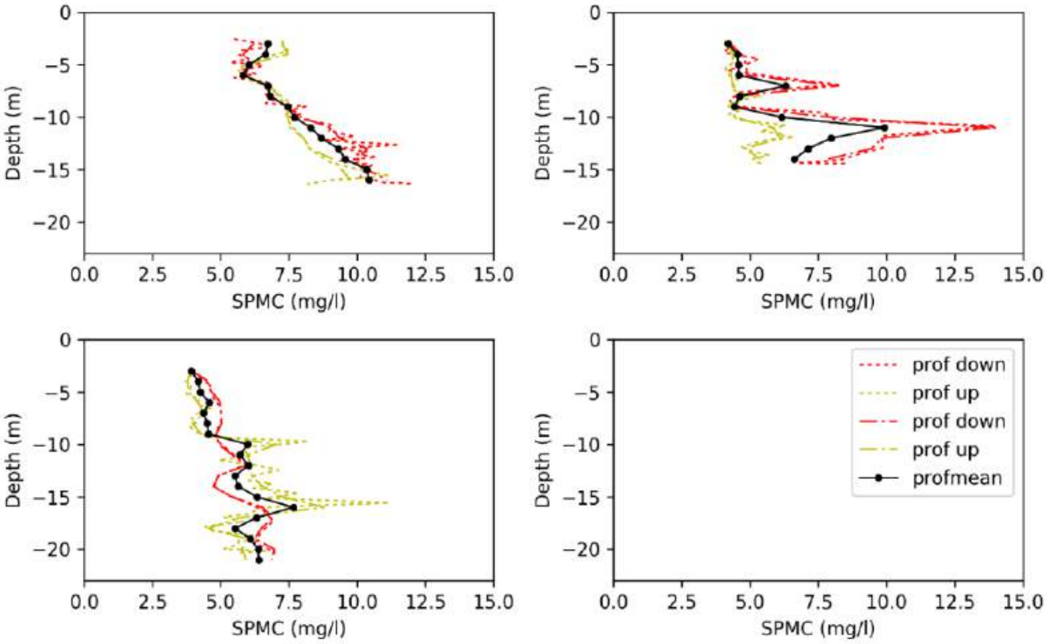

Figure 22. Sediment concentration profiles for the first profile at Oosthinder (upper left), Noordhinder (upper right) and 13h cycle (down left). Dotted lines: profiles each second; dashed: profiles averaged over 1 m (below surface); full line: average between profile up and profile down.

Although the time difference between the two profiles that are compared to each other is low, the differences can however still be important with differences up to 4 mgl^{-1} (Figure 23). However, the mean difference is close to zero and the mean absolute difference remains less than 1 mgl^{-1}, which is acceptable.

3.3.2. Overall profiles

The overall mean profile (Figure 24) shows higher concentration near the bottom than at the surface. The SPM concentrations are higher at the Oosthinder than at Noordhinder and south of Noordhinder, during the 13h cycle. However, the Oosthinder profiles are taken closer to maximum spring tide. Surprisingly, both the SPM concentration seems to decrease again near the bottom for both the measurements at Noordhinder and south of Noordhinder.

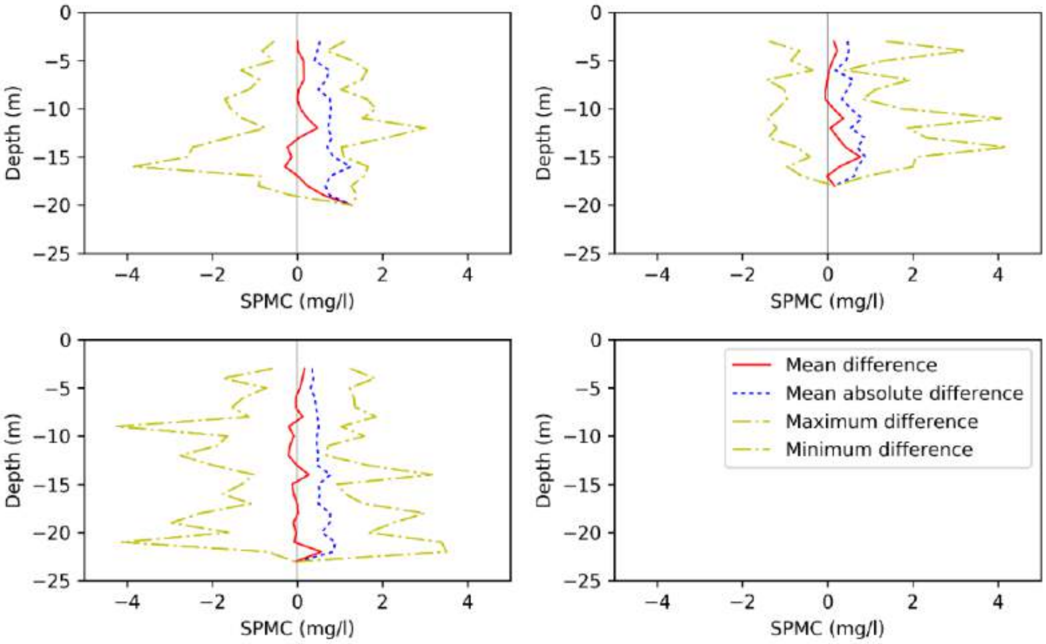

Figure 23. Mean difference in two SPM concentration profiles that are combined (red full line), mean absolute difference (blue dotted line) and minimum and maximum difference (yellow dashed line). Left upper: measurements at Oosthinder: right upper: measurements at Noordhinder; left down: measurements during 13h cycle.

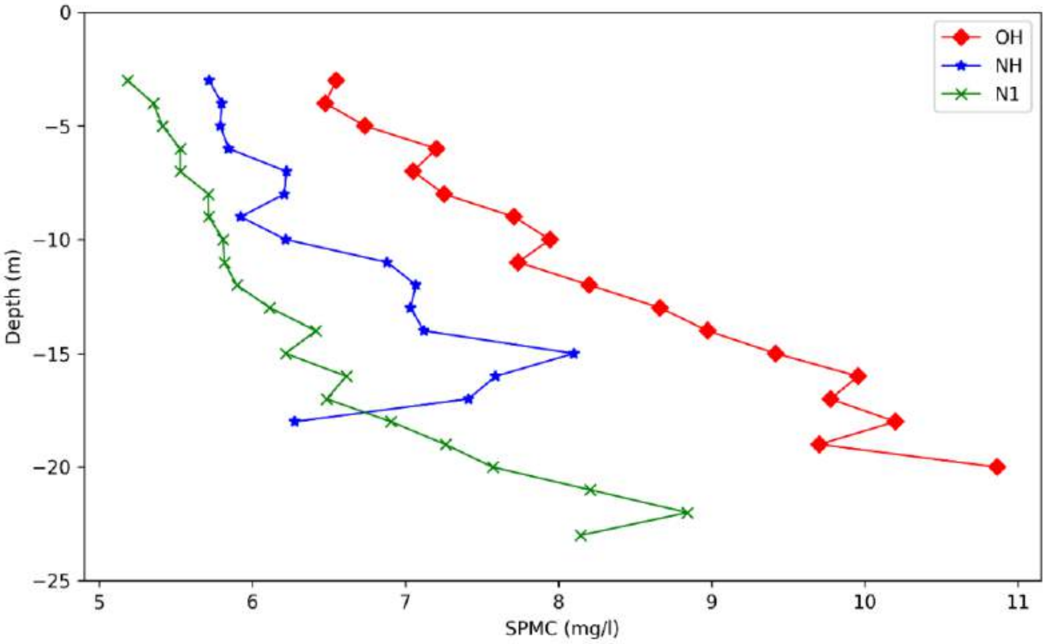

Figure 24. Overall mean SPM concentration profiles. Red: measurements at Oosthinder (OH); blue: measurements at Noordhinder (NH); green: measurements during 13h cycle (N1).

3.3.3. Variation over time and depth

To get an overall view, also the entire water column needs consideration. Since the measurements are done from the ship, the profile measurements are always with respect to the water level. To get the depth above the bottom, the total water depth is needed. The Online Data Acquisition System (ODAS) of the RV Belgica logs the total water depth. The water height during the sailing of the tracks over the Oosthinder and Noordhinder are varying over more than 20 m, from 15 m water depth, to more than 40 m. The profiles are taken on the top of the sand bank. During the measurements at Oosthinder, the water depth, during the taking of the profiles can also vary over several meters. During the 13h measurements, the RV Belgica was anchored at the same position, and the variation of the water depth is mainly due to the tides and the drift of RV Belgica.

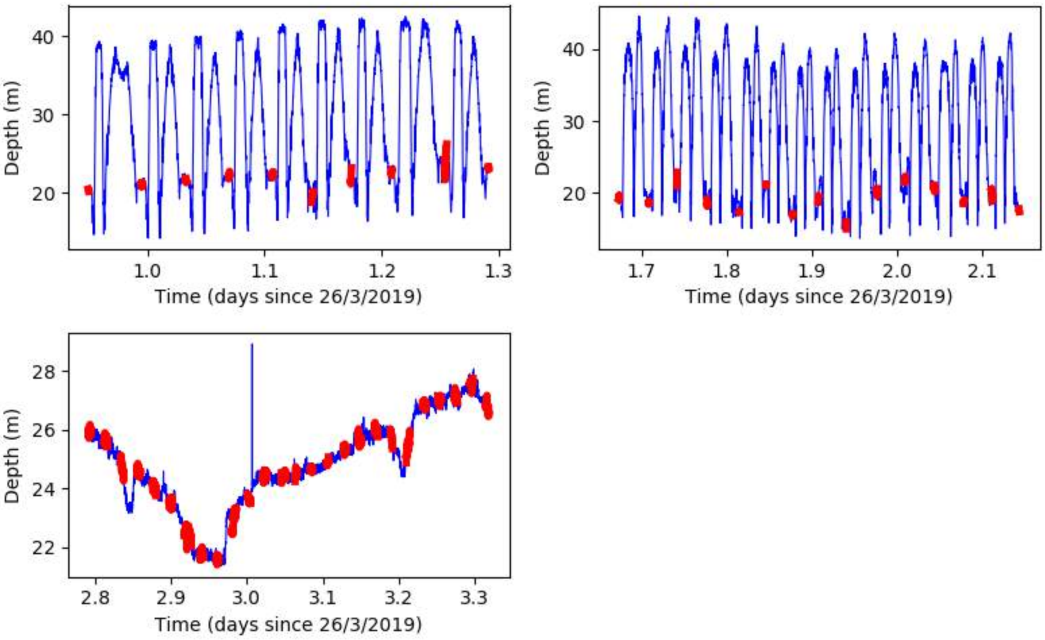

Figure 25. Total water depth during the measurement at Oosthinder (left upper), Noordhinder (right upper) and the 13h cycle, south of Noordhinder (left down). Blue curve: continuous water depth; red curve: water depth during the taking of the profiles.

The contour plots of the variation over time and depth at the three sites are shown in

Figure 26 to

Figure 28.

The measurements at Oosthinder show the highest SPM concentrations, with higher concentrations near the bottom at high tide up to more than 13 mg/l. During low tide, the concentration decreases, certainly at the bottom.

The measurements at Noordhinder are not very clear, and it is not clear from the total water depth, when the measurements at high tide and low tide are taken. This is mainly due to the fact that the measurements were not taken exactly at the same position. One can expect that the high tide is around profile 14, when the SPM concentrations are clearly higher, certainly at the bottom.

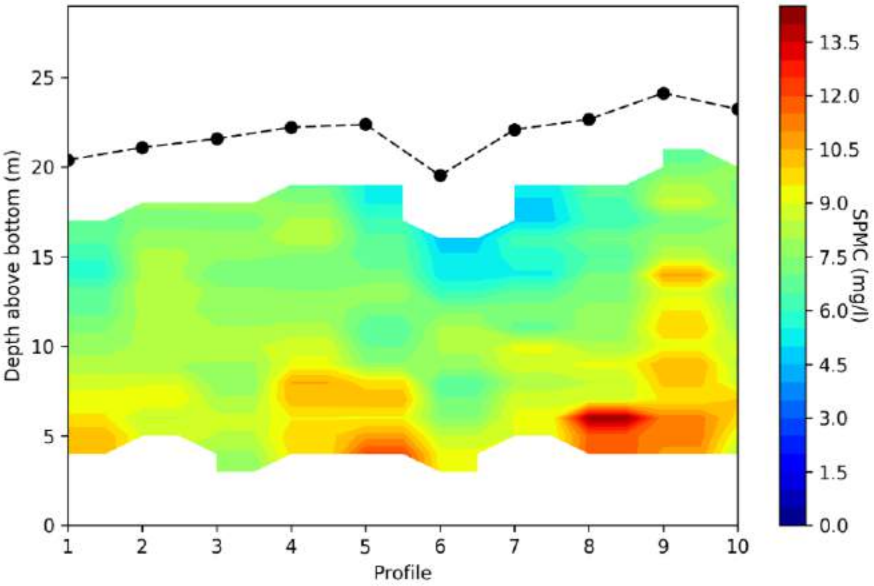

Figure 26. Variation of SPM concentration over depth and time at station Oosthinder. Time between the different profiles is approximate 1 hour. The black line is the indication of the water depth.

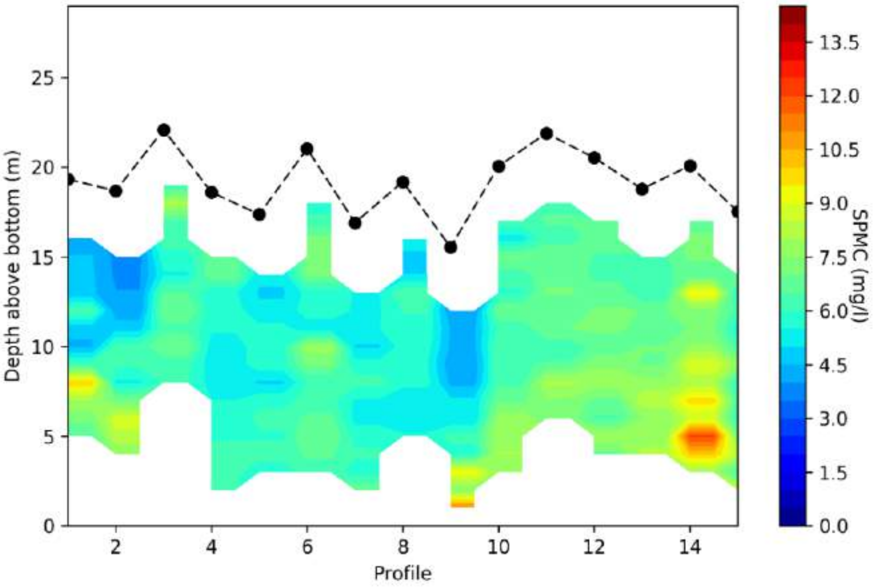

Figure 27. Variation of SPM concentration over depth and time at station Noordhinder. Time between the different profiles is approximate 1 hour. The black line is the indication of the water depth.

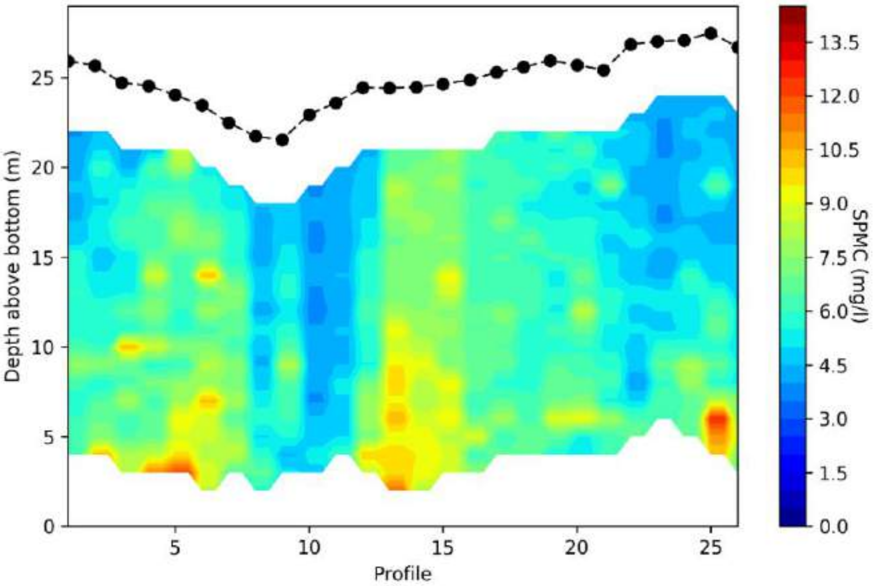

Figure 28. Variation of SPM concentration over depth and time during 13h cycle south of Noordhinder. Time between the different profiles is approximate 0.5 hour. The black line is the indication of the water depth.

The measurements during the 13h cycle show profiles each half hour and are more detailed. These measurements are taken almost at the same position and the high water and low water tides are clearly visible in the total water depth. During low tide, the concentration is clearly lower, with more constant concentration over the water column. During high water the concentration near the bottom is the highest, but surprisingly with a stronger gradient, and with lower SPM concentrations near the water surface.

3.3.4. Extrapolation of SPM concentration profiles

During oceanographic profiling, the SPM concentration near the surface is not considered, due to spikes and disturbances of the measurements. Also, near the bottom, no data are available, due to the fact that the equipment may not risk hitting the bottom, where it could be damaged. To get more information, certainly at the bottom, the profiles can be extrapolated by fitting the data to a SPM concentration profile.

The well-known Rouse profile is based on an equilibrium between fall velocity and diffusion, with an eddy diffusivity which is assumed to vary parabolically with the height. The Van Rijn (1984) profile on the other hand, assumes that the eddy diffusivity varies parabolically in the lower half of the water column, but that it is constant in the upper half of the water column. He obtains the following profile:

$$c(z) = c_a \left[\frac{z}{z_a}\frac{(h-z_a)}{(h-z)}\right]^{-\beta} \qquad \text{for } z_a < \mathrm{z} < \frac{h}{2} \qquad (5)$$

$$c(z) = c_a \left[\frac{z_a}{(h-z_a)}\right]^{\beta} . \exp\left[-4\beta\left(\frac{z}{h}-\frac{1}{2}\right)\right] \qquad \text{for } \frac{h}{2} < \mathrm{z} < \mathrm{h}$$

with	$c(z)$	SPM concentration as a function of depth
	z	depth above the sea bottom
	z_a	reference height near the sea bed at which height the reference concentration c_a is calculated
	c_a	reference concentration
	h	total water depth
	β	Rouse parameter or suspension parameter = $w_s/\kappa u_*$
	w_s	fall velocity
	κ	Von Karman's constant (=0.40)
	u_*	shear velocity or friction velocity

Soulsby (1997) argues that the Van Rijn profiles are more suitable to be used at sea, since the Rouse profile results in a prediction of zero sediment concentration near the surface, which is in contradiction with observations, especially when waves are present. The Van Rijn profile probably best corresponds to data. This profile is therefore used to extrapolate the data.

The agreement between the data and the Van Rijn profile is good. The Goodness-of-Fit Q (Press et al., 1992) is for all profiles near 1. The agreement is good for both profiles that have a very low gradient, as for profiles having a high gradient (Figure 29).

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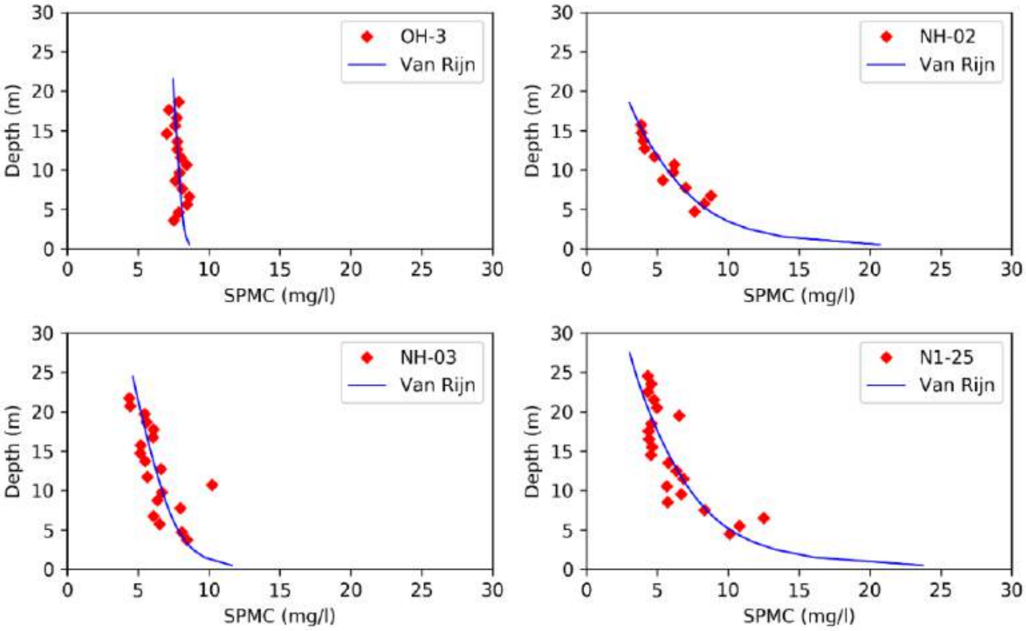

Figure 29. Examples of the fitting of the data with a Van Rijn (1984) SPM concentration profile.

The variation of the reference concentration near the bottom and the Rouse parameter, being an indication of the gradient in the SPM concentration, is relatively similar, indicating that the low gradient profiles are occurring for low concentrations near the bottom, while higher gradients are occurring for higher reference concentrations (Figure

30). The reference concentration at 0.1 m above the bottom is varying between 5 mg/l to up to 40 mg/l. The Rouse parameter varies between less than zero to almost 0.4. in these figures, a clear tidal cycle is apparent. This has to be confirmed by model results.

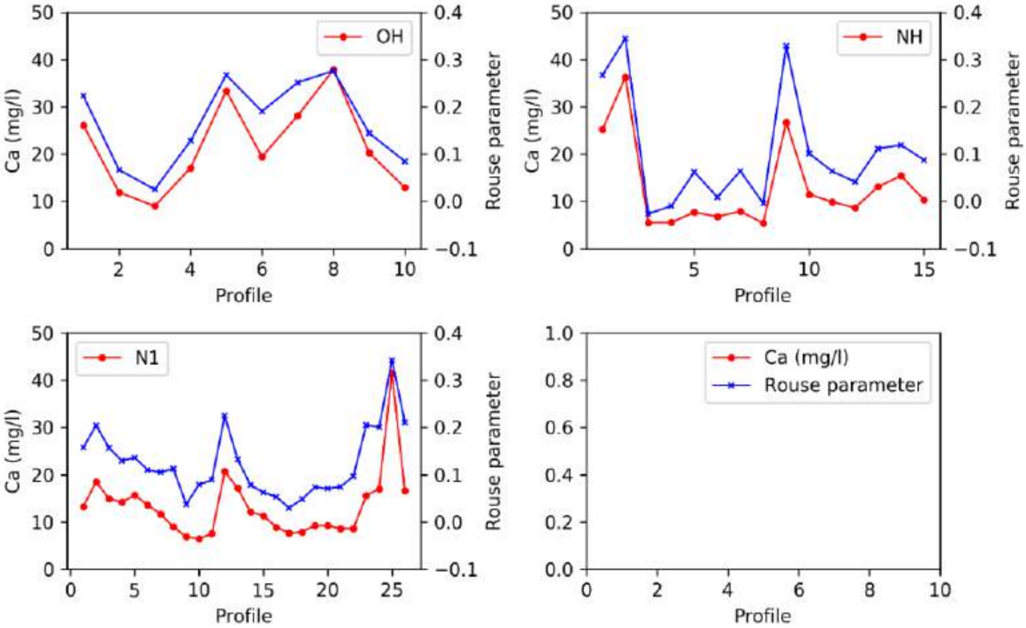

Figure 30. Variation of reference concentration at 0.1 m above the bottom and of the Rouse parameters at the different locations.

The final contour plots with the variation of the SPM concentration over time and over the depth, after smoothing out and extrapolation by using the Van Rijn profile are given in Figure 31 to Figure 33. The plots are smoother and have higher concentrations near the bottom, due to the extrapolation.

Due to the changing position (Figure 34), the total water depth is changing as well, mainly influencing the total water depth at the Noordhinder. For the quasi stationary measurements during the 13h cycle, the drift of RV Belgica, is clearly visible around the anchor position. For the track measurements, the position of the profiles can differ more, influencing also the total water depth.

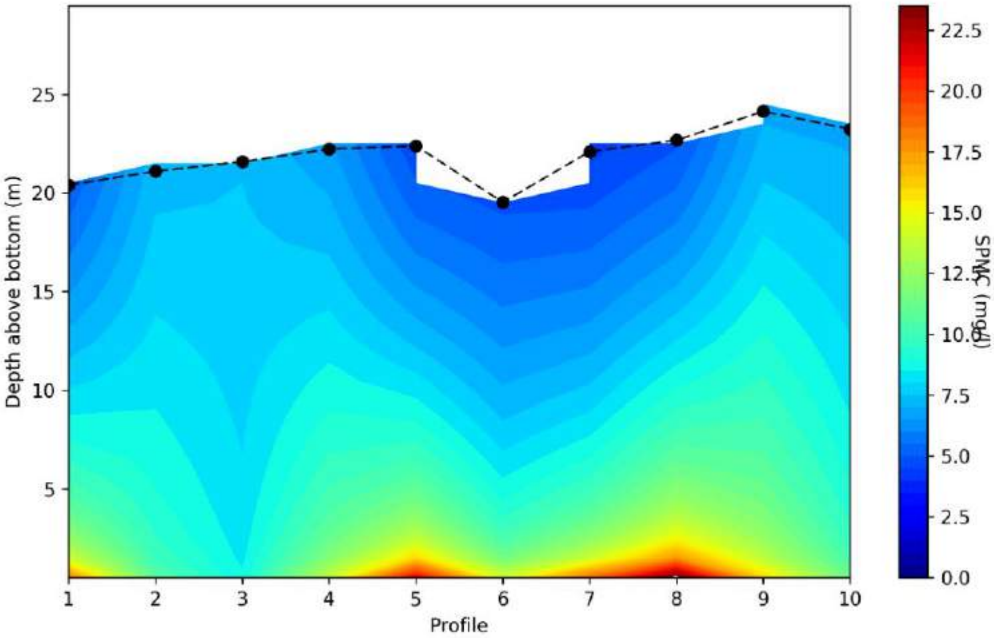

Figure 31. Variation of SPM concentration over depth and time at station Oosthinder. Time between the different profiles is approximate 1 hour. The black line is the indication of the water depth.

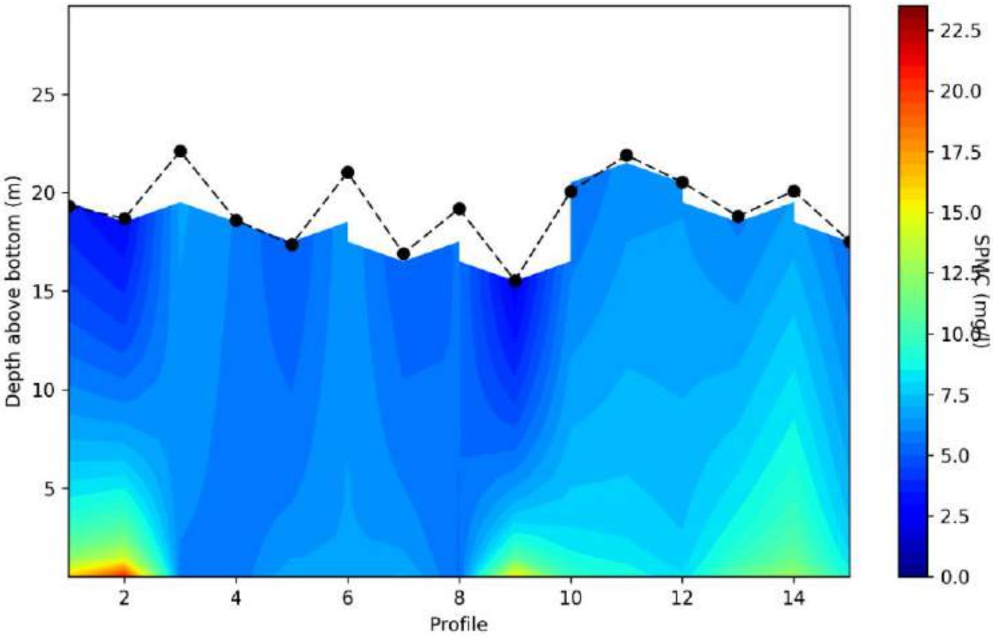

Figure 32. Variation of SPM concentration over depth and time at station Noordhinder. Time between the different profiles is approximate 1 hour. The black line is the indication of the water depth.

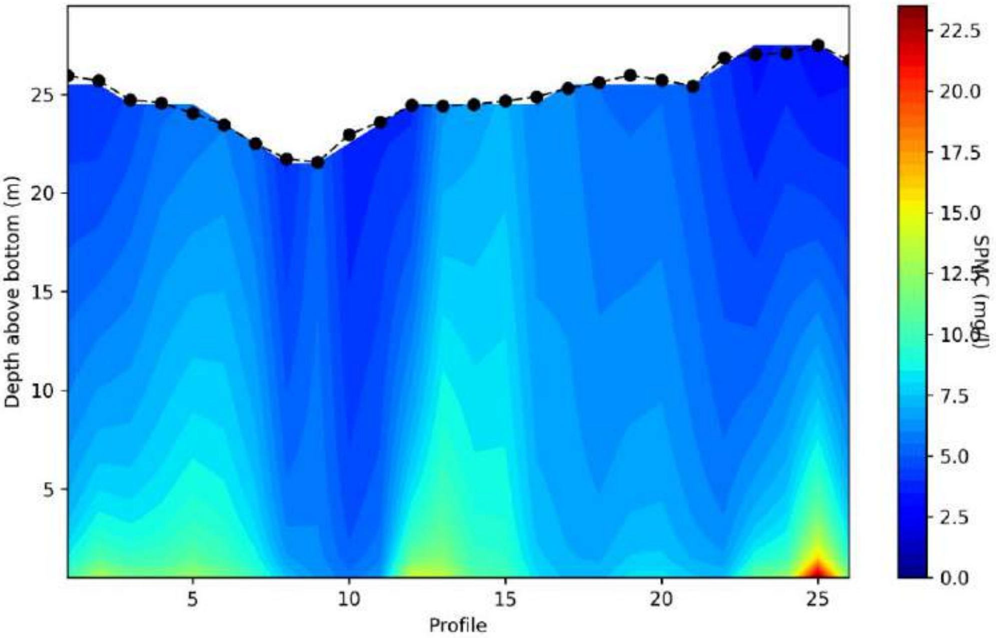

Figure 33. Variation of SPM concentration over depth and time during 13h cycle south of Noordhinder. Time between the different profiles is approximate 0.5 hour. The black line is the indication of the water depth.

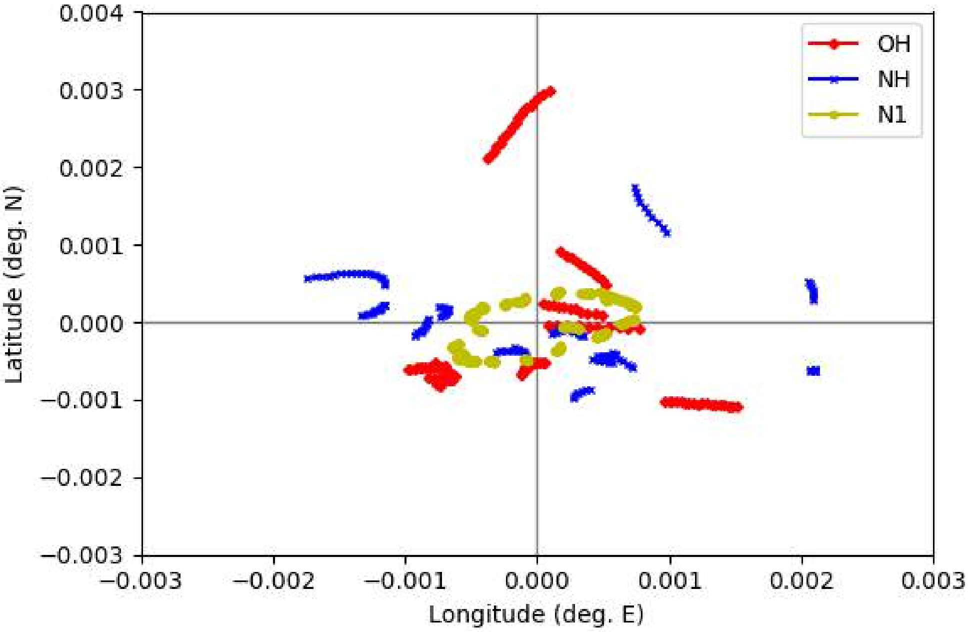

Figure 34. Variation of position around the central position of the measurements for the three locations.

4. Conclusions

In the present report, the CTD and OBS measurements taken during RV Belgica campaign 2019/09 were analysed. A cross-bank trackline was sailed over the Oosthinder, while taking profiles over the water column and taking water samples at the top of the sand bank each hour. Similar measurements were taken when sailing cross-bank tracklines over the Noordhinder. Finally, a 13-hour measurement cycle was measured at a position south of the extraction zone 4a, Noordhinder sandbank. Here, profiles and water samples were taken each half hour.

To calibrate the OBS Seapoint sensor, water samples were taken that were filtered on board of RV Belgica, and measurements were taken with a Hach turbidimeter as well. Unfortunately, no good correlation was found, both between the OBS sensor readings and the SPM filtrations, and between the Hach turbidities and the SPM filtrations. Therefore, no good calibration could be set up between the Seapoint measurements and the SPM concentrations in the water column. Furthermore, the datasets in the offshore Hinder Banks with lower SPM concentrations in the water column, showed that the stable relationship between the Hach turbidity results and the SPM concentrations, as put forward by Fettweis et al. (2019), was not really applicable. The same conclusion was drawn for the relationship that was found by Van Lancker et al. (2016) between the Hach turbidity results and the SPM concentration. Finally, a relationship based on a linear regression, forced through the origin, was used to convert the OBS Seapoint voltages to SPM concentrations.

Final results show a clear variation of the SPM concentration over the water depth and over the tide, with higher concentrations near the bottom and during high water. The overall concentrations seem higher than expected. Data are extrapolated to the sea bottom, using the Van Rijn profile. Results show a clear tidal cycle variation with concentrations up to almost 40 mg/l at 0.1 m above the bottom. The highest concentrations are found at the Oosthinder, although the measurements at the Noordhinder were made in shallower water conditions. However, it is not clear yet whether this is due the timing of the measurements of the Oosthinder profiles taken closer to maximum Spring tide, or whether a higher turbidity characterizes this sandbank.

5. Acknowledgments

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COLOPHON

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ROYAL BELGIAN INSTITUTE OF NATURAL SCIENCES
OPERATIONAL DIRECTORATE NATURAL ENVIRONMENT

Ecosystems Data Processing and Modelling
Suspended Matter and Seabed Monitoring and Modelling

Sediment analyses of ST1407, ST1807 and ST1909

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Prepared for Flemish Authorities, Agency Maritime Services & Coast, Coast. Contract 211.177 <MOZ4> and ZAGRI

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1. Introduction

In the framework of examining the effects of the exploitation of non-living resources in the territorial sea and the continental shelf of the Belgian part of the North Sea (BPNS), this report focusses on spatial and temporal changes in seabed sediment composition in two areas of marine aggregate extraction. It is part of the MOZ4 programme that since 2013 focuses on the monitoring of hydrodynamics and sediment transport in relation to marine aggregate extraction in the far offshore zone of the Hinder Banks. Overall aim is to increase process and system knowledge of the extraction areas, with a particular interest on the compliancy of the activities itself with respect to the European Marine Strategy Framework Directive (MSFD). More specifically changes in seafloor integrity and hydrographic conditions are assessed (see Van Lancker et al. 2016 for an overview of the monitoring programme).

In view of monitoring seabed changes, sediment samples are taken to (i) characterize, in detail, sediment composition, (ii) evaluate deposition of the dredging-induced overflow deposits in the near and far field, and (iii) validate mathematical model results, necessary for impact quantification.

2. Study area

In the BPNS sand and gravel extraction is only permitted in controlled (concession) zones: Zone 1 Thorntonbank; Zone 2 Kwintebank, Buitenratel and Oostdyck; Zone 3 Sierra Ventana; Zone 4 Hinder Banks (Fig. 1). Zone 1 contains a designated reference area for monitoring the environmental impact of the sand extraction operations and wind farms. Here extraction is prohibited. Sections of zones 2 and 3, where the exploitation has taken place intensively, are as well closed.

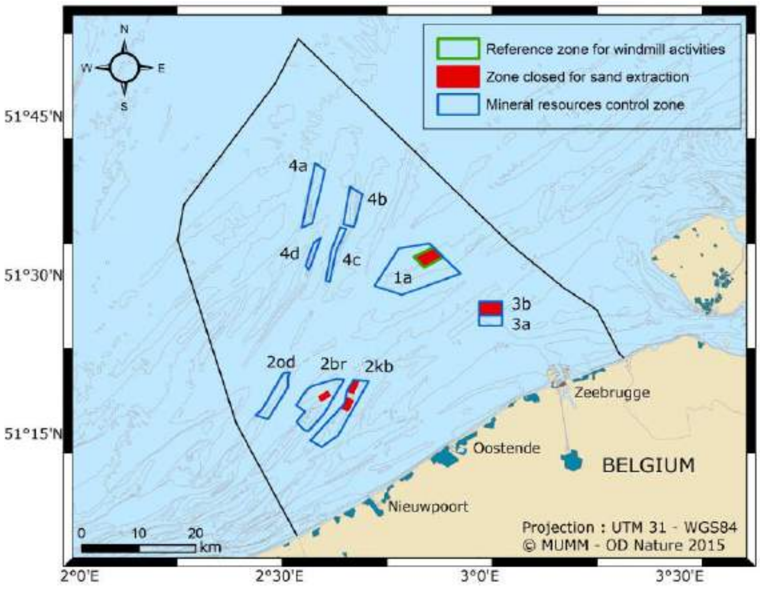


Figure 1. Extraction zones in the Belgian part of the North Sea. Data from FPS Economy, Continental Shelf Service.

The Hinder Banks (Noordhinder, Oosthinder and Westhinder) are a sandbank complex, located 40 km offshore in the BPNS with depths ranging from -8 m to -27 m LAT (Lowest Astronomical Tide). The sandbanks are superimposed with large sand dunes with heights of more than 5 m, and with smaller amalgamating sand waves towards its flanks. The troughs in between the sandbanks reach a maximum of -40 m LAT of water depth.

3. Literature

On behalf of the Flemish Government, Agency for Maritime Services and Coast, Coastal Division, the distribution and characteristics of the aggregates in exploration zone 4 on the BPNS were investigated in 2008 (Fig. 2). In a first phase, a high-resolution seismic survey was conducted with a line spacing of 500 m to determine the most suitable locations for vibrocoring. In a second phase, 120 vibrocores of 4 to 5 m length were taken to characterise the sedimentological area of interest together with the 44 seismic profiles. The vibrocores were analysed for grain-size distribution and carbonate content; lithologs were as well produced. Details can be found in Mathys et al. (2009) and Depret NV & G-tec Marine Environment (2009).

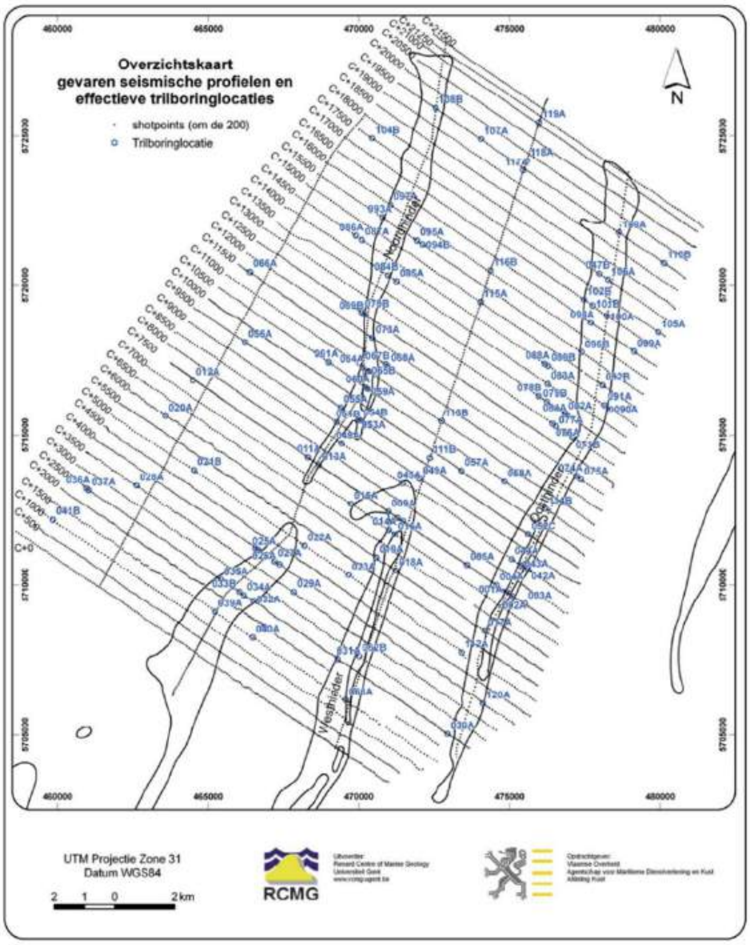


Figure 2. Seismic lines and vibrocore locations of exploration zone 4 in the BPNS (Mathys et al. 2009).

4. Methodology

4.1. *Sediment samples*

Sector 4c (Oosthinder) has been sampled repeatedly in 2014 (16), 2018 (8) and 2019 (8) during RV Belgica campaigns ST1407, ST1807 and ST1909. Neighbouring samples are combined as locations 1 to 8 (Fig. 3). Reineck box cores are taken (Table 2), subsampled with cylindrical tubes with an inner diameter of 36 mm and sliced per centimetre in depth. The sliced subsamples are frozen on board for later laboratory analyses. In 2019, the same procedure was applied for 14 box cores in sector 4a (Noordhinder). A good spatial representation over the sandbank, in and outside the intensive dredged areas as well as far field areas where previously sediment plumes were observed, has been achieved.

4.2. *Sediment analyses*

All samples were analysed on organic matter, carbonate content and particle size at the sedimentological laboratory of Ghent University, Department of Geology.

4.2.1. Organic matter and carbonate content

The total organic matter content (OM%) and carbonate content ($CaCO_3$%) are measured by using the Loss-On-Ignition (LOI) method of Dean (1974) and Heiri et al. (2001). Four grams of sediment from each slice of the samples were put in pre-weighed porcelain crucibles and dried in an oven at 105 ºC for 17 hours. The samples were subsequently placed in a desiccator for half an hour in order to reach room temperature and were weighed. In the next step, samples were placed in a muffle furnace at 550 ºC for 4 hours. After cooling to room temperature in a desiccator, samples were weighed again. The difference between the weight of samples at 105 ºC and 550 ºC represents the amount of organic matter. The samples were then returned to the muffle furnace and heated at 1000 ºC for 5 hours. The weight difference between 550 ºC and 1000 ºC represents the amount of CO_2 evolved from carbonate minerals. The actual carbonate content of a sample is calculated as the weight of CO_2 lost between 550 ºC and 1000 ºC divided by 0.44, representing the mass fraction of CO_2 in carbonate ($CaCO_3$). Three replicates were taken from the top layer of a core (upper 1 cm) to verify the accuracy of the method.

4.2.2. Particle-size distribution

The 1-cm sliced sediment samples from the cores were analysed using a Malvern Mastersizer 3000 laser particle analyser. Prior to the laser measurements, the terrigenous fraction was isolated by treating the samples (in 10 ml DI water) with boiling H_2O_2 (2 ml, 35%), HCl (1 ml, 10%) and NaOH (1 ml, 0.2 M), to remove organic matter, carbonates and biogenic silica, respectively (procedure adapted from Mulitza et al. 2008). Samples were boiled with sodium hexametaphosphate to ensure complete disaggregation of the particles. A sieving was needed to separate the fine from the coarse fraction (2 mm for ST1407; 1 mm for ST1807 and ST1909). Coarse particles cannot be analysed by laser diffraction. Both fractions of the samples were dried in the oven overnight (70 ºC). The dry samples were then cooled down and weighed. For the fine fraction of each sample, a very small portion was introduced in the Malvern Mastersizer. Three replicates were taken from the top of a core (upper 1 cm) to quantify the precision of the measurements.

To calculate grain-size parameters representative of the entire sediment sample, results obtained by laser diffraction were recalculated accounting for the percentage of the weight of the coarse fraction. After combining the Malvern and sieving results, Gradistat (Blott & Pye 2001) was used to calculate the complete particle-size distribution (PSD) of each subsample, and the associated sediment parameters. To merge datasets all grain sizes above 1000 µm were assumed as bioclastic gravel (e.g. shells, shell fragments or shell hash), and are excluded for the calculations of the mean and sorting. This assumption is based on photographic material, as well as notes taken during the scientific campaigns.

Mean and sorting are calculated according to two methodologies (Table 1; Blott & Pye 2001). The Folk and Ward (F&W) parameters are based on a limited number of values (e.g. the mean is calculated based on the percentiles D16, D50 and D84). To take advantage of the high-resolution results of the Malvern Mastersizer, geometric parameters of the method of moments (M&M) are used (e.g. the mean is calculated based on every single Malvern class). However, the F&W mean is often used as the fine and coarse tails, where uncertainty is high, are not included in the calculation (e.g. wash out of fines, deflocculation, shell hash).

Table 1. Geometric mean of the Folk and Ward method, and the method of moments (Blott & Pye 2001).

Geometric (modified) Folk and Ward method	Geometric method of moments
$M_G = \exp \frac{\ln P_{16} + \ln P_{50} + \ln P_{84}}{3}$	$\bar{x}_g = \exp \frac{\Sigma f \ln m_m}{100}$

4.3. *Multibeam backscatter*

The Continental Shelf Service of FPS Economy provided multibeam backscatter data on the locations of the sediment samples. Backscatter strength (BS) quantifies the amount of acoustic intensity scattered back to the sonar receiver following a complex interaction of the transmitted signal with the seabed (Montereale-Gavazzi et al. 2018). Due to the various scattering properties of different seabed substrates, backscatter can help determine sediment type and possibly derive some of its physical characteristics (Montereale-Gavazzi et al. 2018).

4.3.1. Acquisition

The multibeam echosounder (MBES) data were acquired during 14 acoustic surveys carried out with the Belgica research vessel (Kongsberg MBES 300 kHz EM3002d dual-head system) between 2012 and 2019: ST1210, ST1213, ST1308, ST1326, ST1406, ST1412, ST1429, ST1513, ST1533, ST1728, ST1806, ST1822, ST1918 and ST1930. See RV Belgica website for details on the respective campaigns (https://odnature.naturalsciences.be/belgica/).

4.3.2. Processing

For each of the surveys, FPS Economy followed the same process to derive backscatter mean and standard deviation: (1) correction of the raw, uncompensated backscatter signal by using the real grazing angle measurement, the real time sound attenuation and the instantaneous insonified area; (2) extraction of backscatter values within the restricted angles of ± 30° to 50°. From the backscatter mosaics, mean and standard deviation were extracted in a circular buffer of 35 m around each sampling location.

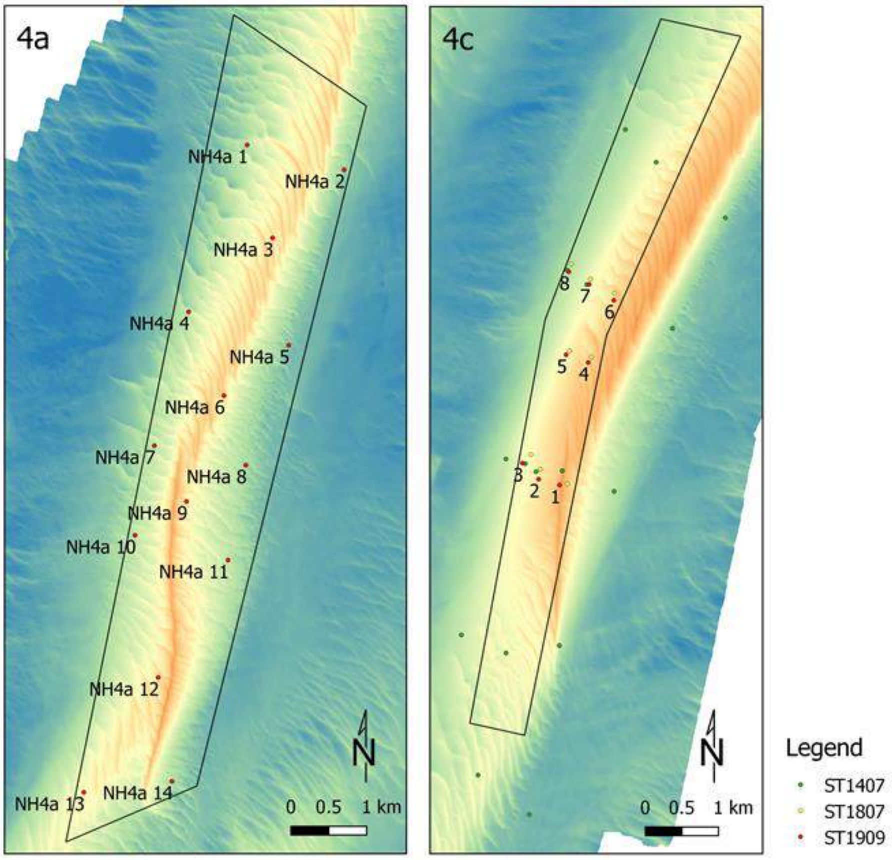


Figure 3. Box cores of 2014, 2018 and 2019 in sector 4a and 4c. MBES data from FPS Economy, Continental Shelf Service.

Table 2. Box cores of 2014, 2018 and 2019 in sector 4a and 4c.

Campaign	ID	Gear	Time (UTC)	Latitude	Longitude
ST1407	01	Reineck box core	2014-03-26 20:23:00	51,48353242	2,622870138
ST1407	02	Reineck box core	2014-03-26 20:34:57	51,48818185	2,613082518
ST1407	03	Reineck box core	2014-03-27 18:14:41	51,52442868	2,628823718
ST1407	04	Reineck box core	2014-03-27 18:24:12	51,52429884	2,623826123
ST1407	05	Reineck box core	2014-03-27 17:55:02	51,5252451	2,621776001
ST1407	06	Reineck box core	2014-03-26 21:20:48	51,52579799	2,618080755
ST1407	07	Reineck box core	2014-03-26 21:50:05	51,54658664	2,633333388
ST1407	08	Reineck box core	2014-03-26 22:00:15	51,54830759	2,629591118
ST1407	09	Reineck box core	2014-03-26 20:57:19	51,50484669	2,609749461
ST1407	10	Reineck box core	2014-03-26 22:33:11	51,56505518	2,640546383
ST1407	11	Reineck box core	2014-03-27 19:02:27	51,50363811	2,628445296
ST1407	12	Reineck box core	2014-03-27 17:43:02	51,5220124	2,638745319
ST1407	13	Reineck box core	2014-03-27 17:27:11	51,54141978	2,649727768
ST1407	14	Reineck box core	2014-03-27 17:11:21	51,55462486	2,659724184
ST1407	15	Reineck box core	2014-03-27 18:41:01	51,50272591	2,618282771
ST1407	16	Reineck box core	2014-03-26 22:20:14	51,56119198	2,64646439
ST1807	A04	Reineck box core	2018-03-21 16:24:00	51,52460202	2,624629475
ST1807	A05	Reineck box core	2018-03-21 16:10:35	51,52632816	2,622820535
ST1807	A07	Reineck box core	2018-03-21 17:39:04	51,5472578	2,634023915
ST1807	A08	Reineck box core	2018-03-21 17:50:41	51,54904614	2,630390403
ST1807	B04	Reineck box core	2018-03-21 16:42:57	51,52288226	2,62978993
ST1807	D01	Reineck box core	2018-03-21 17:27:23	51,54558489	2,638627891
ST1807	D02	Reineck box core	2018-03-21 17:00:05	51,53797037	2,634310206
ST1807	D03	Reineck box core	2018-03-21 17:09:12	51,53870312	2,630109707
ST1909	OH4c 1	Reineck box core	2019-03-27 13:10:55	51,52273219	2,628330682
ST1909	OH4c 2	Reineck box core	2019-03-27 13:15:20	51,52341296	2,624339621
ST1909	OH4c 3	Reineck box core	2019-03-27 13:27:31	51,52531418	2,621224032
ST1909	OH4c 4	Reineck box core	2019-03-27 13:39:53	51,53731903	2,633673092
ST1909	OH4c 5	Reineck box core	2019-03-27 13:46:29	51,53823546	2,62945048
ST1909	OH4c 6	Reineck box core	2019-03-27 13:56:41	51,54473991	2,638504526
ST1909	OH4c 7	Reineck box core	2019-03-27 14:08:27	51,54661955	2,633787536
ST1909	OH4c 8	Reineck box core	2019-03-27 14:15:03	51,54810423	2,629880533
ST1909	NH4a 1	Reineck box core	2019-03-28 17:29:04	51,6635235	2,58533678
ST1909	NH4a 2	Reineck box core	2019-03-28 17:04:16	51,66052892	2,604561198
ST1909	NH4a 3	Reineck box core	2019-03-28 16:45:58	51,65209611	2,590470981
ST1909	NH4a 4	Reineck box core	2019-03-28 16:27:46	51,64295467	2,573949572
ST1909	NH4a 5	Reineck box core	2019-03-28 16:12:01	51,63891078	2,593764474
ST1909	NH4a 6	Reineck box core	2019-03-28 15:57:46	51,63267463	2,581048447
ST1909	NH4a 7	Reineck box core	2019-03-28 15:44:36	51,62646812	2,56733753
ST1909	NH4a 8	Reineck box core	2019-03-28 14:00:06	51,62413684	2,585419903
ST1909	NH4a 9	Reineck box core	2019-03-28 13:46:31	51,61962696	2,573747978
ST1909	NH4a 10	Reineck box core	2019-03-28 13:33:04	51,61542933	2,563615829
ST1909	NH4a 11	Reineck box core	2019-03-28 13:19:16	51,61244033	2,582023366
ST1909	NH4a 12	Reineck box core	2019-03-28 13:02:22	51,59794869	2,568364974
ST1909	NH4a 13	Reineck box core	2019-03-28 12:31:10	51,58377191	2,553801974
ST1909	NH4a 14	Reineck box core	2019-03-28 12:46:42	51,58519144	2,571189944

5. Results

The sediment parameters of 2014, 2018 and 2019 are tabulated for the sectors 4a and 4c. The upper centimetres are plotted for the Folk and Ward mean (in µm) and sorting (in Φ), as well as for the content of organic matter, carbonate and bioclastic gravel (in %). The results are compared against a time series of multibeam backscatter values of the sampled locations in sector 4c from 2012 to 2019. Finally, particle-size distribution curves of the top centimetre and sediment composition of the upper centimetres are shown for the eight locations in sector 4c.

5.1. *Sector 4a*

The mean of the sliced sediment samples is around 350 to 500 µm (excluding NH4a 4 and NH4a 14 with means of 500 to 600 µm), while the sorting lies between a Φ-value of 0.4 and 0.6. NH4a 1 and NH4a 7 have a higher sorting value between 0.6 and 0.8. The content of organic matter and the carbonate content are less than 5% for almost all samples. NH4a 1 to NH4a 4 have an organic matter content between 2% and 5%, while the other samples are limited to a maximum of 1% or 2%. Samples NH4a 7 and NH4a 13 have an increased carbonate content. Mud was not detected in any sample. Bioclastic gravel, which was excluded for the calculations of the mean and sorting, lies between 5% and 25% for NH4a 1, NH4a 2, NH4a 4, NH4a 7 and NH4a 14. All other samples have less than 5% bioclastic gravel. Figure 4 maps the sediment properties D50, OM% and $CaCO_3$% anno 2019. A tabulated overview of the measured parameters of the seabed is presented in Tables 3, 4 and 5.

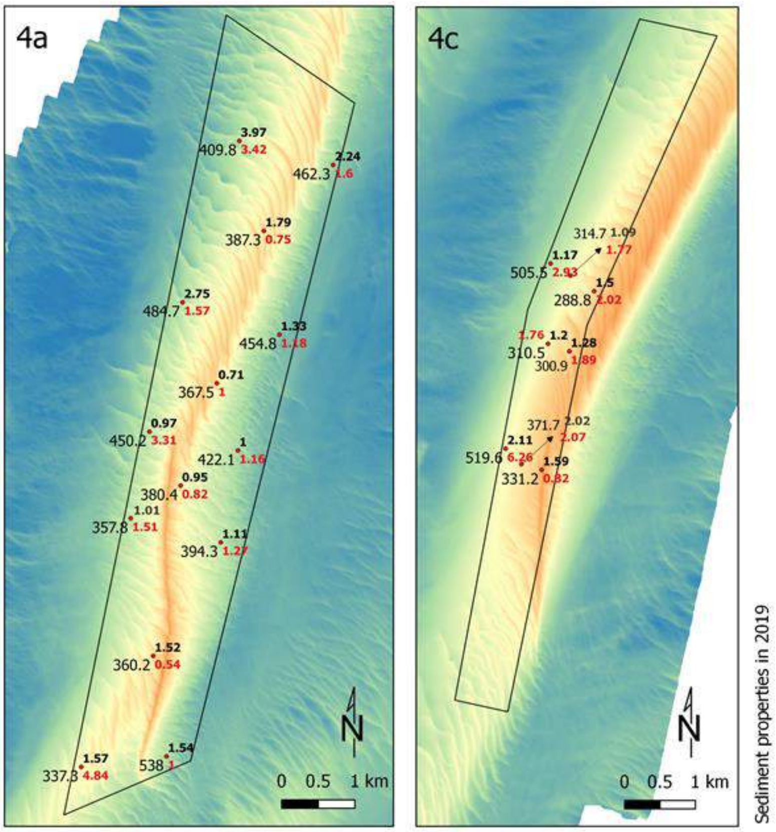


Figure 4. Sediment properties (D50, **OM%** and **$CaCO_3$%**) for sector 4a and 4c in 2019. MBES data from FPS Economy, Continental Shelf Service.

Table 3. The geometric mean and logarithmic sorting of F&W with the content of organic matter, carbonate and bioclastic gravel of the upper centimetres of the box cores taken in sector 4a during campaign ST1909 (NH4a 1 to NH4a 5).

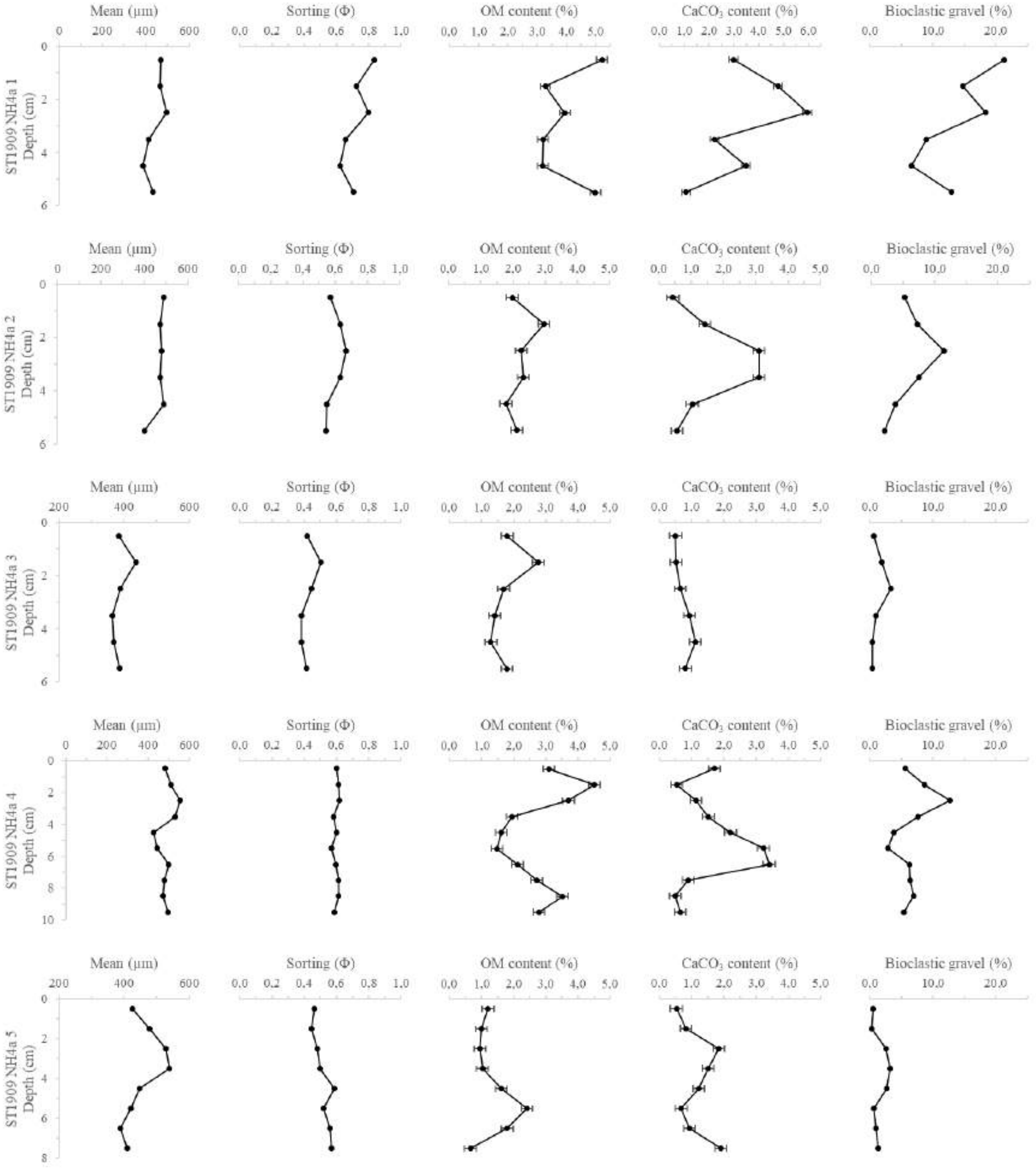


Table 4. The geometric mean and logarithmic sorting of F&W with the content of organic matter, carbonate and bioclastic gravel of the upper centimetres of the box cores taken in sector 4a during campaign ST1909 (NH4a 6 to NH4a 10).

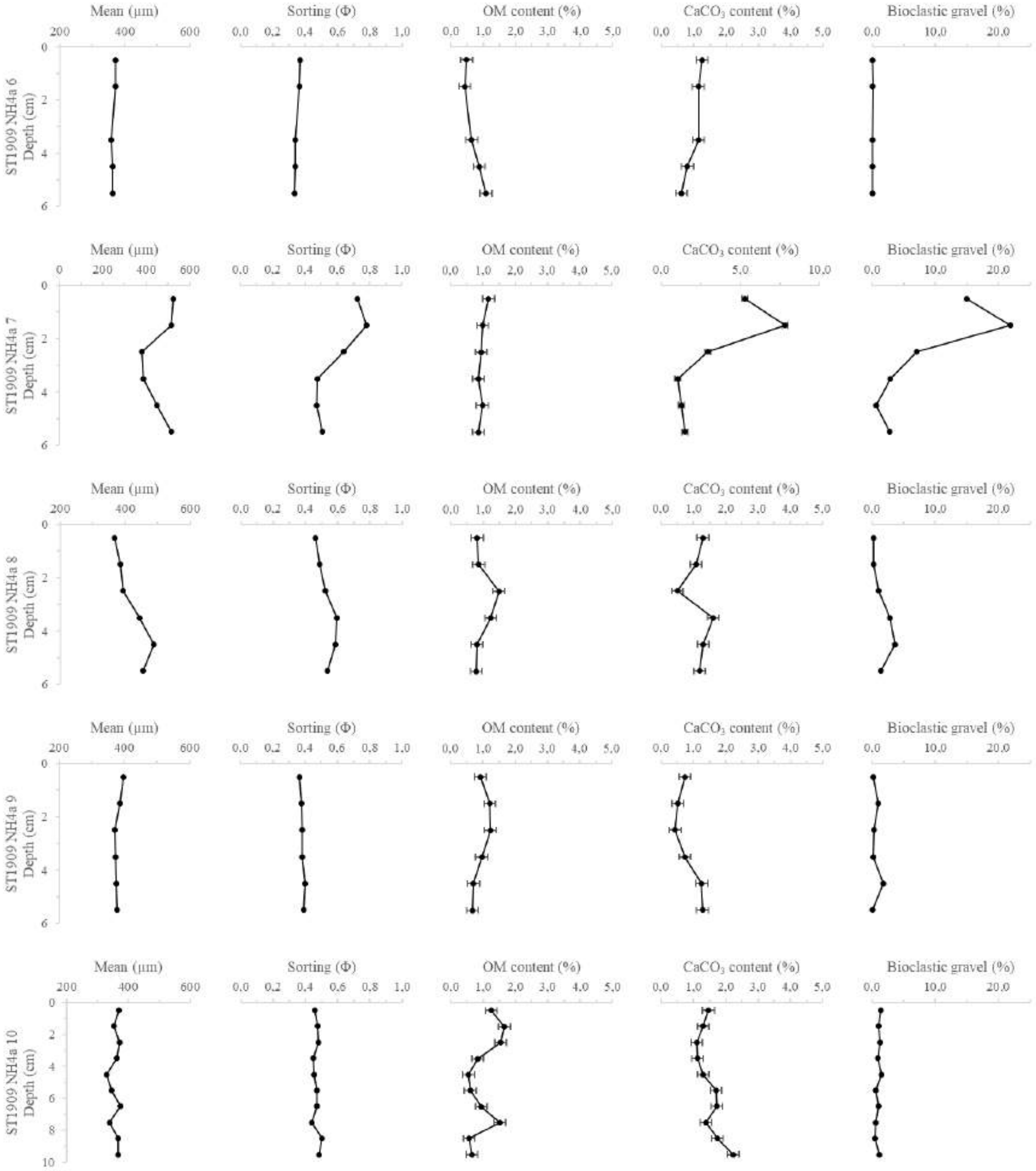
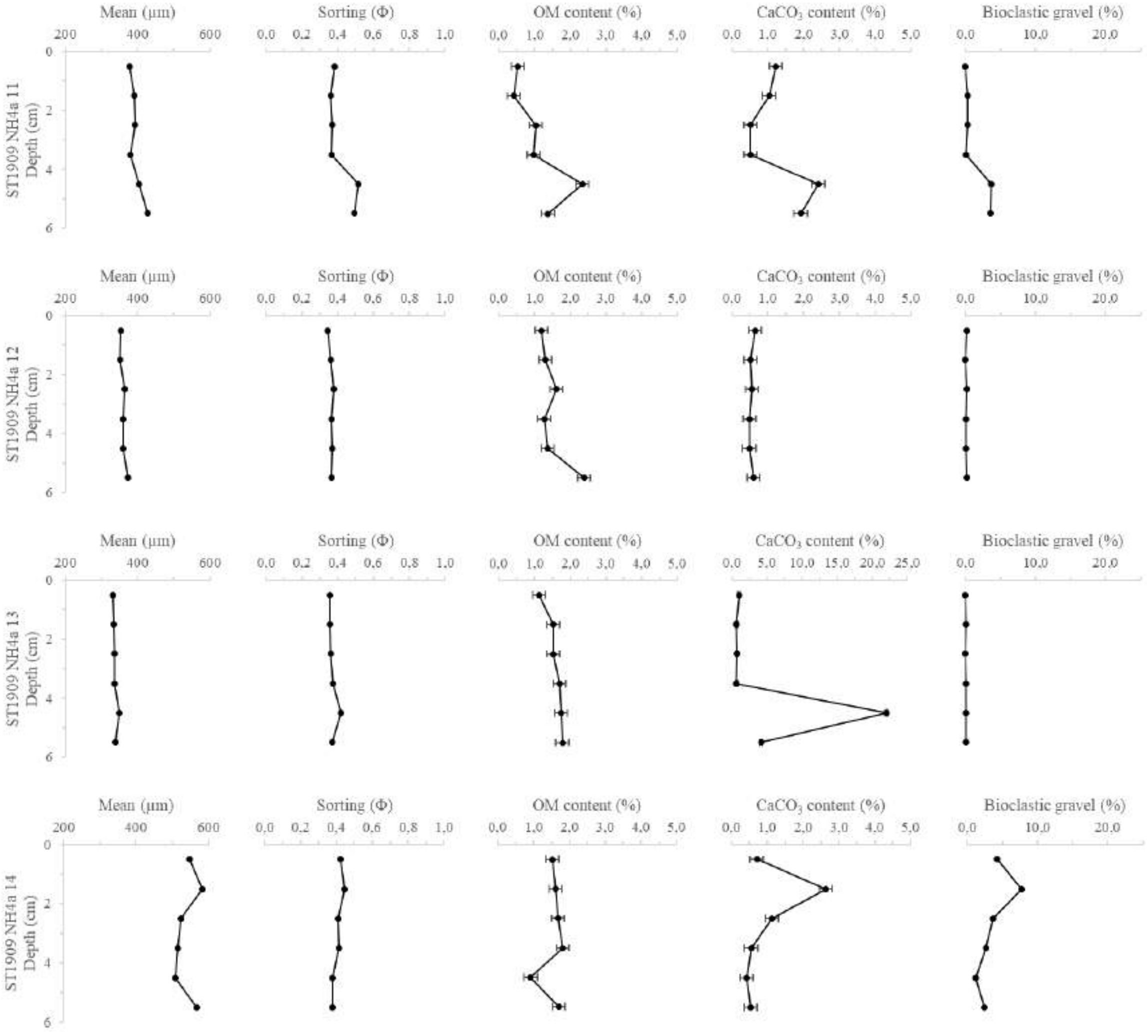


Table 5. The geometric mean and logarithmic sorting of F&W with the content of organic matter, carbonate and bioclastic gravel of the upper centimetres of the box cores taken in sector 4a during campaign ST1909 (NH4a 11 to NH4a 14).



5.2. Sector 4c

The majority of the sediment samples of 2014, 2018 and 2019 have a mean around 300 µm. Samples in the vicinity of locations 1 and 3 show higher mean values up to 400 µm and 550 µm, respectively. The geometric mean of samples near location 8 lies between 400 µm and 600 µm. The Φ-value of the sorting starts at 0.4 to 0.6, and with outliers up to 0.8 (ST1909 OH4c 2) and 2.5 (ST1407 7). Locations 1, 2, 4, 5 and 6 remained relatively stable between 2014 and 2019. Sampled differences occur near locations 3, 7 and 8. The content of the organic matter is less than 5% for all samples. Since 2014, the content of organic matter has increased near locations 1, 2 and 3, decreased near location 7 and remained stable near location 8. Locations 4, 5 and 6 decreased slightly in organic matter content from 2018 to 2019. The same 5% limit applies to the content in carbonates for the samples of 2018 (excluding A05) and 2019 (excluding OH4c 3). All samples of 2014 have a higher carbonate content (5% - 20%). Only the upper centimetres of ST1807 D03 and the lower part of ST1407 7 exhibit a certain concentration of mud, 2% and 10% (up to 20%), respectively. Some samples at locations 1, 3 and 8 show a relative amount of bioclastic gravel. Figure 4 maps the sediment properties D50, OM% and $CaCO_3$% anno 2019. Tables 6 and 7 show a comparative time series of the geometric mean and logarithmic sorting, and other sediment parameters as percentages in organic matter, carbonate and bioclastic gravel.

A decrease in multibeam backscatter (in dB), approximately from -20 dB to -30 dB, is detected on locations 1 - 2 - 5 and 7, while for locations 3 - 4 - 6 and 8 backscatter values are more stable from 2012 to 2019 (Table 8). A further distinction can be made between locations 3 and 8 with a value of -20 dB, and locations 4 and 6 with a value of -30 dB. Remarkable is the upward trend of the ST1807 B04 sample, while neighbouring samples ST1909 OH4c 1 and ST1407 3 show a decrease in backscatter reflectivity at the same location 1.

The grain-size distributions of the top centimetre per location have been plotted in Table 9. Locations 1 and 2 are quite stable since 2014. Although, a small shift of the 2018 samples is present. For location 1 this involves a limited shift to coarser fractions, for location 2 a slight shift to finer particles. Locations 4 and 6 appear to be the most stable locations over the past two years, while location 5 shows a shift towards finer fractions. In 2019, the grain-size distribution curve of location 7 shifted to a more coarse substrate. The most variable locations are locations 3 and 8. From 2014 to 2018, location 3 became coarser, but was refined again in 2019. The opposite occurred on location 8; a refinement of the sediment from 2014 to 2018 and a coarsening in 2019. Sediment composition of the upper centimetres at the eight locations is presented in Table 10.

Table 6. The geometric mean and logarithmic sorting of F&W with the content of organic matter, carbonate and bioclastic gravel of the upper centimetres of the box cores taken in sector 4c during campaigns in 2014, 2018 and 2019 (Locations 1 to 4).

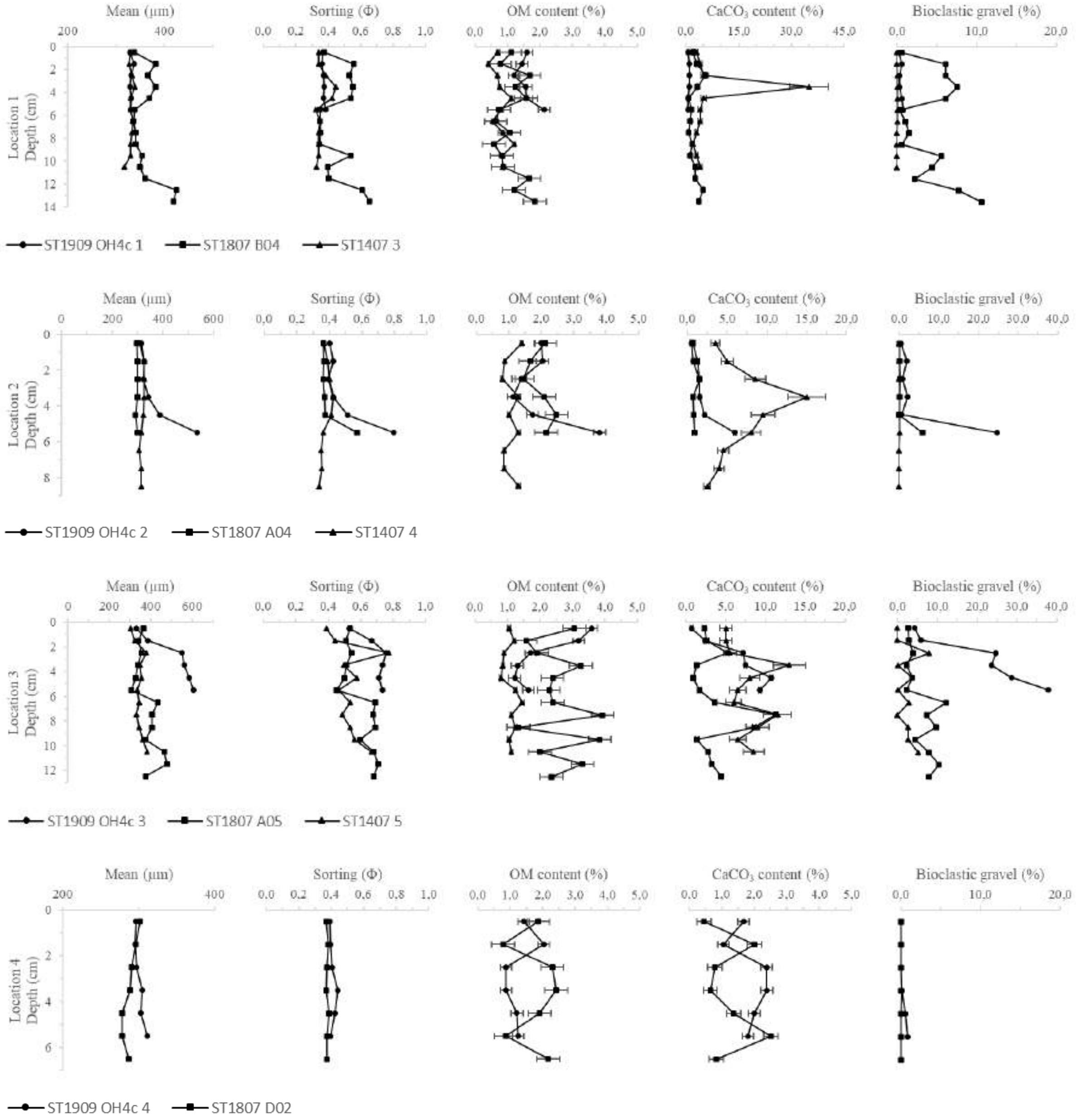


Table 7. The geometric mean and logarithmic sorting of F&W with the content of organic matter, carbonate and bioclastic gravel of the upper centimetres of the box cores taken in sector 4c during campaigns in 2014, 2018 and 2019 (Locations 5 to 8).

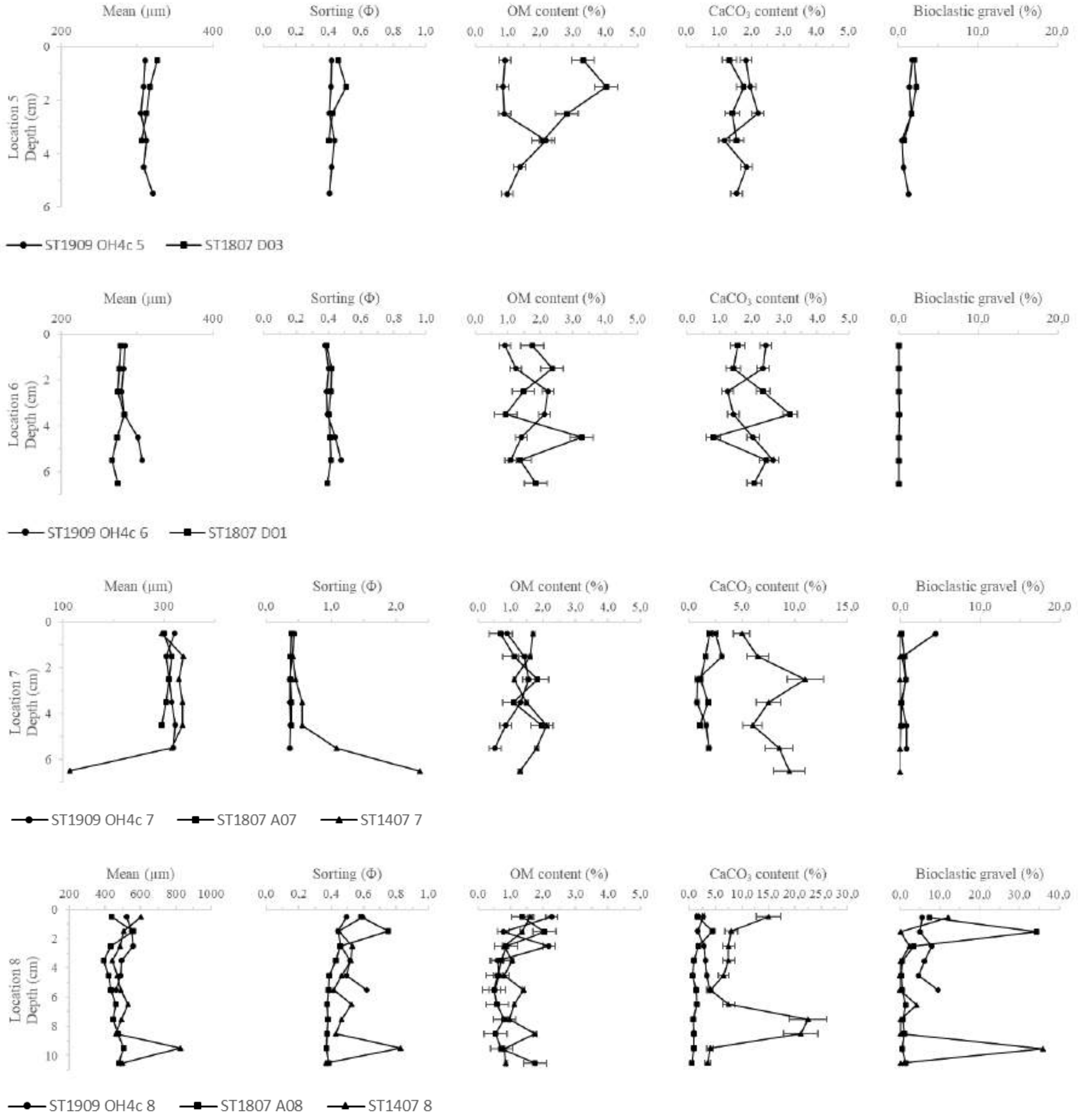


Table 8. Multibeam backscatter time series at the eight locations in sector 4c.

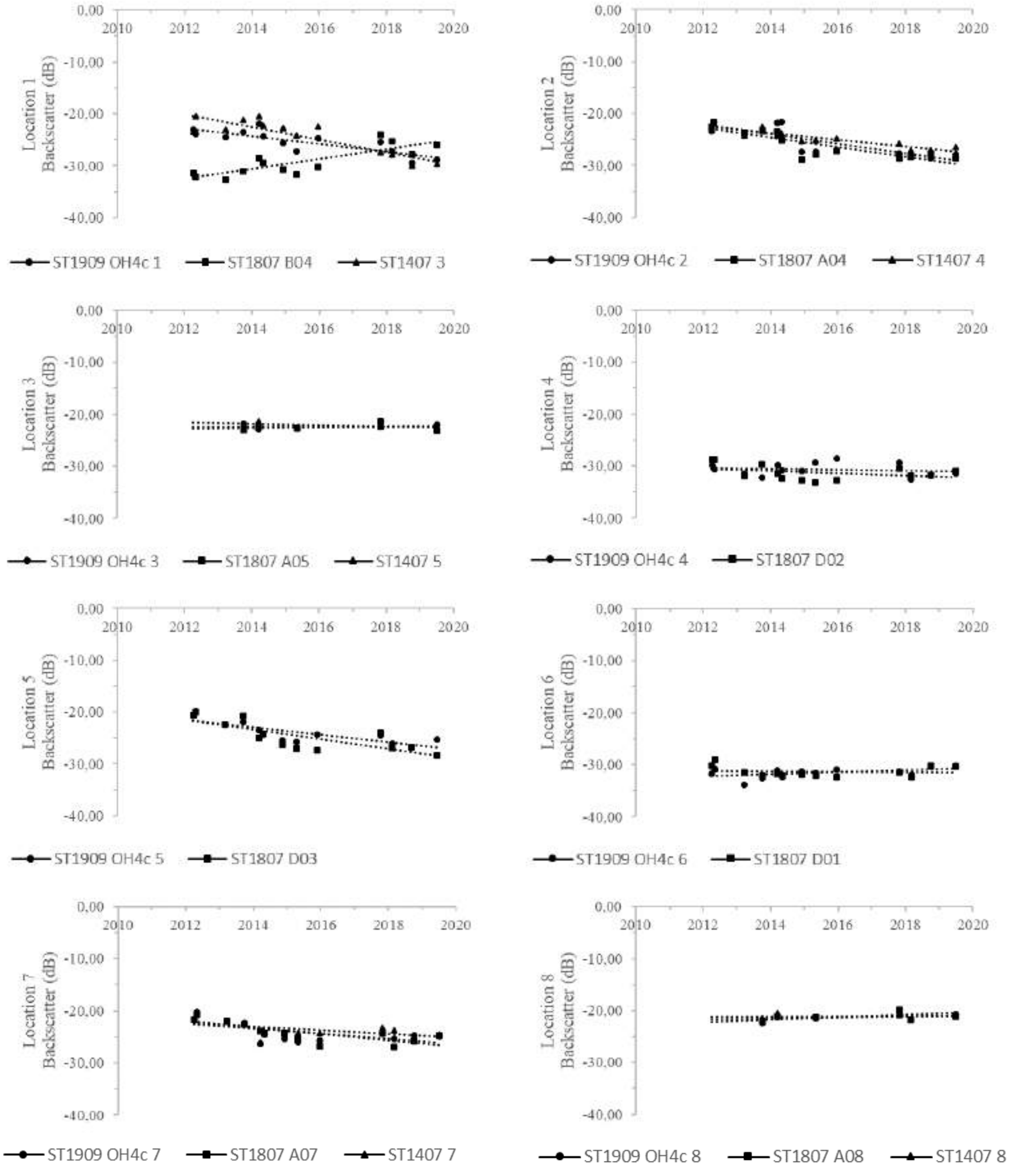


Table 9. Particle-size distribution curves at the eight locations (upper 1 cm) in sector 4c.

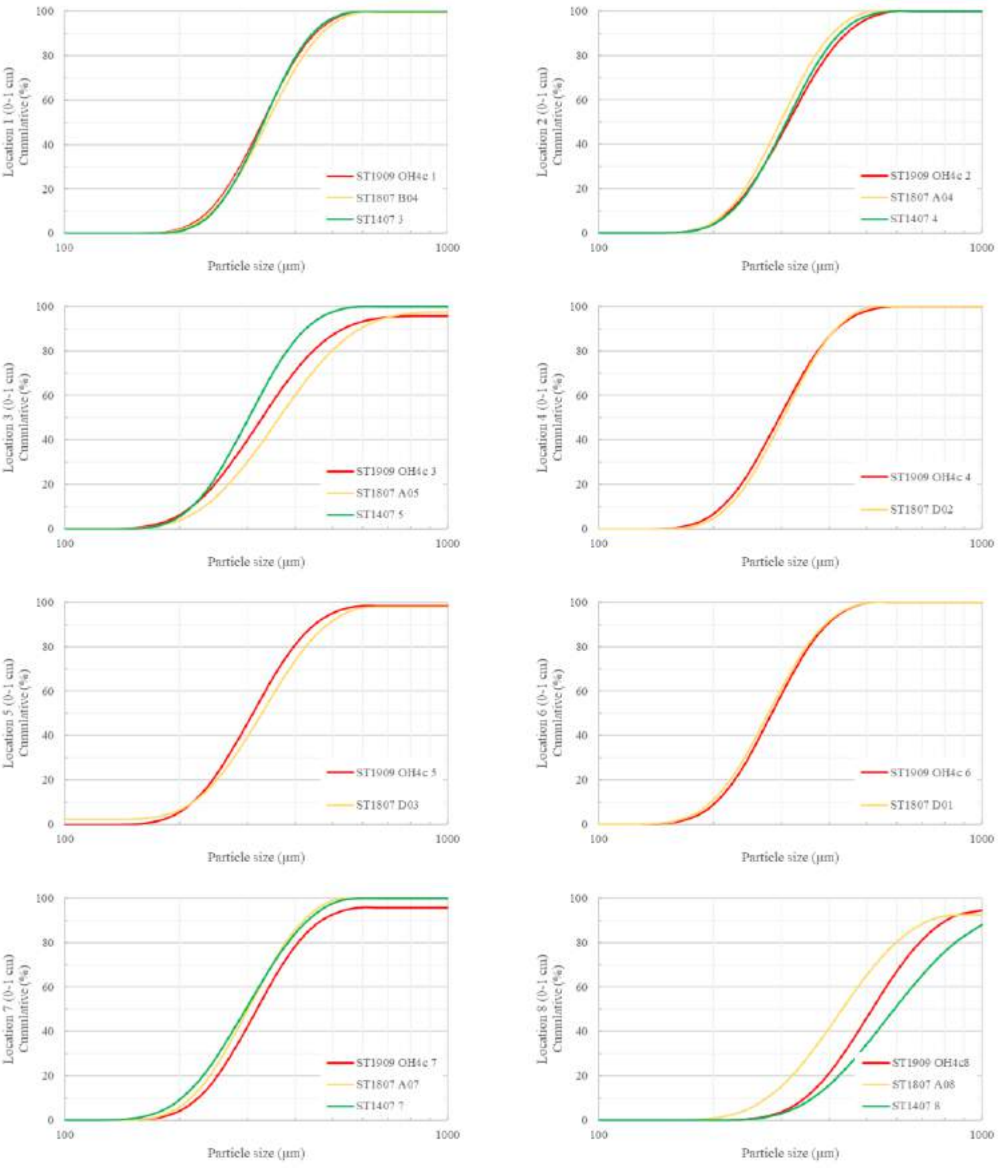


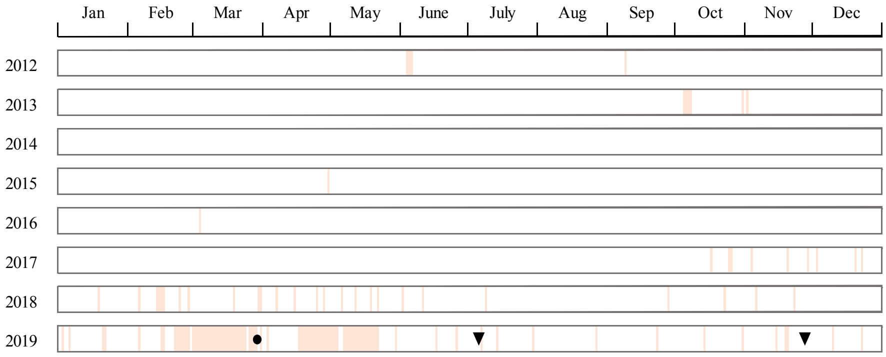
Table 10. Sediment composition at the eight locations (upper 6 cm) in sector 4c.

6. Discussion and conclusion

6.1. Sector 4a

Sand extraction in sector 4a intensified at the beginning of 2019. Mainly two periods of frequent extraction occurred in February-March and April-May. At the end of the first period of continuous seabed disturbance, 14 locations on the Noordhinder were sampled. Backscatter data from the FPS Economy are available from mid-2019. An overview is given in Table 11.

Table 11. Available backscatter (▼) and sediment (●) data plotted on a time series of sand extraction (▭) in sector 4a.



Limited extraction in sector 4a already occurred in 2017 and 2018 near locations NH4a 1 and NH4a 4 (Fig. 6d and 6e). In 2019, sand was extracted before, during and shortly after the spring campaign ST1909. A majority of the sector had already been subject to physical disturbance earlier that year (Fig. 5a). NH4a 1 to NH4a 6, NH4a 8, NH4a 11 and NH4a 14 were located within the extraction, while the other samples were in the immediate vicinity of the activities. Afterwards sand extraction was more concentrated in the northern area of sector 4a (Fig. 5b). Only samples NH4a 3, NH4a 4 and NH4a 6 were located within this densely disturbed area.

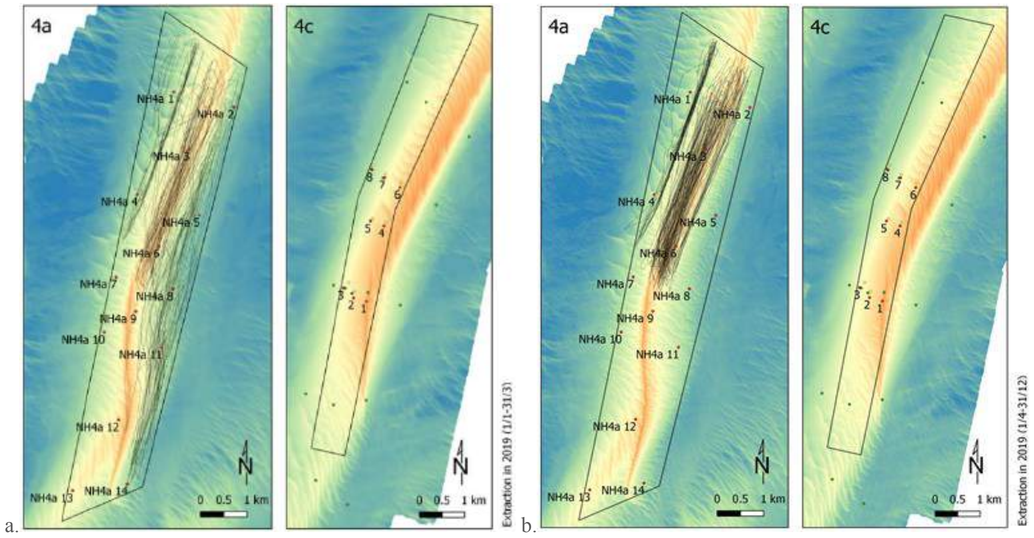


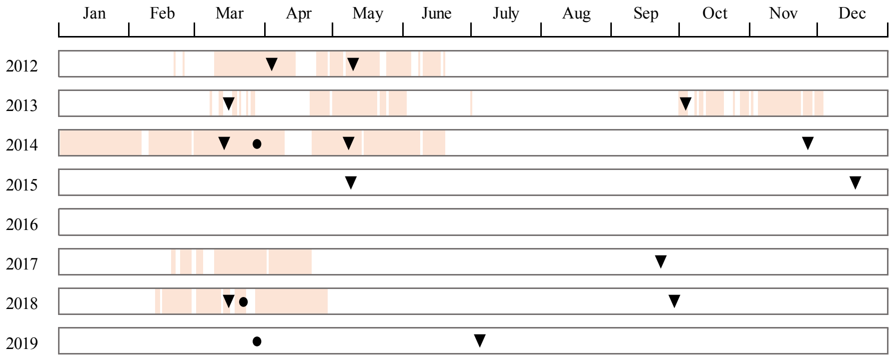
Figure 5. Electronic Monitoring System (EMS) track lines of operating sand extraction vessels in sector 4a and 4c in 2019. Two periods of intensive extraction are defined in a. February-March, and b. April-May. EMS and MBES data from FPS Economy, Continental Shelf Service.

In general, increased values of organic matter have been calculated for all samples. At locations where sand was regularly extracted from 2017 to March 2019 (e.g. NH4a 1 to NH4a 4), the content of organic matter was significantly higher (2% to 5%). At the other locations the values were less significant, but still increased (1% to 2%).

6.2. Sector 4c

In 2012, 2013, 2014, 2017 and 2018 sand extraction in sector 4c took place at regular times in the beginning of the year. In 2013 there was an exceptional period of extraction in October and November. No extraction occurred in 2015, 2016 and 2019. The 16 sediment samples of 2014 were taken during an intensive extraction period. In 2018, eight sediment samples were taken when extraction took place in the area, whereas these conditions did not apply to the eight repeated sediment samples in 2019. Backscatter data from the FPS Economy are available for several moments in time. A summary is given in Table 12.

Table 12. Available backscatter (▼) and sediment (●) data plotted on a time series of sand extraction (▭) in sector 4c.



Sand extraction in sector 4c mainly took place in the eastern part of the sector, only in 2014 the extraction was more extensive (Fig. 6). Locations 1, 4 and 6 are located in the most disturbed areas of the sector. Locations 2, 5 and 7 were heavily disturbed from 2012 to 2014, but experienced lower disturbance in 2017 and 2018. The least disturbed locations are locations 3 and 8. For all samples, no disturbance occurred in 2015, 2016 and 2019.

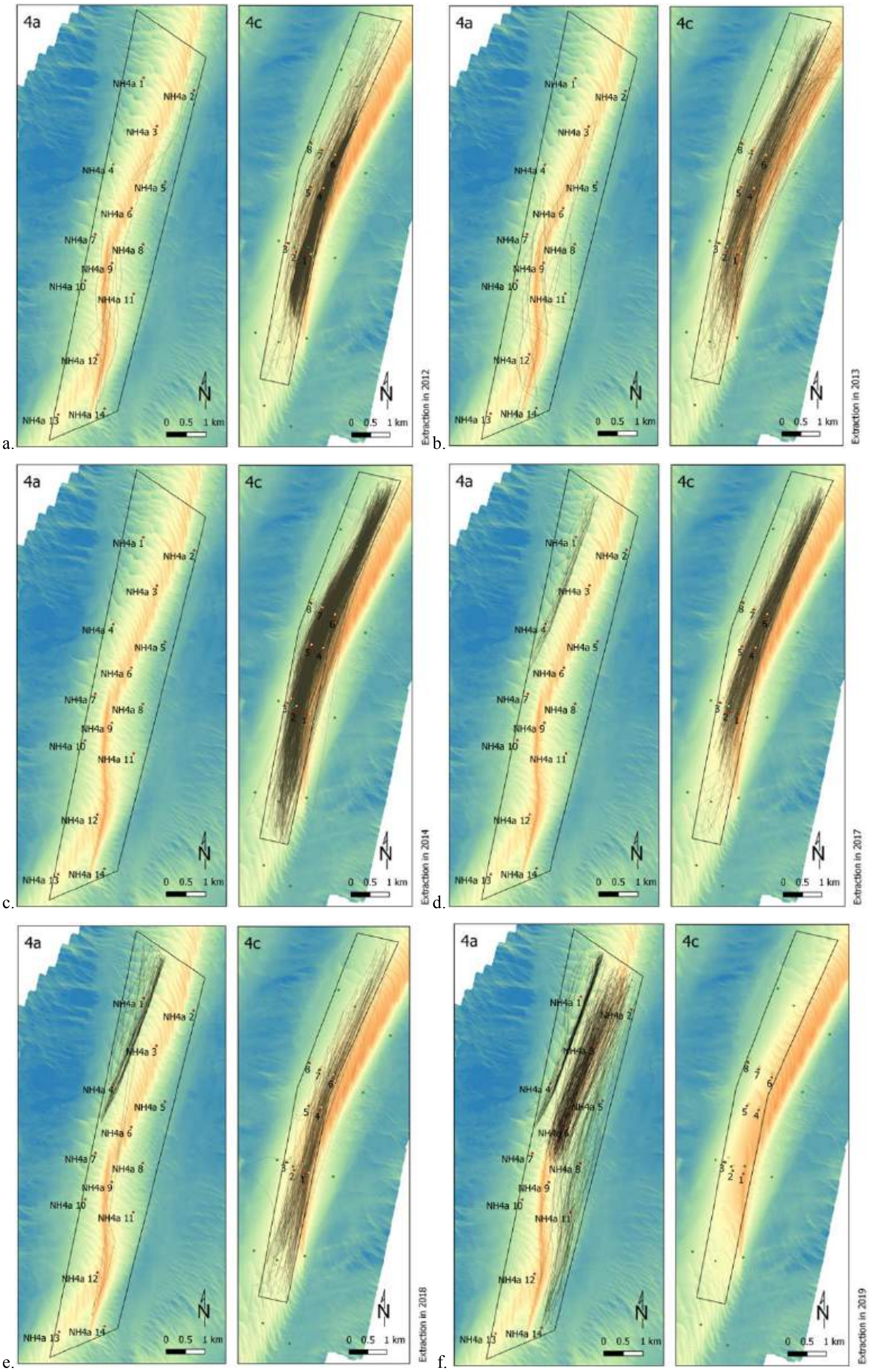


Figure 6. Electronic Monitoring System (EMS) track lines of operating sand extraction vessels in sector 4a and 4c from 2012 to 2019. In 2015 and 2016 no extraction took place in sector 4a and 4c. EMS and MBES data from FPS Economy, Continental Shelf Service.

An increase in organic matter content at heavily disturbed locations 1 and 2 has been observed. Location 3 is less disturbed but still has high organic content values. The decrease in organic content from 2018 to 2019 at locations 3 to 7 can be explained by the non-extraction year 2019 for sector 4c. Presumably locations 1 and 2 are too disturbed to observe such a decline. As such, the drop is more limited for locations in the most disturbed areas of the sector, locations 4 and 6, than for location 5 where extraction diminished. Extraction near location 7 has been decreasing since 2014, resulting in a small decrease in organic matter. At location 8, the influence of extraction was limited and organic matter content remained stable over time. Table 13 gives an indication of the average and maximum organic matter content for each location per sampling year.

Table 13. Average (maximum) organic matter content (in %) of the upper centimetres per location, per sampling year.

	Loc1	Loc2	Loc3	Loc4	Loc5	Loc6	Loc7	Loc8
2014	0.80	1.08	1.10	/	/	/	1.59	1.13
	(1.20)	(1.40)	(1.45)				(2.10)	(1.75)
2018	1.13	1.99	2.59	1.76	3.06	1.86	1.34	0.95
	(1.84)	(2.47)	(3.93)	(2.41)	(4.04)	(3.27)	(1.96)	(2.05)
2019	1.59	2.02	2.11	1.28	1.20	1.50	1.09	1.17
	(2.13)	(3.80)	(3.60)	(2.04)	(2.17)	(2.24)	(1.57)	(2.26)

For the majority of the locations sampled in 2014, the carbonate content has decreased as extraction of sand progressed in time. Location 3 remained an area of higher carbonate content, which does not apply to location 8 where there is a more significant drop. Still, a high amount of bioclastic gravel and a low degree of disturbance is present in both locations. Locations 4, 5 and 6 are too disturbed that a trend without samples from 2014 is not possible. Table 14 gives an indication of the average and maximum carbonate content for each location per sampling year.

Table 14. Average (maximum) carbonate content (in %) of the upper centimetres per location, per sampling year.

	Loc1	Loc2	Loc3	Loc4	Loc5	Loc6	Loc7	Loc8
2014	6.55	6.72	7.68	/	/	/	7.71	9.74
	(35.00)	(15.00)	(13.00)				(11.00)	(22.50)
2018	2.53	0.98	3.78	1.23	1.52	1.98	1.47	1.39
	(5.69)	(1.51)	(11.29)	(2.52)	(1.77)	(3.17)	(1.95)	(4.39)
2019	0.82	2.07	6.26	1.89	1.76	2.02	1.77	2.93
	(1.08)	(5.91)	(10.69)	(2.39)	(2.20)	(2.65)	(3.10)	(3.92)

Organic matter and carbonate content are plotted in relation to the sorting of the upper centimetres of the eight locations in sector 4c (Fig. 7 and 8), resulting in a significant influence by extraction over time. The quantity of organic matter in the samples increased from 2014 to 2018, but reduced again after a year without extraction in 2019. The carbonate content does the opposite. The amount of carbonate decreased from 2014 to 2018, but regained some percentages in 2019.

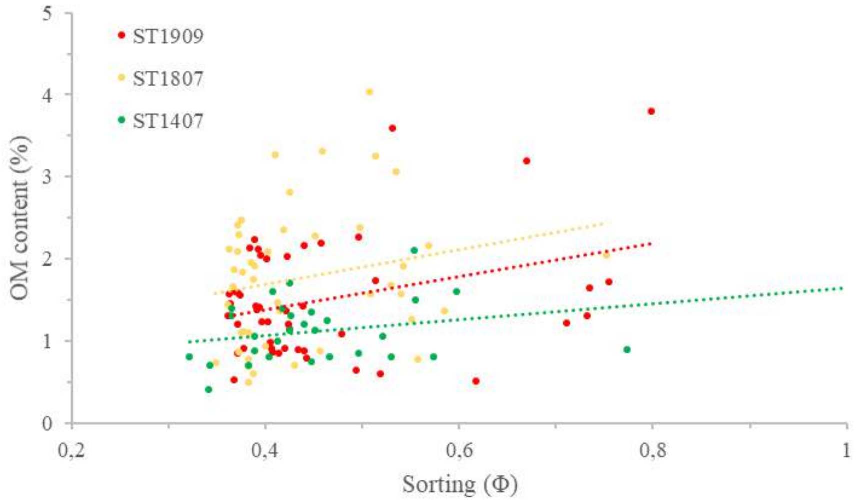


Figure 7. Scatter plot of the sorting versus the organic matter content of the eight locations (upper 6 cm) in sector 4c.

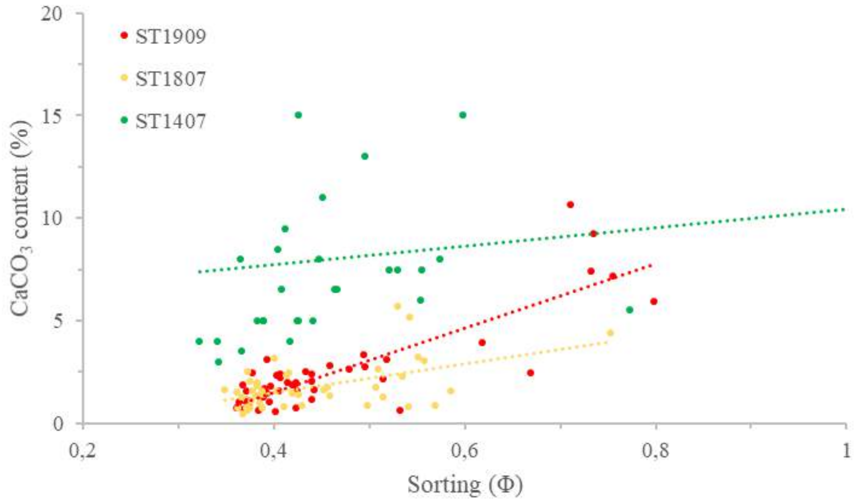


Figure 8. Scatter plot of the sorting versus the carbonate content of the eight locations (upper 6 cm) in sector 4c.

Multibeam backscatter data confirms the change in the sediment matrix at locations 1, 2, 5 and 7 in sector 4c. They follow an evolution from an undisturbed or slightly disturbed environment (e.g. locations 3 and 8; -20 dB) to an area with intensive disturbance (e.g. locations 4 and 6; -30 dB). Locations 3 and 8 with low disturbance are stable over time. Multibeam backscatter values for locations 4 and 6 remain stable as well, regardless the intensive extraction, but no clear explanation can be given without initial long-term information. Presumably, they are so continuously disturbed that the locations remain 'stable'. The upward backscatter trend of ST1807 B04 can be explained by a region with a large amount of bioclastic gravel, as observed in 2018. Bioclastic gravel has different scattering properties than sand or mud.

In order to further explain the above mentioned multibeam backscatter findings, a correlation with the top centimetre of the seabed is recommended. The significant change in the sediment matrix of locations 1, 2, 5 and 7 is not always reflected by a shift towards a finer or coarser substrate. Heavily disturbed locations 4 and 6 show a stable grain-size distribution curve over the past two years. The particle-size distributions of the undisturbed to slightly disturbed locations 3 and 8 are highly variable.

6.3. *Influence of sand extraction on sediment properties*

When evaluating the effect of aggregate extraction on sediment properties, the time series show a change from a carbonate-rich sediment to an organic-rich and carbonate-poor sediment. Further research will have to show whether this change is temporary (physical disturbance) or permanent (physical loss). Grain-size changes are less evident and both fining and coarsening trends are observed. The decrease in carbonate content, which probably explains the decrease in backscatter strength as generally demonstrated by the multibeam datasets of FPS Economy, is likely due to the frequent reworking of the sediment and the re-deposition of the parent material in the near-field, whether or not screened for coarse material. A grain-size change could still occur in areas where geologically other lithological classes appear. For both sectors 4a and 4c, this is the case on the lower flanks of the sandbank where Pleistocene sediments are located near the seabed surface (Fig. 9 and 10).

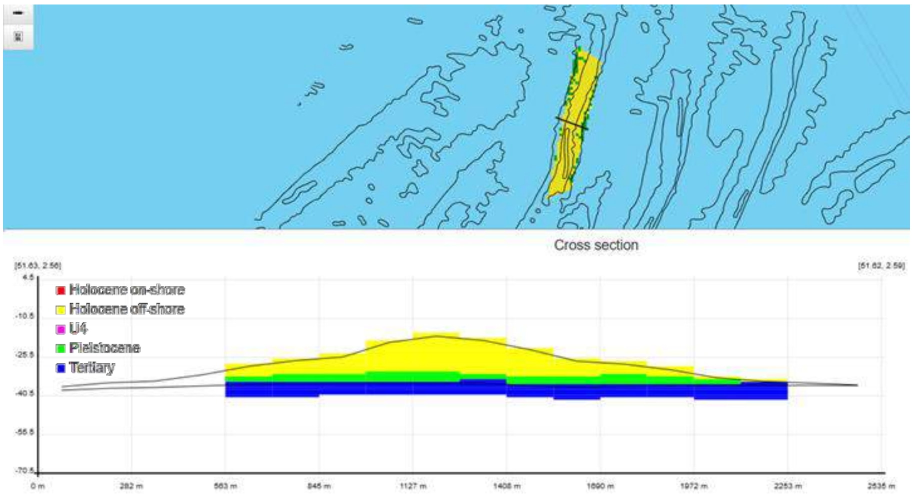


Figure 9. Cross section over sector 4a on the Noordhinder showing the surfacing of Pleistocene sediments at the lower flanks of the sandbanks. Extracted from the TILES decision support system (http://www.bmdc.be/tiles-dss - TILES Consortium 2018).

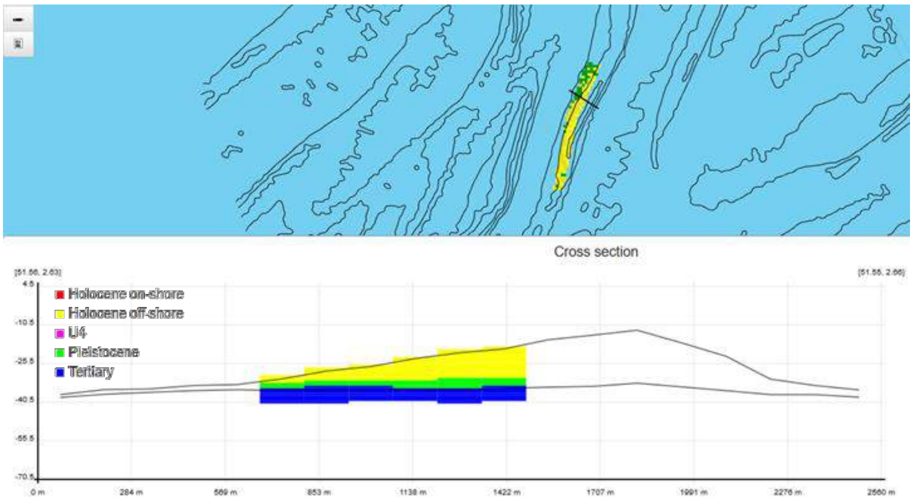


Figure 10. Cross section over sector 4c on the Oosthinder showing the surfacing of Pleistocene sediments at the lower flanks of the sandbanks. Extracted from the TILES decision support system (http://www.bmdc.be/tiles-dss - TILES Consortium 2018).

The origin of the increase in organic matter with increasing extraction intensity at given locations needs further investigation. Offshore seabed sediments of sandbanks are typically low in organic matter (around 1% or lower) (Arndt et al. 2013; Coates et al. 2013, 2015). Enrichment of organic matter by human activity has already been demonstrated in wind farm areas (e.g. Coates et al. 2013; Lefaible et al. 2019). However, it was suggested that the hard-substrate epifauna growing on wind-turbine foundations and scour protection systems were responsible for the higher organic matter input onto the seabed, resulting in changing sedimentological conditions directly around the foundation (Coates et al. 2013). Water samples taken in the Hinder Banks region before extraction activities started, showed SPM with a median particle size of 7 µm (Fettweis 2008). Van Lancker et al. (2016) showed increased particulate organic matter content in water samples collected in the vicinity of dredging vessels. Particle-size analysis of the suspended particulate matter (SPM) showed the presence of very fine particles around 10 µm (after centrifugation). New results from water-rich sediment samples originating from the cargo of dredging vessels showed sizes of around 25 µm (no centrifugation) (Van Lancker et al. 2020), a fraction that was not measured in the seabed sediments. This may be due to outwash of this fraction during the sampling, or it is linked to the presence of organic matter since during the pre-treatment of the seabed samples organic material was removed. More in-depth analysis of all water and sediment samples so far collected is underway, but it seems plausible that extraction remobilizes organic matter content, from the parent bed, whether or not combined with a new source of organic matter. Due to enhanced sediment deposition in the near field organic matter is subsequently mixed into the parent bed and maybe re-extracted again. A new source of organic matter may relate to dredging works in the coastal zone prior to the offshore extraction as was shown by Baeye et al. (2019) and related to mud accumulation to the side walls of the cargo. It is not clear to what extent mortality of benthic and pelagic species during the intensive extraction periods contribute to the increased organic matter content.

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COLOPHON

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☐ confidential

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☐ Dutch
☐ French

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Royal Belgian Institute of Natural Sciences
Operational Directorate Natural Environment

Ecosystems Data Processing and Modelling
Suspended Matter and Seabed Monitoring and Modelling

The typefaces used in this document are Gudrun Zapf-von Hesse’s *Carmina Medium* at 10/14 for body text. and Frederic Goudy’s *Goudy Sans Medium* for headings and captions.

RV BELGICA CRUISE 2019/09 – CRUISE REPORT

Subscribers:	Prof. Dr. Vera Van Lancker[1] / Prof. Dr. Ann Vanreusel[2] / Mr. Giacomo Montereale Gavazzi[1]
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Monitoring/Geology/Education: 25/03/2019 - 29/03/2019

1. Cruise details
2. List of participants
3. Scientific objectives
4. Operational course
5. Track plot
6. Measurements and sampling
7. Remarks
8. Data storage

1. GENERAL FORM RV BELGICA 2019

1.	Cruise number		2019/09
2.	Date/time	Zeebrugge ETD Zeebrugge ETD T&G Zeebrugge T&G Zeebrugge Zeebrugge ETA	25/03/2019: departure cancelled 26/03/2019: 07h08 26/03/2019: 16h28-18h42 28/03/2019: 08h46-10h08 29/03/2019: 14h00
3.	Chief Scientist Participating institutes		Prof. Dr. Vera Van Lancker RBINS OD Nature
4.	Geographical area		Belgian part of the North Sea

2. LIST OF PARTICIPANTS

Institute	Family name	Given name	Gender	25-26/03	26-28/03	28-29/03
RBINS-ODN	Van Lancker	Vera	F	X	X	X
	Terseleer	Nathan	M	X	X	
	Kint	Lars	M	X	X	X
	Baeye	Matthias	M			X
	Van den Branden	Reinhilde	F	X		
	Storms	Simon	M			X
	Scholdis	Tom	M		X	X
	Eneman	Joke	F		X	X
	Moreau	Kelle	M	X		
RTBF	Morelle	Julie	F	X		
	Wantiez	Garry	M	X		
Students Oceans and Lakes	Arango Aragón	Joaquín Emilio	M	X		
	Boileau-Locas	Camille	F	X		
	Delhaye	Louise Julie C	F	X		
	Engelbrecht	Jacobus Albertus Adriaan	M	X		
	Ganoza Gallardo	María José	F	X		
	Gök	Duygu	F		X	
	Henkens	Symine Bertie	F		X	
	Kugonza	Priscilla	F			X
	Lambert	Elke	F			X
	Lear	Daniel	M	X		
	Loquere	Rose Antoneth	F			X
	Melake	Bealemlay Abebe	M	X		
	Mouyabi	Flaviancia	F		X	
	Moya Serrano	Ana Victoria	F		X	
	Mtonga	Cretusi Joseph	M		X	
	Nguyen	Dinh Thanh	M		X	

	Nurbandika	Navisa	F		X	
	Okoth	Ronald Reagan	M		X	
	Pappis	Thatiane	F			X
	Shymbaliova	Nadzeya	F			X
	Sindikubwabo	Vincent	M		X	
	Van Caster	Nathalie Laurence	F			X
	Van Craenenbroeck	Lore	F			X
	Wyns	Paulien Marc	F			X
			Students	7	9	8
			TOTAL	**14**	**14**	**15**

3. SCIENTIFIC OBJECTIVES

OD NATURE-VVL/UG-SMB - STUDENTS

Students will be trained in the framework of the MSc program Oceans and Lakes, course “In-situ and remote sensing tools in Aquatic Sciences”. They will learn to: conduct most of the stages of a scientific expedition at sea (from sample collection to reporting); apply a multidisciplinary approach in marine research; (3) get acquainted with different techniques of data and sample collection at sea; (4) collaborate in a scientific team including the vessel crew in order to achieve common objectives; and (5) gain insight in some important patterns of temporal variation and spatial gradients present on the Belgian Part of the North Sea (BPNS). Measurements and observations are performed in function of scientific projects (ZAGRI/MOZ4, *see below*).

OD NATURE-VVL-ZAGRI/MOZ4

ZAGRI is a continuous research program on the evaluation of the effects of the exploitation of non-living resources of the territorial sea and the continental shelf. MOZ4 focuses on the monitoring of hydrodynamics and sediment transport in relation to marine aggregate extraction in a far offshore zone. Overall aim is to increase process and system knowledge of this area, with a particular focus on the compliancy of the extraction activities with respect to the European Marine Strategy Framework Directive. More specifically changes in seafloor integrity and hydrographic conditions will be assessed. An important parameter is the bottom shear stress, with knowledge needed on both natural and anthropogenically-induced variability. Results will be used for the validation of mathematical models, necessary for impact quantification.

OD NATURE-GMG

INDI67/SEACoP – Monitoring MSFD indicators on seafloor integrity and hydrographic conditions / Joint seabed mapping

Within Europe’s Marine Strategy Framework Directive (MSFD), progress towards Good Environmental Status (GES) needs monitoring in a most time- and cost-effective way. For the GES descriptors 6 and 7, on seafloor integrity and hydrographic conditions, respectively, new integrative indicators (i.e. bottom shear stress, turbidity and seabed/habitat type) need developing. To advance the mapping of seabed/habitat types, a Community of Practice (CoP) on seabed mapping will be established, investigating the main issues preventing joint mapping of the seabed. Within SEACoP (CoP on *‘Surveying for Environmental Assessments’*) the following objectives are targeted: a) estimation of the precision, sensitivities and repeatability of the acoustic devices to detect changes in seabed/habitat types; b) quantification of the external sources of variance in the acoustic signature, including the influence of near-bed and water column suspensions on backscatter data; c) definition of best practice in ground-truthing the acoustic signal, with emphasis on visual techniques; and d) innovation in collaborative seabed mapping.

OD NATURE-LN (AUMS)

The AUMS (Autonomous Underway Measurement System) project is inspired by the success of similar systems deployed on various ships of opportunity in the framework of the European Union FerryBox project (www.ferrybox.org). The instrumentation will greatly enhance the continuous oceanographic measurements made by RV Belgica by taking advantage of the significant technological improvements since the design of the existing (salinity, temperature, fluorescence) systems. In particular, many new parameters can now be measured continuously including important ecosystem parameters such as nitrate, ammonia, silicate, dissolved oxygen and CO2, turbidity, alkalinity and phytoplankton pigments. In addition, the new equipment allows automatic acquisition and preservation of water samples, rendering RV Belgica operations significantly more efficient by reducing onboard human resources. Data will be available in near real-time via OD Nature's public web site and following quality control, from the Belgian Marine Data Centre.

4. OPERATIONAL COURSE

All times are given in local time. All coordinates in WGS84.

Monday 25/03/2019

High Tide Zeebrugge 04h15, 16h43
Low Tide Zeebrugge 10h44, 22h57

09h00-10h30 Embarkation of instruments and personnel.
Weather forecast are too bad to sail out and departure is postponed to Tuesday morning 7h15.
Day in harbor.

Tuesday 26/03/2019

High Tide Zeebrugge 05h01, 17h29
Low Tide Zeebrugge 11h27, 23h40

07h08 Sail off from Zeebrugge

Transit to north of Vlakte van de Raan for multibeam measurements and sampling

08h25-13h04 Multibeam recordings Vlakte van de Raan

13h13-14h15 Reineck boxcoring Vlakte van de Raan (onboard slicing (1cm))

Transit to MOW1 for tripod deployment

15h26 Tripod deployment at position 51°21.655, 003°06.895

Transit to Zeebrugge

16h28-18h42 Touch & Go Zeebrugge
Disembarkation students group 1, OD Nature Reinhilde Van den Branden, RTBF Crew, Kelle Moreau
Embarkation students group 2, OD Nature Tom Scholdis, Joke Eneman
Departure was postponed because of navy ships entering the harbor.

Transit to area in-between Oosthinder and Bligh Bank

21h32-22h38 Video recording in presumed gravel areas (Video transect 1)

23h10 Cross-bank profile Sector 4b-4c (similar to profile of campaign ST1208).

Combination multibeam echosounder and HM-ADCP.
Seacat profiling with water sample at the top of the sandbank

Wednesday 27/03/2019

High Tide Zeebrugge 05h48, 18h19
Low Tide Zeebrugge 12h14

-08h45 End of measurements

10h10-11h23 Video recording in presumed gravel areas (Video transect 2, 3)

11h28-14h05 Multibeam echosounding area in-between Oosthinder and Bligh Bank, in continuation of campaign ST1824

Transect to Sector 4c

14h10-15h30 Reineck boxcoring and onboard slicing (1 cm slices), Sector 4c

Transect to Sector 4a

16h36- Cross-bank profile Sector 4a (similar to profile of ST1208).
Combination multibeam echosounder and HM-ADCP.
Seacat profiling with water sample at the top of the sandbank

Thursday 28/03/2019

High Tide Zeebrugge 06h43, 19h22
Low Tide Zeebrugge 00h30, 13h18

-05h03 End of measurements

Transit to Zeebrugge harbor

08h46-10h08 Touch & Go Zeebrugge
Disembarkation students group 2; Nathan Terseleer
Embarkation students group 3; OD Nature, Matthias Baeye, Simon Storms

Transit to Noordhinder sandbank, sector 4a

13h32-14h58 Reineck boxcoring and onboard slicing (1 cm slices), Sector 4a

15h15-16h05 Deployment BM-ADCP Sector 4a at 16h05. A multibeam line was sailed first to confirm position of the deployment. Position 51°34.338, 002°32.682.

16h43-18h28 Continuation of Reineck boxcoring and onboard slicing (1 cm slices), Sector 4a

19h30 Anchoring near BM-ADCP at the edge of Sector 4a. Position 51°34.160, 002°32.420.
Through-tide measurements using Seacat/LISST200 profiler. First profile at 19h40.

Friday 29/03/2019

High Tide Zeebrugge 07h59, 20h46
Low Tide Zeebrugge 01h56, 14h42
LK min 29/3

-09h00 End of measurements. Van Veen grab sample.

Transit to area in-between Oosthinder and Bligh Bank

09h30-10h30 Seabed sampling (Hamon grab) along video transects.

Transit to Zeebrugge harbor

14h00 Zeebrugge Harbor

End of campaign

RV BELGICA CRUISE 2019/19 – CRUISE REPORT

Subscribers:	Dr. Ilse De Mesel[1a], Dr. Vera Van Lancker (VVL)[1b], Giacomo Montereale Gavazzi[1b]
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Legend: Black: fixed lay-out
Red: example and to be filled in
Blue: to be filled in

Monitoring: 08/07/2019 - 12/07/2019

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1. Cruise details
2. List of participants
3. Scientific objectives
4. Operational course
5. Track plot
6. Measurements and sampling
7. Remarks
8. Data storage

1. CRUISE DETAILS

1.	Cruise number	2019/19
2.	Date/time	08/07/2019 at 12h36 (TD Zeebrugge) – 20h17 (TA Zeebrugge) 09/07/2019 at 09h35 (TD Zeebrugge) – 21h02 (TA Zeebrugge) 10/07/2019 at 08h00 (TD Zeebrugge) – 20h43 (TA Zeebrugge) 11/07/2019 at 13h00 (TD Zeebrugge) – 12/07/2019 08h15 (Ostend harbor)
3.	Chief Scientist Participating institutes	Dr. Ilse De Mesel OD NATURE
4.	Area of interest	Belgian part of the North Sea

2. LIST OF PARTICIPANTS

Institute	NAME	Gender	08/07 – 10/07/19	11/07 – 12/07/19
OD NATURE	Ilse De Mesel	*F*	X	X
	Danae Kapasakali	*F*	X	X
	Francis Kerckhof	*M*	X	X
	Sindhura Stothra Bhashyam	*F*	X	X
	Mirta Zupan	*F*	X	X
	Vera Van Lancker	*F*	X	X
	Giacomo Montereale Gavazzi	*M*	X	X
	Lars Kint	*M*	X	X
	Nathan Terseleer	*M*	X	X
	Alain Norro	*M*	X	
	Anjali Gopakumar	*F*	X	X
Divers (volunteers from OD Nature)	Valerie Woit	*F*	X	
	Marie Vigoni	*F*	X	
	Marc Van Espen	*M*	X	
		Total participants:	14	10

3. SCIENTIFIC OBJECTIVES

OD NATURE– IDM-MSFD GRAVEL-BIO

As part of the European Marine Strategy Framework Directive (MSFD), a series of biodiversity indicators must be monitored. To be able to meet the monitoring obligation, samples must be taken in gravel beds from the Belgian part of the North Sea. The sampling includes the sampling of the endobenthos with a hamon grab and the epibenthos on with a Gilson dredge. In order to be able to monitor the gravel beds in a less destructive way in the long term, video images of the seabed are also collected using a video frame. The data is analyzed for species occurrence and linked to functional features of the community.

OD NATURE-VVL-ZAGRI/MOZ4

ZAGRI is a continuous research program on the evaluation of the effects of the exploitation of non-living resources of the territorial sea and the continental shelf. MOZ4 focuses on the monitoring of hydrodynamics and sediment transport in relation to marine aggregate extraction in a far offshore zone. Overall aim is to increase process and system knowledge of this area, with a particular focus on the compliancy of the extraction activities with respect to the European Marine Strategy Framework Directive. More specifically changes in seafloor integrity and hydrographic conditions will be assessed. An important parameter is the bottom shear stress, with knowledge needed on both natural and anthropogenically-induced variability. Results will be used for the validation of mathematical models, necessary for impact quantification.

OD NATURE-GMG

INDI67/SEACoP – Monitoring MSFD indicators on seafloor integrity and hydrographic conditions / Joint seabed mapping

Within Europe's Marine Strategy Framework Directive (MSFD), progress towards Good Environmental Status (GES) needs monitoring in a most time- and cost-effective way. For the GES descriptors 6 and 7, on seafloor integrity and hydrographic conditions, respectively, new integrative indicators (i.e. bottom shear stress, turbidity and seabed/habitat type) need developing. To advance the mapping of seabed/habitat types, a Community of Practice (CoP) on seabed mapping will be established, investigating the main issues preventing joint mapping of the seabed. Within SEACoP (CoP on *'Surveying for Environmental Assessments'*) the following objectives are targeted: a) estimation of the precision, sensitivities and repeatability of the acoustic devices to detect changes in seabed/habitat types; b) quantification of the external sources of variance in the acoustic signature, including the influence of near-bed and water column suspensions on backscatter data; c) definition of best practice in ground-truthing the acoustic signal, with emphasis on visual techniques; and d) innovation in collaborative seabed mapping.

WinMon – Underwater noise

The construction and operation of offshore wind farms generates noise both above and under water that may be of environmental concern. At the European level, the new EU Marine Strategy Framework Directive (MSFD) has identified noise as one of the pressures that needs to be controlled to achieve the 'good environmental status' of European marine waters. This project concerns the monitoring of the noise above and under water, during the construction and the operational phase of wind farms on the Belgian part of the North Sea. Environmental monitoring of underwater noise in a wind park located inside the Belgian zone of the North Sea. An underwater sound recorder will be moored in the Northwester2 zone in order to monitor the construction-emitted sound.

4. OPERATIONAL COURSE

Because some members of the crew were ill and could not be replaced, it was decided go for daytrips each day. The planning had to be changed completely on board. 2/3 of the work that was planned could not be executed.

Timings are indicative and given in local time. All coordinates in WGS84.

Monday 08/07/2019

09:00-10:30	Embarkation of equipment and personnel
12:36	Departure Zeebrugge
12:36-15:39	**Transit to Flemish Banks, station 25**
15:39-15:52	Deployment Gilson dreg. In the dredge mostly shells were captured; no samples were taken.
15:58	**Transit to station 24**
16:25-16:37	Deployment videoframe
16:51-16:58	Deployment Gilson dreg
17:20-17:31	Sampling Hamon grabs (3 replicates)
17:31-20/17	Transit to Zeebrugge
20:17	Arrival at Zeebrugge

|

Tuesday 09/07/2019

09:35	Departure in Zeebrugge
09:34-12:56	**Transit to Hinder Banks, station 21**
12:57-13:05	Deployment Gilson Dreg
13:24-13:36	Deployment Hamon grab (3 replicates)
13:36-14:46	**Transit to station V2**
14:50-14:57	Deployment Hamon grab
15:10-15:50	Multibeam
16:20-17:54	Scientific diving at location V2. Dive 1: 16:20:55-16:42:59; Dive 2: 17:13:45-17:44:01.

18:10-21:02	Transit to Zeebrugge
21:02	Arrival at Zeebrugge

Wednesday 10/07/2019

08:00	Departure Zeebrugge
08:00-11:10	**Transit to Hinder Banks, location V5**
11:20-12:55	Scientific diving at location V5. Dive 1: 11:35:00-11:55:00. Dive 2: 12:24:00-12:50:00.
13:15-13:27	**Transit to Station 23**
13:27-13:40	Deployment of Gilson dredge
13:48-14:00	Deployment Hamon grab (3 replicates)
14:00-14:15	**Transit to location V5**
14:17-14:30	Deployment Hamon grab (3 replicates)
14:30-15:26	Multibeam at station V5
15:26-16:05	**Transit to station V2**
16:07-16:32	Deployment Hamon grab (3 replicates) at two locations
16:32-17:40	Multibeam at station V2
17:40-20:43	Transit to Zeebrugge
20:43	Arrival at Zeebrugge

Thursday 11/07/2019

13:00	Departure Zeebrugge
13:00-17:10	**Transit to Norther Exploration Zone, location 20**
17:20-17:30	Deployment of Gilson grab
17:38-17:50	Deployment Hamon grab (3 replicates)
18:10-	Multibeam Northern Exploration Zone
	Transit to location 19
19:25-19:35	Deployment of Gilson dredge
19:45-20:15	Deployment Hamon grab (3 replicates)
20:34-21:10	Video around station 19 (two locations)
21:15-	Continuation Multibeam Northern Exploration Zone

Friday 12/07/2019

-02:02	End of Multibeam Northern Exploration Zone
02:15-02:45	Video along three trajectories. Problems with winch necessitating a halt of the video imaging.
03:40	**Transit to Ostend harbor**
08:15	Arrival in the harbor of Ostend from where RV Belgica continued its trajectory to the shipyard in Plassendale. Disembarkment of the scientific teams after passing the sluice in Ostend.

- End of campaign 2019/19 -

5. TRACK PLOT

Cfr. OD Nature website
http://www.odnature.be/downloads/belgica/campaigns/tracks/tr2019_01.gif

6. MEASUREMENTS AND SAMPLING

PS. To obtain coordinates of the samplings and observations, timestamps need coupling to ODAS 1 sec data acquisition file and to the UTC field.

OD Nature – IDM (MSFD)

Gilson dredge samples were collected in 6 stations (Table 1) and Hamon grabs in 6 stations (table 2).

Table 1: Locations where biological samples were taken from a Gilson dredge.

ID	Gear	Timestamp -down	Timestamp -up	Comment
25	Gilson dredge	2019-07-08 13:43:39	2019-07-08 13:49:50	In the dredge mostly shells were captured; no samples were taken
24	Gilson dredge	2019-07-08 14:48:40	2019-07-08 14:54:24	
21	Gilson dredge	2019-07-09 10:59:42	2019-07-09 11:02:18	
23	Gilson dredge	2019-07-10 11:27:39	2019-07-10 11:33:18	
20	Gilson dredge	2019-07-11 15:21:45	2019-07-11 15:29:50	
19	Gilson dredge	2019-07-11 17:25:29	2019-07-11 17:34:19	

Table 2: Locations where biological samples were taken from a Hamon grab. Three replicates per location.

ID	Gear	Timestamp (UTC)
24_1	Hamon Grab	2019-07-08 15:18:01
24_2	Hamon Grab	2019-07-08 15:21:32
24_3	Hamon Grab	2019-07-08 15:26:45
21_1	Hamon Grab	2019-07-09 11:23:39
21_2	Hamon Grab	2019-07-09 11:26:58
21_3	Hamon Grab	2019-07-09 11:29:52
23_1	Hamon Grab	2019-07-10 11:48:29
23_2	Hamon Grab	2019-07-10 11:51:40
23_3	Hamon Grab	2019-07-10 11:54:14
V5_1	Hamon Grab	2019-07-10 12:17:42
V5_2	Hamon Grab	2019-07-10 12:20:22
V5_3	Hamon Grab	2019-07-10 12:22:18
20_1	Hamon Grab	2019-07-11 15:38:00
20_2	Hamon Grab	2019-07-11 15:40:17
20_3	Hamon Grab	2019-07-11 15:42:26
19_1	Hamon Grab	2019-07-11 18:00:48
19_2	Hamon Grab	2019-07-11 18:03:08
19_3	Hamon Grab	2019-07-11 18:05:30

OD NATURE-ZAGRI/MOZ4/INDI67

Hydrodynamic and sediment transport related measurements, seabed and benthic habitat mapping along gravel areas in the Hinder Banks sandbank area, and in the northern exploration zone (near UK border).

Measurements and observations:

a. **Multibeam echosounding** (MBES, Kongsberg Simrad EM3002D, 300 kHz): collection of depth and backscatter. Aim is to characterize morphology and seabed substrate type: MBES was acquired around most sampling locations of the the campaign (selected number of lines around the locations). For high-resolution characterization sailing speed was reduced to 4 kts and an overlap of coverage of up to 70 % was chosen).
   Only full-coverage mapping in the northern area was possible. Unfortunately, most other planned mapping initiatives were not procured due to the time constraints (Westhinder topzone; some long lines between Oosthinder and Bligh Bank (in complement of campaigns ST1824, ST1909), as well as for monitoring purposes (Oosthinder barchan dune area; Gully between Buiten Ratel and Kwinte Bank; KWGS area).
b. **Hamon grab**: sediment sampling in patches of coarse sands/shells and gravel.
c. **Reineck shallow boxcoring**: cancelled due to time constraints.

d. **Video frame. High resolution imagery of gravel areas.** Video transects over some of the sampling locations.
e. **Scuba Diving.** Scientific diving team RBINS under the lead of A. Norro allowed to obtain high quality observations at two locations: Location V2 and location V5 (Table 5). Aim was to (1) characterize the sand thickness in gravel/shell hash rich areas, (2) take shallow cores to quantify fine-scale sedimentation, (3) collect high-quality photo and/or video material. Four divers participated with firstly one team of two divers taking high-quality imagery (video at V2; still photography at V5), and consecutively the second team of two divers measuring sand thickness and collecting shallow cores.
f. **AUMS** registrations (continuous)

Table 3: Timestamps of the sampling locations

ID	Gear	Timestamp (UTC)	Biological analysis
24_1	Hamon Grab	2019-07-08 15:18:01	Y
24_2	Hamon Grab	2019-07-08 15:21:32	Y
24_3	Hamon Grab	2019-07-08 15:26:45	Y
21_1	Hamon Grab	2019-07-09 11:23:39	Y
21_2	Hamon Grab	2019-07-09 11:26:58	Y
21_3	Hamon Grab	2019-07-09 11:29:52	Y
V2a_1	Hamon Grab	2019-07-09 12:50:09	**N**
V2a_2	Hamon Grab	2019-07-09 12:52:22	**N**
V2a_3	Hamon Grab	2019-07-09 12:55:07	**N**
23_1	Hamon Grab	2019-07-10 11:48:29	Y
23_2	Hamon Grab	2019-07-10 11:51:40	Y
23_3	Hamon Grab	2019-07-10 11:54:14	Y
V5_1	Hamon Grab	2019-07-10 12:17:42	Y
V5_2	Hamon Grab	2019-07-10 12:20:22	Y
V5_3	Hamon Grab	2019-07-10 12:22:18	Y
V2b_1	Hamon Grab	2019-07-10 14:07:35	**N**
V2b_2	Hamon Grab	2019-07-10 14:09:36	**N**
V2b_3	Hamon Grab	2019-07-10 14:11:38	**N**
V2c_1	Hamon Grab	2019-07-10 14:26:26	**N**
V2c_2	Hamon Grab	2019-07-10 14:28:27	**N**
V2c_3	Hamon Grab	2019-07-10 14:30:28	**N**
20_1	Hamon Grab	2019-07-11 15:38:00	Y
20_2	Hamon Grab	2019-07-11 15:40:17	Y
20_3	Hamon Grab	2019-07-11 15:42:26	Y
19_1	Hamon Grab	2019-07-11 18:00:48	Y
19_2	Hamon Grab	2019-07-11 18:03:08	Y
19_3	Hamon Grab	2019-07-11 18:05:30	Y

Table 4: Indicative timings of the video frame operations (to be revised with actual recordings)

Location	Date	Timestamp From-to (UTC)	Remark
24	2019-07-08	14:25-14:37	+GoPro5. Poor visibility
19 (two locations)	2019-07-11	20:34-21:10	+GoPro6
Transects (3) Northern Exploration zone	2019-07-12	00:15-00:45	+GoPro6. Poor visibility*

**Halting of recordings because of entanglement of the winch cable*

Table 5: Timestamps of the scientific diving operations.

Location	Date	Dive	Timestamp From-to (UTC)	Remark
V2	2019-07-09	1	14:20:55 - 14:42:59	Video recordings (GoPro6)
		2	15:13:45 - 15:44:01	Sand thickness estimations + corings (3)
V5	2019-07-10	1	09:35:00 - 09:55:00	Still photography

2	10:24:00 - 10:50:00	Sand thickness estimations + corings (2) + sampling (2)

Table 7: Area of interest for multibeam acquisition in northern exploration zone.

NORTH MM.MMM	
51° 40.382	002° 25.972
51° 34.097	002° 14.393
51° 36.703	002° 15.145
51° 37.815	002° 16.400
51° 37.744	002° 18.924
51° 41.431	002° 25.321

OD Nature WinMon UW NOISE

This part of the program was cancelled.

7. REMARKS

Because the ship was understaffed the campaign needed rescheduling and, except for Thursday night, no night trips were possible. The ship returned to the harbor of Zeebrugge each evening and left the harbor in the morning. As a result part of the program was cancelled. Commander, officers and crew are thanked for making the best of the available time.

8. DATA STORAGE

OD NATURE-MSFD GRAVEL-BIO: Biological data. Contact person: RBINS: Steven Degraer. Stored at RBINS OD NATURE. Archiving planned through OD NATURE-BMDC.

OD NATURE-ZAGRI/MOZ4/INDI67: Multibeam data, Video data, Seabed samples. Contact person: RBINS: Vera Van Lancker. Stored at RBINS OD NATURE. Archiving planned through OD NATURE-BMDC.

5. TRACK PLOT

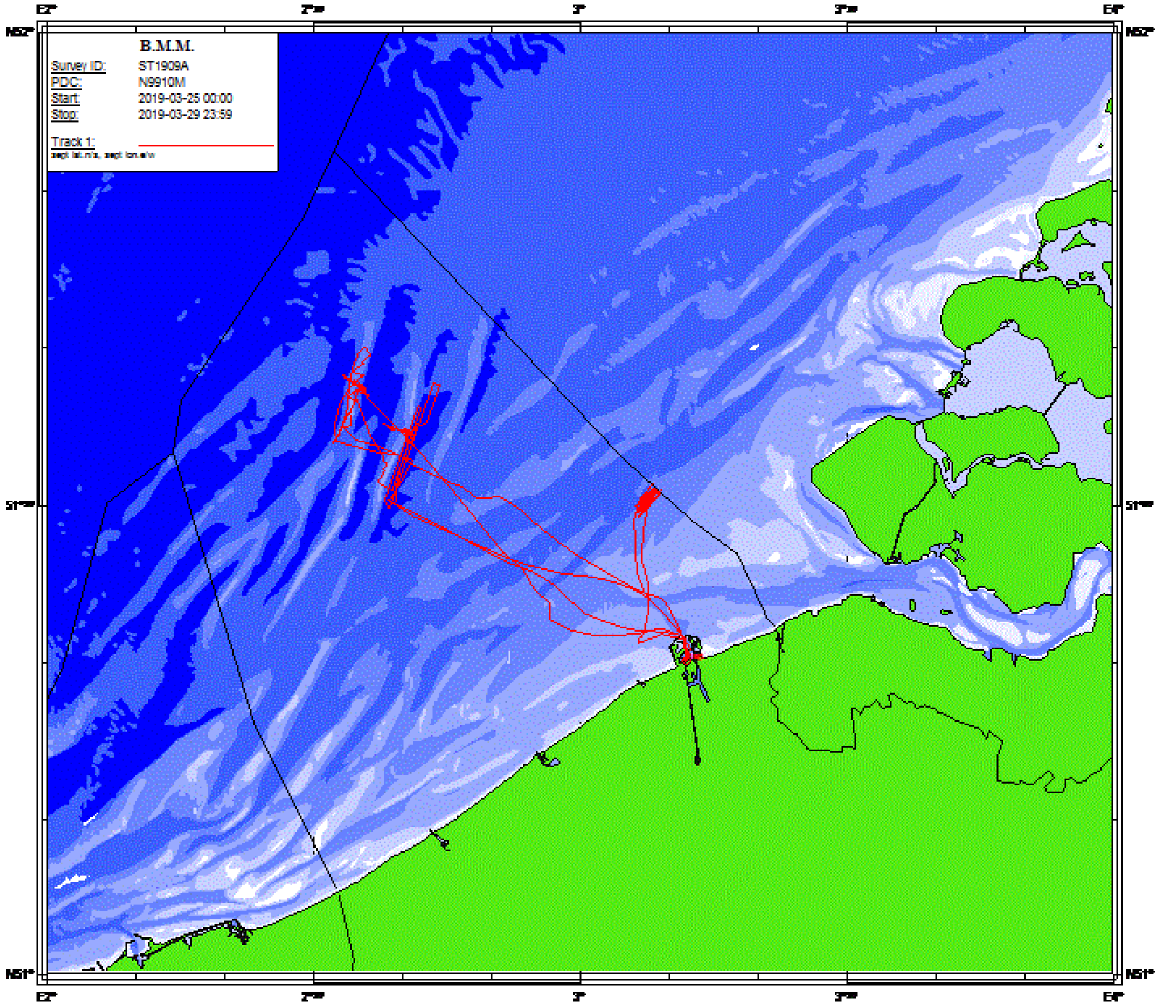

Figure 1: Track plot RV Belgica campaign ST1909.

6. MEASUREMENTS AND SAMPLING

6.1. OD NATURE-VVL ZAGRI/MOZ4/INDI67/MONIT/STUDENTS/)

Hydrodynamic and sediment transport related measurements, seabed mapping and observations in the Hinder Banks sandbank area. Focus is on marine aggregate concession zone 4 (Sector 4a, 4c), and adjacent Habitat Directive Area ‘Flemish Banks’.

Measurements and observations:

a. **Multibeam echosounding** (MBES, Kongsberg Simrad EM3002D, 300 kHz): collection of depth and backscatter. Aim is to characterize morphology and seabed substrate type: Vlakte van de Raan, area in-between Oosthinder and Bligh Bank.
   Not accomplished: Westhinder topzone, Noordhinder sandbank south
b. **Collection of shallow cores (Reineck boxcorer)**. Aim is to detect changes in the grain-size distribution in the upper vertical sediment column. Areas of interest: Vlakte van de Raan, Oosthinder Sector 4c, Noordhinder Sector 4a.
   Not accomplished: Westhinder topzone, Noordhinder sandbank south.

c. **MBES/ADCP profiling** (Hull-mounted Acoustic Doppler Current Profiler (HM-ADCP), RDI 600 kHz; and MBES Kongsberg Simrad EM3002D, 300 kHz). Seacat profiles (CTD, LISST200x, SEAPOINT) with water sampling on the top of the sandbank. Aim was to sail a cross-bank transect back and forth over sandbank areas and to characterize water column and seabed variation throughout a tide.
Areas of interest: Oosthinder Sector 4b-4c, Oosthinder Sector 4a.
Not accomplished: Noordhinder south.

d. **Through-tide measurements**. Aim: to quantify the quality and dynamics of the water column throughout a tidal cycle, a frame with oceanographic sensors and a water sampler (10L Niskin bottle was lowered to the seabed every 30’. The Seacat frame (SBE 09 STD-system) was used, a.o. equipped with a CTD to measure conductivity, temperature and depth, and a Seapoint turbidity meter. An additional frame was attached to the Seacat frame in which a Laser in-situ Scatterometer and Transmissometer (LISST200x, Sequoia) was mounted. The vertical profiling was carried out as slowly (< 0.30 m/s). A van Veen sample was taken after the through-tide measurement. Data was recorded also from RV Belgica’s hull-mounted acoustic Doppler current profiler (HM-ADCP, 600 kHz). Areas of interest: Noordhinder Sector 4a.

e. **Deployment of a bottom-mount Acoustic Doppler Current Profiler (BM-ADCP) (RDI, 1200 kHz)**
Areas of interest: Noordhinder Sector 4a.

f. **Hamon Grab**, for sediment sampling in patches of coarse sands and gravel. Area of interest: gully in-between Oosthinder sandbank and Bligh Bank

g. **Video frame. High resolution imagery of gravel areas.**

h. **AUMS** registrations (continuous)

Area of interest 1: Vlakte van de Raan

Reineck boxcores were taken (see Table 5) and multibeam sailed (Figure 1).

Area of interest 2: *in-between Oosthinder and Bligh Bank (OH-BB)*

Table 1: Main transects of interest in the area in-between Oosthinder and Bligh Bank (OH-BB) (mostly sailed during campaign ST1824, November 2018). For this campaign: Sailing of DP1 and DP5; Parallel lines to D13, D12, D11, D10, D9 to make a denser network.

ID_text	LAT DD MM.mmm (from)	LON DD MM.mmm (from)	LAT DD MM.mmm (to)	LON DD MM.mmm (to)
D00.5	51° 36.670' N	2° 48.910' E	51° 38.601' N	2° 43.181' E
D01	51° 38.165' N	2° 42.908' E	51° 36.201' N	2° 48.616' E
D02	51° 37.473' N	2° 42.475' E	51° 35.476' N	2° 48.163' E
D03	51° 36.806' N	2° 42.058' E	51° 34.785' N	2° 47.731' E
D04	51° 36.082' N	2° 41.606' E	51° 34.028' N	2° 47.257' E
D05	51° 33.334' N	2° 46.823' E	51° 35.416' N	2° 41.189' E
D06	51° 34.705' N	2° 40.744' E	51° 32.586' N	2° 46.356' E
D07	51° 31.880' N	2° 45.914' E	51° 34.026' N	2° 40.319' E
D08	51° 31.137' N	2° 45.449' E	51° 33.316' N	2° 39.875' E
D09	51° 30.431' N	2° 45.008' E	51° 32.637' N	2° 39.451' E
D10	51° 29.692' N	2° 44.545' E	51° 31.931' N	2° 39.009' E
D11	51° 28.982' N	2° 44.102' E	51° 31.250' N	2° 38.583' E
D12	51° 30.544' N	2° 38.141' E	51° 28.243' N	2° 43.639' E
D13	51° 29.842' N	2° 37.703' E	51° 27.525' N	2° 43.239' E
DP1	51° 40.269' N	2° 44.224' E	51° 29.842' N	2° 37.703' E
DP3	51° 29.157' N	2° 39.337' E	51° 38.862' N	2° 45.406' E
DP4	51° 28.851' N	2° 40.031' E	51° 38.536' N	2° 46.088' E
DP5	51° 28.701' N	2° 40.450' E	51° 38.347' N	2° 46.482' E
DP6	51° 27.864' N	2° 42.429' E	51° 36.786' N	2° 48.009' E
DP7	51° 27.541' N	2° 43.201' E	51° 36.670' N	2° 48.910' E

Gravel samples were taken with a Hamon grab, see Table 6. For video recordings, see Table 7.

Area of interest 3: *Oosthinder sandbank Marine Aggregate Extraction Sector 4c, 4b*

Table 2: Cross-bank HM-ADCP profiling in-between Sector 4c and Sector 4b

4b-4c Transect From DD MM.MMM		**4b-4c Transect To** DD MM.MMM	
51° 34.965’	2° 38.886’	51° 34.587’	2° 40.836’

For details on water sampling, see Table 8.

Area of interest 4: *Noordhinder sandbank Marine Aggregate Extraction Sector 4a*

Table 3: Position and time of BM-ADCP deployment (Noordhinder Sector 4a (RDI, 1200 kHz).

ID	Date (local time)	Lat_wgs84	Lon_wgs84
BM-ADCP NH-4a	28/03/2019 16h05	51°34.338 N	002°32.682 E

Van Veen grab sample was taken, see Table 5.

Table 4: Cross-bank HM-ADCP profiling Sector 4a (similar to profile of ST1208).

4a Transect From MM.MMMM		**4a Transect To** MM.MMMM	
51° 38.117’	2° 33.710'	51° 37.448’	2° 35.596’

For details on water sampling, see Table 8.

A stationary 13-hr cycle was sampled, see Table 9.

Table 5: Seabed sampling along Vlakte van de Raan (VLR), Oosthinder Sector 4C (OH4C), Noordhinder 4a (NH4a)

ID	Timestamp (UTC)	Gear
VLR1	2019-03-26 12:13:03	Reineck core
VLR2	2019-03-26 12:25:55	Reineck core
VLR3	2019-03-26 12:38:25	Reineck core
VLR4	2019-03-26 12:47:29	Reineck core
VLR5	2019-03-26 13:01:26	Reineck core
VLR6	2019-03-26 13:14:13	Reineck core
OH4C 1	2019-03-27 13:10:55	Reineck core
OH4C 2	2019-03-27 13:15:20	Reineck core
OH4C 3	2019-03-27 13:27:31	Reineck core
OH4C 4	2019-03-27 13:39:53	Reineck core
OH4C 5	2019-03-27 13:46:29	Reineck core
OH4C 6	2019-03-27 13:56:41	Reineck core
OH4C 7	2019-03-27 14:08:27	Reineck core
OH4C 8	2019-03-27 14:15:03	Reineck core
NH4a 1	2019-03-28 17:29:04	Reineck core
NH4a 2	2019-03-28 17:04:16	Reineck core
NH4a 3	2019-03-28 16:45:58	Reineck core
NH4a 4	2019-03-28 16:27:46	Reineck core
NH4a 5	2019-03-28 16:12:01	Reineck core
NH4a 6	2019-03-28 15:57:46	Reineck core
NH4a 7	2019-03-28 15:44:36	Reineck core
NH4a 8	2019-03-28 14:00:06	Reineck core
NH4a 9	2019-03-28 13:46:31	Reineck core
NH4a 10	2019-03-28 13:33:04	Reineck core

NH4a 11	2019-03-28 13:19:16	Reineck core
NH4a 12	2019-03-28 13:02:22	Reineck core
NH4a 13	2019-03-28 12:31:10	Reineck core
NH4a 14	2019-03-28 12:46:42	Reineck core
NH4a_VV1	2019-03-29 08:04:46	Van Veen grab

Table 6: Gravel sampling with Hamon grab in-between Oosthinder sandbank and Bligh Bank

ID	Timestamp (UTC)	Gear
OHBB_1	2019-03-29 08:53:25	Hamon Grab
OHBB_2	2019-03-29 09:10:52	Hamon Grab
OHBB_3	2019-03-29 09:30:33	Hamon Grab
OHBB_4	2019-03-29 09:38:58	Hamon Grab

Table 7: Video recordings along the area in-between Oosthinder and Bligh Bank

ID	Timestamp (UTC)	Remark
Video transect 1	2019-03-26 20h32-21h38	Video recording in presumed gravel areas
Video transect 2, 3	2019-03-27 09h10-10h23	Video recording in presumed gravel areas

Table 8: Water sampling along cross-bank transects: Oosthinder sandbank and Noordhinder sandbank.

Cross-bank transect Oosthinder Sector 4b-4c (26 -27/03/2019)							
Station	**Time UTC closing bottle**	**Lower depth to (m) (ea_depth_33 -3m)**	**Remark**	**Turbidity Hach Meas1**	**Turbidity Hach Meas2**	**Turbidity Hach Meas3**	**Turbidity Hach Average**
OH1	2019-03-26 22:48:00	17		2.16	2.14	2.45	2.25
OH2	2019-03-26 23:54:00	17		1.89	1.24	1.63	1.59
OH3	2019-03-27 00:47:00	19		0.588	1.24	0.595	0.81
OH4	2019-03-27 01:41:00	19		1.2	1.81	0.979	1.33
OH5	2019-03-27 02:35:00	18		1.77	2.24	2.08	2.03
OH6	2019-03-27 03:23:00	16		2.21	1.42	1.92	1.85
OH7	2019-03-27 04:10:00	18		1.96	2.17	1.91	2.01
OH8	2019-03-27 05:01:00	19		2.06	1.9	1.89	1.95
OH9	2019-03-27 06:06:00	21		1.76	1.59	2.06	1.80
OH10	2019-03-27 06:59:00	20		1.2	1.11	1.32	1.21
seacat on deck: 0.54 db							

Cross-bank transect Noordhinder, Sector 4a (27-28/03/2019)							
Station	**Time UTC closing bottle**	**Lower depth to (m) (ea_depth_33 -3m)**	**Remark**	**Turbidity Hach Meas1**	**Turbidity Hach Meas2**	**Turbidity Hach Meas3**	**Turbidity Hach Average**
NH1	2019-03-27 16:10:00	15		1.48	1.51	1.56	1.52
NH2	2019-03-27 17:00:00	15		1.81	1.83	1.81	1.82
NH3	2019-03-27 17:48:00	16	wide spread	1.13	1.26	1.29	1.23
NH3	2019-03-27 17:48:00			1.54	2.11	1.24	1.63
NH3	2019-03-27 17:48:00			1.54	1.72	1.97	1.74
NH4	2019-03-27 18:39:00	17		1.42	0.969	1.28	1.22
NH5	2019-03-27 19:33:00	14		0.826	0.803	1.32	0.98
NH6	2019-03-27 20:19:00	18		1.28	1.03	0.983	1.10
NH7	2019-03-27 21:03:00	14		0.769	0.771	1.29	0.94
NH8	2019-03-27 21:47:00	14		1.23	1.05	1.96	1.41
NH9	2019-03-27 22:34:00	14		1.43	1.75	1.87	1.68
NH10	2019-03-27 23:26:00	18		1.05	0.985	1.36	1.13
NH11	2019-03-28 00:13:00	15	highly variable depth	0.948	1.26	0.843	1.02
NH12	2019-03-28 01:03:00	18		1.12	1.45	1.29	1.29
NH13	2019-03-28 01:53:00	15		1.80	1.28	1.50	1.53
NH14	2019-03-28 02:41:00	17		1.94	2.87	1.30	2.04
NH15	2019-03-28 03:27:00	15		4.34	2.41	2.87	3.21

Table 8: Water sampling during 13-hrs sampling, Noordhinder sandbank.

13h cycle Noordhinder south Sector 4a (28-29/03/2019)

Station	Start UTC descent profile	Time UTC closing bottle and back up	Lower depth to (m) (ea_depth_33 -3m)	Remark on depth (m)	Turbidity Hach Meas1	Turbidity Hach Meas2	Turbidity Hach Meas3	Turbidity Hach Average
NH13h_01	18:40	2019-03-28 18:59:00	22		1.29	1.84	1.70	1.61
NH13h_02	19h	2019-03-28 19:30:00	22		1.22	1.10	1.25	1.19
NH13h_03	19h34	2019-03-28 20:00:00	22		0.77	1.82	1.98	1.52
NH13h_04	20h06	2019-03-28 20:30:00	22	24.46	2.31	1.79	2.02	2.04
NH13h_05	20h37	2019-03-28 21:00:00	22		1.19	1.58	1.91	1.56
NH13h_06	21h07	2019-03-28 21:31:00	22	23.72	2.00	2.23	1.96	2.06
NH13h_07	21h34	2019-03-28 22:00:00	20		1.88	1.75	1.50	1.71
NH13h_08	22h08	2019-03-28 22:31:00	20	22.6	0.48	0.94	0.66	0.69
NH13h_09	22h33	2019-03-28 23:00:00	19	21.4	0.56	0.20	0.67	0.48
NH13h_10	23h03	2019-03-28 23:33:00	19		0.72	0.42	0.70	0.61
NH13h_11	23h36	2019-03-29 00:00:00	20	23.29	0.72	0.74	0.57	0.68
NH13h_12	0h04	2019-03-29 00:30:00	20	24.39	1.04	1.07	1.13	1.08
NH13h_13	0h37	2019-03-29 01:07:00	22		1.78	2.28	2.43	2.16
NH13h_14	1h11	2019-03-29 01:30:00	22		1.45	1.29	1.31	1.35
NH13h_15	1h34	2019-03-29 02:00:00	22		2.70	1.90	1.63	2.08
NH13h_16	2h03	2019-03-29 02:30:00	22		1.52	1.75	1.63	1.63
NH13h_17	2h33	2019-03-29 03:01:00	22		1.77	1.21	1.38	1.45
NH13h_18	3h08	2019-03-29 03:30:00	22		1.65	2.09	1.89	1.88
NH13h_19	3h36	2019-03-29 04:00:00	22		1.84	1.81	2.35	2.00
NH13h_20	4h06	2019-03-29 04:30:00	22		1.75	1.06	0.541	1.12
NH13h_21	4h35	2019-03-29 05:00:00	22		1.25	0.703	1.11	1.02
NH13h_22	5h07	2019-03-29 05:30:00	22		1.35	1.88	1.33	1.52
NH13h_23	5h39	2019-03-29 06:00:00	22	26.65	8.57	3.27	3.26	5.03
NH13h_24	6h07	2019-03-29 06:30:00	23		1.51	0.841	0.895	1.08
NH13h_25	6h38	2019-03-29 07:00:00	23	26.65	1.79	1.66	1.80	1.75
NH13h_26	7h07	2019-03-29 07:30:00	24	27.28	1.06	1.10	2.09	1.42
NH13h_27	7h37	2019-03-29 07:59:00	24		1.09	1.33	1.18	1.20

slow descent and ascent under 30 cm/s was targeted: Seacat on deck: 0.36

7. REMARKS

Officers and crew are warmly thanked for their flexibility and assistance during all operations, also in providing information to the students.

8. DATA STORAGE

OD NATURE

- Multibeam data, Video data, Seabed samples. Contact person: RBINS: Vera Van Lancker
- ADCP, Seacat and LISST data: RBINS MDO Ostend. Contact person: Joan Backers

RV BELGICA CRUISE 2019/30 – CRUISE REPORT

Subscribers:	Dr. Vera Van Lancker[1] / Mr. Koen Degrendele[2] / Mr. Giacomo Montereale Gavazzi[1]
Institutes:	[1]Operational Directorate Natural Environment (OD Nature) [2]FPS Economy, SMEs, self-employed and Energy, Continental Shelf Department (FPS-CSS)
Addresses:	[1]OD Nature-BRU: Vautierstraat 25, B-1000 Brussels [2]FPS-CSS: NGII - Koning Albert II Laan 16 , B-1000 Brussels
Telephones:	+32(0)2 627 43 45 (VVL); +32(0)2 277 84 11 (KD)
E-mails:	vvanlancker@naturalsciences.be, koen.degrendele@economie.fgov.be, gmonterealegavazzi@naturalsciences.be

Monitoring: 25/11/2019 - 29/11/2019

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1. General form RV Belgica 2019
2. List of participants
3. Scientific objectives
4. Operational course
5. Track plot
6. Measurements and sampling
7. Remarks
8. Data storage

1. GENERAL FORM RV BELGICA 2019

1.	Cruise number		2019/30
2.	Date/time	Zeebrugge/Port ETD Zeebrugge/Port ETA	25/11/2019: 11h45 28/11/2019: 12h00
3.	Chief Scientist Participating institutes		Dr. Matthias Baeye RBINS OD Nature, FPSEconomy-CSS
4.	Geographical area		Belgian part of the North Sea

2. LIST OF PARTICIPANTS

Institute	Family name	Given name	Gender	25-28/11
RBINS-OD Nature	BAEYE	Matthias	M	sc1
	TERSELEER	Nathan	M	sc7
	KINT	Lars	M	sc8
	VAN DEN BRANDEN	Reinhilde	F	sc4
	MONTEREALE-GAVAZZI	Giacomo	M	sc2
FPS Econ - CSS	DEGRENDELE	Koen	M	sc5
	ROCHE	Marc	M	sc6
	HERPOELAERT	Ilse	F	sc3
			TOTAL	**8**

3. SCIENTIFIC OBJECTIVES

OD NATURE-VVL-ZAGRI/MOZ4

ZAGRI is a continuous research program on the evaluation of the effects of the exploitation of non-living resources of the territorial sea and the continental shelf. MOZ4 focuses on the monitoring of hydrodynamics and sediment transport in relation to marine aggregate extraction in a far offshore zone. Overall aim is to increase process and system knowledge of this area, with a particular focus on the compliancy of the extraction activities with respect to the European Marine Strategy Framework Directive. More specifically changes in seafloor integrity and hydrographic conditions will be assessed. An important parameter is the bottom shear stress, with knowledge needed on both natural and anthropogenically-induced variability. Results will be used for the validation of mathematical models, necessary for impact quantification.

CSS-KD

Implementation of the continuous investigation laid down in section 3, §2, subsection 3, of the law of June 13th 1969, concerning the exploration and exploitation of non-living resources on the Belgian Continental Shelf, and the concession decisions.

The follow up of the repercussions of the sand extraction on the stability of the sand banks and surrounding area in the exploitation zones, in order to formulate policies concerning the exploitation in the concession zones on a scientific base. The sediments of the Belgian continental shelf will be investigated in order to:

1. Establish the impact of sand extraction on the sand budget and seabed sediments.
2. Survey the sand winning sites to detect significant changes of the seabed sediments and the morphology of the seabed and sand banks in order to guarantee the availability of sand to extract in the future.

OD NATURE-GMG

Within Europe's Marine Strategy Framework Directive (MSFD), progress towards Good Environmental Status (GES) needs monitoring in a most time- and cost-effective way. For the GES descriptors 6 and 7, on seafloor integrity and hydrographic conditions, respectively, new integrative indicators (i.e. bottom shear stress, turbidity and seabed/habitat type) need developing. To advance the mapping of seabed/habitat types, a Community of Practice (CoP) on seabed mapping will be established, investigating the main issues preventing joint mapping of the seabed. Within SEACoP (CoP on *'Surveying for Environmental Assessments'*) the following objectives are targeted: a) estimation of the precision, sensitivities and repeatability of the acoustic devices to detect changes in seabed/habitat types; b) quantification of the external sources of variance in the acoustic signature, including the influence of near-bed and water column suspensions on backscatter data; c) definition of best practice in ground-truthing the acoustic signal, with emphasis on visual techniques; and d) innovation in collaborative seabed mapping.

OD NATURE-LN (AUMS)

The AUMS (Autonomous Underway Measurement System) project is inspired by the success of similar systems deployed on various ships of opportunity in the framework of the European Union FerryBox project (www.ferrybox.org). The instrumentation will greatly enhance the continuous oceanographic measurements made by RV Belgica by taking advantage of the significant technological improvements since the design of the existing (salinity, temperature, fluorescence) systems. In particular, many new parameters can now be measured continuously including important ecosystem parameters such as nitrate, ammonia, silicate, dissolved oxygen and CO2, turbidity, alkalinity and phytoplankton pigments. In addition, the new equipment allows automatic acquisition and preservation of water samples, rendering RV Belgica operations significantly more efficient by reducing onboard human resources. Data will be available in near real-time via OD Nature's public web site and following quality control, from the Belgian Marine Data Centre.

ESA-MC (GNSS)

For the European Space Agency continuous GNSS (Global Navigation Satellite system) data is autonomously acquired in the maritime environment for performance evaluation under different conditions.

4. OPERATIONAL COURSE

All times are given in local time (UTC+2h) All coordinates in WGS84.
Throughout the campaign, measurements are made with the AUMS system.

Monday 25/11/2019

11h45 Departure

Transit to KWGS

14h43 – 16h26: EM3002D survey on KWGS.

16h32 – 20h09: EM3002D survey on KBMA.

20h17 – 22h29: EM3002D survey on KBMA.

Transit to Westhinder

Tuesday 26/11/2019

00h00 – 09h30: EM3002D survey Ecogravel area

10h00 – 14h00: Videosurveys (II-2,II-3, II-10 II-5)
Hamon grabs (II-7, II-11, II-6, II-8, II-4, II-9, II-1)

14h00: Start of continuous Seawater pump – LISST200x data acquisition

14h00 – 15h30: EM3002D survey Ecogravel area

15h30 – 17h30: Videosurveys (I-2,I-1, I-8 I-6)

17h30 – 19h00: EM3002D survey Ecogravel area

Transit to Sector 4a

20h16 – 03h12: EM3002D survey on Sector 4a (Noordhinder).

Transit to Sierra Ventana

Wednesday 27/11/2019

05h11 – 17h47: EM3002D survey on Sector 3b (Sierra Ventana).

Transit to Appelzak

20h00 –

Thursday 28/11/2019

08h00: HM-ADCP calibration exercise (seawater pump, LISST200x, HACH)

Transit to Zeebrugge harbor

End of campaign

5. TRACK PLOT

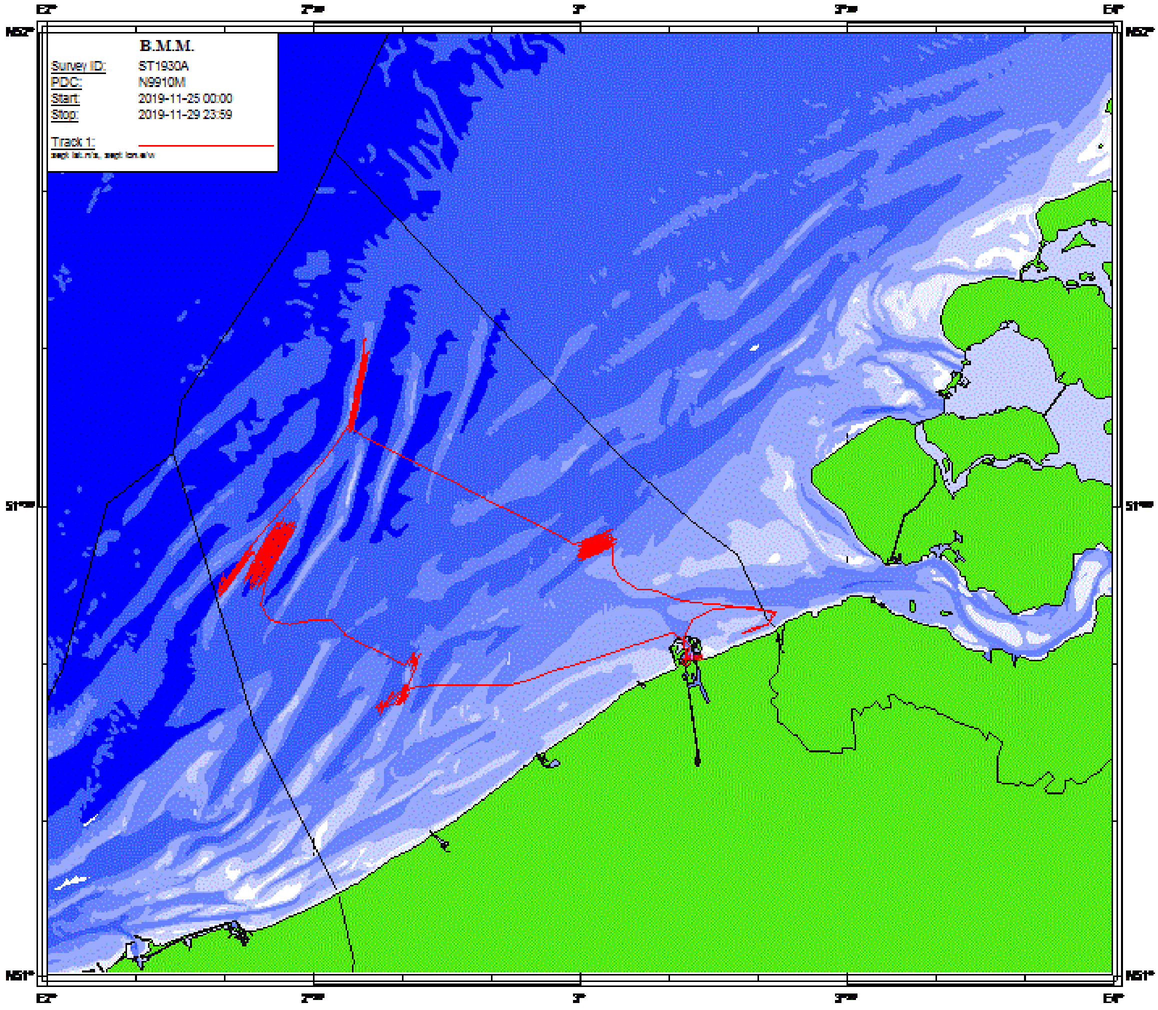

Figure 1: Track plot of campaign 2019/30

6. MEASUREMENTS AND SAMPLING

6.1. OD NATURE-VVL

Table 1

Anchored, tide-cycle in location: APPELZAK

DATE	LOCAL TIME	OPERATOR	HACH 1	HACH 2	HACH 3	mean	stdev	Remarks:	LISST200X vol conc µL/L
27-Nov	16:45	MB	16.4	17.6	16.3	16.8	0.7	von humboldt	ok
27-Nov	19:38	MB	135	138	145	139	5.1		ok
27-Nov	19:45	MB	154	149	158	154	4.5		ok
27-Nov	20:00	MB	183	184	182	183	1.0		SAT
27-Nov	20:15	MB	141	137	136	138	2.6		
27-Nov	20:25	MB	125	130	127	127	2.5		
27-Nov	20:45	MB	107	104	106	106	1.5		
27-Nov	21:00	MB	95.8	100	99.2	98.3	2.2		
27-Nov	21:15	MB	85.4	85.8	86.8	86.0	0.7		750
27-Nov	22:00	MB	67.7	66.9	69.6	68.1	1.4		600
27-Nov	22:15	MB	61.5	61.9	62.1	61.8	0.3		600
27-Nov	23:00	MB	68.3	63.6	62.4	64.8	3.1		580
27-Nov	23:31	MB	63.2	57.4	61.2	60.6	2.9		533
28-Nov	03:36	MB	84.6	83.8	80.4	82.9	2.2		850
28-Nov	07:01	MB	207	202	203	204	2.6		SAT
28-Nov	07:15	MB	176	171	171	173	2.9		SAT
28-Nov	07:30	MB	119	119	119	119	0.0		1300
28-Nov	08:25	MB	105	103	104	104	1.0		1000
28-Nov	08:45	MB	270	275	267	271	4.0		SAT
28-Nov	09:00	MB	188	183	184	185	2.6		SAT
27-Nov	19:04	MB	201	197	202	200	2.6		SAT
27-Nov	19:28	MB	140	146	146	144	3.5		ok

6.2. OD NATURE-GMG

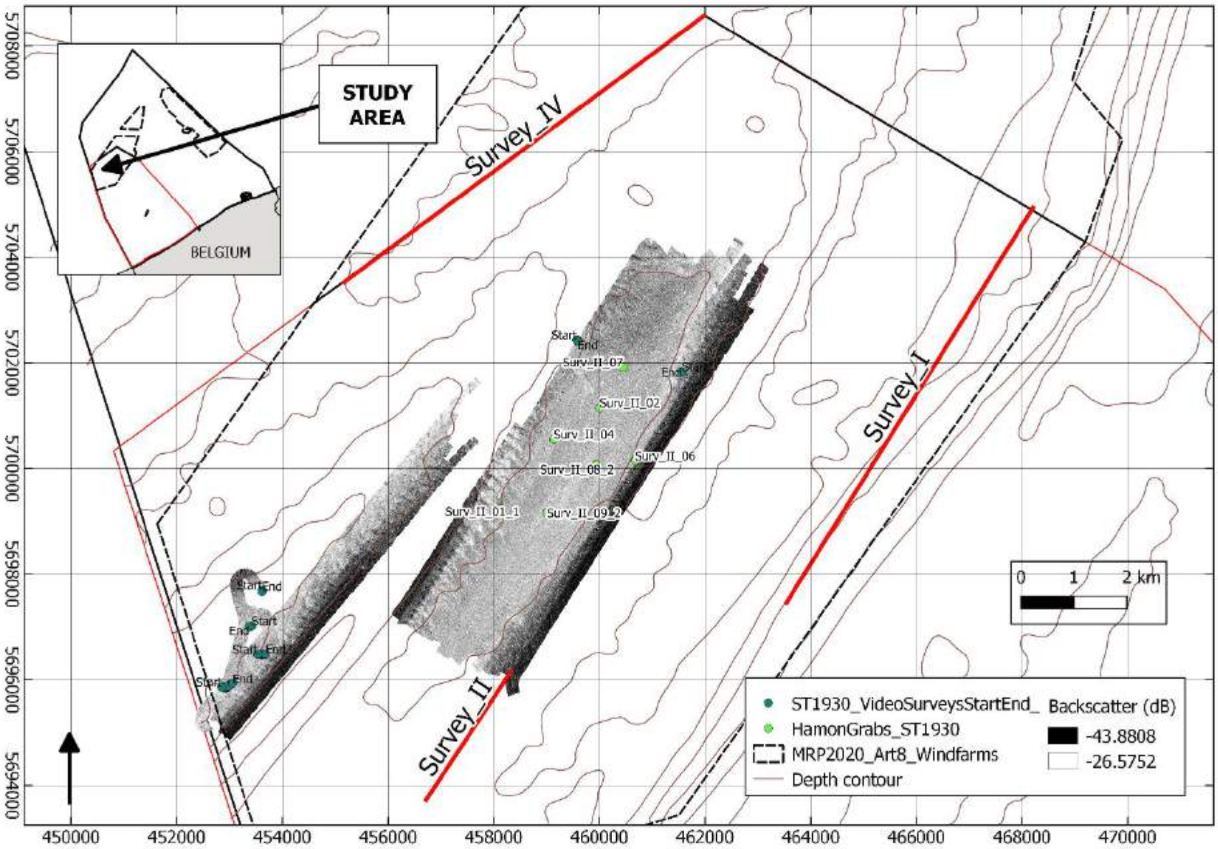

Figure 2 – Cartographic overview of study area and multibeam backscatter survey and ground-trtuh locations (video and hamon grabs)

Table 2 – Start and end points of video acquisition

ID	X	Y	Note
Survey_I_1b	2.321958	51.41199	Start
Survey_I_1b	2.324996	51.41257	End
Survey_I_2	2.331783	51.41763	Start
Survey_I_2	2.333836	51.41767	End
Survey_I_8	2.330025	51.42247	Start
Survey_I_8	2.329425	51.42232	End
Survey_I_6	2.332768	51.42852	Start
Survey_I_6	2.332775	51.42835	End
Survey_II_5	2.446692	51.46634	Start
Survey_II_5	2.446561	51.46621	End
Survey_II_2	2.417982	51.47163	Start
Survey_II_2	2.418174	51.47141	End

Table 3 – Hamon Grab samples coordinates

Sample_ID	Y	X
Surv_II_08_1	51.4505	2.423388
Surv_II_04	51.45467	2.411907
Surv_II_01_1	51.443	2.39761
Surv_II_08_2	51.45027	2.423347
Surv_II_02	51.4601	2.424332
Surv_II_09_1	51.44225	2.410222
Surv_II_09_2	51.44207	2.410223
Surv_II_01_2	51.44282	2.397595
Surv_II_07	51.46702	2.430612
Surv_II_06	51.45112	2.434088

6.3. CSS-KD

```
Survey KWGS1930:

List of all lines:
------------------------------------------------------------------------------------------
Line prefix, heading[deg], length[m], number of pings, average depth[m], average swath[m],
average speed[m/s], duration(h:m:s), First and last position
------------------------------------------------------------------------------------------
0000_20191125_134312 207.84 1735 2941 27.17  132.40  4.55 00:06:21 N51°17'31.88" E2°38'10.17" N51°16'41.93" E2°37'29.53"
0001_20191125_135600  25.99 1742 2238 27.09  131.93  6.03 00:04:49 N51°16'43.69" E2°37'24.97" N51°17'33.72" E2°38'05.95"
0002_20191125_142631 206.97 1734 2903 26.69  129.65  4.71 00:06:08 N51°17'34.55" E2°38'01.20" N51°16'44.81" E2°37'20.14"
0003_20191125_143759  26.82 1742 2350 26.50  128.83  5.87 00:04:57 N51°16'46.27" E2°37'15.76" N51°17'36.57" E2°37'56.60"
0004_20191125_144834 206.23 1784 2890 26.43  128.37  4.90 00:06:04 N51°17'37.75" E2°37'51.80" N51°16'46.38" E2°37'09.85"
0005_20191125_145921  26.82 1800 2502 26.32  127.78  5.73 00:05:14 N51°16'48.65" E2°37'07.10" N51°17'40.79" E2°37'48.46"
0006_20191125_150939 205.36 1767 2837 26.24  127.34  4.99 00:05:54 N51°17'41.26" E2°37'42.51" N51°16'50.25" E2°37'01.44"
0007_20191125_152205 117.49  839 1340 25.66  124.12  5.11 00:02:44 N51°17'21.60" E2°37'19.19" N51°17'10.12" E2°37'58.34"
------------------------------------------------------------------------------------------
The total survey:
------------------------------------------------------------------------------------------
KWGS1930 consists of 8 lines.
Max depth 29.90 meter, Min depth 24.48 meter, Average depth 26.00
Total number of positions are     2539.00
Total number of valid depths are  10154502.00
Total time of logging 00:42:11 (h:m:s)
```

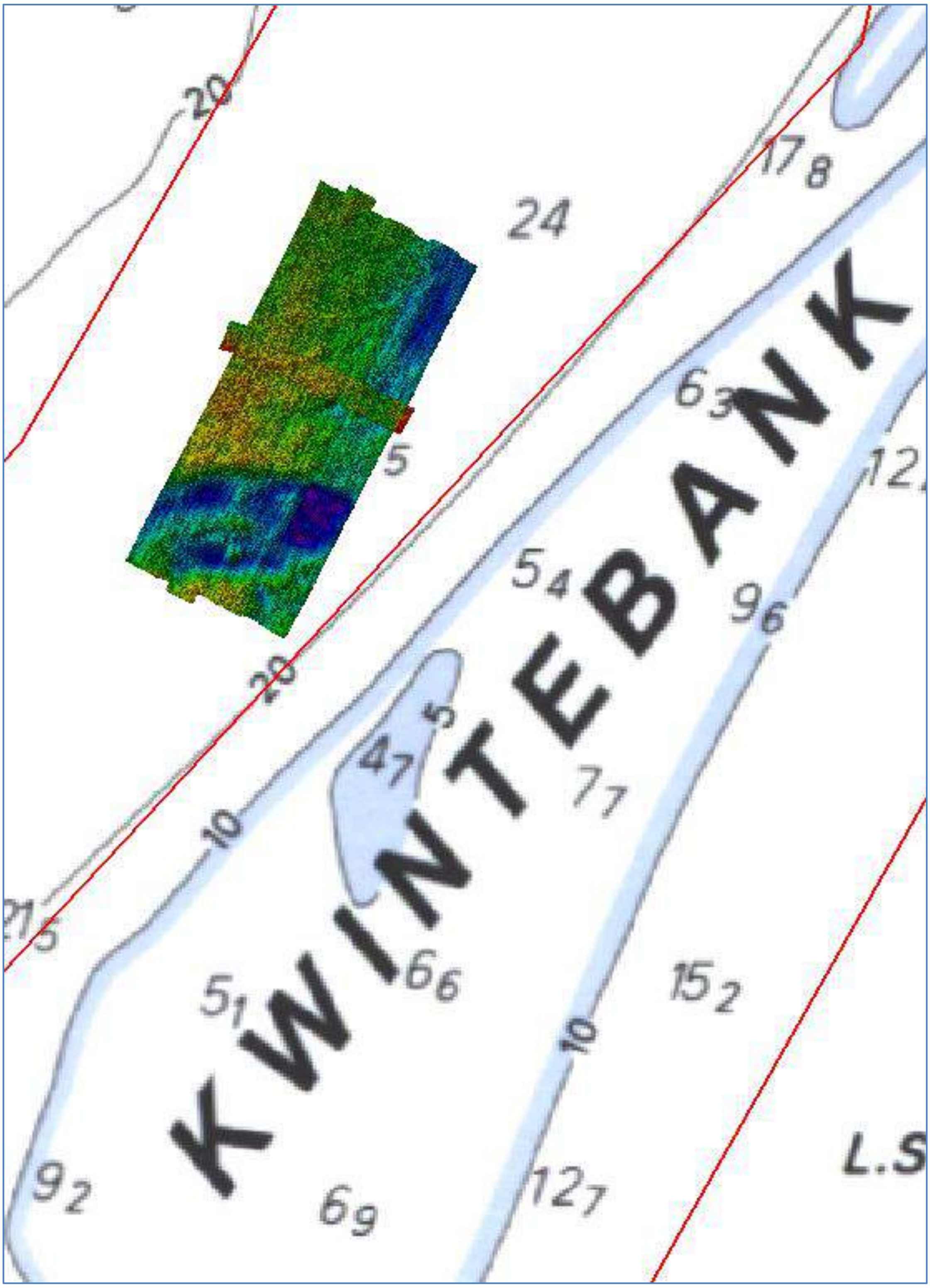

Figure 3: KWGS surveyed area

Survey KBMA1930:

List of all lines:

```
 ------------------------------------------------------------------------------------------
 Line prefix, heading[deg], length[m], number of pings, average depth[m], average swath[m],
 average speed[m/s], duration(h:m:s), First and last position
------------------------------------------------------------------------------------------
 0000_20191125_153227  29.73 1664 3236 18.65   86.10  5.39 00:05:09 N51°17'39.98" E2°39'28.91" N51°18'28.14" E2°40'07.35"
 0001_20191125_154208 201.41 1659 3650 16.86   76.33  5.30 00:05:13 N51°18'27.10" E2°40'09.43" N51°17'38.89" E2°39'31.85"
 0002_20191125_155204  31.23 1750 4177 15.21   68.15  5.35 00:05:27 N51°17'37.95" E2°39'32.71" N51°18'28.47" E2°40'13.34"
 0003_20191125_160202 200.35 1780 4487 14.70   64.18  5.33 00:05:34 N51°18'26.80" E2°40'13.88" N51°17'35.03" E2°39'33.62"
 0004_20191125_161429  26.85 1059 2979 13.03   55.84  5.24 00:03:22 N51°18'03.23" E2°39'57.50" N51°18'34.22" E2°40'17.20"
 0005_20191125_162120 199.81 1675 4570 13.81   59.44  5.27 00:05:18 N51°18'26.18" E2°40'17.49" N51°17'37.71" E2°39'39.16"
```

```
0006_20191125_163031  32.94 1599 4290 14.55   62.55  5.21 00:05:07 N51°17'36.62" E2°39'39.64" N51°18'22.53" E2°40'17.53"
0007_20191125_163922 195.19 1763 5017 14.85   64.40  4.82 00:06:06 N51°18'25.10" E2°40'17.27" N51°17'36.05" E2°39'43.46"
0008_20191125_165014  32.16 1711 4687 14.51   62.81  5.17 00:05:31 N51°17'32.71" E2°39'43.47" N51°18'22.22" E2°40'22.79"
0009_20191125_170053 198.97 1786 4755 14.21   60.93  5.43 00:05:29 N51°18'24.74" E2°40'21.92" N51°17'32.67" E2°39'42.15"
0010_20191125_171108  35.32 1875 5064 13.11   64.33  5.04 00:06:12 N51°17'35.21" E2°39'34.85" N51°18'27.93" E2°40'22.20"
0011_20191125_172133 199.09 1760 3636 14.18   80.56  5.55 00:05:17 N51°18'25.61" E2°40'26.82" N51°17'34.17" E2°39'47.92"
0012_20191125_173034  29.09 1936 4533 14.01   80.26  4.98 00:06:29 N51°17'32.14" E2°39'49.40" N51°18'28.52" E2°40'29.73"
0013_20191125_174000 200.73 1797 3760 14.03   79.97  5.63 00:05:19 N51°18'23.73" E2°40'33.48" N51°17'31.60" E2°39'52.41"
0014_20191125_174906  30.59 1692 4301 13.34   75.97  4.90 00:05:45 N51°17'28.76" E2°39'53.73" N51°18'18.04" E2°40'31.54"
0015_20191125_175822 201.46 1923 4297 13.22   73.02  5.67 00:05:39 N51°18'20.58" E2°40'37.10" N51°17'25.04" E2°39'52.44"
0016_20191125_180759  29.92 1712 4617 13.04   72.38  4.77 00:05:59 N51°17'28.13" E2°39'59.39" N51°18'17.57" E2°40'37.09"
0017_20191125_181743 203.56 1936 4243 12.93   71.57  5.80 00:05:34 N51°18'18.52" E2°40'41.42" N51°17'23.71" E2°39'54.67"
0018_20191125_182636  29.03 1729 4538 12.88   73.69  4.72 00:06:06 N51°17'27.06" E2°40'04.88" N51°18'17.74" E2°40'42.37"
0019_20191125_183529 201.79 1704 3602 13.33   74.97  5.80 00:04:54 N51°18'16.11" E2°40'45.71" N51°17'26.82" E2°40'06.36"
0020_20191125_184433  28.33 1817 4626 13.73   78.48  4.69 00:06:27 N51°17'26.57" E2°40'08.95" N51°18'19.44" E2°40'47.76"
0021_20191125_185308 198.91 1399 3059 13.03   73.31  5.81 00:04:01 N51°18'09.46" E2°40'27.66" N51°17'28.12" E2°39'58.34"
0022_20191125_190126  27.78 1762 4412 14.05   80.27  4.69 00:06:16 N51°17'29.70" E2°39'50.56" N51°18'21.07" E2°40'26.19"
------------------------------------------------------------------------------------------
The total survey:
------------------------------------------------------------------------------------------
KBMA1930 consists of 23 lines.
Max depth 24.22 meter, Min depth 6.78 meter, Average depth 14.00
Total number of positions are     7597.00
Total number of valid depths are  48937144.00
Total time of logging 02:06:14 (h:m:s)
```

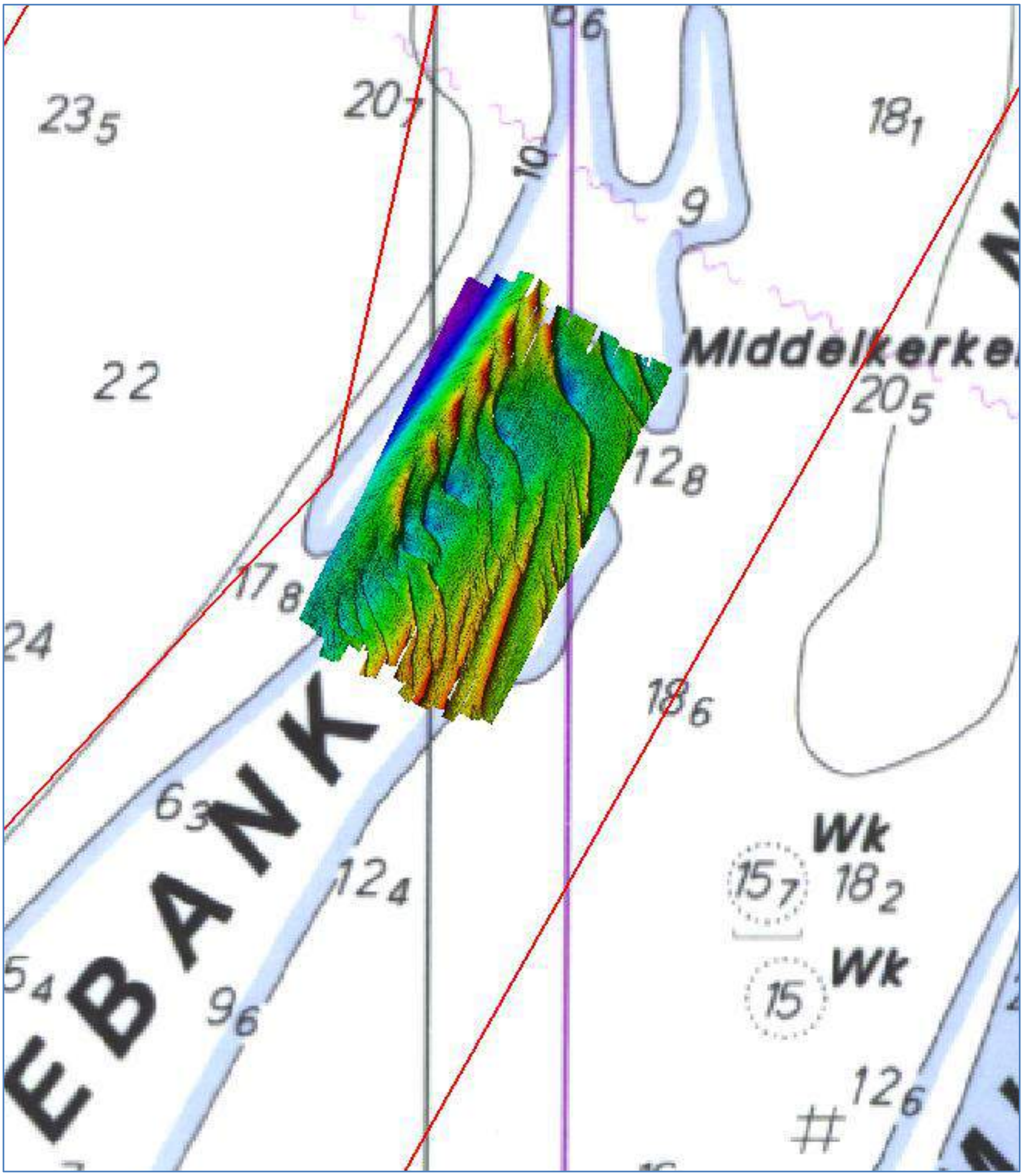

Figure 4: KBMA surveyed area

Survey KBMB1930:

List of all lines:

```
 ---------------------------------------------------------------------------------------
 Line prefix, heading[deg], length[m], number of pings, average depth[m], average swath[m],
 average speed[m/s], duration(h:m:s), First and last position
 ---------------------------------------------------------------------------------------
0000_20191125_191721  31.89 1700 3482 16.65  100.91  4.73 00:05:59 N51°19'41.76" E2°41'23.69" N51°20'30.41" E2°42'04.46"
 0001_20191125_192701 200.63 1705 3464 16.84  101.16  4.75 00:05:59 N51°20'28.80" E2°41'58.59" N51°19'39.87" E2°41'18.03"
 0002_20191125_193843  33.26 1759 4253 17.24  104.82  3.86 00:07:36 N51°19'41.45" E2°41'14.49" N51°20'31.53" E2°41'57.42"
 0003_20191125_194939 199.72 1947 3732 18.13  110.95  4.64 00:07:00 N51°20'33.15" E2°41'54.00" N51°19'37.00" E2°41'10.05"
 0004_20191125_200125  31.12 1782 3805 19.12  118.09  3.95 00:07:31 N51°19'43.00" E2°41'06.01" N51°20'34.01" E2°41'48.82"
 0005_20191125_201244 203.98 1820 3226 20.12  125.55  4.53 00:06:42 N51°20'36.24" E2°41'46.78" N51°19'44.16" E2°41'03.26"
 0006_20191125_202423  30.30 1901 3641 20.95  131.07  3.99 00:07:56 N51°19'44.97" E2°40'57.29" N51°20'38.67" E2°41'44.18"
 0007_20191125_203607 206.19 1822 3092 21.23  133.63  4.51 00:06:44 N51°20'38.47" E2°41'38.74" N51°19'46.41" E2°40'54.99"
 0008_20191125_204812  26.68 1795 3245 21.44  135.56  4.14 00:07:14 N51°19'49.58" E2°40'53.86" N51°20'40.78" E2°41'36.00"
 0009_20191125_205917 209.29 1777 2963 21.70  139.23  4.33 00:06:50 N51°20'40.40" E2°41'30.96" N51°19'49.86" E2°40'47.59"
 0010_20191125_210925  24.76 1916 3046 22.06  141.91  4.38 00:07:17 N51°19'47.68" E2°40'39.94" N51°20'42.48" E2°41'26.05"
```

```
0011_20191125_212038 210.61 1795 2571 25.05  164.97  4.17 00:07:11 N51°20'43.83" E2°41'21.17" N51°19'52.34" E2°40'38.46"
-------------------------------------------------------------------------------------------
The total survey:
-------------------------------------------------------------------------------------------
KBMB1930 consists of 12 lines.
Max depth 29.60 meter, Min depth 12.61 meter, Average depth 19.00
Total number of positions are     5051.00
Total number of valid depths are  20533182.00
Total time of logging 01:23:59 (h:m:s)
```

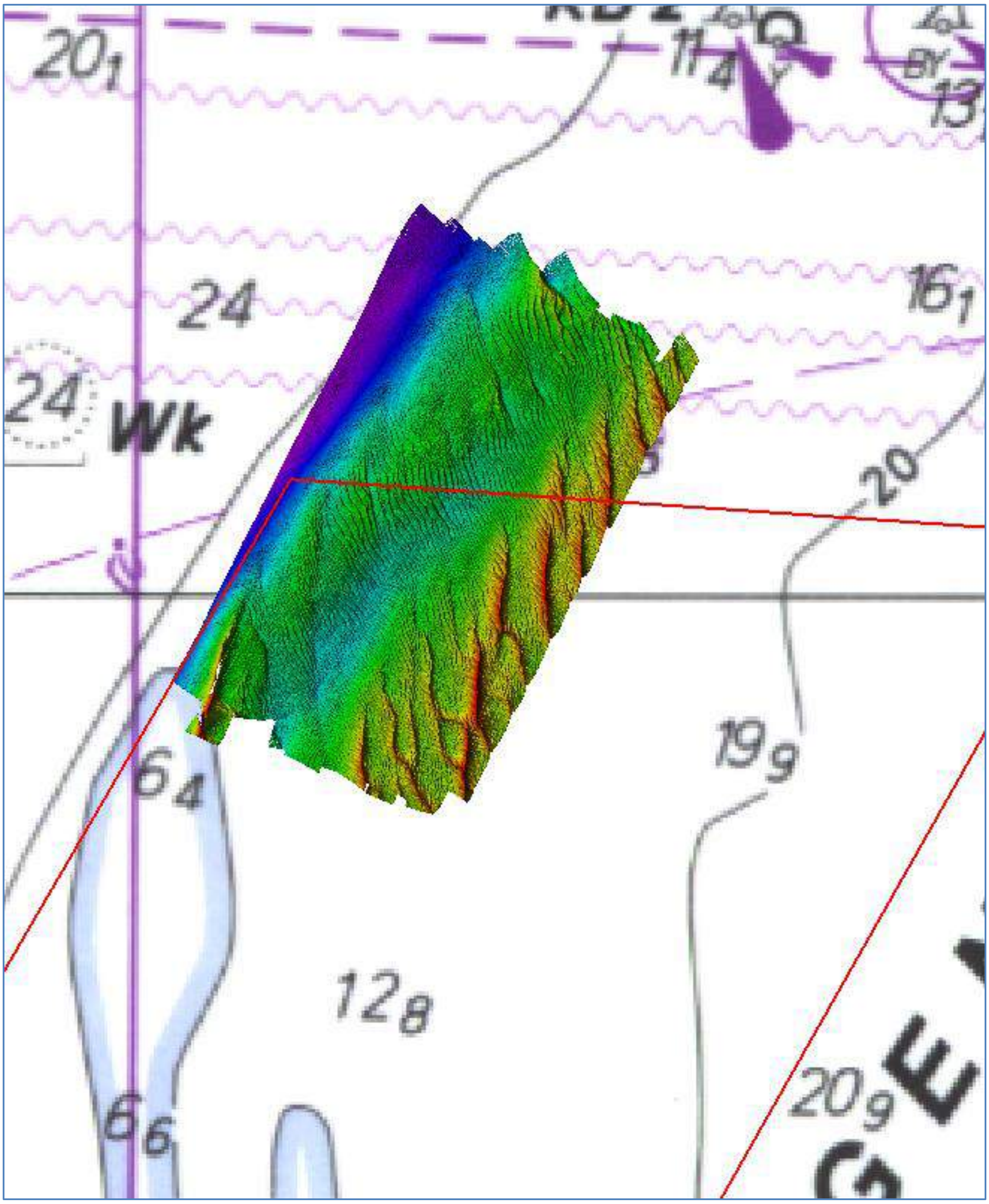

Figure 5: KBMB surveyed area

Survey S4a1930:

```
List of all lines:
-------------------------------------------------------------------------------------------
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average speed[m/s], duration(h:m:s), First and last position
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0001_20191126_194612  18.87 2642 4367 20.49  128.99  4.61 00:09:33 N51°39'00.72" E2°35'21.27" N51°40'24.09" E2°35'51.22"
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```
0002_20191126_200243 182.96 6049 9483 21.57  136.46  4.56 00:22:07 N51°40'25.18" E2°35'54.08" N51°37'14.12" E2°34'47.96"
0003_20191126_203235  18.36 5097 7649 22.77  145.31  4.47 00:19:00 N51°37'13.03" E2°34'51.37" N51°39'53.59" E2°35'49.72"
0004_20191126_205717 185.45 5158 7743 24.12  155.33  4.23 00:20:19 N51°39'54.29" E2°35'54.88" N51°37'11.62" E2°34'56.39"
0005_20191126_212314  15.26 5153 6259 27.05  177.63  4.62 00:18:35 N51°37'10.51" E2°35'02.29" N51°39'53.13" E2°36'00.63"
0006_20191126_214719 195.72 5186 9289 21.12  134.72  3.97 00:21:45 N51°39'53.85" E2°35'57.68" N51°37'15.79" E2°34'38.40"
0007_20191126_221458  11.15 5168 4981 30.32  202.30  5.14 00:16:45 N51°37'09.33" E2°35'07.49" N51°39'52.42" E2°36'05.66"
0008_20191126_224016 196.08 6688 7965 34.22  229.49  3.72 00:29:59 N51°39'51.08" E2°36'12.26" N51°36'20.13" E2°34'56.42"
0009_20191126_231016 206.94 3746 4928 36.38  244.73  3.25 00:19:11 N51°36'20.02" E2°34'56.38" N51°34'38.40" E2°34'02.90"
0010_20191126_233233   4.11 4653 4267 28.16  185.58  5.83 00:13:18 N51°35'04.02" E2°34'10.31" N51°37'30.95" E2°35'00.69"
0011_20191126_235727 211.73 5952 8833 30.31  201.00  3.31 00:29:59 N51°37'07.54" E2°35'03.03" N51°35'44.35" E2°34'15.91"
0012_20191127_002727  37.24 4655 5375 28.61  188.10  4.71 00:16:28 N51°35'44.54" E2°34'15.98" N51°37'18.12" E2°35'38.87"
0013_20191127_004753 284.40  755 1076 31.68  210.63  3.56 00:03:32 N51°37'06.93" E2°35'15.90" N51°37'17.76" E2°34'43.31"
0014_20191127_010052 202.34 4732 12794 20.39  134.78  2.63 00:29:56 N51°37'21.16" E2°34'40.28" N51°34'52.85" E2°33'53.35"
0015_20191127_013403   2.16 2586 2629 25.17  163.03  5.77 00:07:28 N51°34'54.05" E2°34'08.45" N51°36'16.19" E2°34'31.85"
0016_20191127_014616 198.82 3530 7730 28.62  188.66  2.39 00:24:39 N51°36'42.29" E2°34'48.63" N51°34'55.84" E2°34'11.72"
------------------------------------------------------------------------------------------
The total survey:
------------------------------------------------------------------------------------------
S4a1930 consists of 17 lines.
Max depth 45.40 meter, Min depth 5.85 meter, Average depth 25.00
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Total number of valid depths are  60613863.00
Total time of logging 05:32:33 (h:m:s)
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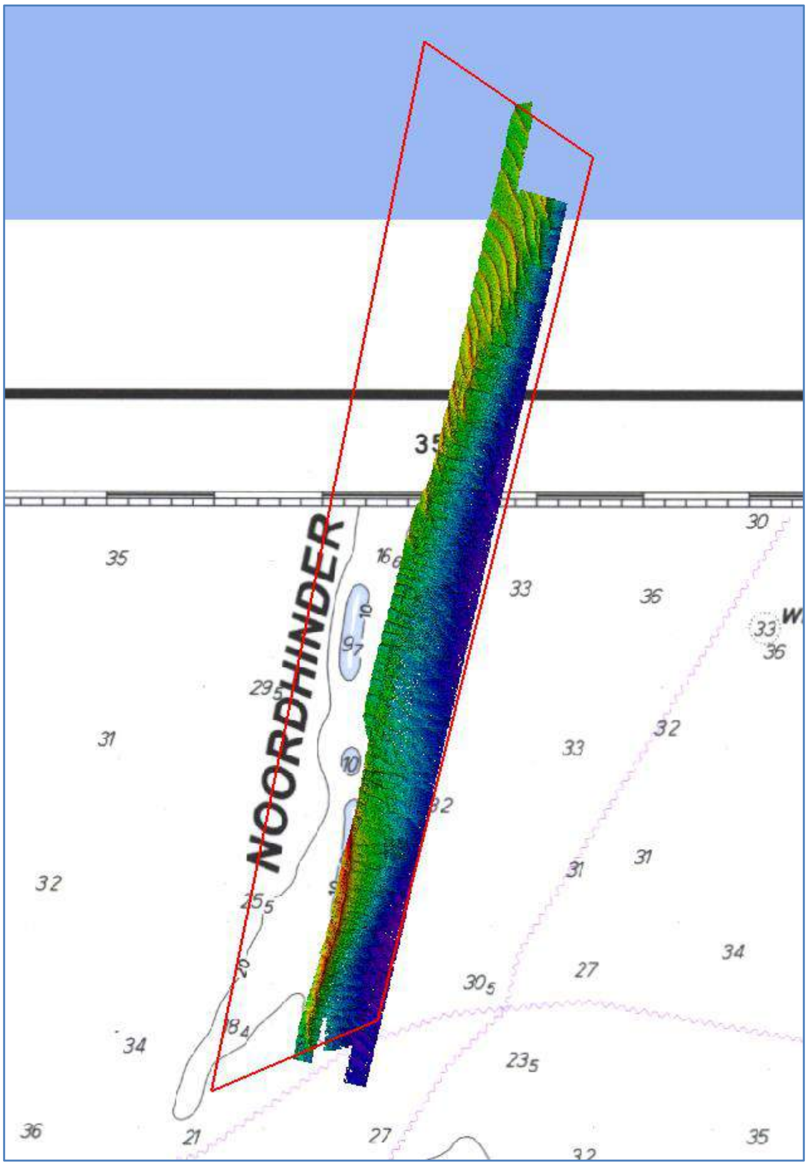

Figure 6: Sector 4a surveyed area

Survey SV1930:

```
List of all lines:
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 Line prefix, heading[deg], length[m], number of pings, average depth[m], average swath[m],
 average speed[m/s], duration(h:m:s), First and last position
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 0001_20191127_043436 245.32 4788 8041 21.76  137.74  4.51 00:17:42 N51°28'31.62" E3°03'41.08" N51°27'39.54" E2°59'48.15"
 0002_20191127_045614  74.23 4442 8073 21.64  136.59  4.20 00:17:38 N51°27'36.96" E2°59'53.36" N51°28'25.61" E3°03'29.86"
 0003_20191127_051557 244.17 4412 10414 21.51  135.63  3.25 00:22:38 N51°28'21.57" E3°03'26.55" N51°27'32.41" E2°59'52.36"
 0004_20191127_054033  73.86 4563 8728 21.06  132.33  4.08 00:18:38 N51°27'30.22" E2°59'53.78" N51°28'17.68" E3°03'34.24"
 0005_20191127_060035 247.40 4416 7822 20.88  131.05  4.45 00:16:33 N51°28'15.61" E3°03'26.33" N51°27'26.38" E2°59'51.75"
 0006_20191127_061856  69.21 4456 7485 20.47  128.08  4.77 00:15:35 N51°27'23.39" E2°59'53.73" N51°28'13.28" E3°03'30.31"
 0007_20191127_063635 250.69 4372 7336 20.31  127.07  4.81 00:15:09 N51°28'08.41" E3°03'25.84" N51°27'20.49" E2°59'53.04"
 0008_20191127_065359  67.23 4439 7699 19.83  123.66  4.73 00:15:39 N51°27'16.81" E2°59'53.03" N51°28'06.88" E3°03'28.61"
 0009_20191127_071436 252.41 4498 7683 19.46  120.85  4.92 00:15:14 N51°28'04.41" E3°03'31.88" N51°27'14.31" E2°59'53.24"
 0010_20191127_073501  65.78 4474 8445 18.85  116.44  4.57 00:16:19 N51°27'10.35" E2°59'52.31" N51°28'00.87" E3°03'29.41"
 0011_20191127_075601 253.85 4520 8273 18.51  113.94  4.84 00:15:34 N51°27'57.71" E3°03'30.88" N51°27'08.25" E2°59'50.61"
 0012_20191127_081808  65.11 4451 9529 18.38  112.76  4.16 00:17:51 N51°27'05.93" E2°59'51.02" N51°27'55.54" E3°03'27.37"
 0013_20191127_084126 253.51 4521 10534 17.72  107.83  4.00 00:18:49 N51°27'53.91" E3°03'29.15" N51°27'03.04" E2°59'49.84"
 0014_20191127_090734  65.28 4562 10148 18.18  111.00  4.08 00:18:37 N51°27'00.72" E2°59'48.33" N51°27'51.57" E3°03'30.11"
 0015_20191127_093134 253.01 4428 8466 17.51  106.37  4.95 00:14:54 N51°27'48.17" E3°03'27.02" N51°26'59.44" E2°59'51.40"
 0016_20191127_095152  65.59 4532 9884 17.68  107.46  4.29 00:17:36 N51°26'56.96" E2°59'49.86" N51°27'47.65" E3°03'29.87"
 0017_20191127_101505 252.04 4674 10757 17.56  106.37  4.12 00:18:54 N51°27'46.68" E3°03'36.51" N51°26'54.60" E2°59'49.46"
 0018_20191127_103906  32.56 1320 2703 25.26  163.75  3.17 00:06:56 N51°26'53.27" E2°59'48.26" N51°27'03.76" E3°00'20.14"
 0019_20191127_104900  64.59 1861 5587 18.11  109.72  3.04 00:10:13 N51°27'00.32" E3°00'31.17" N51°27'23.33" E3°01'59.61"
 0020_20191127_110227  68.05 1798 3789 15.50   90.42  5.14 00:05:50 N51°27'23.25" E3°02'03.20" N51°27'43.12" E3°03'30.58"
 0021_20191127_111306 249.01 4665 15592 18.24  111.32  2.73 00:28:29 N51°27'36.26" E3°03'28.18" N51°26'49.06" E2°59'44.54"
 0022_20191127_114319  73.09 5145 8889 19.20  118.64  4.94 00:17:22 N51°26'57.53" E2°59'52.80" N51°27'57.35" E3°03'49.85"
 0023_20191127_120311 241.59 4366 16624 17.94  109.33  2.43 00:30:00 N51°27'47.17" E3°03'59.78" N51°26'57.42" E3°00'28.95"
 0024_20191127_123312 128.99 5893 13398 21.92  138.96  3.28 00:29:59 N51°26'57.41" E3°00'28.89" N51°27'32.02" E3°03'17.67"
 0025_20191127_130312  73.53  686 1259 17.54  106.45  5.20 00:02:12 N51°27'32.07" E3°03'17.93" N51°27'40.41" E3°03'50.81"
 0026_20191127_131241 240.60 4798 17372 17.29  104.36  2.67 00:29:59 N51°27'36.17" E3°03'48.88" N51°26'42.43" E2°59'56.20"
 0027_20191127_134241 244.47  131  321 26.98  176.55  2.48 00:00:53 N51°26'42.40" E2°59'56.08" N51°26'41.34" E2°59'49.55"
 0028_20191127_135116  79.21 4542 9135 17.02  102.58  4.86 00:15:35 N51°26'42.69" E3°00'00.15" N51°27'31.39" E3°03'40.69"
 0029_20191127_141430 239.75 5026 17917 16.77  100.38  2.79 00:30:00 N51°27'30.81" E3°03'48.12" N51°26'34.56" E2°59'44.30"
 0030_20191127_144431 270.58   87  174 26.39  171.65  3.22 00:00:27 N51°26'34.54" E2°59'44.14" N51°26'35.18" E2°59'39.86"
 0031_20191127_145015  77.80 4573 10225 16.07   95.11  4.67 00:16:20 N51°26'34.60" E2°59'51.90" N51°27'25.70" E3°03'34.04"
 0032_20191127_151433 258.01 1678 3122 23.64  151.55  3.75 00:07:27 N51°28'18.33" E3°03'34.91" N51°28'15.37" E3°02'08.25"
 0033_20191127_153356  79.08 1134 2631 14.75   85.33  4.91 00:03:51 N51°27'19.80" E3°01'43.28" N51°27'30.92" E3°02'39.21"
 0034_20191127_154623 240.53 1914 7274 13.23   73.83  3.41 00:09:21 N51°27'27.85" E3°03'05.95" N51°27'06.39" E3°01'33.08"
 0035_20191127_155954  75.82 1630 4435 12.38   67.67  5.13 00:05:18 N51°27'06.37" E3°01'44.57" N51°27'24.65" E3°03'03.68"
 0036_20191127_161132 241.78 1073 4043 12.01   64.78  3.83 00:04:40 N51°27'16.86" E3°02'42.88" N51°27'04.93" E3°01'50.76"
 0037_20191127_163017  76.27 4467 11036 14.42   82.88  4.75 00:15:40 N51°26'33.02" E2°59'51.85" N51°27'22.54" E3°03'28.92"
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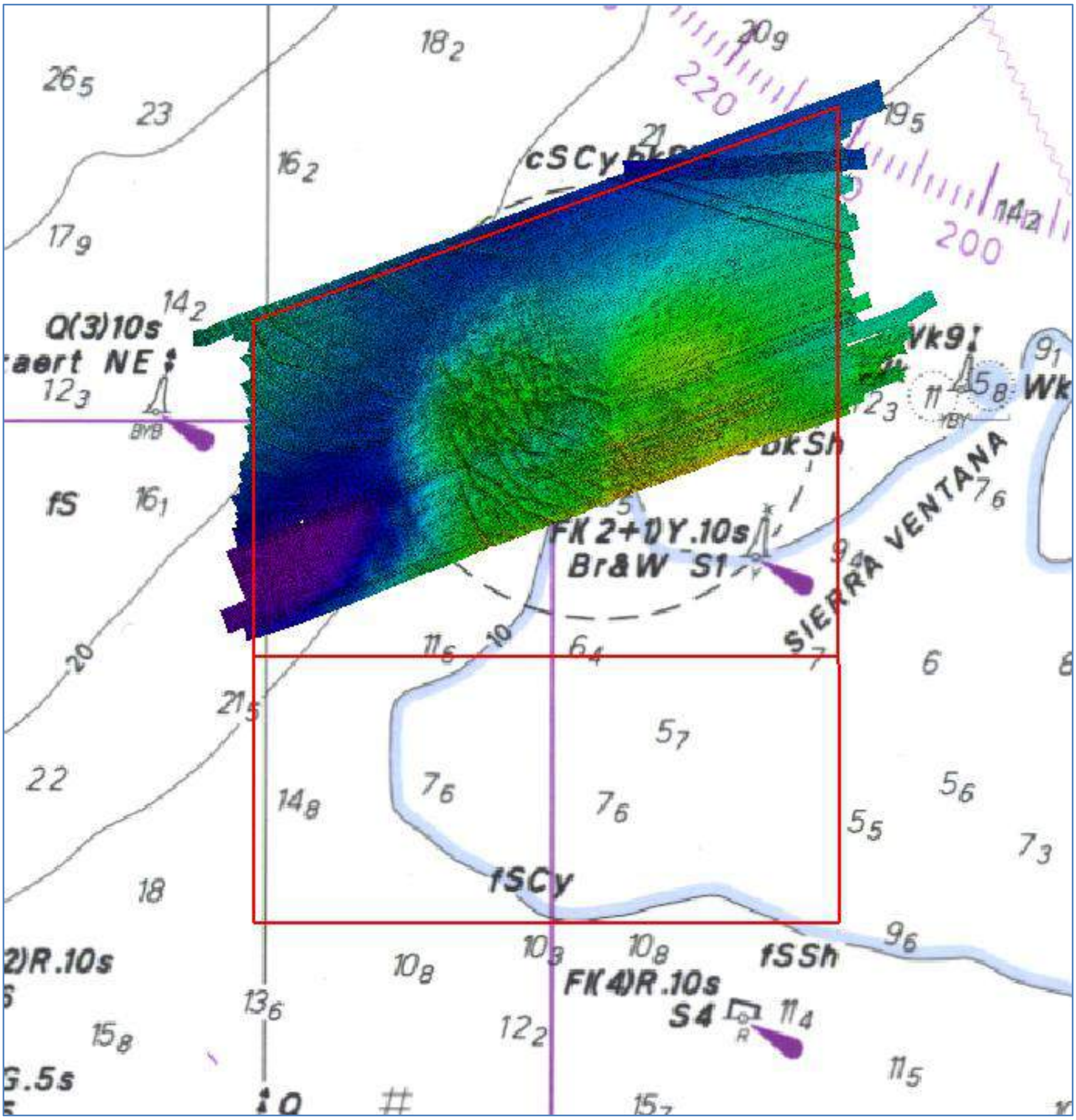
Figure 7: Sector 3b surveyed area

7. REMARKS

The crew of the Belgica is acknowledged for the valuable and greatly appreciated cooperation and excellent navigation.

8. DATA STORAGE

OD NATURE: Multibeam data, Video data, Seabed samples (contact Vera Van Lancker/ Giacomo Montreale Gavazzi) and ADCP data (contact Joan Backers)
FPS Economy – Continental Shelf Department: multibeam data (contact Koen Degrendele)

Annex E. Publications 2016-2019

PhD thesis

Montereale Gavazzi, G.O.A., 2019. Development of seafloor mapping strategies supporting integrated marine management: application of seafloor backscatter by multibeam echosounders. PhD Thesis, Ghent University, Ghent, Belgium, 392 pp. (available upon request)

A1 publications

Montereale Gavazzi G, Roche M, Lurton X, Terseleer N, Degrendele K, Van Lancker V., 2018. Seafloor change detection using multibeam echosounder backscatter: Case study on the Belgian part of the North Sea. Marine Geophysical Research, 1-19 (open access: https://link.springer.com/article/10.1007/s11001-017-9323-6).

Montereale Gavazzi, G., Roche, M., Degrendele, K., Lurton, X., Terseleer, N., Baeye, M., Francken, F., and Van Lancker, V., 2019. Insights into the short-term tidal variability of multibeam backscatter from field experiments on different seafloor types. Geosciences, 9(1), 34. (open access: https://doi.org/10.3390/geosciences9010034)

Book chapter

Van Lancker, V., 2017. Bedforms as Benthic Habitats: living on the edge, chaos, order and complexity. In Atlas of Bedforms in the Western Mediterranean (pp. 195-198). Springer, Cham.

Van Lancker, V., H. Vandenreyken, B. Lauwaert, A. De Backer en L. Devriese, 2018. Zand- en grindwinning, in: Devriese, L., Dauwe, S., Verleye, T., Pirlet, H., Mees, J. (Ed.) Kennisgids Gebruik Kust en Zee 2018 - Compendium voor Kust en Zee, 79-90.

Van Lancker, V., H. Vandenreyken, B. Lauwaert, A. De Backer and L. Devriese, 2018. Sand and gravel extraction, in: Devriese, L., Dauwe, S., Verleye, T., Pirlet, H., Mees, J. (Ed.) Knowledge Guide Coast and Sea 2018 - Compendium for Coast and Sea.79-89.

Van Lancker, V., Kint, L. & Montereale Gavazzi, G., 2018. Fysische verstoring en verlies van de zeebodem (D6). In: Belgische Staat. Evaluatie van de goede milieutoestand van de Belgische mariene wateren. Kaderrichtlijn Mariene Strategie. BMM, Federale Overheidsdienst Volksgezondheid, Veiligheid van de Voedselketen en Leefmilieu, Brussel, België. (https://odnature.naturalsciences.be/msfd/nl/assessments/2018/page-d6).

Abstracts and Proceedings (poster/oral presentations)

Baeye, M., F. Francken, V. Van Lancker and D. Van den Eynde, 2017. Marine aggregate mining in the Hinder Banks: on-board sampling of the turbid dredging overflow. Proceedings Studiedag Zand en Grind – Belgisch zeezand – een schaars goed? Oostende, 9/6/2017, 1 pp. + Poster.

Francken, F., D. Van den Eynde and V. Van Lancker, 2017. Application of a large dataset of sediment transport parameters: variability in sediment transport in the HBMC area. Proceedings Studiedag Zand en Grind – Belgisch zeezand – een schaars goed? Oostende, 9/6/2017, 10 pp. + Poster.

Montereale Gavazzi, G., J. De Bisschop, M. Roche, K. Degrendele, M. Baeye, F. Francken and V. Van Lancker, 2016. Can multibeam-derived acoustic backscatter be used to monitor changes in seabed habitats? Abstract North Sea Open Science Conference, 7-10 November, Ostend, Belgium.

Roche, M., K. Degrendele, A. De Backer, D. Van den Eynde and V. Van Lancker, 2018. Monitoring the direct impact of sand extraction on the bathy-morphology and the seabed sediment in the Belgian part of the North Sea. Lessons of ten years of measurements. GeoHab 2018, Marine Geological and Biological Habitat Mapping, Santa Barbara, U.S.

Roche, M., Degrendele, K., Urban, P., Baeye, M., Van Lancker, V., Fettweis, M., Greinert, J., Depestele,

J., Mertens K., and Augustin, J.-M. (2020) Quantifying sediment plumes induced by human activities by using MBES and SBES water column data combined with in situ measurement and water sampling: feasible?. Abstract for Geohab conference Venice, Italy.

Terseleer, N., K. Degrendele, L. Kint, M. Roche, D. Van den Eynde, V.R.M. Van Lancker, 2019. Automated estimation of seabed morphodynamic parameters. Extended Abstract, Marine and River Dune Dynamics – MARID VI, 1-3 April 2019, Bremen, Germany, 6 pp

Van den Eynde, D., M. Baeye, M. Fettweis, F. Francken and V. Van Lancker, 2016. Changes in bottom shear stress, due to aggregate extraction, in the area of the Hinder Banks (Belgian Continental Shelf). Abstract + Poster, VLIZ Marine Science Day, 12 February, Brugge.

Van den Eynde, D., M. Baeye, M. Fettweis, F. Francken and V. Van Lancker, 2016. Changes in bottom shear stress, due to aggregate extraction, in the area of the Hinder Banks (Belgian Continental Shelf). Abstract for the ICES Annual Science Conference, 19-23 September, Riga, Latvia.

Van den Eynde, D., M. Baeye, M. Fettweis, F. Francken and V. Van Lancker, 2016. Effect of aggregate extraction on MSFD descriptor 7 (hydrographic condition) in the Hinder Banks area (Belgian Continental Shelf). Abstract North Sea Open Science Conference, 7-10 November, Ostend, Belgium.

Van den Eynde, D., M. Baeye, M. Fettweis, F. Francken and V. Van Lancker, 2016. Changes in bottom shear stress, due to aggregate extraction, in the area of the Hinder Banks (Belgian Continental Shelf). Abstract 18th Physics of Estuaries and Coastal Seas Conference. 9-14 October, Scheveningen, The Netherlands.

Van den Eynde, D., F. Francken and V. Van Lancker, 2017. Effects of extraction of sand on the bottom shear stress on the Belgian Continental Shelf. Proceedings Studiedag Zand en Grind – Belgisch zeezand – een schaars goed? Oostende, 9/6/2017, 20 pp.

Van Lancker, V., F. Francken, L. Kint, G. Montereale Gavazzi, N. Terseleer and D. Van den Eynde, 2016. Large dunes hosting hotspots of biodiversity: testing proxies of occurrence and habitat change. Marine and River Dune Dynamics, MARID V, 4-5 April, Bangor, UK, Extended abstract, 3 pp.

Van Lancker, V.R.M., M. Baeye, D. Evangelinos, G. Montereale Gavazzi, N. Terseleer and D. Van den Eynde, 2016. MSFD-compliant investigative monitoring of the effects of intensive aggregate extraction on a far offshore sandbank, Belgian part of the North Sea. Abstract ICES Annual Science Conference, 19-23 September, Riga, Latvia.

Van Lancker, V.R.M., Baeye, M., Evangelinos, D., Montereale-Gavazzi, G., Terseleer, N. & Van den Eynde, D. (2016). MSFD-compliant investigative monitoring of the effects of intensive aggregate extraction on a far offshore sandbank, Belgian part of the North Sea. North Sea Open Science Conference, Ostend (BE), 7-10/11/2016. (poster presentation)

Van Lancker, V., M. Baeye, D. Evagelinos, F. Francken, G. Montereale Gavazzi and D. Van den Eynde, 2017. MSFD-compliant assessment of the physical effects of marine aggregate extraction in the Hinder Banks, synthesis of the first 5 years. Proceedings Studiedag Zand en Grind – Belgisch zeezand – een schaars goed? Oostende, 9/6/2017, 18 pp.

Van Lancker, V., F. Francken, M. Kapel, L. Kint, N. Terseleer, D. Van den Eynde, K. Degrendele, M. Roche, G. De Tré, R. De Mol, T. Missiaen, V. Hademenos, J. Stafleu, S. van Heteren, P.-P. van Maanden and J. van Schendel, 2017. Flexible querying of geological resource quantities and qualities, a sustainability perspective. Proceedings Studiedag Zand en Grind – Belgisch zeezand – een schaars goed? Oostende, 9/6/2017, 13 pp.