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OPERATIONAL DIRECTORATE NATURAL ENVIRONMENT

Section Ecosystem Data Analysis and Modelling
Suspended Matter and Seabed Modelling and Monitoring Group (SUMO)

Effect of wind farms on the siltation of gravel beds

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Table of Contents

1. Introduction

In the framework of the European Directive 2009/28/EC on the promotion of electricity produced from renewable energy sources in the internal electricity market, Belgium targets a contribution of 13 % of the total energy consumption, to be produced by renewable energy sources by 2020 (Belgische Staat, 2010). Offshore wind farms in the Belgian part of the North Sea (BPNS) are expected to contribute around 43 % to achieve that goal. As for now, a zone of 238 km² of the BPNS is reserved for the production of electricity. This zone was foreseen in the Belgian Marine Spatial Plan (MSP), which was approved by the Royal Decree of March 20, 2014, and was valid for 6 years.

In 2003, the first wind farm C-Power requested a domain concession. Since then, a total of nine wind farms obtained a domain concession and an environmental permit for the installation of wind farms (see Figure 1). At present, seven wind farms are operational (Rentel, Belwind, C-Power, Nobelwind, Northwind and Norther, Nortwester2), while two additional wind farms (Mermaid and Seastar) are under construction.

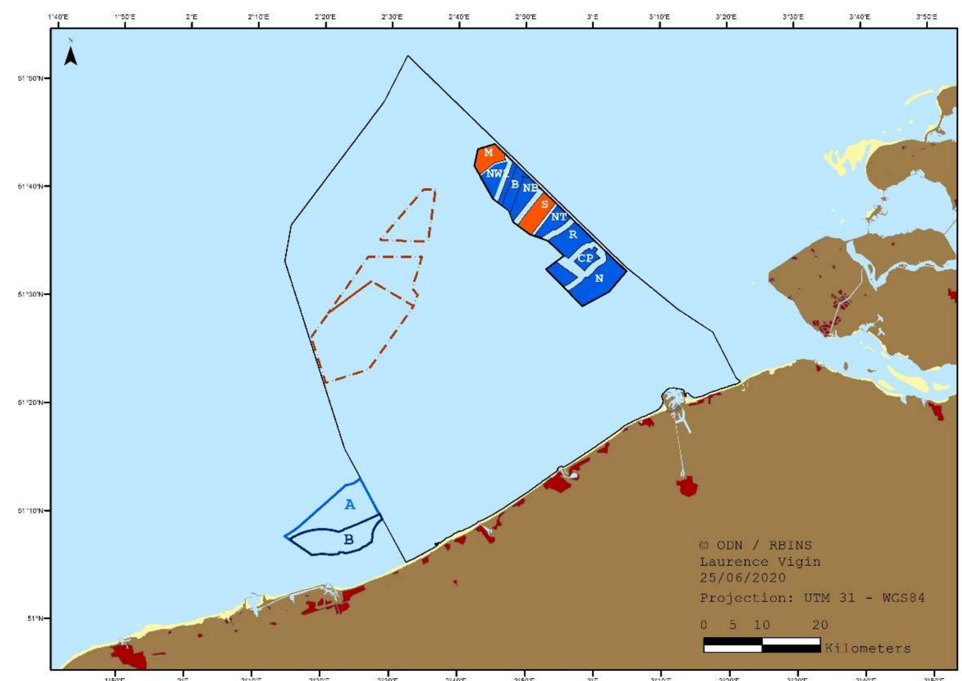

Figure 1: Current and planned zones for renewable energy in and around the Belgian Part of the North Sea with indications of wind farms that are operational (blue) and currently under construction (orange). The proposed sites for the Dunkerque offshore wind farm are indicated by A and B. Locations of the new renewable energy zone, as foreseen in the Marine Spatial Plan 2020-2026, are shown by the dashed lines.

To increase the contribution of renewable energy by offshore wind, a further extension of the zone, reserved for wind farms, has been planned. This year, a new MSP came into effect (Royal Decree of 22 July 2019; Belgische Staat, 2019). This MSP includes a new large area for renewable energy (Figure 1). Three zones are defined: a zone Noordhinder

Noord and Noordhinder Zuid, and a zone Fairybank. Remark that the zone Fairybank is located in a special zone for nature conservation 'Vlaamse Banken' (European code BEMNZ0001), a so called Habitat Directive Area (Figure 2).

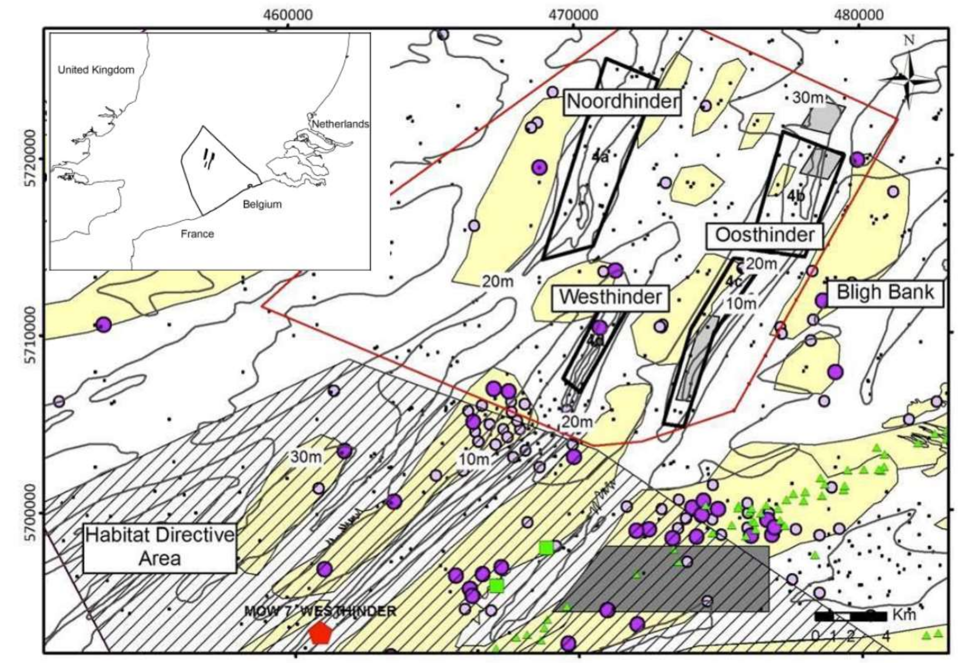

Figure 2: Area of the Hinder Banks, where intensive marine aggregate extraction is allowed in zone 4 (red line) along 4 sectors (black polygons). Within and outside these sectors geomorphological monitoring is carried out by COPCO (light grey polygons). A Habitat Directive area (hatched) is present at 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). In the gravel refugia (green squares), west of the Oosthinder, ecologically valuable gravel beds are present. Indicated also is the position of the Westhinder measuring pole MOW7 (Flanders Hydrography) (red pentagon) providing hydro-meteorological data. Dark grey polygon in the Habitat Directive area is an anchorage zone (from: Van Lancker et al., 2016).

Near the northern limit of the 'Vlaamse Banken' area, ecologically valuable gravel beds are located (e.g., Houziaux et al., 2008; Van Lancker et al., 2015, 2016). These beds have the status of "reefs" (Habitat type code 1170). At present and in contrast to 100 years ago, gravel fauna has become very marginal because of intensive fisheries (Houziaux et al., 2008). The effect of the sand and gravel extraction areas, which are located north of the Habitat Directive area (Figure 2), could be important as well. These effects are studied in the framework of the ZAGRI contract, funded by the revenues of the private sector, and the MOZ4 contract, financed by the Flemish Authorities, Agency Maritime Services and Coast, Coast. Investigative monitoring is conducted by the Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environments (RBINS, OD Nature), the Continental Shelf Service of FPS Economy (COPCO) and the Institute for Agricultural and Fisheries Research (ILVO).

Following-up on the findings of Houziaux et al. (2008), Van Lancker et al. (2015) reported on the status of the gravel beds, previously recognized as biodiversity hotspots. They are still observed at the foot of the steep (lee) side of morphologically distinct barchan dunes, present at the western extremity of the Oosthinder sandbank. Barchan dunes are steep dunes, composed of coarse sands, and occur typically where high currents prevail over hard substrates (Belderson et al., 1982). Since the rich gravel beds occurred near the lee side of the barchans, Houziaux et al. (2008) hypothesized that fishing nets would jump over these biodiversity hotspots, hence they were called refugia (Van Lancker et al., 2016).

Apart from fisheries and sand and gravel extraction, also the installation and operation of new wind farms in the three new zones could have effects on the siltation and/or smothering of the gravel areas in the Habitat Directive area. This is the subject of the current report.

The main effect of the installation and operation of wind farms to be expected is an increase in suspended particulate matter concentrations (SPMc) (e.g., Rumes et al., 2013, 2015; Van den Eynde et al., 2010, 2013), due to (1) dredging and relocation works during preparation of the sea bottom; (2) the installation of monopiles, jacket foundations or gravity based foundations; (3) dynamic and/or static scour around the foundations or around the erosion protection; (4) the cable burial and/or (5) the development of sediment plumes in the wake of wind turbines.

The increase in SPMc will decrease the light to the marine environment, which is a key environmental variable, coupling physics to marine biochemistry and ecology. Weak light penetration reduces light availability for photosynthesis, changing the energy fluxes through the marine food web (e.g., Newell et al., 1998, 2004; Eggleton et al., 2011; Borst et al., 2013; Capuzzo, 2015). In some cases, some specific sensitive receptors (e.g., oysters) are defined that are used to define the maximum increase in SPMc, to prevent impact (Marine Management Organization, 2014).

The sediment that is brought in suspension will settle down and will deposit on the bottom, changing the sediment composition at the area of deposition, that could alter the habitat (e.g., Cruz-Motta and Collins, 2004, Erftemeijer and Lewis, 2006, Erftemeijer et al., 2012).

In addition, recent research highlighted that the different wind turbines generate sediment plumes (Li et al., 2014; Vanhellemont and Ruddick, 2014; Baeye and Fettweis, 2015; Foster, 2018). The cause and the exact nature of these plumes is still under debate. Monitoring at the wind farm Mermaid is therefore foreseen (BMM, 2015).

Since it can be expected that the effects of seabed removal with trailing suction hopper dredgers (TSHD) could be larger than the effects of the installation and operation of the wind farms, these operations and the possible effects on the gravel beds are briefly considered as well, although they are at a larger distance from the gravel beds with high ecological potential.

2. Material and methods

2.1. *Study area*

Hitherto, the location of gravel beds in Belgian waters is only known indicatively. In 2007 a first map was released showing areas with a high potential of gravel occurrences, based on a combination of available data at that time (Belspo MAREBASSE, Van Lancker et al., 2007) (see Figure 3 for the data sources). An important predictor was minimal thickness to absence of Quaternary sediments based on Maréchal and Henriet (1983). The map was later refined to support the inclusion of the gravel habitat type 1170 within the delineation of the Flemish Bank Habitat Directive (Degraer et al., 2009). In the framework of the Belspo QUEST4D project (Van Lancker et al., 2012) and the aggregate resources project Belspo TILES (Van Lancker et al., 2019), data on the thickness of the Quaternary have been thoroughly updated, and the nature of Quaternary sediments was quantified in detail using a voxel modelling approach (Hademenos et al., 2019). This information can now be queried in a publicly available decision support system (DSS, TILES consortium, 2018; Figure 4a and Figure 4b). Figure 4a shows that most of the gullies in between the sandbanks have a high probability of gravel occurrences. The TILES outcome also predicts gravel in the north-western corner of the southern wind farm designated zone, hitherto not mapped. Figure 4b shows that in the southern area of interest, there is a lack of borehole information, resulting in a higher uncertainty of the results.

For the Hinder Banks region, available maps remain very qualitatively. In the framework of the MOZ4/ZAGRI projects and the European Marine Strategy Framework Directive (MSFD), RBINS is conducting regular surveys using very-high resolution multibeam technology (MBES, depth and backscatter), in combination with sampling and videography. These observations showed the very patchy nature of gravel occurrences (e.g., Van Lancker et al., 2016; Montereale Gavazzi, 2019). The mapping built on the multibeam baseline survey of FPS Economy, Continental Shelf Service in the aggregate concession zone 4, Hinder Banks. They continue monitoring the aggregate sectors within this zone, including the area s4d in the Noordhinder Noord area.

A detailed gravel mapping initiative is currently on-going (Van Lancker and Montereale Gavazzi, 2019) whereby new data products will be made available based on new insights into acoustic seafloor classification (Montereale Gavazzi, 2019, Montereale Gavazzi et al., 2019). This approach integrates multibeam-derived depth and backscatter data, and their derivatives, in combination with ground truthing by sampling and video observations. The resolution of this mapping is 1 m.

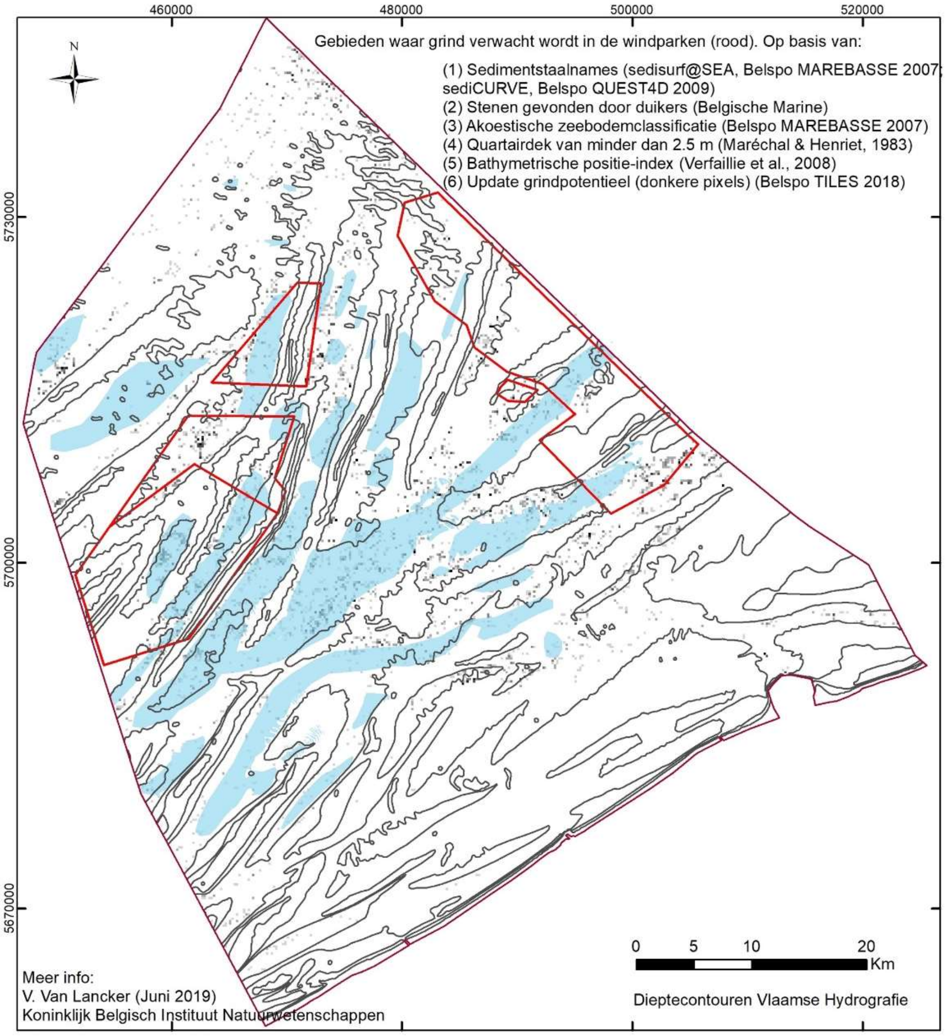

Figure 3: Map with high potential of gravel occurrences (blue areas). Areas with darker pixels, having a higher gravel potential, result from an update of geological data on the Quaternary sediments (TILES Consortium, 2018) (From: Van Lancker & Montereale Gavazzi, 2019). The red areas are reserved for wind farms.

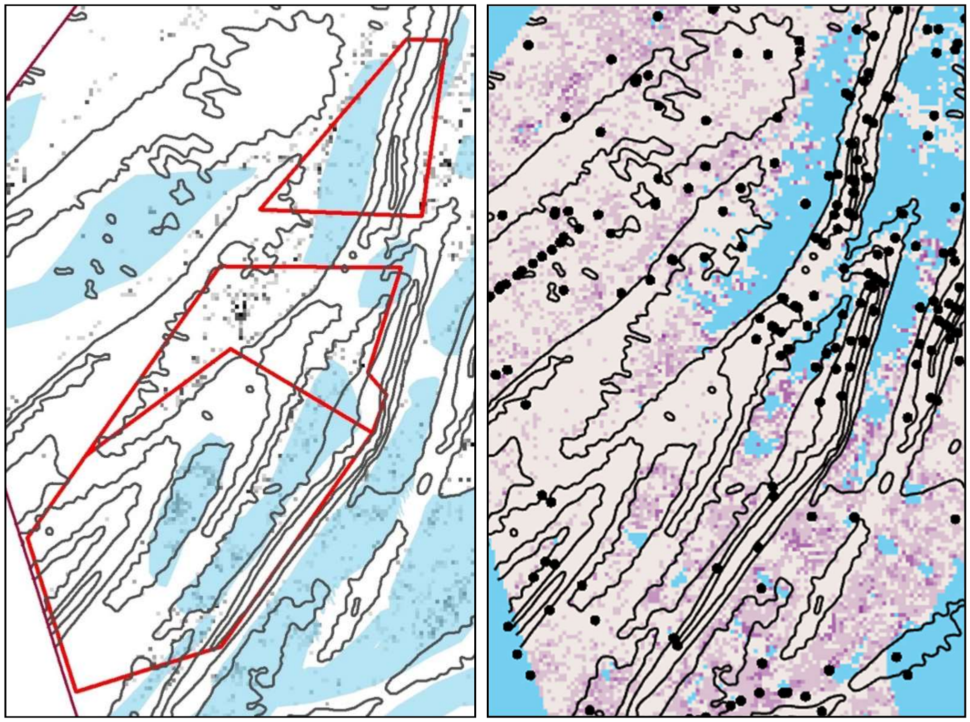

Figure 4: a) (Left): Map with high potential of gravel occurrences (see Figure 4 for legend). Zoom on the area of the new wind farms. b) (Right): TILES DSS extract with blue areas having a limited Quaternary cover; and dark purple areas having a high degree on heterogeneity. Dots are borehole locations (From: Van Lancker & Montereale Gavazzi, 2019).

2.2. *Literature study*

The possible effect of the installation and operation of offshore wind farms is described in the necessary Environmental Impact Reports (EIR). The environmental impacts were evaluated by the Management Unit of the North Sea Mathematical Models of the RBINS, who prepared an Environmental Impact Assessment (EIA) and an advice to the Minister. The advice included some conditions and required monitoring. The last two EIAs were for the Mermaid and the Seastar wind farms (Rumes et al., 2013, 2015). In these reports, the knowledge until then is summarized and condensed and the conditions and the monitoring for the permit are based on the previous results.

Information from the monitoring of the existing wind farms in Belgium was reported in yearly reports since 2009, edited by the RBINS (e.g., Degraer et al., 2018, 2019). In Van den Eynde (2010, 2013) the effects on the sea bottom were discussed more in detail.

Furthermore, data and information was used from the above mentioned ZAGRI and MOZ4 projects (Van Lancker et al., 2015, 2016; Van den Eynde et al., 2019), as well as from the Belspo INDI67 project (Fettweis et al., 2020), targeting developing new methodologies for the monitoring of the environmental status of marine waters. Where relevant, data from satellite images are used.

Information from EIRs and monitoring results, prepared for offshore wind farms in other countries, are considered, as well as summary reports from governmental bodies, responsible for the environmental permits.

2.3. Numerical simulations

To have more information on the dispersion of material in the water column in the area of the new wind farms, the dumping of material in the water column and deposition at the bottom is simulated with numerical models. The main goal is to present some results that are specific for the situation.

Model results will remain illustrative and must be looked at with the necessary precautions. Also, the current resolution does not allow to model the effects in detail.

Even today, accuracy of sediment transport models is relatively low. Shen et al. (2019b) states that currently available three-dimensional models are not able to make satisfying quantitative predictions of sediment properties, which raises the question whether we can do any better (Toorman, 2012). Toorman et al. (2019) state that "Sediment research is difficult; cohesive sediments behave even more complex. Some of the questions are (very) old and have not found adequate solutions for many years." This is also observed in the monitoring and validation of model results.

Developers invest a lot of effort in Environmental Statements, based on numerical model results, but monitoring is absolutely necessary to validate the model predictions (CEFAS, 2010). Measured SPMc are often lower than the model predictions (Elliott et al., 2017) and the zone of initial deposition of rejected material is often less than predicted by models (Hitchcock, 2002).

2.3.1. Numerical models

2.3.1.1. Hydrodynamic model

The currents and water elevations are calculated with the hydrodynamic model OMNECS_BCZ (Yu, 1993; Ozer et al., 2000). The model is a two-dimensional hydro-dynamic model, based on a semi-implicit ADI numerical scheme. The model is implemented on the BPNS on a geographical grid with a resolution of about 278 m x 257 m. The extension of the model grid and the bathymetry is shown in Figure 5. The model comprises the entire BPNS and a part of the Western Scheldt. On the open boundaries, the model is coupled with a two-dimensional model for the entire North-West European Continental Shelf with a resolution of about 4 km x 4 km.

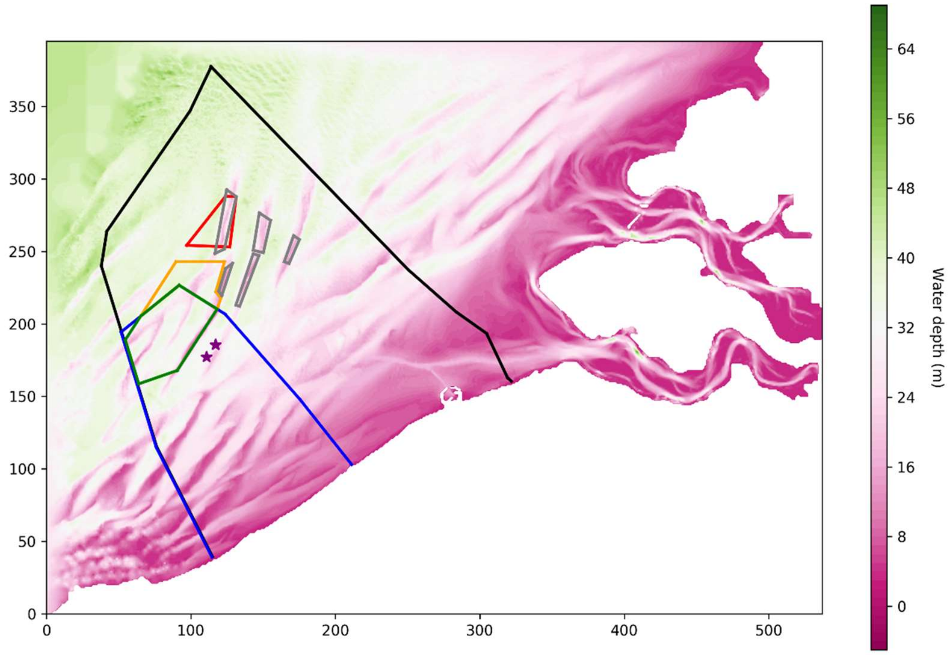

Figure 5: Bathymetry of the numerical model. Indication of Habitat Directive Area 'Vlaamse Banken' (blue); new zones for renewable energy Noordhinder Noord (red), Noordhinder Zuid (orange), Fairybank (green); sand extraction zones (grey); gravel beds refugia areas (purple stars).

2.3.1.2. *Wave model*

The waves, which can also be important for the erosion of material deposited on the bottom, are calculated with the 3th generation wave model WAM (WAMDI Group, 1988; Günther et al., 1992). The model calculates the full wave spectrum and some integrated parameters, such as the significant wave height, wave frequency and wave direction under the influence of the prevailing wind. In the southern North Sea (Figure 6), the model has a resolution of 2.33 x 2.47 km. At the open boundaries, the model is coupled to a model of the central North Sea (resolution 6.7 x 7.4 km) and with a model for the entire North Sea (resolution 28 km x 33 km). The model is extended enough to the north to ensure that the model can generate all waves that are arriving at the Belgian coast. The model has been validated extensively in Van den Eynde (2013).

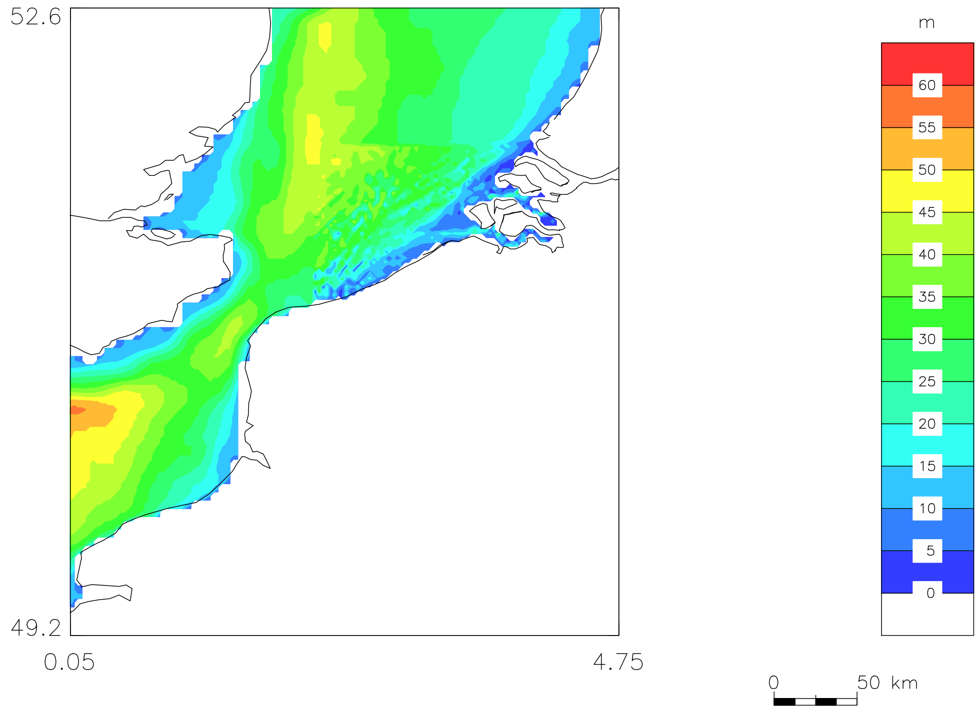

Figure 6: Bathymetry of the high resolution WAM model WAM-LOCL.

2.3.1.3. *Sediment transport model*

For the modelling of the dispersion and transport of (fine-grained) material the model MU-STM is used (Van den Eynde and Fettweis, 2006). The model is a two-dimensional model, calculating the advection and diffusion of the material in suspension. The model uses the semi-Lagrangian second moment method (Egan & Mahoney, 1972; de Kok, 1994) to calculate the advection of the material in suspension. This method has the advantage of minimal numerical diffusion. The erosion is modelled following Ariathurai-Partheniades (Ariathurai, 1974), while the sedimentation is calculated using the formula of Krone (1962).

The model has been used to calculate the sediment balance on the BCP (Fettweis and Van den Eynde, 2003), to compare the model results with in-situ measurements of radioactive tracer experiments (Van den Eynde, 2003), to simulate the fine-grained sediment transport and dredging material dumping at the BCP (Van den Eynde and Fettweis, 2006), and to check the possible impacts of alternative dumping sites (Van den Eynde and Fettweis, 2015).

2.3.2. Simulations

The simulations with the hydrodynamic and wave models have been executed for the period 01/09/2013 to 01/01/2014. However, for the sediment transport simulations, only a period of 15 days was used, covering a full neap-spring tidal cycle.

A total of 38 different simulations have been executed with the sediment transport model, with dumping on five sites: Dump 1 to Dump 5 (Table 1; Figure 7). While the first dumping site is located in the center of the Noordhinder Noord area, the second dumping site is in the center of the Fairybank area. The third point, where dumping is simulated, is in the south of the marine aggregate extraction area 4c, outside the new areas for wind farms. These three sites are in or very nearby the new wind farm area. Dumping sites Dump4 and Dump 5 are located in the center of extraction area 4b and north of the Noordhinder Noord area.

Table 1: Name, geographical coordinates, model coordinates and water depth of the dumpings points and output points (I: xxx; J: xxx).

Name	Longitude (°E)	Latitude (°N)	I	J	Water depth (m)
Refugia 1	2.55159	51.43056	118	186	29.9
Refugia 2	2.52778	51.41204	112	178	33.6
Dump 1	2.55555	51.62500	119	270	36.3
Dump 2	2.40476	51.44908	81	194	34.1
Dump 3	2.61508	51.49769	134	215	23.4
Dump 4	2.67857	51.60417	150	261	19.1
Dump 5	2.35714	51.56482	69	244	37.4
MOW 1	3.11508	51.36111	260	156	10.3

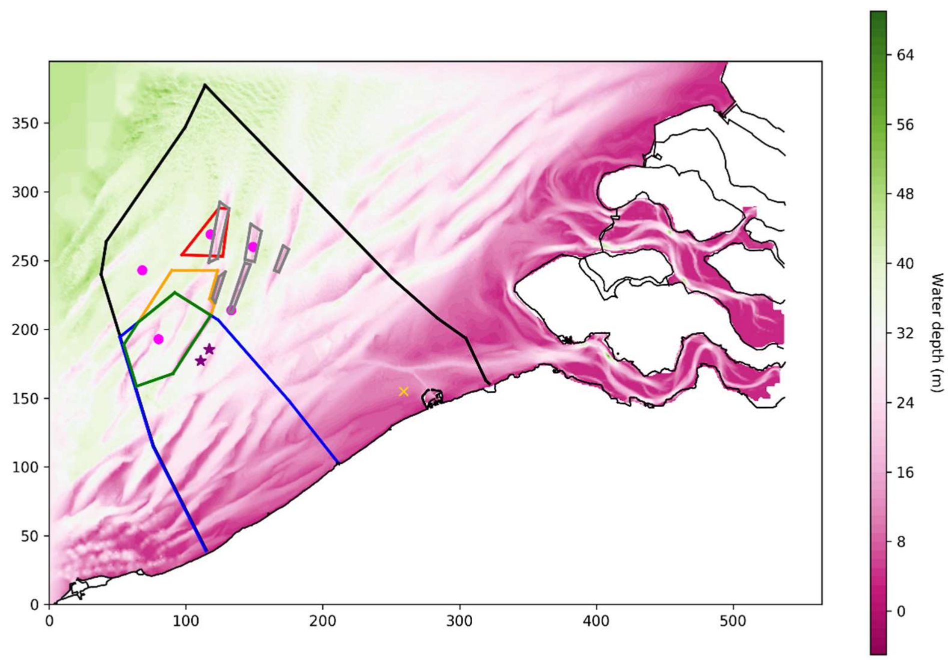

Figure 7: Bathymetry of the numerical model. Indication of Habitat Directive Area 'Vlaamse Banken' (blue); new zones for renewable energy (red), gravel beds refugia areas (purple stars, Ref 1 = most North, Ref 2 = most south), Zone 4 extraction areas (grey) and dumping points (blue circles: Dump 1 = in center of zone Noordhinder Noord, Dump 2 = in center of zone Fairybank, Dump 3 = east of zone Noordhinder Zuid, south of extraction zone 4c, Dump 4 = center of extraction zone 4b, Dump 5 = north of Noordhinder Noord) and MOW1 (green cross).

Two activities are simulated. The first simulations are representative for extraction activities and the overflow during these activities. During this activity, it is assumed that 140 tons of dry material (TDM) is lost in the water column or at the bottom. This is around 50 % higher than a worst-case scenario (see infra, 3.2.3.1). The second type of simulations, simulate a dumping of material. The amount of material dumped is in this case taken from the study Van den Eynde and Fettweis (2015) where the effects of the recirculation of an alternative dumping site near Zeebrugge was studied. Based on dredging data, it was assumed that during one dumping between 1350 and 1680 TDM was dumped, with a variation between the number of dumpings in one day between 1 and 10 dumpings. Here a total of 1400 TDM is dumped. Finally, some continuous dumping activities over the complete simulation period are simulated. Each 4 hours 240 TDM is dumped, for a total of 1440 TDM during a full day, for the full simulation period. The four hours is a rough estimate of a dredging dumping cycle, 240 TDM is an (worst-case) estimate of the fine material dumped. In the EIR for Mermaid wind farm, 136 TDM was dumped every 2.5 hours (IMDC, 2014b).

In all cases, half of the material was dumped at the bottom, while the other half was put in the water column. This is a worst-case scenario, since Johnson et al. (1988, 1992) mention that for a typical maintenance the material, containing both sand and clay/silt, only 10 % of the material remains in suspension and is transported by the prevailing currents.

The model simulates advection and diffusion. Deposition and resuspension are taken into account. Initially no material is found at the bottom, so no influence of the natural variability of the SPMc is taken into account. Only the 'excess' concentration is modelled.

The sediment parameters in the model were taken from previous experiences with the model (Van den Eynde, 2003; Fettweis and Van den Eynde, 2003; Van den Eynde and Fettweis, 2006, 2015). The critical bottom stress of erosion and for deposition is 0.5 Pa; no consolidation is taken into account. The fall velocity is set to 1 mm s^{-1}. It is clear that the selection of these parameters will influence the model results. This is tested in some additional simulations.

3. Results

3.1. *Literature review*

3.1.1. Installation of the foundations

During the installation of the foundations, dredging works and relocation works are needed to prepare the seabed. It can be expected that these dredging operations will be more important for gravity-based foundations (GBF) than for monopiles or jacket foundations. For the Seastar wind farm, it is estimated that seabed preparation works for monopiles would need a dredging of 19,000 m³, while for jacket foundations only 16,000 m³ would be necessary (Rumes et al., 2013). GBF would need a total of 90,000 m³ sand to be dredged, which is a factor five higher. The dredging and the relocation of this material will create sediment plumes and an increase in SPMc. During the dredging, small sediment plumes are generated by the drag head of the dredging vessel. It is estimated that 1 % of the dredged material will be brought into suspension (IMDC, 2014b). This was based on a study that collected results from more than 43 dredging projects (Anchor Environmental CA L.P., 2003). Furthermore, it was estimated that the overflow loss of fine-grained material during dredging was around 67 % of which 17 % remains in the water column as a passive plume.

A larger sediment plume is generated during the disposal of the dredged material. For a typical maintenance, the material, containing both sand and clay/silt, is transported to the bottom as a dense jet (Johnson et al., 1988, 1992). Only 10 % of the material remains in suspension and is transported by the prevailing currents. On the other hand, Van den Eynde et al. (2010) estimated that around 30 % of the material is lost during dredging and relocation operations. This is also used in IMDC (2014b).

These SPMc increases will be mainly controlled by the tidal action. In the immediate vicinity of the disturbance, a dynamic plume typically exists and settles out fast because of the relatively high settling velocity of sand grains. When fine-grained matter (i.e., silt-sized) is present in the sand matrix, passive plumes come into play and are advected by the prevailing tidal current with varying intensities (for example neap vs. spring tide). There is a known flocculation tendency of fine matter that may form aggregates (with resulting higher settling velocities), even during very short-term intra-tidal phases (Lee et al., 2012; Chen et al., 2018; Shen et al. 2018a, 2018b; Shen et al., 2019a, 2019b). The passive plume may travel long distances of about several kilometers before depositing (Hitchcock and Bell, 2004). Freshly deposited fine matter layers could be easily resuspended and subsequently transported by the next prevailing tidal current, unless it is buffered in the sand matrix (e.g., Rusch et al., 2000). This was evidenced along the south of the Oosthinder sandbank (Hinder Banks region), with the hypothesis that the source of the fine-grained material was related to overflow of nearby intensive aggregate extraction (Van Lancker et al., 2017).

When for the installation of the monopiles or jacket foundation, the suction bucket technique is used instead of drilling, sediment plumes are also generated. The suction bucket technique is a new technique, where the monopile is anchored in the bottom under the influence of its own weight and a created vacuum (IMDC, 2014a). A small amount (10-20 m³ per turbine) of sediment can be dispersed, but the amount of suspended sediments is within the range of the natural background values.

Numerical simulations were performed of the dispersion of a sediment plume, generated during dredging and disposal operations for the wind farm Seastar near the Lodewijckbank IMDC (2014b). It was estimated that the sandy bottom contained 3 % of fine-grained material. The spilled sand was expected to settle down rapidly. The simulations of the dispersion of the fine-grained material showed that the background value of 4 mg l^{-1} (Van den Eynde et al., 2013) is only exceeded in 2.6 h, corresponding to 7.5 % of the time of the dredging activities. The sediment plume could travel 1600 m and had a width of 600 m, but the concentration was in 96 % of the time lower than 10 mg l^{-1} (Figure 8).

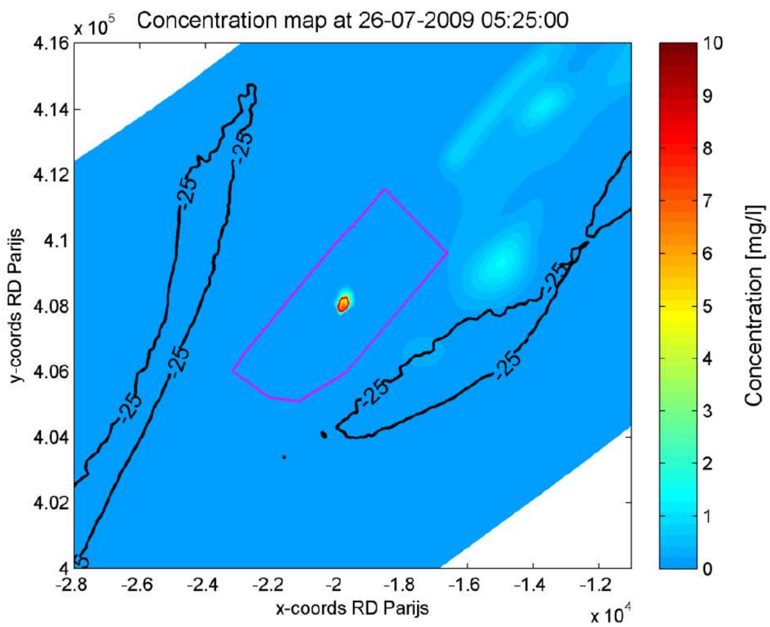

Figure 8: Example of dispersion of a plume caused by dredging and disposal activities at the Seastar wind farm (Lodewijckbank) (from: IMDC, 2014b).

It was concluded that the increase in SPMc was only local and temporary and would not affect the environment significantly.

Also in Rumes et al. (2015) it was concluded that during dumping and dredging activities for the preparation of monopiles and jacket foundations, no additional monitoring will be recommended (BMM, 2015). Similar recommendations were made by the UK authorities (DECC, 2008a, 2008b; Carroll et al., 2010; CEFAS, 2010).

When using GBF and the suction bucket technique, less monitoring has been executed and less information is available. Therefore, additional monitoring was recommended for this type of foundation (BMM, 2015). However, during the installation of the GBFs in the C-Power wind farm no increase in SPMc was observed (Van den Eynde et al., 2013).

3.1.2. Scour

Due to the interaction of the currents and the foundation, erosional processes are expected. Behind the pole complex three-dimensional horseshoe vortexes are generated, that will erode the material (Figure 9). The size of these erosion pits varies. Different studies and formulae to calculate the (maximal) erosion depth are available in literature. In some cases, the development of this erosion pit is allowed and the foundations are secured by drilling it deeper in the ground. Using this dynamic erosion protection, for some time an erosion pit is developing creating sediment plumes. When using a static erosion protection, the development of the erosion is avoided by installing an erosion protection layer, formed by larger stones and/or filter layers. However, in this case, secondary erosion can occur, at the edges of the erosion protection.

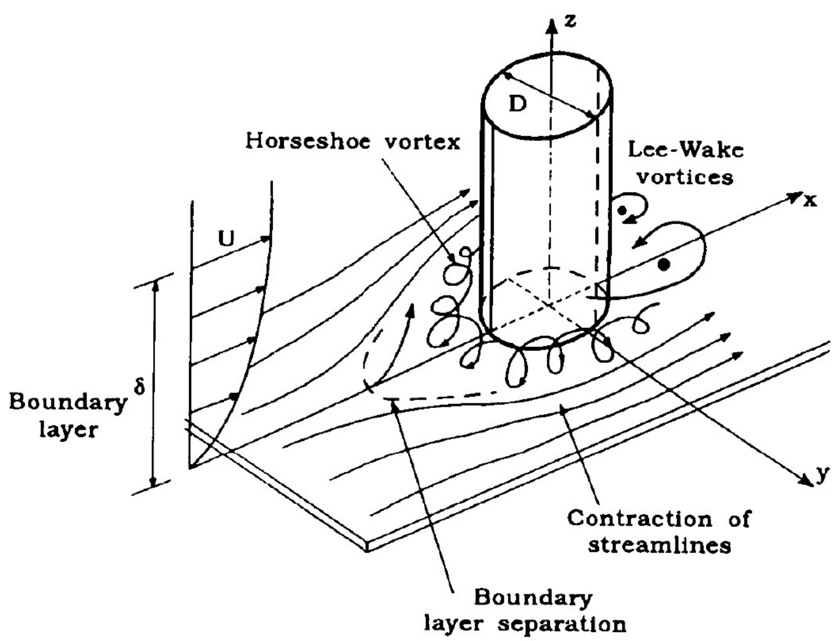

Figure 9: 3D-flow around the base of a vertical pile (from: Sumer and Fredsøe, 1999)

Scientific literature on scour around wind turbines in coastal waters reveals its complex character (e.g., Sumer et al., 1994; Sumer and Fredsøe, 1998; Sumer and Fredsøe, 1999; Sumer et al., 2001; Sumer and Fredsøe, 2001a; Sumer and Fredsøe, 2001b; Whitehouse et al., 2010; Harris et al., 2011; Whitehouse et al., 2011). Some effects are discussed in the EIA for the C-Power farm (BMM, 2004).

In Sumer and Fredsøe (1999) a maximum ratio between the equilibrium depth of the erosion pit and the diameter of the pile is found to be 1.3. In Sumer and Fredsøe (2001a) values are found between 1.5 and 2. For pole diameters of 2 m, this would lead to erosion pits of 7.5 to 10 m depth. The time needed to reach an equilibrium of is still under debate. Sumer and Fredsøe (2001a) mention that under laboratory conditions, the equilibrium depth is reached after only 5 h.

It is clear that the dynamic erosion protection with the generation of erosion pits will generate a temporary erosion of sand. As in the new wind farm the seafloor is composed of mostly gravel and coarser sand, the sand will be deposited rapidly in the neighborhood of the piles. Furthermore, the amount of sand that will be eroded is restricted. On the other hand, using static erosion protection will use a larger area that will be disturbed. Furthermore, secondary erosion pits can be formed, with the same small and temporary increase in SPMc in the water column.

3.1.3. Cable burial

In the wind farms cables will be laid between the wind turbines and the transformation platform and from the wind farm to land.

BERR (2008) reviewed the cable techniques and the environmental effects for offshore wind farms and concludes that the environmental impact is highly transitory, localized in extent, generally restricted to 2 to 3 m width, and for short duration. It is mentioned that compared to other influencing factors, like storm effects, fishing effects and aggregate extraction, the effects of cable burial are generally less important.

Different cable laying methods were considered such as ploughs, jetting systems, ROV's, sledges and dredging systems (BERR, 2008). The methods that can be used and the physical disturbances are of course also a function of the site conditions, e.g., the seabed type and the tidal and wave conditions. A rank of the level of disturbance resulting from cable burial operations was assessed. Overall, using a plough is the least disturbing technique, while dredging is evaluated as the most disturbing technique.

There still is very limited research and advice on the quantification of the volume of the material that is disturbed and brought into suspension during cable burial operations (BERR, 2008). The estimation can be based on the area of disturbance multiplied by the rate of the progress. A cutter tool of 250 mm wide and 1000 mm deep at a rate of progress of 250 m h^{-1}, will cut 62 m^3 h^{-1}. Reviewing subsea video gives an estimate that 10 to 15 % of the cut material will backfill into the trench. The remaining material will be deposited at the sides of the trench or will be brought into suspension (BERR, 2008). Sands however will be deposited very rapidly. Measurements of the plume generated by the drag head have shown that the sediment introduced in the water column is in the order of 1 % of the material introduced by screening and overflowing.

Results from six wind farms were summarized. Model results showed a deposition depth of a few mm at 200 m at either side of the cable. In other cases, the deposition footprint extended only 20 m at either side, but with a deposition of 10 mm. The fine sediment increased the background SPMc with only a few percent. Another numerical study showed that, when the cable laying was executed in a chalk bottom, the dispersion drops to less than 1 mg l^{-1} above background within a single flood or ebb excursion, but that the footprint could be up to 9 km on either side of the cable route. For more sandy bottoms, even with a high concentration of silt, most of the resuspended sediment is likely to remain within 1 to 2 m near the bottom and will settle within half an hour or less, within 20 m from the cable. Another study showed that jetting induces less material in the water column than trenching (by dredging) and backfilling. At 200 m from the operation, the maximum values varied from 18 mg l^{-1} to 75 mg l^{-1}. The Danish Energy Agency uses a maximum value of 45 mg l^{-1}.

More recently, 3D particle dispersion modelling has been executed (Smartwind, 2013). Five scenarios were modelled. Different model parameterization were used, including assumptions on the amount of fine-grained material in the sea bed as well as on the amount of material brought into suspension. With the parameters used, trailer suction resulted in an increase of (depth-averaged) SPMc of 40 mg l^{-1} up to 200 m from the cable route, with a cumulative deposition of 2 mm in an area of 60 m x 250 m (which will be resuspended again). Sand wave jetting resulted in a larger increase of up to 900 mg l^{-1} near the cable itself, but the duration was less than 1 h (Figure 10). Footprint deposition would rise up to 5 mm. Ploughing sand resulted in no measurable increase, while jetting sand would result in an increase of up to 12 mg l^{-1}. The results indicated a limited and short time effect.

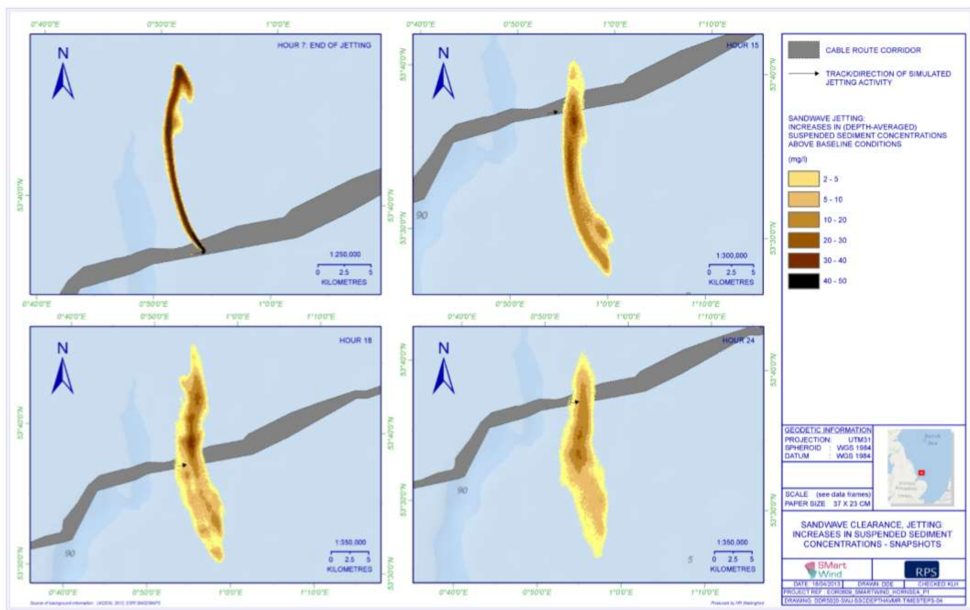

Figure 10: Sand wave clearance: jetting – Predicted increases in (depth-averaged) SPMc above baseline conditions at four points in time throughout the model simulation for sand wave 1 (From: Smartwind, 2013).

Swanson and Isaji (2006) also modelled the effects of cable installation. The cable laying resulted in an increase of less than 50 mg l^{-1} in some areas with peaks of up to 500 mg l^{-1}. A deposition of 1 to 5 mm was modelled, occurring within a few hundred meter from the cable route. In a similar modelling study of jet plowing, an increase of SPMc to a maximum of 5000 mg l^{-1} in an area of 0.02 ha was found (Swanson et al., 2015). The plume dissipated within 6 hours, and the deposition was restricted to 0.1 to 0.5 mm over 35 ha. Similar results were obtained by Vinhateiro et al. (2018), however thicker deposits were predicted (up to 10 mm).

It is clear that different models give variable results, depending on the local situation and on the model parameters and assumptions (Smartwind, 2013). However, all models indicate that the plume and the maximum concentration will decrease quite rapidly.
Limited monitoring results are available. During cable installation using a jet plowing mechanism, no sediment plume was observed away from the vessel (Elliott et al., 2017). The sediment plumes were lower than predicted by the models. Near the cable itself (1.5 to 7 m), deposition was up to 25 cm thick.

BERR (2008) concluded that the effect that are likely to be short term and relatively localized and that ploughing and jetting are the least disturbing techniques. In Belgium, it was specified that the cables should be buried 1 m below the base of the migrating sand dunes (Rumes et al., 2013) to avoid unburial and free spanning of cables. In this case sand dunes have to be dredged in advance. This is the reason that dredging techniques have been used instead of the less impacting jetting or ploughing technique, e.g. for the export cables for the BOG platform (Rumes et al., 2014).

3.1.4. Sediment plumes created by the wind turbines

The hydrodynamic wakes created by wind turbines will lead to another possible increase in SPMc. Until recently, these wakes did not receive a lot of attention. Atmospheric wakes were noted (e.g., Hassager et al., 2013) a little bit earlier than the hydrodynamic wakes. The first published maps of surface sediment concentration plumes are probably by Vanhellemont and Ruddick (2014) and Li et al. (2014). The first in-situ observations are probably described by Baeye and Fettweis (2015). They showed five times higher SPMc (15 mg l^{-1}) for an offshore wind farm in the Belgian part of the North Sea. While in Vanhellemont and Ruddick (2014) scouring and the development of erosion pits were considered as a possible source, Baeye and Fettweis (2015) put forward that the source could be of biological nature since the seabed may consist of fine matter originating from biological processes occurring at the foundation of the mono-pile, scour rock protection and the immediate seafloor as shown by Coates et al. (2014).

Since then, different modelling studies have been executed to model the turbulent wakes around the monopiles (Christie, 2014; Carpenter et al., 2016; Cazenave et al., 2016; Grashorn and Stanev, 2016; Rivier et al., 2016; Rogan et al., 2016; Miles, 2017). Recently also Legrand et al. (2018) executed some simulations on the turbulent wakes behind some monopiles (Figure 11). They, and others, showed that the turbulence behind the monopiles increased, which could increase both the bottom shear stress behind the monopiles and the turbulent diffusion, increasing the possibility of fine-grained particles to be transported higher in the water column.

Plumes have been observed in Belgium from a series of aerial surveys (pers. comm. SURV/MUMM) mostly corresponding to periods of ebb and flood maximal currents under spring tide conditions. Under those cyclical conditions, (near-)surface fine-grained material will be washed out from the sand matrix. The plume extent will vary both vertically and horizontally (up to several kilometers) as a function of the prevailing conditions.

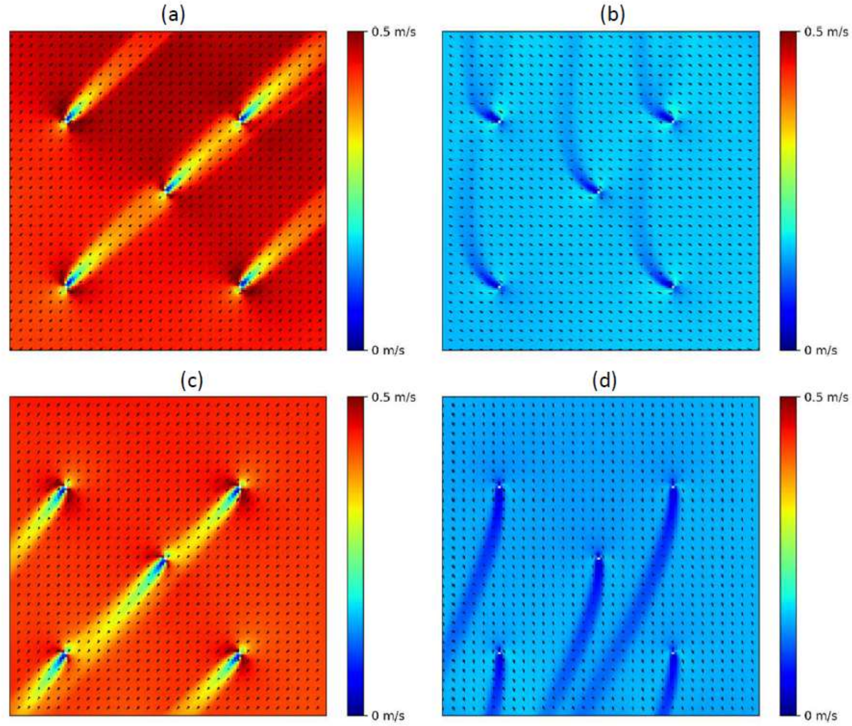

Figure 11: Bottom current at different moments in the tide a) flood; b) tidal reversal c) ebb d) tidal reversal (From: Legrand et al., 2018).

Recently, more in-situ measurements on sediment plumes and its nature have been executed (Floeter et al., 2017; Forster, 2018). Forster (2018) measured an (averaged) increase of about 42 % of the SPMc in the sediment plume, near the surface and an increase of 10 % to 20 % in the midwater and near the bottom. From the possible explanations, the evidence supports the hypothesis that the plumes are caused by redistribution of suspended sediments in the water column due to an increase in vertical mixing in the monopile wake. This was confirmed by the fact that the near-bed concentration of sediment was actually lower within the plume than outside the plume. Furthermore, it was shown that the percentage of organic material in filtered water samples did not vary with the depth or the sample location, indicating that the sediment plumes were not directly of biological nature. Furthermore, the increase in SPMc would probably be well within the range of variability encountered in any given spring-neap tidal cycle, and that therefore will have limited ecological effects.

On the other hand, Orpin et al. (2004) showed that near sensitive environments even limited anthropogenic sediment discharges could have significant effects.

These observations and research results are only obtained recently and need further confirmation in other situations. It was recommended to investigate the nature and the magnitude of the sediment plumes behind the monopiles and jacket foundations in the

Belgian coastal waters in the monitoring program for the Mermaid wind farm (BMM, 2015).

3.1.5. Sediment plumes due to aggregate extraction

Due to dredging works, or marine aggregate extraction, three types of dredge plumes can be expected, each having a typical behavior (Spearman et al., 2011) (Figure 12): (1) a surface plume dispersing away from the TSHD; (2) a dynamic plume, representing the coarser part of the initial plume, and descending in the near field; and (3) a passive plume, bringing together the finest fractions from the surface and dynamic plumes, and from a near-bed plume caused by the drag head. The dispersion of the passive plume can easily extend several kilometer from the vessel (e.g., Newell et al., 1999; Hitchcock and Bell, 2004).

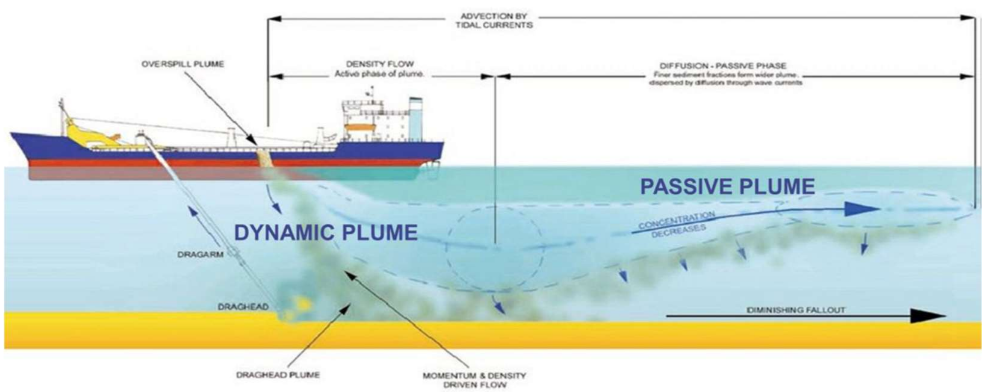

Figure 12: Dynamic and passive plumes, as a consequence of the overflow of a trailing hopper suction dredger (TSHD) (From: Spearman et al., 2011).

In the study area of the Hinder Banks, such plumes were evidenced in 2013 using the unmanned surface vehicle Wave Glider from Liquid Robotics (Van Lancker and Baeye, 2015). In 2014, measurements were carried out to quantify the extent and impact of such plumes (Van Lancker et al., 2016). During sand extraction (sandbank in sector 4c), SPMc were measured up to 15 mg l^{-1}. 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 10 mg l^{-1}. Concentrations in the surface waters were around 1 to 2 mg l^{-1}, for neap and spring tide respectively. Median SPMc in the lower waters was 11 to 15 mg l^{-1} in the deepest areas and up to 19 mg l^{-1} over the sandbank crests (Van Lancker et al., 2016).

Enrichment of fine-grained material was found embedded in the sand matrix of the refugia areas, though no direct link could be made with the extraction activities.

Van Lancker et al. (2016) does put forward a step-wise impact hypothesis where fine-grained material resulting from aggregate extraction activities is first deposited in the near-field gullies and are then resuspended, amongst other by fishing activities. Longer lasting deposition could then occur in morphologically complex areas that preferentially trap fine-grained sediments (Van Lancker, 2017). They do recognize that cumulative and in-combination effects should be considered as well (Figure 13).

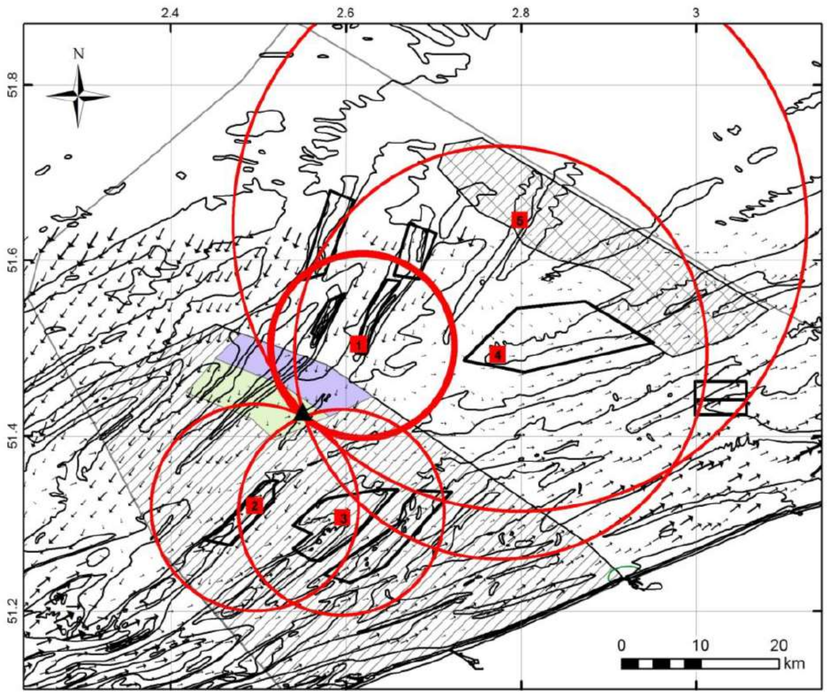

Figure 13: Gravel beds with high ecological potential in the Habitat Directive Area (central triangle) with the distances to the different pressures (red squares). (1) Extraction in Sector 4c, Hinder Banks; (2) and (3) Extraction in zone 2: Oostdijck and Buiten Ratel; (4) Extraction in zone 1 Thornton Bank. All of these may act cumulatively. In-combination effects may also exist, hence deposition may exist from turbidity plumes generated around the wind turbine structures (5). Note that these are minimally 30 km away. Importantly to note is the omni-presence of fisheries activities. On the BPNS, the influence of these activities on water column turbidity and seabed texture has not been assessed yet. To give insight in the spreading of fine-grained material, the direction and magnitude of maximum currents are indicated. A proposal for fisheries management areas is indicated where in the north part (purple) fisheries would be prohibited in the future; in the south part (green) only alternative fishing would be allowed (from: Van Lancker et al., 2016).

Measurements have been executed by Baeye et al. (2019) in the TSHD Brueghel (capacity 12000 m^3), that was used for marine aggregate extraction. It must be remarked that the extraction of marine aggregates was combined with dredging works in the Zeebrugge harbor. Although the hopper is cleaned after the dumping of the dredged material, there was still a residue that contributed to the overflow of fine-grained material during aggregate extraction. Measurements of the overflow showed a SPMc of up to 1 g l^{-1} with particles having a median grain diameter of 24 µm. A total of 85 % of the overflow consisted of fine-grained material, whilst only 15 % consisted of rapidly settling sand. From estimations of one extraction event, a total of around 16 ton of sediments was spilled in the overflow. The measured overflow of 1 g l^{-1} is lower than found by Hitchcock and Bell (2004) and Duclos et al. (2013) measuring concentrations of 6 g l^{-1} in the overflow of a TSHD.

Birklund and Wijsman (2005) summarize different results of the effect of marine aggregate extractions and differentiate between the sediment spill and the sediment plumes. Near the ship, a dense (dynamic) plume is formed, as described by Spearman et al. (2011). They do highlight that screening of the material will largely influence the amount of overspill.

3.2. *Numerical model results*

3.2.1. Tidal elevations, currents and waves

Water elevations, currents and tidal ellipses at the stations Dump2 and MOW1 during a full spring-neap tidal cycle, with spring-tide round 8/9/2013, are given in Figure 14 to Figure 16.

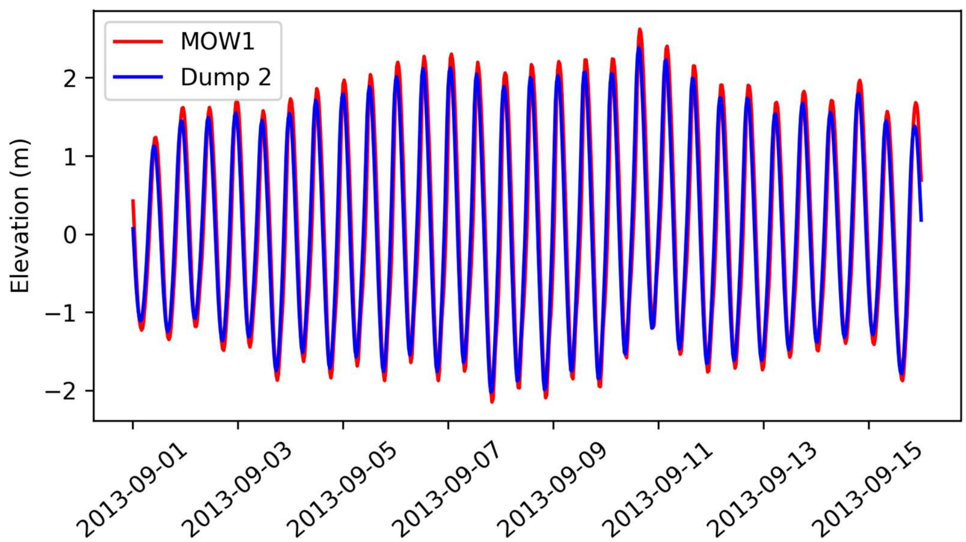

Figure 14: Tidal elevations in stations MOW1 and Dump 2

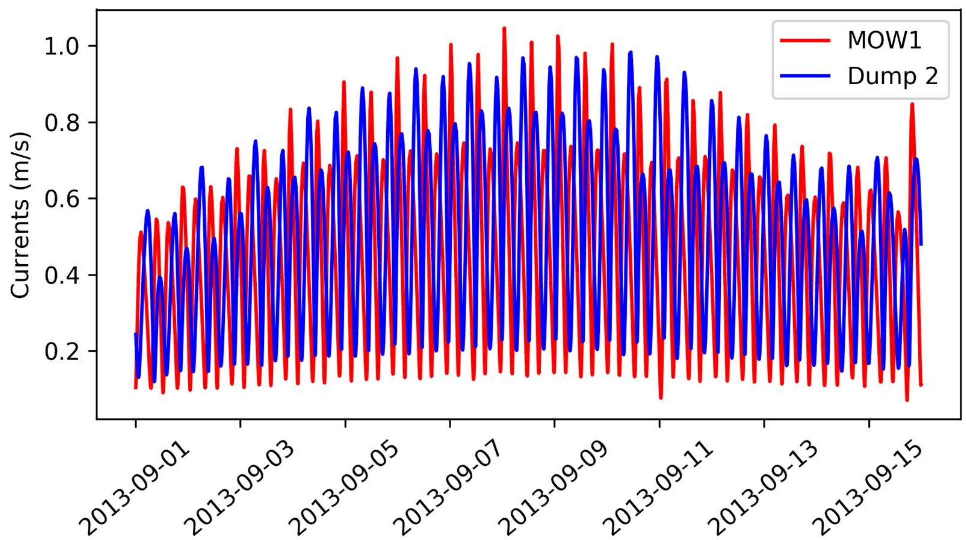

Figure 15: Currents in stations MOW1 and Dump 2.

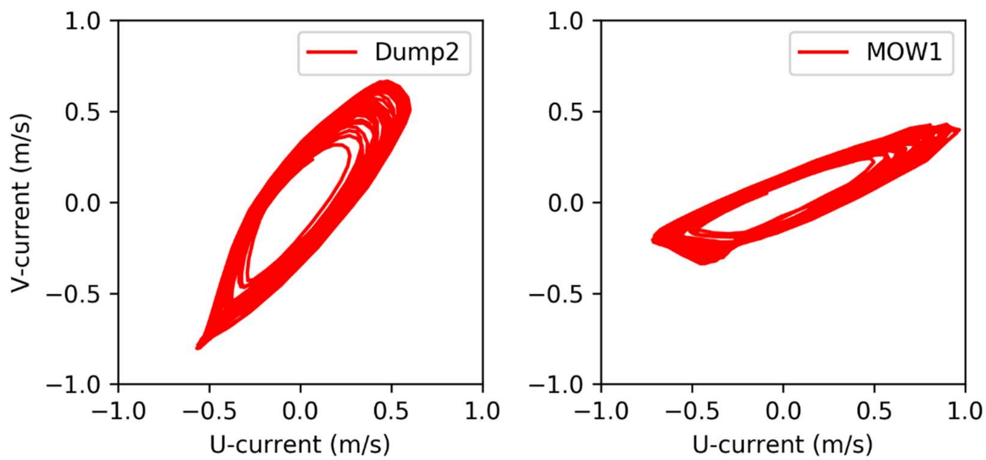

Figure 16: Tidal ellipses in stations MOW1 and Dump 2.

The tidal elevation and the current speed are slightly higher at MOW1, near the coast, than at Dump 2, more offshore. The tidal ellipses show that the tidal ellipses are more elongated near the coast, at MOW1, and more circular at the offshore stations, at Dump 2. Moreover, the direction of the flood and ebb-currents are different. While the nearshore currents are more east-west oriented, driven by the coast, the offshore currents are more directed northeast-southwest.

During the first ten days of the simulated period, the waves are relatively low, below 1.0 m (Figure 17). Around 11/09, a peak in wave height is occurring with a significant wave height, higher than 2.5 m at MOW1 and higher than 3.0 m at Dump 2, more offshore. Also, at 14/09 and 15/09, two new peaks in significant wave height are observed, with waves up to 1.5 m at MOW1.

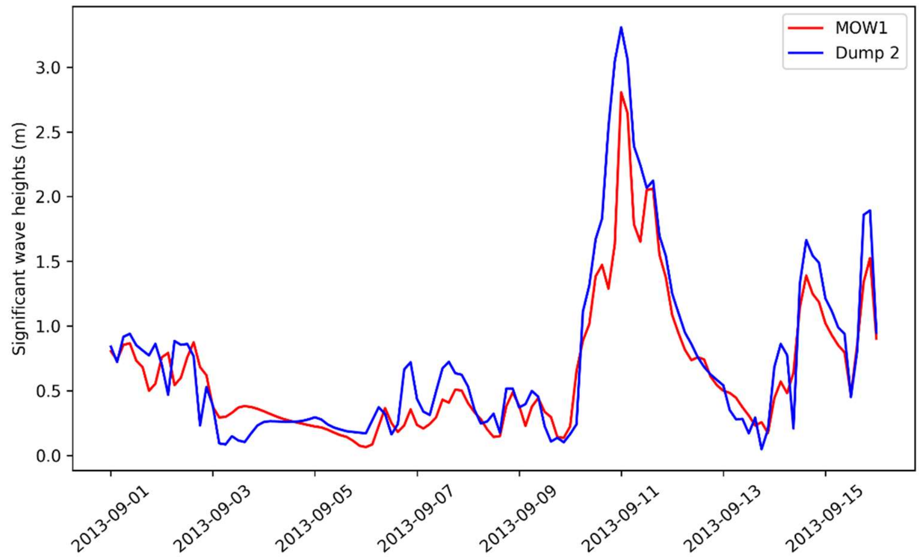

Figure 17: Significant wave height in stations MOW1 and Dump 2.

3.2.2. Bottom shear stress, residual currents and transports

The bed or bottom shear stress determines the erosion and resuspension of the material or the deposition of the material on the sea bed and is as such the link between the material in the water column and the material on the sea bed. The bed shear stress is therefore an important parameter to consider, when looking at possible smothering of the gravel beds.

The highest bottom shear stress is found in the mouth of the Western Scheldt and the Eastern Scheldt, and near the harbor of Dunkerque (Figure 18). The latter could be an artefact due to boundary conditions. More offshore the mean bottom shear stress is below 0.8 Pa.

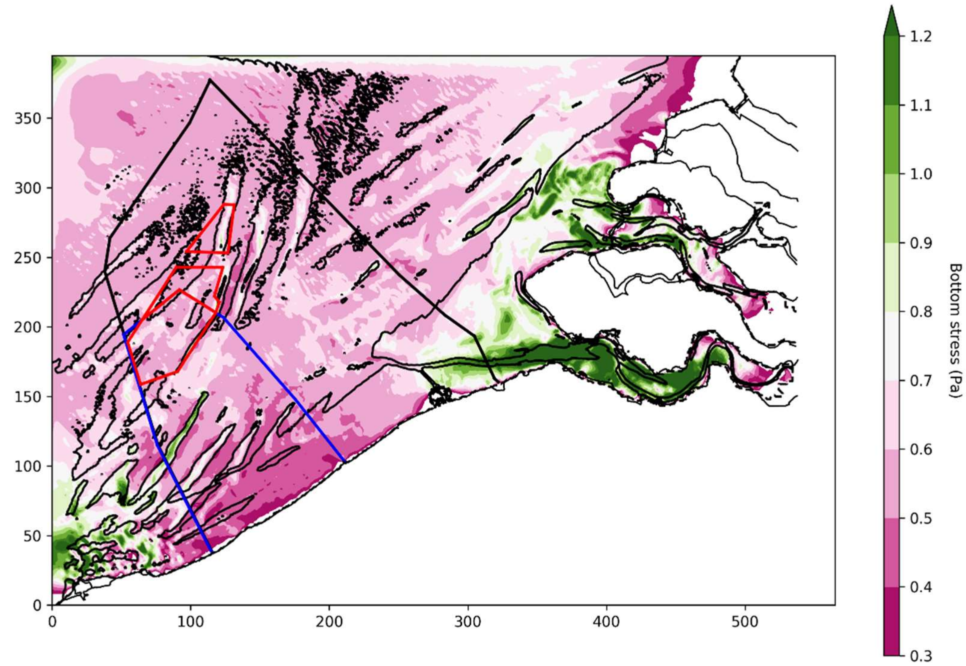

Figure 18: Mean bottom shear stress during one spring-neap tidal cycle at the BCP. Waves are not taken into account.

In the area of the new wind farm zone, the highest bottom shear stress, up to 0.9 Pa and higher, are found at the top of the sand banks in the Noordhinder Noord and the south of the Fairybank area (Figure 19). Elsewhere, the mean bottom stress varies between 0.5 Pa and 0.8 Pa. This means that at the entire area, the mean bottom stress will be high enough to resuspend the fine material continuously during higher water speeds. This is even the case when waves are not accounted for.

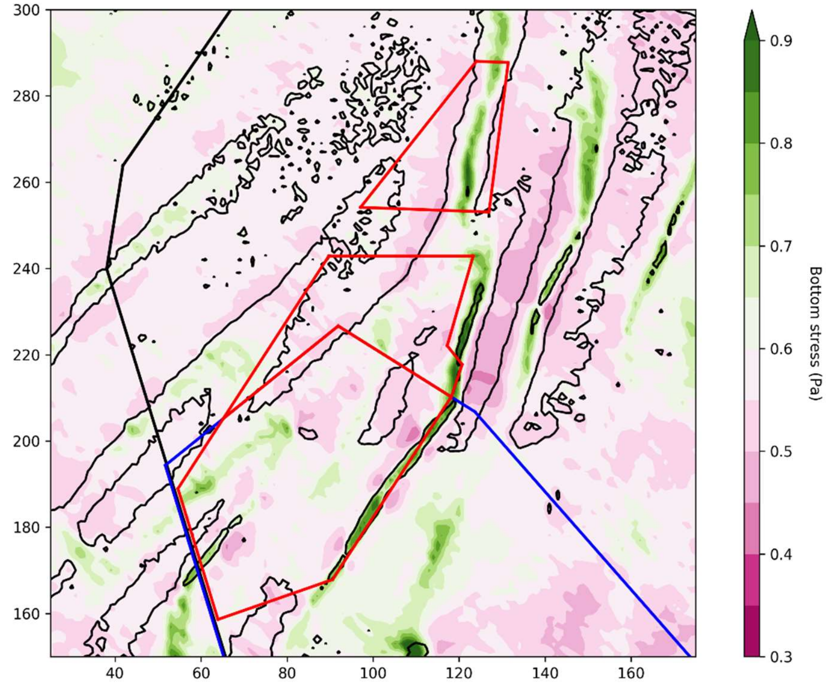

Figure 19: Mean bottom shear stress during one spring-neap tidal cycle near the area where the new wind farms are planned.

The residual currents are the vectoral mean of the currents over the spring-neap tidal cycle and could be considered as a proxy of the bed load or the sand transport, occurring near the bottom and is not influenced by the water depth itself. The residual currents are mainly in southwest direction, except on the shallower sand banks in the south of the Noordhinder-Noord and Fairybank areas (Figure 20Figure 20.

The residual transports are the vectoral means of the currents, but weighted by the actual water depth $\overrightarrow{U_t} = \sum_n \vec{U}.h\,/n$. The residual transport is accounting for the different water depths during ebb and flood currents and is thus a proxy for the transport of material in the water column (uniformly distributed over the water column), or the transport of the fine-grained material. The residual transport is more variable (Figure 21).

Of course, the sediment transport itself is (highly) non-linear and will differ from the conclusions that could be drawn from investigating the residual currents and transports. Furthermore, the distance travelled by the sediment during a tidal cycle will be much larger than the transport calculated using these residual currents or transports.

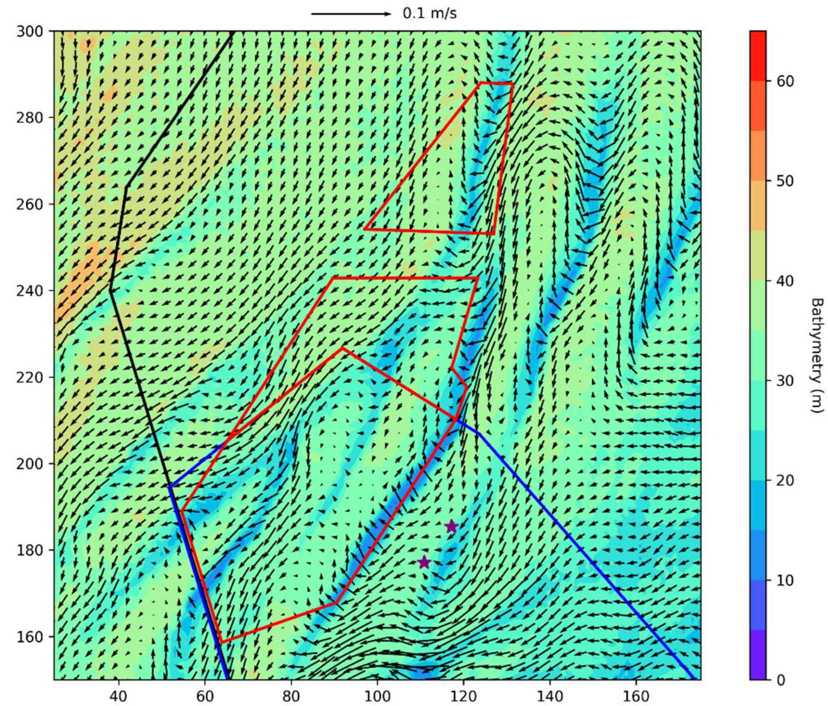

Figure 20: Residual currents during one spring-neap tidal cycle near the area where the new wind farms are planned.

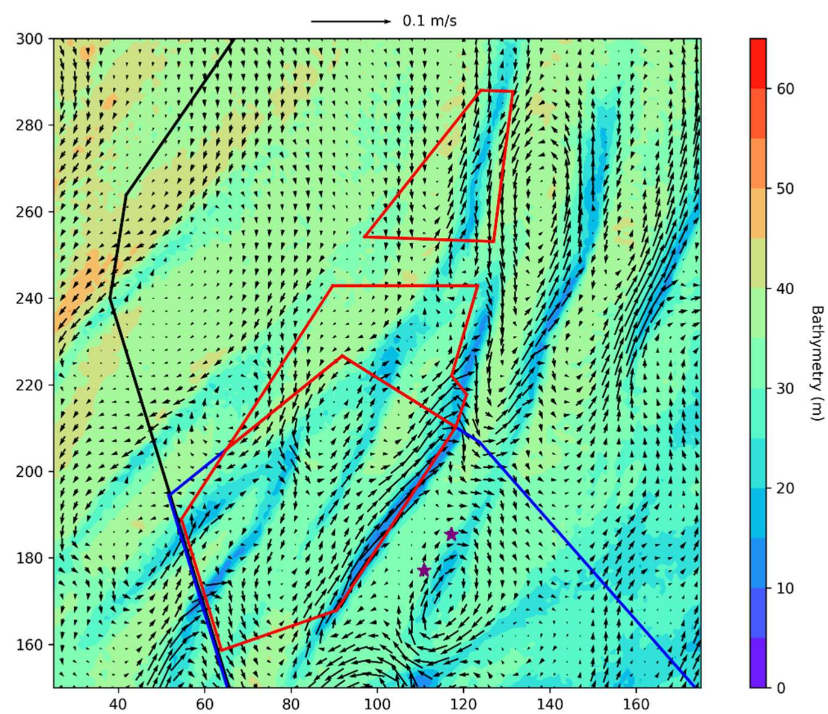

Figure 21: Residual transports during one spring-neap tidal cycle near the area where the new wind farms are planned.

3.2.3. Sediment dispersion

3.2.3.1. Extraction operations

The amount of material dumped in these simulations, i.e. 140 TDM, from which 50 % stays in the water column, is higher than can be expected from extraction activities or from cable lying operations. In IMDC (2014b) it was assumed that during dredging operations, 2.5 TDM was brought into suspension at the drag head and 53 TDM from overload. They assumed that during a dumping operation 80 TDM of fine-grained material was brought into the water column. Baeye et al. (2019) estimated, based on an overflow SPMc of 1 g l^{-1} during extraction activities, that 16 TDM of fine-grained material is brought into suspension during one extraction operation. Even when using an SPMc in the overflow of 6 g l^{-1} (Duclos et al., 2013; Hitchcock and Bell, 2004), the amount is only 96 TDM. During cable operations, assuming 15 % of the material is brought into suspension, a plume of 6 m^3 h^{-1} is assumed, representing 16 TDM. The amount of 140 TDM is therefore almost 50 % higher than the maximum expected amount of material lost during the overflow, or due to cable lying activities.

In Figure 22, the maximum concentration is shown in the model grid, together with the maximum layer thickness of the material at the bottom, during the first two days of the simulation. At the first time step, the maximum concentration is around 42 mg l^{-1} for simulation Dump 3, which is dependent of the amount of material in the water column, the area over which the material is deposited (a full grid cell of 257 m x 275 m) and a water depth of 24 m. At the sites Dump 1 and Dump 2, the water depth is around 36.5 m and 34 m respectively. The material is very rapidly deposited at the bottom and the maximum concentration is very rapidly decreasing. Within 1h12 the concentration is decreased from 42 mg l^{-1} to less than 4 mg l^{-1}, which is considered to be the background value (Van den Eynde et al., 2013). In less than 1 hour, also at the other dumping positions, the maximum concentration decreased to the background value. In around 3 or 4 h, the maximum concentration decreased further to less than 1 mg l^{-1}. The maximum thickness of material at the bottom is 0.8 mm, again function of the amount of material put at the bottom and the extent of the area (one grid cell). The maximum bottom thickness is not increasing, indicating the material in suspension is rapidly dispersed and diffused over neighboring grid cells, where it is deposited. For simulation Dump 2, after one day, some material is again resuspended, resulting in a decrease in the maximum layer thickness in the model grid.

After the quick deposition at the bottom during the first days, the material will come into suspension again during the period with higher currents and as an effect of the higher waves (Figure 23). At the end of the period, during neap tide, some material is starting to be deposited again.

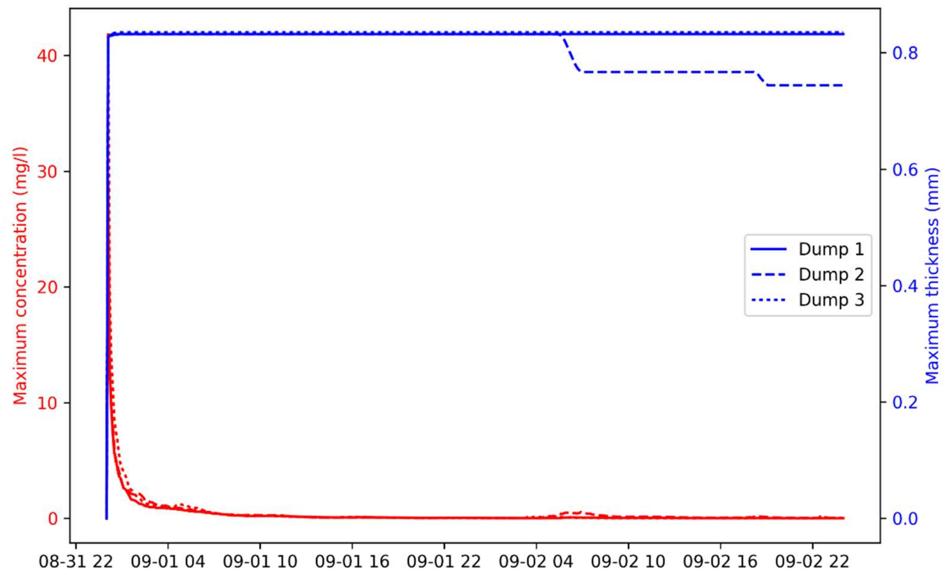

Figure 22: Maximum concentration in the model grid and maximum layer thickness of material at the bottom for simulation of dumping of 140 TDM. Full period presented is two days. Solid lines: Dump 1; dashed lines: Dump 2; dotted line: Dump 3.

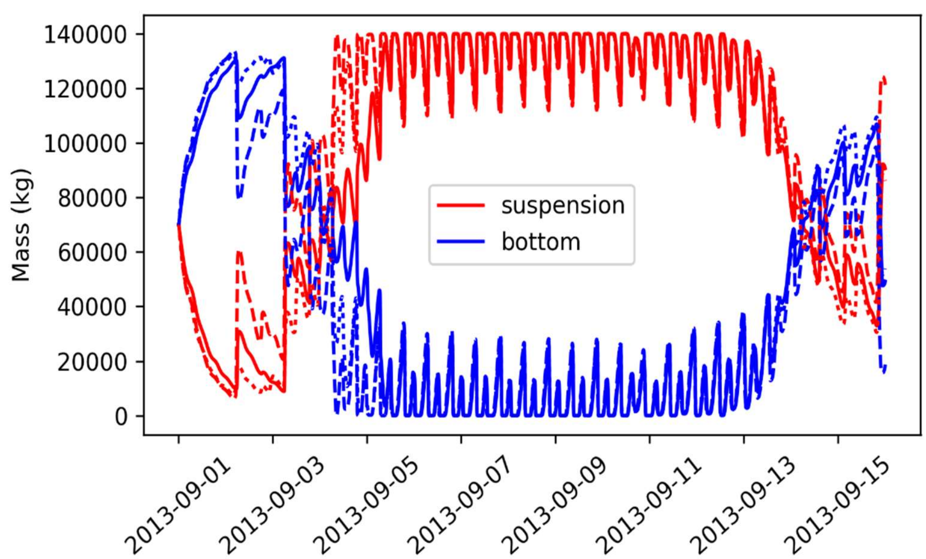

Figure 23: Mass in suspension and at the bottom in the model grid for simulation of dumping of 140 TDM. Solid lines: Dump 1; dashed lines: Dump 2; dotted line: Dump 3.

In Figure 24 to Figure 26, the concentration of SPM is presented after dumping at site Dump 1, after 1, 10 and 15 days respectively. One can see that the material is spread out over a large area, but that the concentration is very limited. This is partly due to the larger water depths and the circular current ellipses. After day 10, there is no material found at the bottom, so all material at that moment is in suspension, but is dispersed over a large area, so that the concentration is limited to less than 1 mg l^{-1}. The effect of the dumping after some time seems limited and negligible compared to the background concentration. The two-dimensional model gives depth-averaged concentrations, with an underestimation of the concentrations near the bottom, which are expected to be higher than the depth-averaged values, since the profile is following the well-known Rouse profile (Soulsby, 1997). n, The concentration will be limited anyhow.

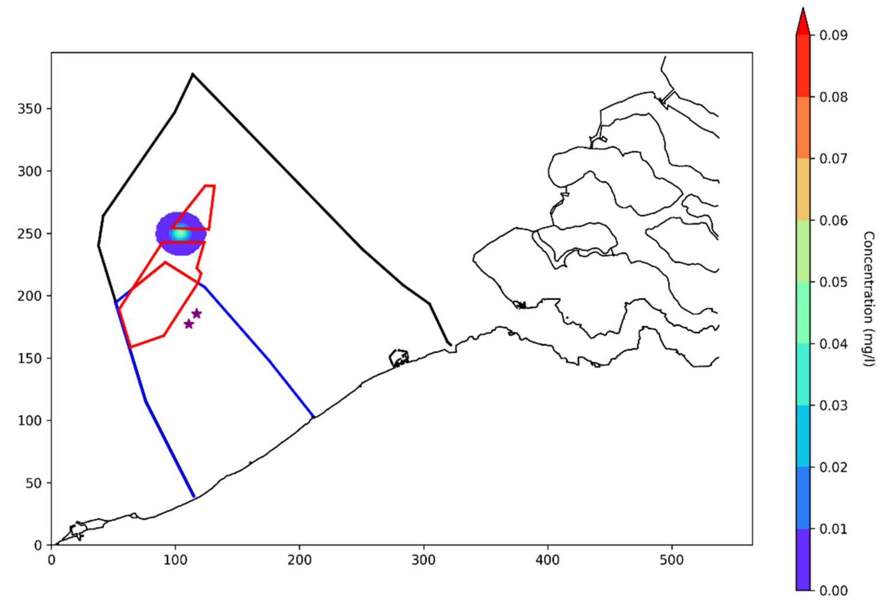

Figure 24: Concentration of material after dumping 140 TDM at site Dump 1, after 1 day.

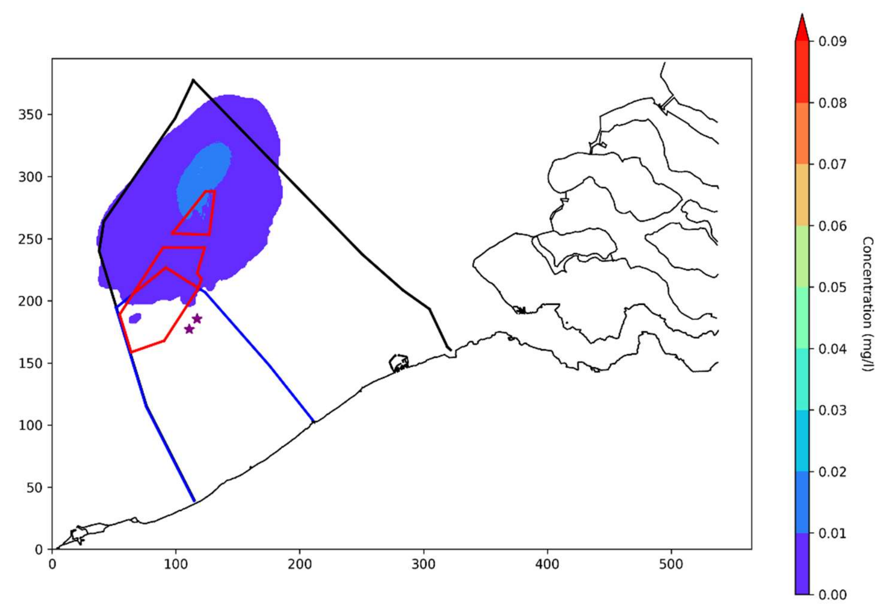

Figure 25: Concentration of material after dumping 140 TDM at site Dump 1, after 10 days.

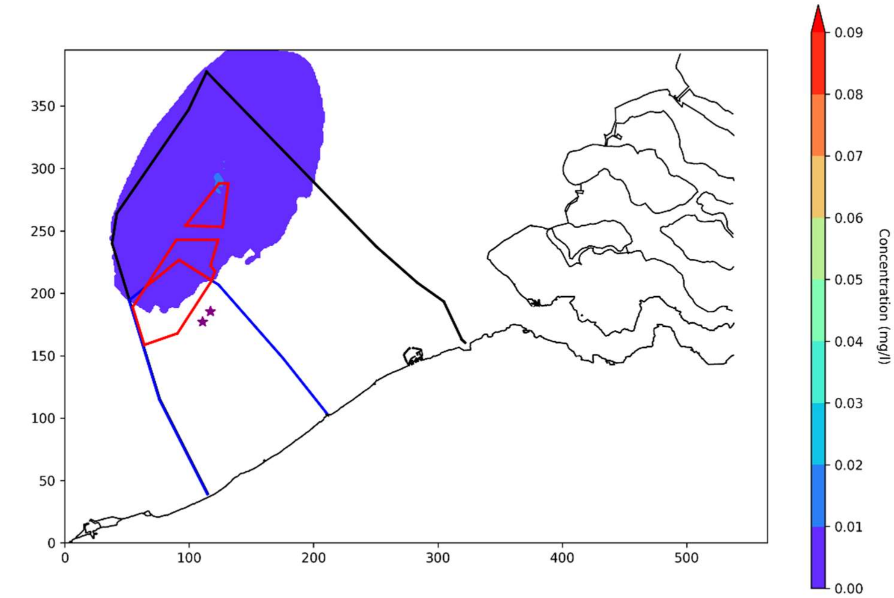

Figure 26: Concentration of material after dumping 140 TDM at site Dump 1, after 15 days.

In Figure 26 and Figure 27, results after 15 days for the simulations with dumping at Dump 2 and Dump 3 are presented. Similar results are found with very low excess concentrations. The main direction of the transport for the three simulations is in north-eastern direction. Only for dumping at the Dump 2 site, in the Fairybank area, the two Refugia areas in the Habitat Area are reached. Also for the dumping at site Dump 3, near the extraction zone 4c, in this simulation, no fine-grained material is transported to the Refugia areas.

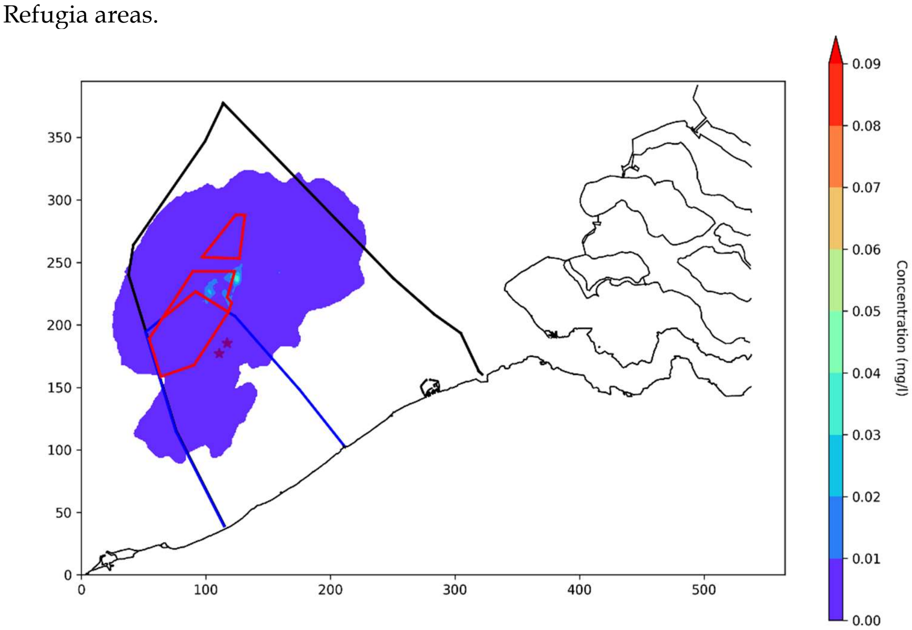

Figure 27: Concentration of material after dumping 140 TDM at site Dump 2, after 15 days.

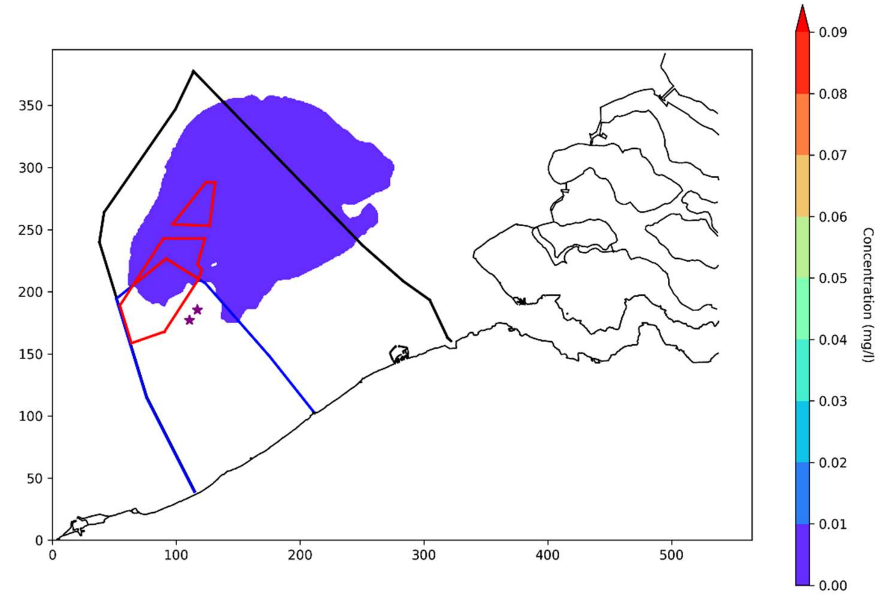

Figure 28: Concentration of material after dumping 140 TDM at site Dump 3, after 15 days.

Different other simulations have been executed to test the effect of different sediment parameters, or the timing of the dumping. Due to the relatively high water depths and the relatively low dumpings, the increase in concentration in the different simulations remain limited.

3.2.3.2. *Dumping activities*

For the simulation of dumping activities, 1400 TDM is dumped, from which 50 % stays in the water column, while 50 % is deposited at the bottom. Results of dumpings at site Dump 2, in the wind farm area Fairybank, Dump site 4, in extraction zone 4b and Dump 5, north of the new wind farm area, are presented.

Due to the higher amount of dumped material, the maximum concentration is also around 10 times higher. At dumping site 4, with a water depth of only 19 m, the maximum (depth-averaged) concentration just after the dumping is around 470 mg l^{-1}. For the dumping at Dump 2 or Dump 5, the maximum concentration is respectively 290 or 265 mg l^{-1}. Also here the material is very rapidly dispersed over a larger area and deposited at the bottom. The maximum concentration drops to 4 mg l^{-1} in about 7 h. After 14 h, the maximum concentration drops further to 1 mg l^{-1}. The maximum thickness is 8.3 mm in this case.

Over a longer period, all the material is resuspended and brought into suspension (Figure 30). Since there is much more material to bring in suspension, it takes more time compared to the former simulations (extraction related), where only 140 TDM was dumped.

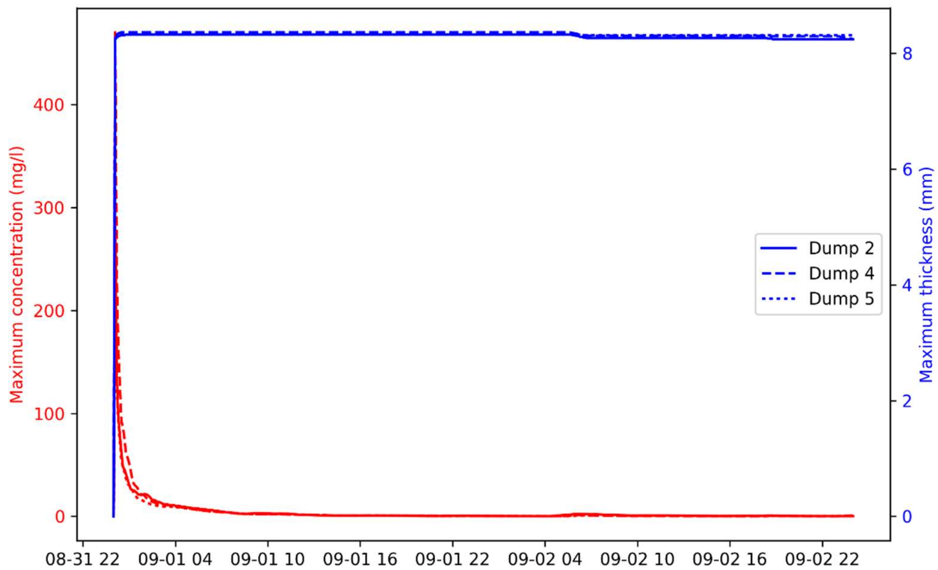

Figure 29: Maximum concentration in the model grid and maximum layer thickness of material at the bottom for simulation of dumping of 1400 TDM. Full period presented is two days. Solid lines: Dump 2; dashed lines: Dump 4; dotted line: Dump 5.

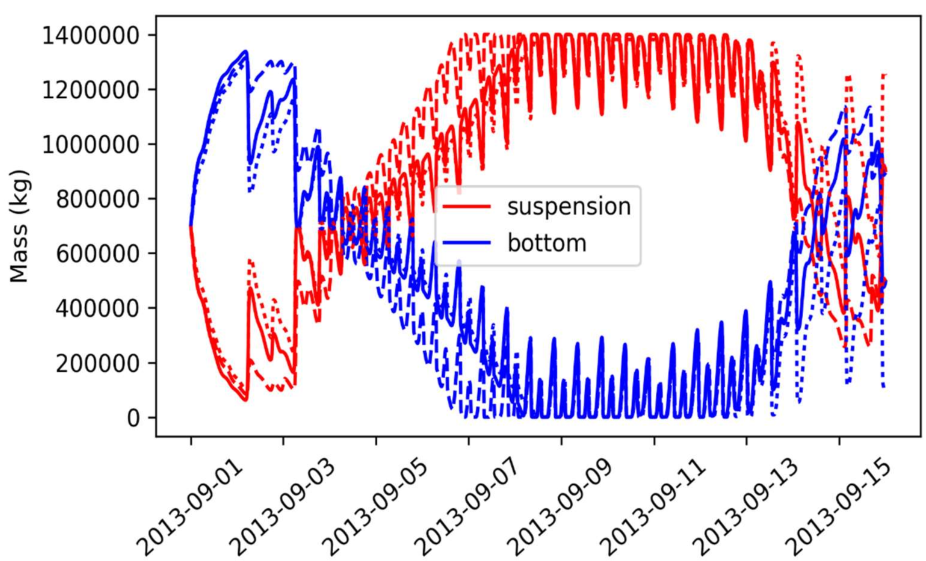

Figure 30: Mass in suspension and at the bottom in the model grid for simulation of dumping of 1400 TDM. Solid lines: Dump 2; dashed lines: Dump 4; dotted line: Dump 5.

Also when dumping 1400 TDM at the sites Dump 2, Dump 4 or Dump 5, the material is dispersed quite rapidly, resulting in low (depth-averaged) concentrations (Figure 31 to Figure 33).

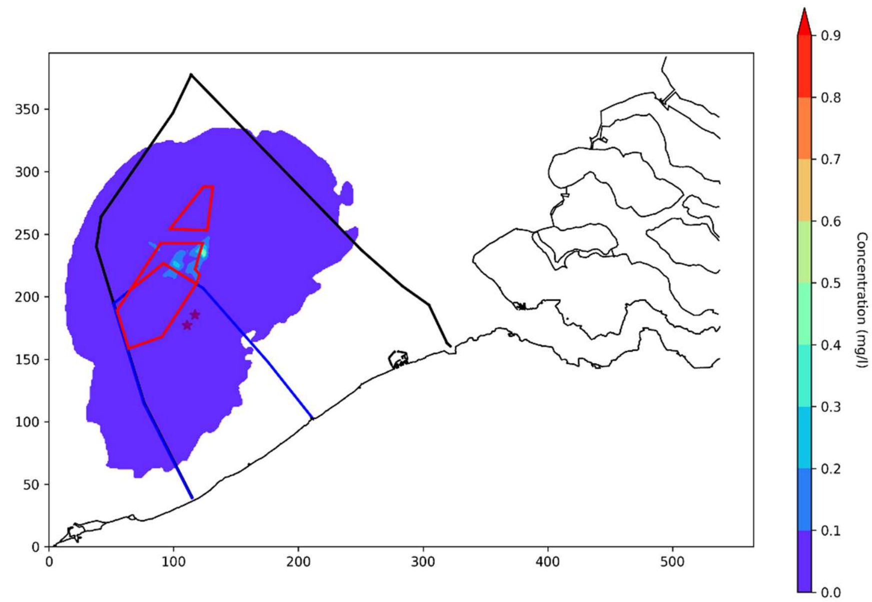

Figure 31: Concentration of material after dumping 1400 TDM at site Dump 2, after 15 days.

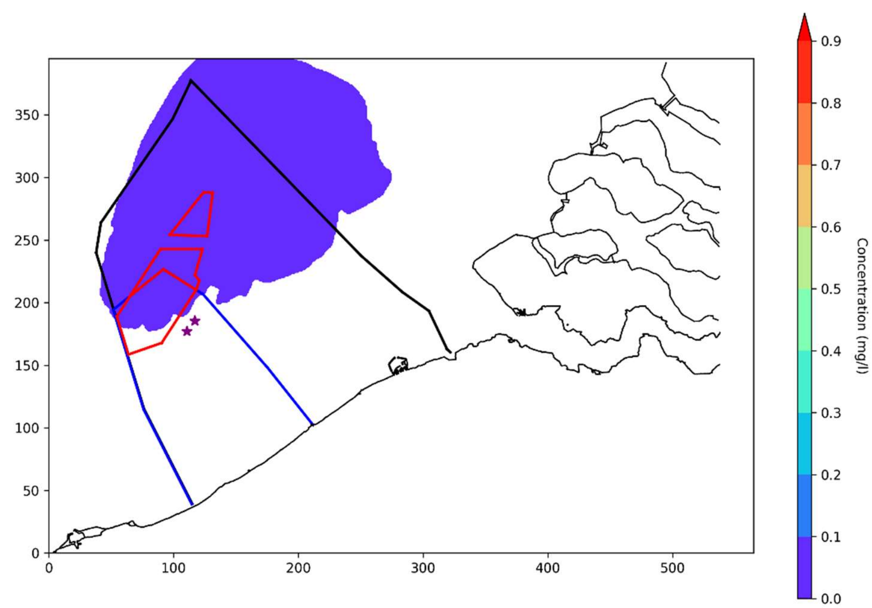

Figure 32: Concentration of material after dumping 1400 TDM at site Dump 4, after 15 days.

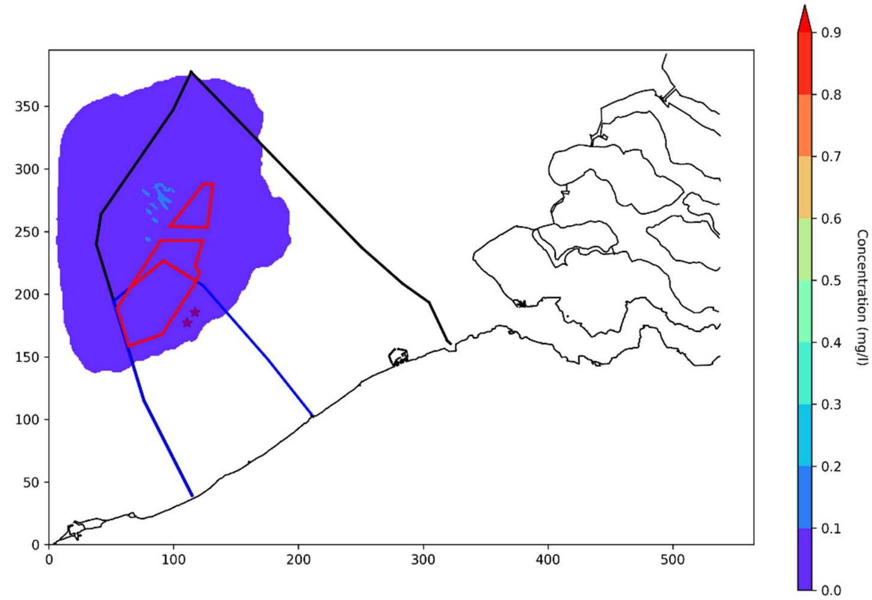

Figure 33: Concentration of material after dumping 1400 TDM at site Dump 5, after 15 days.

While for the dumping at Dump 4, in extraction zone 4b, the material does not reach the Refugia area, this is the case for dumping at Dump 5, north of the new wind farm area. However, the concentrations remain very low.

Finally, some simulations were executed with continuous dumping, where each 4 hours 240 TDM is dumped at the site Dump 5. Since only 240 TDM is dumped each time, the maximum concentration is much lower, but is increasing each 4 h to almost 35 mg l^{-1} (Figure 34). After two days, the maximum thickness at the dumping site increased up to 8 mm. This thickness at the dumping site increases further over the period, up to 80 mm after 15 days (Figure 35), while the maximum concentration always decreases rapidly after the initial increase during dumping. Due to the continuous dumpings, the material at the bottom does not have the time to be resuspended and increases to build up at the dumping site. Almost half of the material dumped stays at the bottom, during the period (Figure 36).

The (depth-averaged) concentration increases due to the continuous dumping but stays below 1.2 mg l^{-1} except at the dumping site (Figure 37). The material at the bottom is negligible, less than 1 mm, except at the dumping site itself. Overall, the effect seems localized and temporary as well.

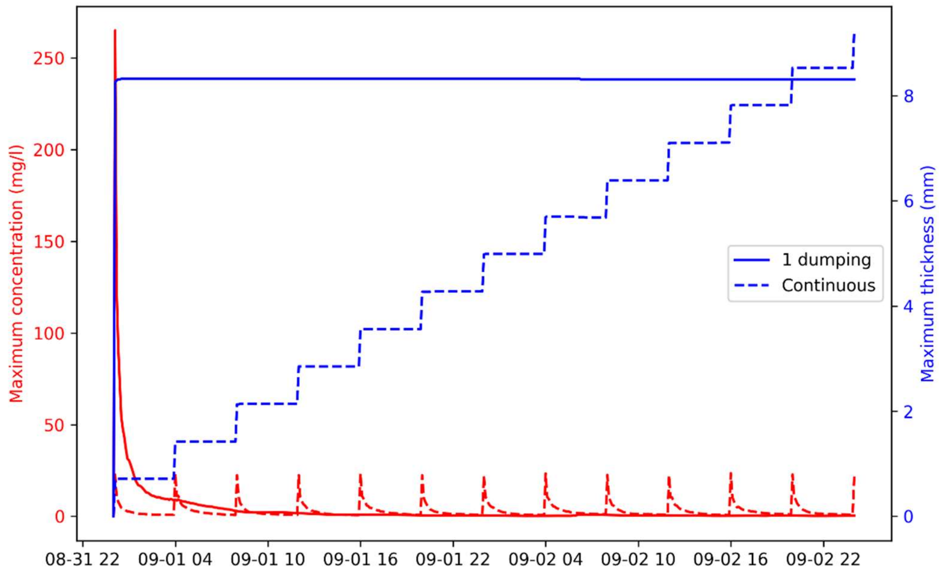

Figure 34: Maximum concentration in the model grid and maximum layer thickness of material at the bottom for simulation of dumping at Dump 5. Full period presented is two days. Solid lines: one dumping; dashed lines: continuous dumping.

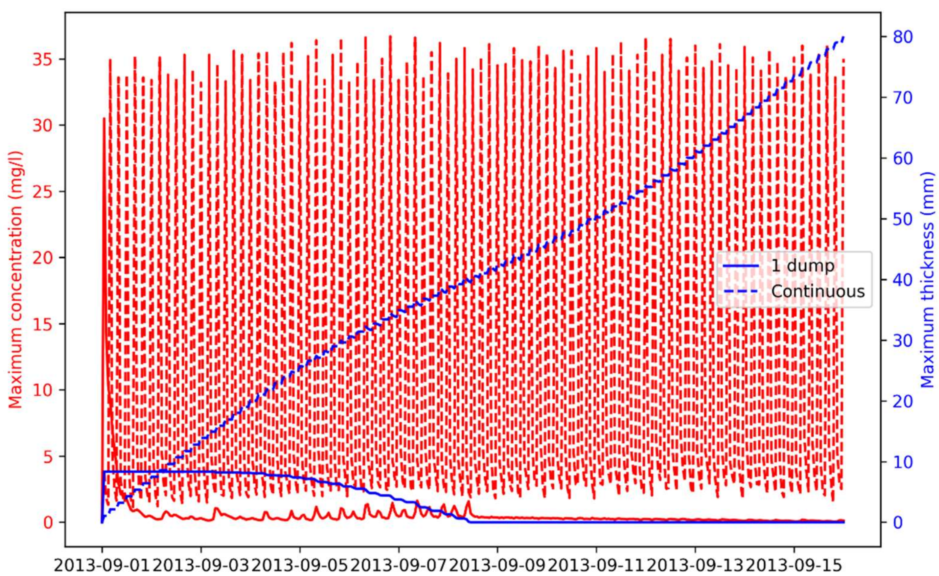

Figure 35: Maximum concentration in the model grid and maximum layer thickness of material at the bottom for simulation of dumping at Dump 5 for the full period, time step = 1 h. Solid lines: one dumping; dashed lines: continuous dumping.

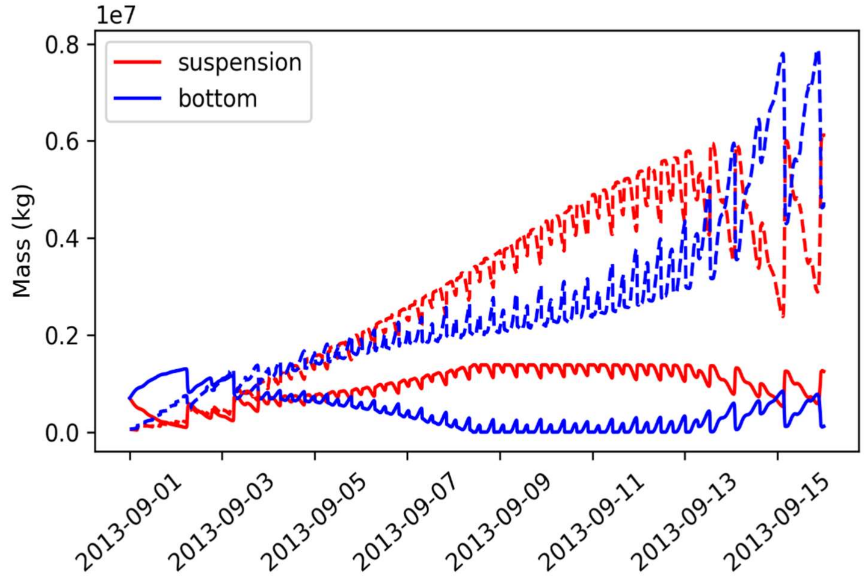

Figure 36: Mass in suspension and at the bottom in the model grid for simulation of dumping at Dump 5 for the full period. Solid lines: one dumping; dashed lines: continuous dumping.

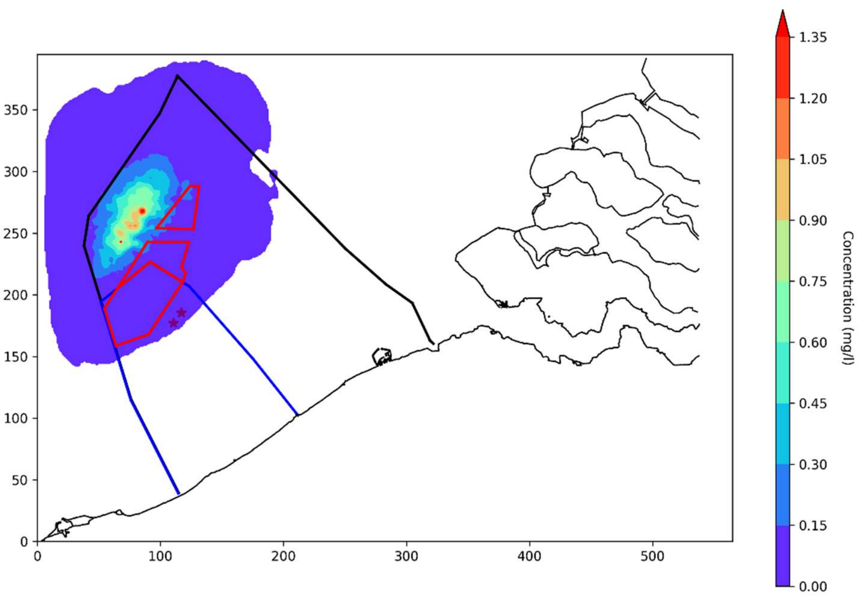

Figure 37: Concentration of material after continuous dumping at site Dump 5, after 15 days.

4. Discussion and recommendations

Results indicate limited effects of the wind farm-related operations on the siltation of the gravel beds. The largest effect is expected by the preparation of the sea bed and the related dredging and dumping activities and the associated increase in SPMc.

Since it is not very well known how vulnerable gravel beds are for an increase in SPMc, the increase in SPMc should be avoided as much as possible. Therefore, it is recommended to use only monopiles or jacket foundations. The use of GBFs should be avoided. In case the installation of GBFs is necessary, an adequate monitoring plan should be set up. If floating offshore wind turbines (WindEurope, 2018; Roddier et al., 2010) would become commercially feasible, it can be expected that their environmental effects would be less important.

The disposal of (temporary) material should not be at the gravel beds themselves, but should be at a sufficient distance, to avoid settling of passive sediment plumes. Outside the dumping site itself, model results indicate that the effects of the dumping and the passive plumes will be local and temporary (IMDC, 2014b). This was confirmed by the two-dimensional modelling study that was presented in this study. At the dumping site, the material is depositing rapidly, while the increase in sediments at the bottom is limited to the dumping site. The increase in (excess) depth-averaged SPMc, outside the dumping area, remains limited to less than 1.5 mg l^{-1}. Due to the two-dimensional model, the SPMc near the bottom will be underestimated. Furthermore the model does not account for material exchange at the seabed (i.e., buffering of fine-grained material in the sand matrix),

Also cable burial activities will induce an increase of SPMc, although the effects are expected to be local and limited. Using dredgers for the cable lying will be more impacting than the use of a plough or a jetting technique. These techniques are therefore recommended. During cable installation in areas of moving dunes, the sea bed preparation however will need dredging works.

The use of plough or jetting will result anyhow in material, which is deposited nearby the cable operations. Different macroinvertebrates, that also occur in the gravel beds (e.g., *O. Ophiura, Aequipecten opercularis, Ciona Instestinalis, Psamoichinius miliaris, Crepidula fornicata, Mytilus edulis*) showed an increased mortality, when buried under a sediment layer of 7 cm (Hendrik et al., 2016; Hutchison et al., 2016; Powell-Jennings and Callaway, 2018). Therefore, it is recommended that the cable laying would be at least 20 m away from the ecological important gravel beds, to keep the deposited material to a maximum of 10 mm.

Concerning the erosion protection, not much information is available. It is clear that using dynamic erosion protection SPMc will increase during a short period, but that static erosion protection will affect a larger area, and that secondary erosion will be possible. The use of gravel beds for static erosion protection is at the moment under investigation by Ghent University.

The sediment plumes in the wakes of the wind turbines are only recently considered. Although the nature of these plumes is still not completely known, some indications exist that the sediment plumes are an effect of increased turbulence in the wake of the turbines and that the plumes are not of biological nature (Forster, 2018). More monitoring is foreseen in the sediment plumes in the Mermaid wind farm. This will give some more information on the magnitude of these wakes in the Belgian coastal waters. Results will still remain site-specific.

The marine aggregate extraction is at some distance from the gravel beds. However, also these pressures can influence the gravel beds (Van Lancker et al., 2016). Cumulative and in-combination effects were flagged, including beam trawling, taking place almost everywhere on the BPNS. It is therefore clear that the effects of the installation and the exploitation of the wind farms must be considered in relation to the other pressures.

Although the model results indicate that the fine-grained material will be resuspended quite rapidly from the bottom, there are indications that fine-grained material can be trapped in the sand matrix (Vanaverbeke et al., 2008; Huettel and Rush, 2000). Therefore, although the study indicates that the SPMc increase will be local and temporary, this needs further investigation. Some indications of this trapping of fine-grained material in the sand matrix, possibly linked to aggregate extraction in the Hinderbank area, was already demonstrated (Van Lancker et al., 2017).

Finally, the increase in SPMc always needs to be seen in reference with the natural variation of the SPMc in the area, e.g. under the influence of storms. Since 2011, SPMc monitoring is being conducted in the Hinder Banks region (Van Lancker et al., 2016), though, hitherto, long-term continuous measurements, as recommended for SPMc monitoring programmes, are limitedly available. Establishing long-time series of SPMc, at dedicated offshore locations, is therefore recommended, especially since effects of SPMc increases on ecologically valuable gravel habitats is not known. This is also recommended, e.g. in The United Kingdom (Cooper and Beiboer, 2002; CEFAS, 2010).

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