SUSANA

Sustainable use of sand in nature-based solutions

D3.3 – Cumulative sediment dispersal mapping of seafloor-disturbing activities

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LIST OF ABBREVIATIONS

ES	Ecosystem services
BPNS	Belgian part of the North Sea
AB	Advisory board
OSERIT	Oil Spill Evaluation and Response Integrated Tool
EEZ	Exclusive Economic Zone
LAT	Lowest Astronomical Tide
NBS	Nature-based Solutions
SPM	Suspended particulate matter

0. Summary

Building nature-based solutions (NBS) for coastal protection requires huge volumes of sand. Coarse-grained, high-quality sand is limited, so alternative sources of sand (with more fine grains) are considered. Concerns remain regarding the ecological repercussions of sand extraction on the marine ecosystem in the near and far field of the extraction activities. . Estimating impacts in the far field remains a complex and challenging task as more human activities need to be taken into account. Multiple datasets of seafloor-disturbing fisheries, extraction, dredging and disposal have therefore been compiled and this over a full year (2019). A distinction was made, not only by the origin of the sediment plumes, but also by release depth and sediment distribution. These datasets include detailed information on the location, time and estimated mass of sediment released into the water column. The study focused on two sediment fractions: silt and fine sand.

Three-dimensional hydrodynamic models were used to force a Lagrangian dispersion model simulating the transport and fate of sediment particles. Running more than one hundred thousand numerical simulations, the releases of silt (20 µm) and fine sand (150 µm) particles per disturbing event in the year 2019 were tracked for 14 days. For comparative analyses, the mass of sediment released by the various activities was accounted for. Dispersal maps were created at a resolution of 1 x 1 km with a time resolution of 1 day of activity. These can be further aggregated into other time intervals such as monthly, seasonally, or yearly. Per region of interest the main influencing human activities can be backtracked. This approach enabled a comprehensive understanding of the spatial distribution and relative magnitude of human-induced sediment deposition on the seabed.

1. Introduction

Improving coastal safety along sandy coastlines relies typically on nature-based solutions (NBS) for which huge quantities of sand are needed. The extraction of these sands, typically offshore, needs to deal with the finite nature of sand resources and with subsequent impacts on the marine ecosystem. The direct near-field effects in areas where extraction takes place are relatively well understood (e.g., Wyns et al., 2021). In contrast, several important questions remain regarding the far-field impact associated with increased sediment dispersion following seafloor disturbance. However, sand extraction is not the only actor, and fisheries, dredge disposal and dredging take place concurrently. From a cumulative impact perspective, and for sustainable marine management to become effective, also these actors need to be accounted for. Hitherto, human-induced sediment dispersal was mostly studied on a case-by-case basis, and for single activities only. For the first time, this is now done for the main seafloor-disturbing activities, and over a full year.

2. Description of the datasets

2.1 Introduction

Sediment particles are released increasingly by seafloor-disturbing activities (e.g. dredging and disposal, extraction, and fisheries). Differentiation can be made in the sediment plumes that are created by release depth (e.g. near the seabed for drag-head and impact clouds, throughout the water column for lateral dispersal, and near the water surface for overflow). Activity data (location, time, size and gear) were acquired for the entire Belgian part of the North Sea (BPNS) over a full year (i.e. 2019), and combined with available sediment information (e.g. lithological classes, grain-size distribution, settling and resuspension rates, etc.).

2.2 Seabed-disturbing activities

Dredging ensures the safety and efficiency of the maritime transport by deepening and maintaining the depth of the navigation and access channels to maritime and inland ports, and in the harbours themselves. Distinction has been made between dredging zones: Nieuwpoort, Oostende, Blankenberge and Zeebrugge (Scheur West, Scheur Oost, and Pas van Zand). Dredged sediments are deposited in five designated **disposal** zones: S1, S2, Bruggen en Wegen Nieuwpoort (BWN), Bruggen en Wegen Oostende (BWO), and Bruggen en Wegen Zeebrugge-Oost (BWZO). Spatial data of dredgers (i.e. BIS data) were requested from the Flemish Department of Mobility and Public Works, containing vessel (size) and dredging (volume) information every 10 seconds (dredging) and 60 seconds (disposal).

Extraction of high-quality sand is increasingly used as a basic raw material for construction and coastal nourishments. Sand extraction is permitted in dedicated zones: Thornton Bank (1a), Kwinte Bank (2kb), Buitenratel (2br), Oostdyck (2od), Vlakte van de Raan or Sierra Ventana (3a), and Hinder Banks: Noordhinder (4a), Oosthinder (4b and 4c), and Westhinder (4d). Spatial data of dredgers (i.e. EMS data) were requested from the Federal Public Service Economy, Continental Shelf Service, containing vessel (size) and extraction (volume) information every 30 seconds.

Fisheries are omnipresent, still limited to passive fishing only in some sections of Habitat Directive Areas and prohibited in munition dump site, around shipwrecks recognized as underwater cultural heritage and in wind and sea farms with a safety zone of 500 m. Spatial data of dredgers (i.e. AIS data) were requested from the Global Fishing Watch, containing vessel (gear) and fishing hours per day. The fisheries data was combined and cumulated into cells of 4 km to 4 km, to decrease the number of release points and the number of simulations.

2.3 Sediment plumes and release depth

All seabed-disturbing activities generate sediment plumes (Figure 1). Dredging, extraction and trawling (fisheries) create a **drag-head plume** of sediment particles that are stirred up to 4 m above the seabed (Durrieu de Madron et al. 2005; Mengual et al. 2016). During dredging and sand extraction, most of the sediments are sucked into the hopper, after which an **overflow plume** is formed near the water surface with a delay of about 30 minutes (Evangelinos 2014). A minority of sand from the extraction areas is used for beach and foreshore nourishments, while dredged sediments are deposited in designated areas with **lateral dispersal** from the vessel's draught depth to the seabed and **impact clouds** up 1.5 m due to the surge (Gundlach et al. 2021).

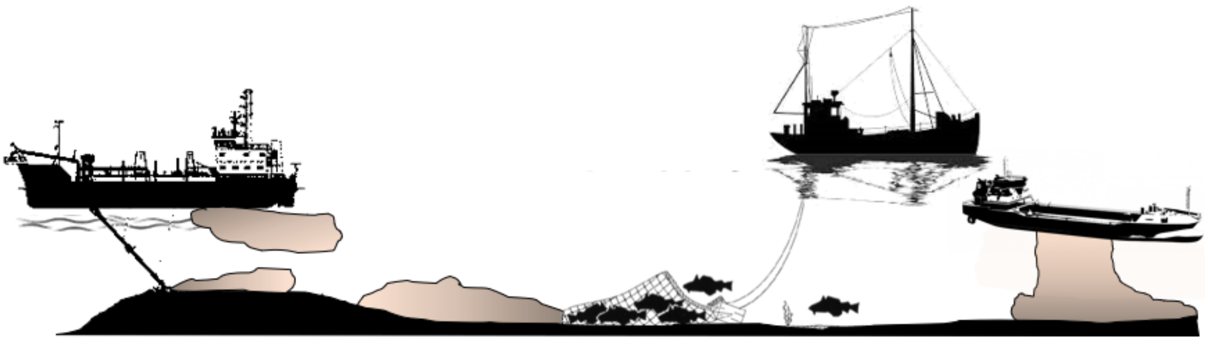

Figure 1 : Sediment plumes resulting from seabed-disturbing activities. From left to right related to sand extraction, fisheries, and dredging and disposal.

2.4 Settling and resuspension rates of sediments

Mud (20 µm) and **fine sand (150 µm)** were used for the modelling of the sediment dispersal, corresponding to settling velocities of 0.32 mm/s and 15.91 mm/s (based on Soulsby 1997), respectively. Resuspension rates depend on the sediment composition of the seabed (cfr. drag-head plume) or in the hopper (cfr. overflow and disposal), as well as on the vessel (gear) size. A distinction in magnitude of dispersal was made based on hopper volume for dredgers and spatial zonation from the coastal baseline for fishing vessels (small: < 3000 m³, < 3 nm; medium: 3000-6000 m³, 3-12 nm; large: > 6000 m³, > 12nm). Based on a literature study, a summary table of the release of mud and fine sand in kg/s from the main seabed-disturbing activities has been compiled (Table 1).

Table 1. Parameters affecting resuspension rates of sediment plumes from seabed-disturbing activities.

Human activity	**Sediment plume**	**Release depth**	**EU broad-scale seabed habitat**	**Sediment composition**			**Resuspension rates**						
				Mud (20 µm)	Fine sand (150 µm)		SMALL	MEDIUM	LARGE	SMALL	MEDIUM	LARGE	
Dredging	Drag head	Seabed +4m	Circalittoral mud	20	40	%	1.67	3.33	6.67	3.33	6.67	13.33	kg/s
	Overflow	Water surface	-	75	25	%	30	90	300	10	30	100	kg/s
Disposal	Lateral dispersal	Draught depth to seabed	-	50	50	%	63	125	250	63	125	250	kg/s
	Impact cloud	Seabed +1.5m	-	50	50	%	8333	16667	33333	8333	16667	33333	kg/s
Extraction	Drag head	Seabed +4m	Circalittoral sand	2	30	%	0.17	0.33	0.67	2.50	5.00	10.00	kg/s
	Overflow	Water surface	-	80	20	%	0.40	1.20	2.70	0.10	0.30	0.80	kg/s
Fisheries	Drag head	Seabed +4m	Littoral sediment	5	60	%	0.42	0.83	1.67	5.00	10.00	20.00	kg/s
			Infralittoral mud	5	60	%	0.42	0.83	1.67	5.00	10.00	20.00	kg/s
			Infralittoral sand	1	50	%	0.08	0.17	0.33	4.17	8.33	16.67	kg/s
			Circalittoral mud	20	40	%	1.67	3.33	6.67	3.33	6.67	13.33	kg/s
			Circalittoral sand	2	30	%	0.17	0.33	0.67	2.50	5.00	10.00	kg/s
			Circalittoral coarse sediment	1	20	%	0.08	0.17	0.33	1.67	3.33	6.67	kg/s
			Offshore circalittoral mud	5	30	%	0.42	0.83	1.67	2.50	5.00	10.00	kg/s
			Offshore circalittoral sand	1	10	%	0.08	0.17	0.33	0.83	1.67	3.33	kg/s
			Offshore circalittoral coarse sediment	1	20	%	0.08	0.17	0.33	1.67	3.33	6.67	kg/s

References: Sediment composition: De Wit et al. 2014 (overflow), Van Lancker et al. 2023 (seabed); Drag-head plume: Mills and Kemps 2016, Becker et al. 2015, van Rijn 2023; Overflow: Spearman et al. 2011 (large vessel), Becker et al. 2015 (small vessel); Disposal plumes: Gundlach et al. 2021.

2.5 Sediment dispersal datasets

Four datasets were compiled, one for each seabed-disturbing activity. The sets contain the following series of parameters per activity: identification number, date and time, easting and northing coordinates (in m; WGS84 UTM31), seabed depth (in m Lowest Astronomical Tide (LAT)), loaded draught depth (in m), vessel information (size and type), release of mud and fine sand for the emerging sediment plumes (in kg/s).

3. Description of the model

The model used is OSERIT (Dulière et al. 2013), a Lagrangian drift and fate model developed by the Institute of Natural Sciences (RBINS). OSERIT utilizes Lagrangian particles to depict the movement of chemicals, oil, objects and sediment in the sea. In this study, each particle was given a certain amount in kilograms of sediment of the same fraction (mud or fine sand). These particles move independently of each other under the influence of 3D currents, waves and turbulent diffusivity (both along the vertical and horizontal directions). A setting velocity based on Soulsby (1997) is prescribed to each Lagrangian particle. Sediment deposition occurs when a Lagrangian particles hit the seabed. Resuspension is estimated from the sediment dynamics simulated by the SEDTRANS05 model (Neumeier et al., 2008). Resuspension occurs when the near bed velocity (sum of 3D currents and orbital waves velocity) exceeds some thresholds values, at a height from the seabed estimated also from the SEDTRANS05 model (Table 2). OSERIT has no active sediment layer at the seabed. It does not describe the total accumulation (deposition) or erosion (resuspension) of the seabed. It does not change the sediment composition of the seabed, either.

Table 2: Parameters used for the modeling of the sediment fraction

	Mud	**Fine sand**
Particle diameter [µm]	20	150
Settling velocity [mm/s]	0.32	15.91
Resuspension threshold [m/s]	0.5	0.5
Resuspension height [m]	10	8.5

The timestep of the OSERIT model is of 10 minutes for horizontal processes (advection, horizontal turbulence, underwater Stokes drift) and of 1 minutes for vertical processes (advection, settling velocity, vertical turbulence, sedimentation and resuspension).

The OSERIT met-ocean forcing used in this study are produced by the models used to produce the RBINS marine forecasts (https://odnature.naturalsciences.be/marine-forecasting-centre/):

- 3D currents are computed by the COHERENS hydrodynamical models for the BPNS with a resolution of 250m. These models take into account impacts of wind, tides and baroclinic effects (impact of temperature and salinity on the seawater density). It resolves the dynamics between sandbanks.
- Wave parameters are computed by the WAM model as implemented at RBINS for the BPNS. From the waves parameter, OSERIT computes the Stokes drift velocity.

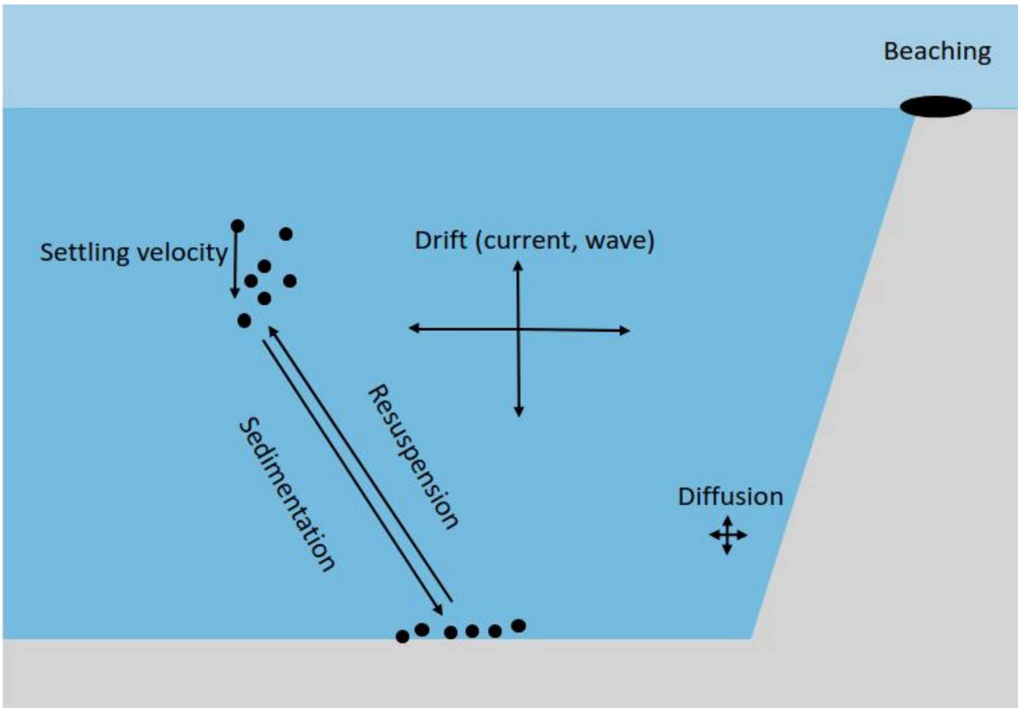

Figure 2: Processes affecting the drift of particles in RBINS' model OSERIT

4. Simulation workflow

To generate sediment dispersal maps, knowledge of the location of the sediment release is required. To achieve this, the OSERIT model is employed in conjunction with the datasets described in section 2. These datasets provide the initial release points for the sediment, and the model subsequently simulates their drift and fate.

4.1 Preparation of the simulations

For one location and time, four simulations have been made (Table 3). Two for fine sand, two for mud. The two simulations for the same sediment fraction differ in terms of release location depth or time depending on the activity of which the details are described in the following sections. For each simulation, the model requires an input file containing metadata, spatial information and rates of sediment release (see 2.5, Sediment dispersal datasets).

Table 3 : Description of the conditions used for each of the 16 sets of simulation.

Human activity	Sediment release location/time	Sediment fraction
Dredging	Drag head	Mud
		Fine sand
	Overflow	Mud
		Fine sand
Disposal	Dispersal cloud	Mud
		Fine sand
	Impact cloud	Mud
		Fine sand
Extraction	Drag head	Mud
		Fine sand
	Overflow	Mud
		Fine sand
Fisheries	Release at max ebb current	Mud
		Fine sand
	Release at max flood current	Mud
		Fine sand

4.1.1 Dredging and extraction

The procedure employed to generate the input files for dredging and extraction were highly comparable. Both activities introduce sediment into the model, releasing it at 4 meters above the seabed due to sediment resuspension caused by the drag head, and at the surface due to vessel overflow. The sediments are released at a constant rate throughout the entire dredging or extraction event. The overflow is initiated 30 minutes after the commencement of the extraction or dredging, but only if the event extends beyond a 30-minutes duration.

4.1.2 Dredge Disposal

In the model, dredge disposal happens instantaneously. The sediment release was distributed to an impact cloud, positioned 1.5 meters above the seabed, and the dispersal cloud, evenly distributed between the draught depth of the ship and the seafloor. In cases where the water column was reported to be smaller than the draught depth, the sediment release was evenly distributed between half of the water column and the seafloor.

4.1.3 Fisheries

In the case of fisheries, the cumulative hours per day of fishing in given area has been used, the Belgian waters had been divided into a grid. Two simulations were conducted for each location and day in the dataset, one at maximum ebb current and another at maximum flood current. The sediments are released at a depth of 4 meters above the seabed.

4.2 Running the model

Once all the files with the initial conditions had been created, the simulations were executed. There were 138.914 simulations. The simulation period was from January 1, 2019, 01:00:00 UTC to December 31, 2019, 23:00:00 UTC. Each simulation spans 14 days after the first particle is released, surpassing the typical water residence time of less than 12 days in Belgian waters (Belgische Staat, 2012). Some simulations were shorter, the ones intended to finish after December 31 at 23:00:00 (i.e. simulations started after December 15). For these simulations, the end time was imposed, resulting in less drift time. A very limited subset of simulations that should have started after the end time was not executed. All the events occurring between the 15 and the 31 of December 2018 have not been considered, this will cause a reduction of sediment dispersal for the 15 first days of January 2019.

Each dredging, dredge disposal and extraction simulation started with 100 particles. For the fisheries simulations 50 particles were released during maximum flood and 50 particles during maximum flood.

4.3 Postprocessing to generate the dispersal maps

The data generated by the simulations consists of the position of all particles over time. Python scripts were written to visualize this information in maps. Maps are created per simulation set. Each set can be mapped per day, per sediment type (mud or fine sand) and per origin (excluding fisheries). For the latter, designated zones of the Marine Spatial Plan were used for seabed disturbing activities: extraction, dredging and disposal.

To generate dispersal maps, the mass of each particle was derived from the estimated total mass released during the respective human-activity event. The mass was estimated by multiplying the resuspension rate by the duration of the seabed disturbance. The total mass released is evenly distributed among all simulated particles for that event. Each settled particle contributes its mass to the total mass of the corresponding grid cell, multiplied by the duration it remains at the seabed. For example, a 25 kg particle settling at the seabed for 40 minutes (2400 seconds) on a specific day in a given cell will contribute 1000 [kg*minutes] to that cell (or 60000 [kg*s]. After the 14-day drifting period, the particle is no longer considered in the count (its simulation is over). The maps are grids of 91x101 cells, ca. 1km² (~1000 m x ~1000m; the area at the bottom of the map is slightly larger than the one at the top). The grids range from 2.1° to 3.4° in Longitude and from 51.0° to 51.9° in Latitude.

The data is stored in NetCDF files (Table 4) as a 4D matrix (or 3D matrix for fishing), the variable is named “dispersal_day”, with the following dimensions:

- Lon (longitude of the cell, in decimal degrees)
- Lat (latitude of the cell, in decimal degrees)
- Time (seconds since 01 01 1970, in GMT, corresponding to the day of the data)
- Origin (area of origin, excluding fisheries)

The units are the same for all the files produced, therefore values can be compared. However, the value should be used in a relative manner, not in absolute "kg*s", since no direct link should be made to accumulation or impact on the seafloor.

Table 4: Conditions used for each output file.

Human activity	location	Sediment fraction	File name
Dredging	Drag head	Mud	dredging_draghead_mud.nc
		Fine sand	dredging_draghead_sand.nc
	Overflow	Mud	dredging_overflow_mud.nc
		Fine sand	dredging_overflow_sand.nc
Dredge disposal	Dispersal cloud	Mud	dumping_disp_mud.nc
		Fine sand	dumping_disp_sand.nc
	Impact cloud	Mud	dumping_imp_mud.nc
		Fine sand	dumping_imp_sand.nc
Extraction	Drag head	Mud	extraction_draghead_mud.nc
		Fine sand	extraction _draghead_sand.nc
	Overflow	Mud	extraction _overflow_mud.nc
		Fine sand	extraction _overflow_sand.nc
Fishing	Release at max ebb current	Mud	fishing_ebb_mud.nc
		Fine sand	fishing_ebb_sand.nc
	Release at max flood current	Mud	fishing_flood_mud.nc
		Fine sand	fishing_flood_sand.nc

5. Dispersal maps

In this section, several examples demonstrate how the produced data can be utilized. The objective is to provide examples rather than maps that should be interpreted directly. The data can be plotted directly from the dataset, such as shown in Figure 3.

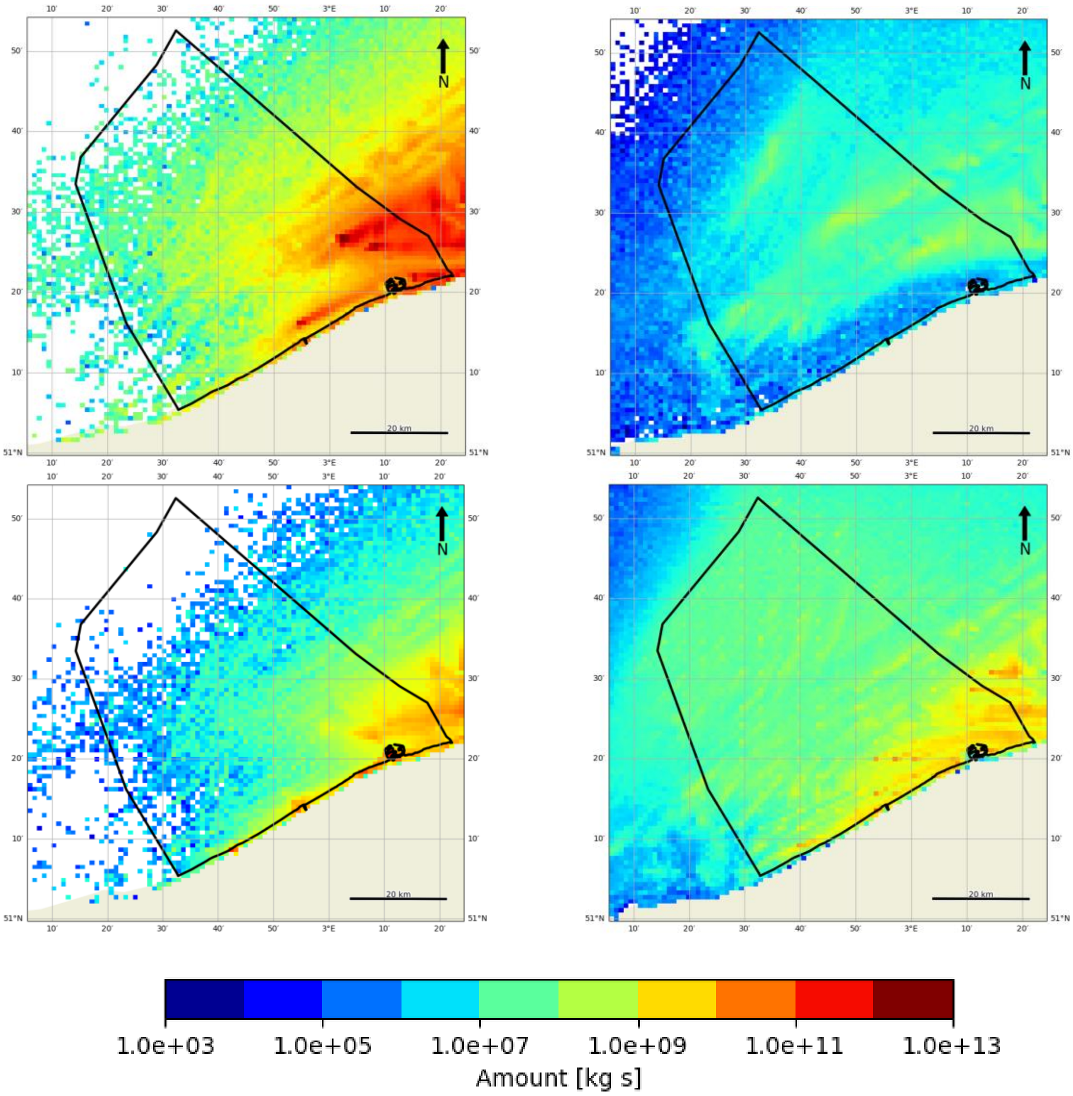

Figure 3: Dispersal map for dredge disposal (top left), extraction (top right), dredging (bottom left), fishing (bottom right) for the entire year of 2019 for the mud fraction. Each area of origin and source location have been added together. The scale is logarithmic.

The data can also be transformed, for instance only showing the area of origin with the highest amount, such as in Figure 4 and Figure 5.

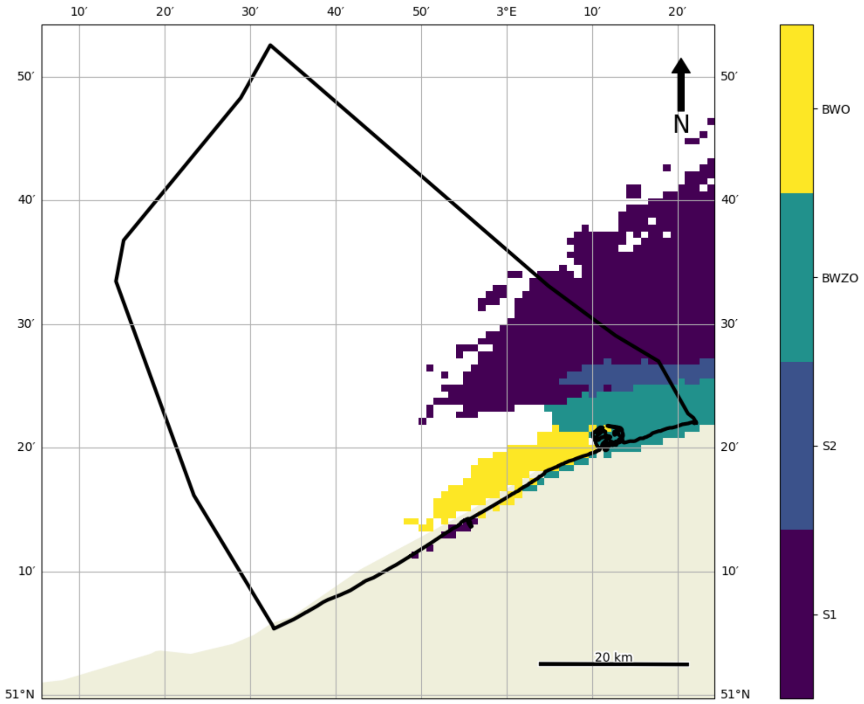

Figure 4 : Dredge disposal map showing the dispersal activity of the mud fraction per disposal ground. The two release depths have been added together. Only the area of origin with the highest value at a given location is shown at a given location, and value under 5×10^9kg s are not showed on the map

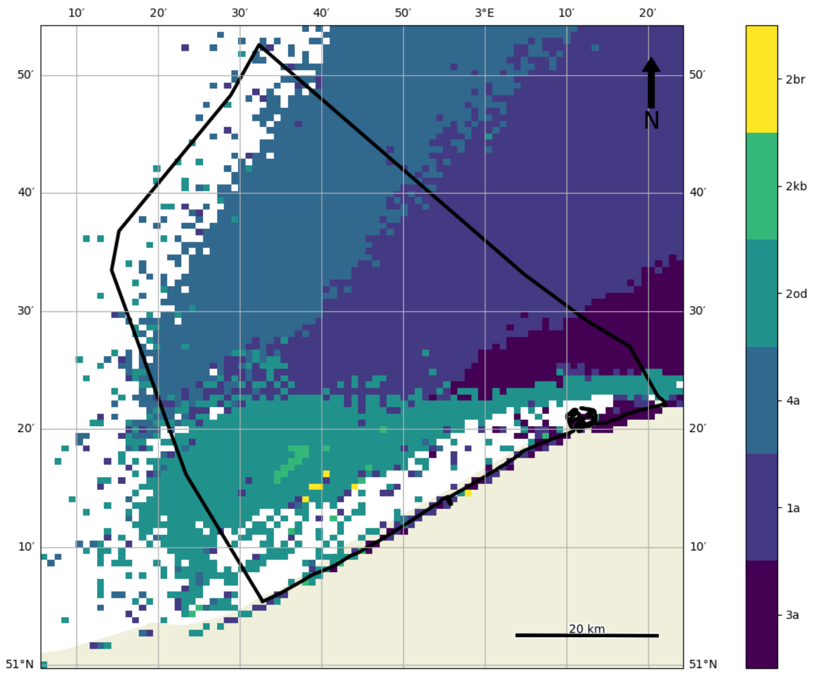

Figure 5 : Dispersal map for the extraction activity for the mud fraction, the two release depths (drag head and overflow) have been added together. Only the area of origin with the highest value at a given location is shown at a given location, and value under 10^6kg s are not showed on the map

The scripts used to make these plots are available on gitlab: https://gitlab.naturalsciences.be/llepers/susana-scripts.

6. Conclusion

To study the far-field dispersal of sediment resulting from human activities, over 100.000 simulations have been conducted using RBINS Lagrangian dispersal model OSERIT. Spanning 2019, these simulations incorporated the waves and current for the entire year.

After the model had been improved to better track the sediment dispersal, simulations were performed for the main seafloor-disturbing activities: fisheries, dredging, sand extraction and dredge disposal. Additionally, they were conducted for two distinct sediment fractions: mud and fine sand. Initial conditions for the simulations were sourced from datasets compiled for this purpose, containing detailed information on sediment quantities (in resuspension rates), release location and time of release within the water column. Furthermore, the simulations accounted for the release depth of sediment for all the activities.

Following a post-processing of simulation results, new dispersal datasets have been generated. These datasets can be used in multiple ways. They can be used to generate dispersal maps for a given period, but can also be used for more advanced analysis, e.g., backtracking the influence of the different activities for a given area.

7. Acknowledgements

The following departments are acknowledged for the maintenance and distribution of spatial information of human activities at sea.

Human Activity	Data provider/owner
DREDGING AND DISPOSAL	Flemish Ministry of Mobility and Public Works, Department of Mobility and Public Works, Maritime Access
EXTRACTION	Federal Public Service Economy, Continental Shelf Service
FISHERIES	Global Fishing Watch

Thanks to Belspo for providing computation power through SpacePole; all the simulations have been executed on this platform.

Research benefitted from a cross-fertilization with the Belgian monitoring programs ZAGRI, related to sand and gravel extraction (paid from private revenues), and the Marine Strategy Framework Directive related to seafloor integrity and hydrographical changes (https://odnature.naturalsciences.be/msfd/nl/monitoring/2020/.

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